Are You Sure You Want to Use MMAP in Your Database Management System? [1]

MMAP = ☺

Junpeng Zhu

Greenplum, VMware, Inc.

Apr, 28, 2022

[1] https://github.com/viktorleis/mmapbench

Outline

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Authors

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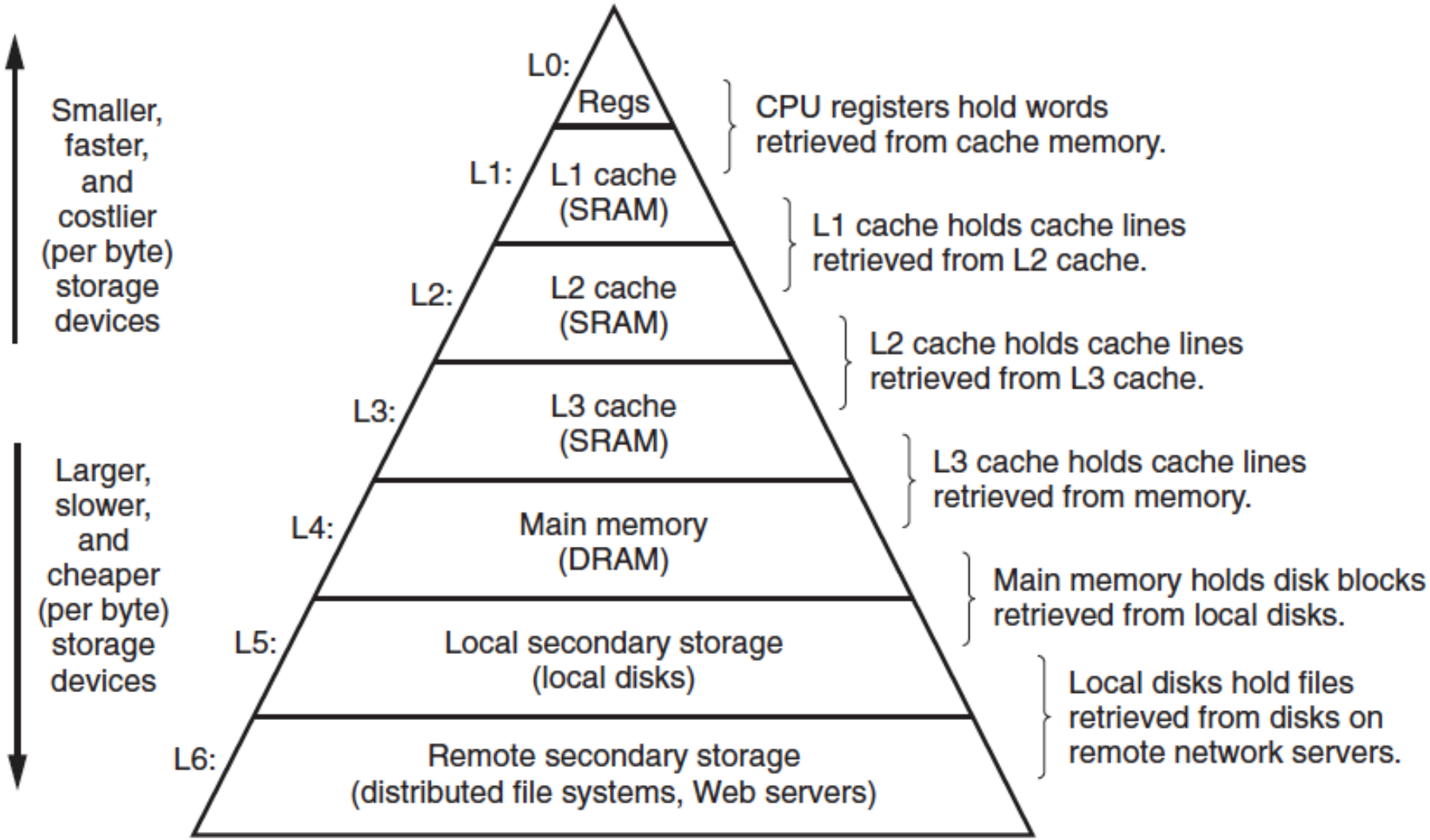
- Andrew Crotty
  - ✓ https://cs.brown.edu/people/acrotty/
  - ✓ Ph.D at Brown, in 2019. Post-doctoral in CMU.
- Viktor Leis
  - ✓ https://dbis1.github.io/team/leis
  - ✓ Ph.D at TUM, full professor at Friedrich Schiller University Jena.
- Andy Pavlo
  - ✓ https://www.cs.cmu.edu/ pavlo/
  - ✓ Ph.D at Brown, associate professor at CMU.
  - ✓ Never use mmap in a DBMS at his tombstone.

Storage hierarchy, Cont.



Architecture of RDBMS, Cont.

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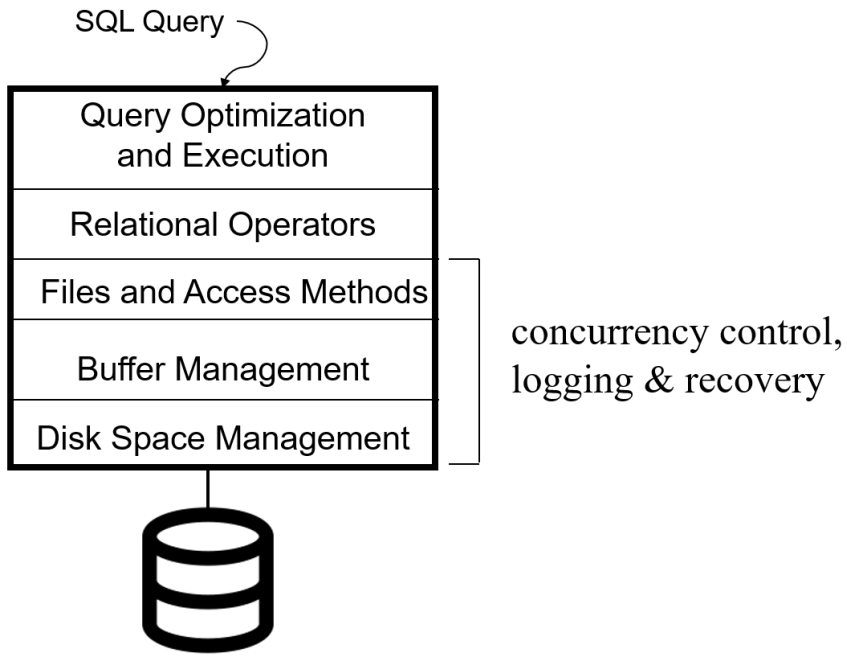
- Query optimization and execution
- Relational operators
- Files and access methods
- Buffer pool management
- Disk space management



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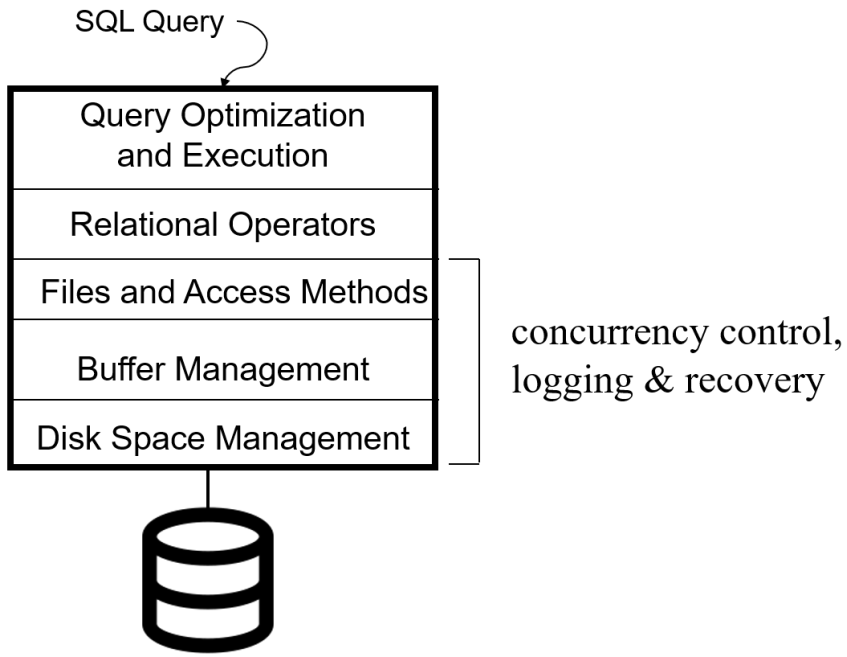

- Crash recovery is awfully difficult!
  - The recovery system depends on behavior of many other components of DBMS, such as concurrency control, buffer management, disk management, and query processing.

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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  - ✓ But, can cause poor performance due to a large random write operations.
- No Steal policy —don't allow buffer pool frames with uncommited 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).

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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.

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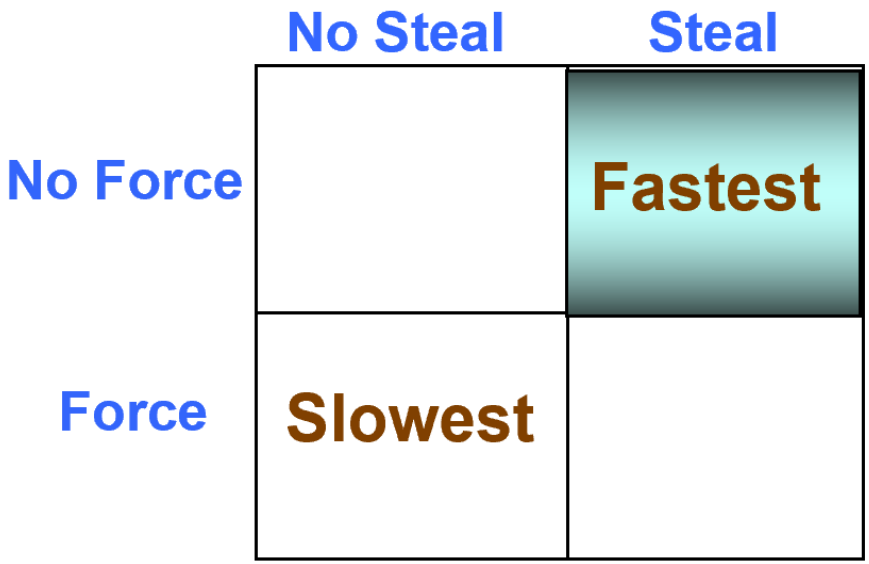
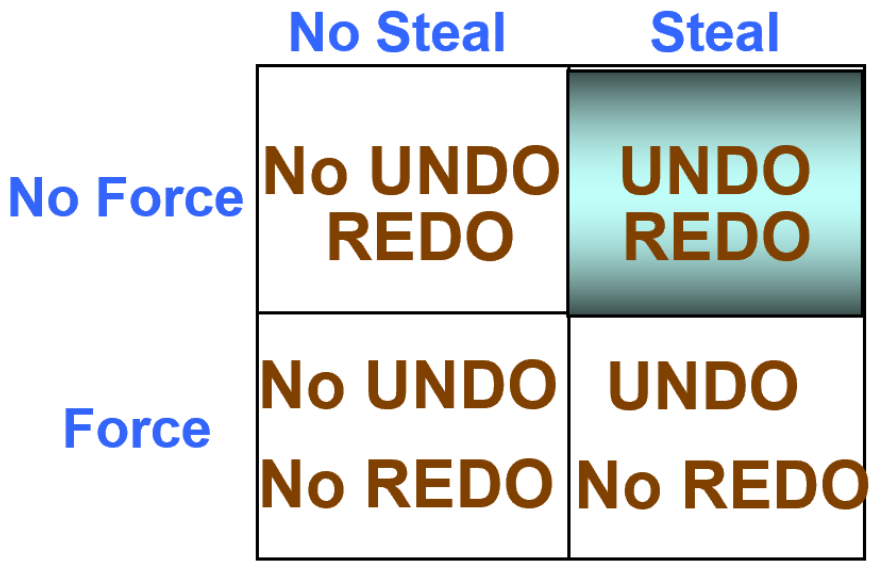
- Steal
  - What if a transaction that performed updates aborts? → WAL Logging
  - What if system crashes before transaction is finished? → WAL Logging
    - ✓ Must remember the old value of P (to support UNDOing the write to page P).

Buffer Pool Management, Cont.

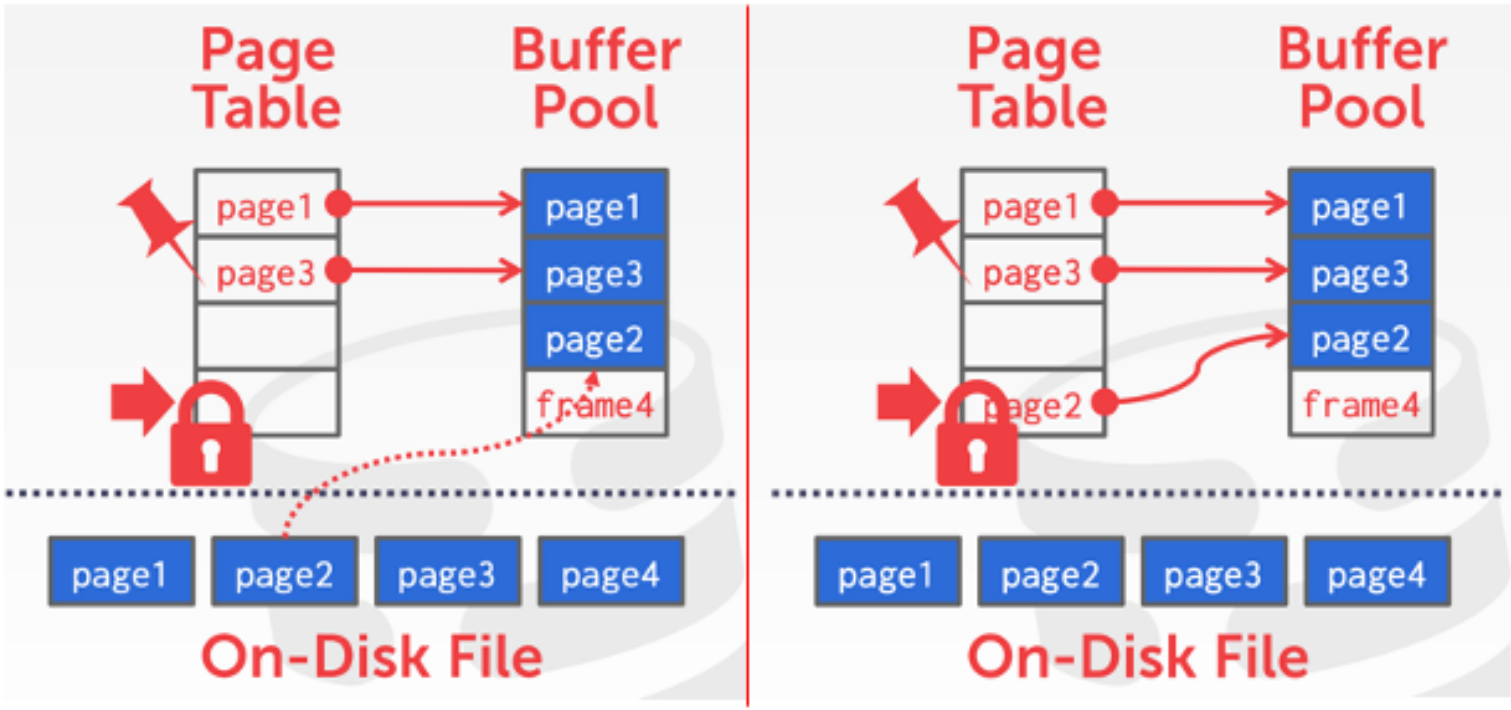


Performance Implications



Log/Recovery Implications

Buffer Pool Management, Cont. [2]



[2] https://15445.courses.cs.cmu.edu/fall2021/slides/05-bufferpool.pdf

MMAP as Buffer Pool Replacement, 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 address space.

[3] https://github.com/Ethanzjp/Snippets/tree/master/gendata_mmap

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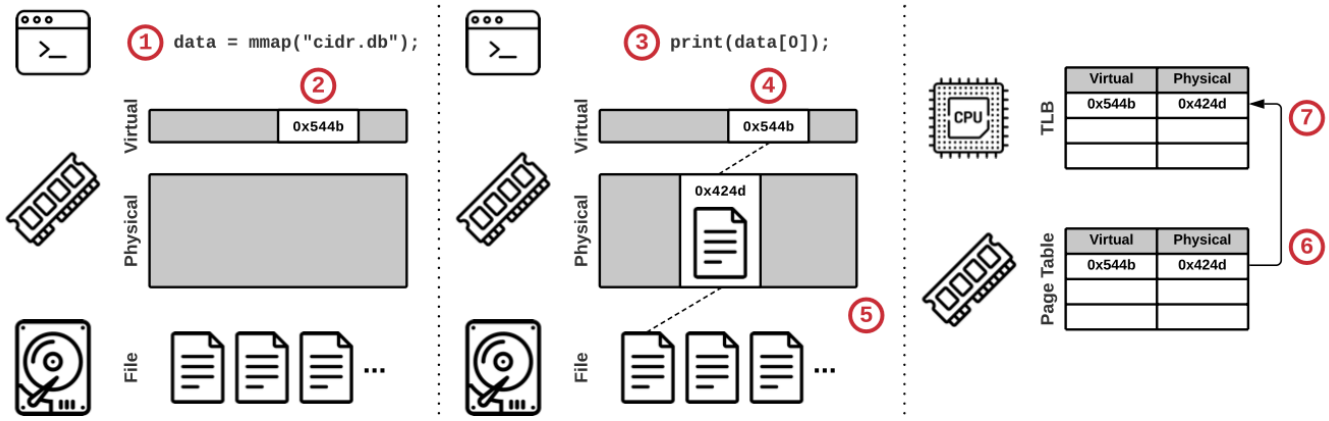

Step-by-step illustration of how a program accesses a file using mmap.

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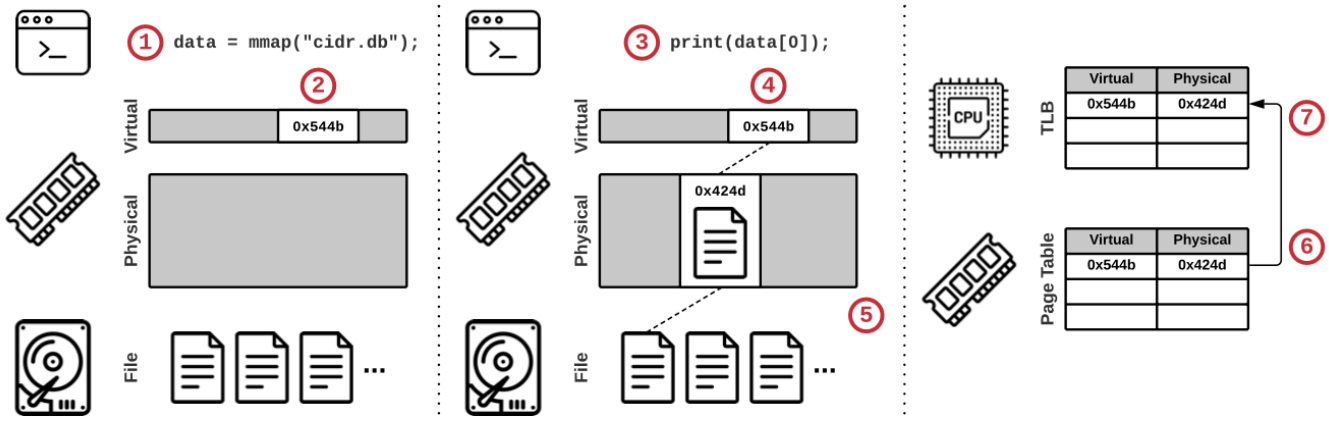

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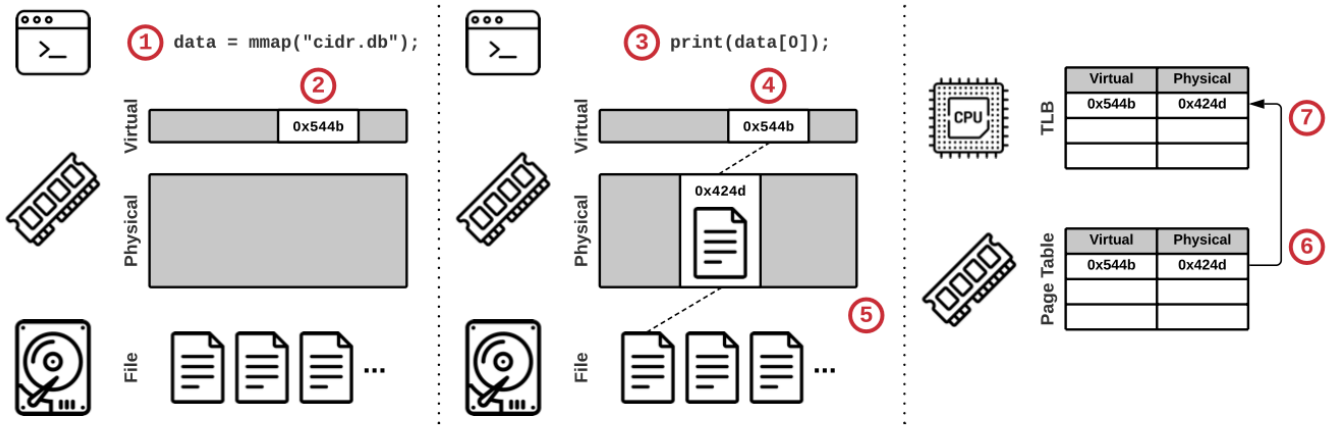
  - ✓ The OS automatically evicts pages if memory fills up.



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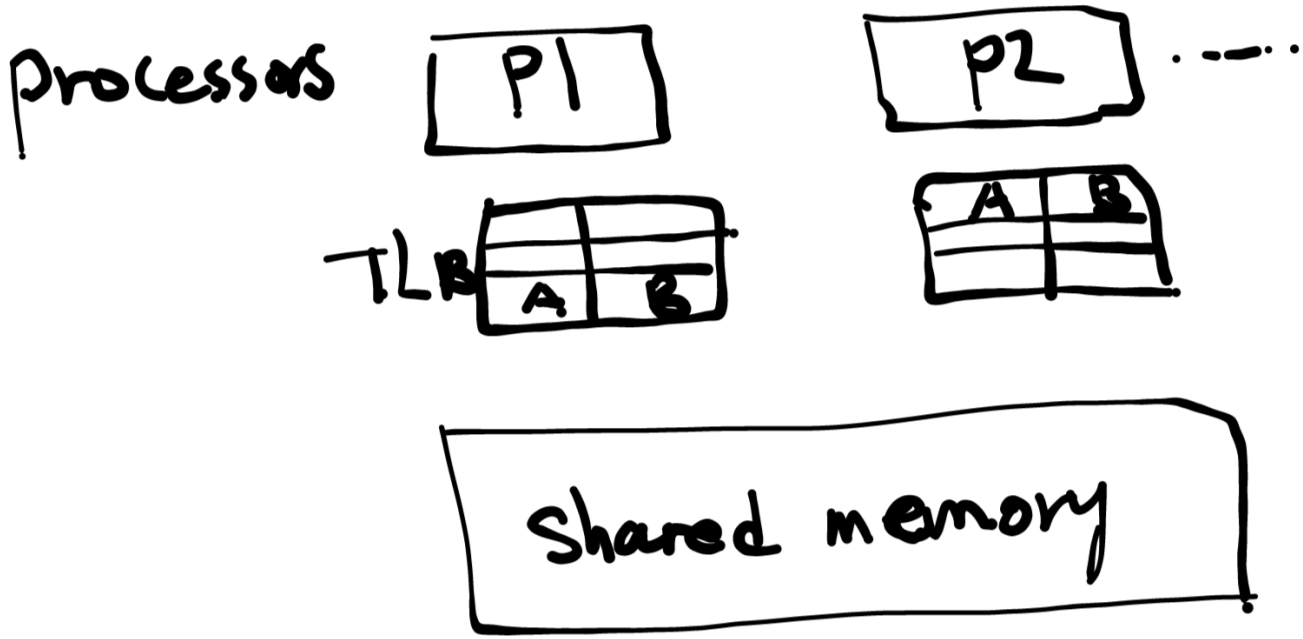
TLB shootdown

- Shared memoty [4]



[4] https://github.com/Ethanzjp/Snippets/blob/master/shared_memory.c

Comparsion of Buffer Pool and MMAP

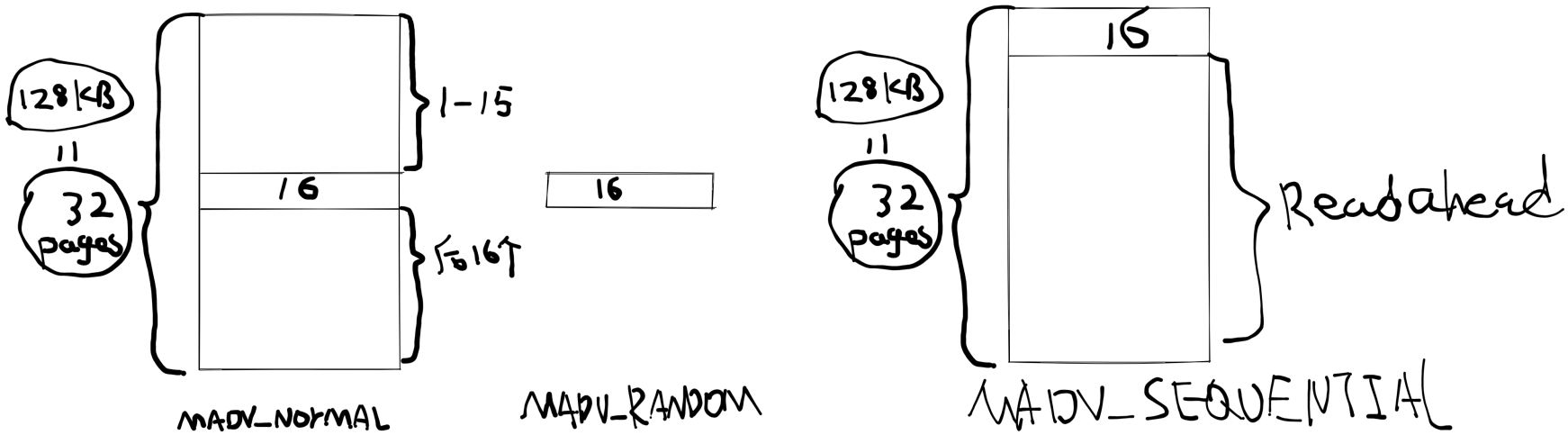
- Buffer Pool
  - ✓ The DBMS maintaining complete control over how and when it transfers pages.
- MMAP
  - ✓ The OS handles all necessary paging behind the scenes rather than the DBMS's buffer pool.
- Stonebraker 1981 opinion [5]

> 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.

[5] https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.75.5448rep=rep1type=pdf

POSIX API, Cont.

- mmap [6]
- madvise hints to the OS about expected data access patterns[7]



- 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] https://man7.org/linux/man-pages/man2/mmap.2.html
[7] https://man7.org/linux/man-pages/man2/madvise.2.html
[8] https://man7.org/linux/man-pages/man2/mlock.2.html
[9] https://man7.org/linux/man-pages/man2/msync.2.html

Modern MMAP-based DBMS

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DBMS	MMAP Use	Details
MonetDB	2002–	[12, 21]
MongoDB	2009–2019	[14, 3]
LevelDB	2011–	[5]
LMDB	2011–	[20]
SQLite	2013–	[7]
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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.
- SingleStore removed mmap-based file I/O after encountering poor performance on simple sequential scan queries.
- RocksDB replace mmap as a fork of LevelDB.

What is the truth?

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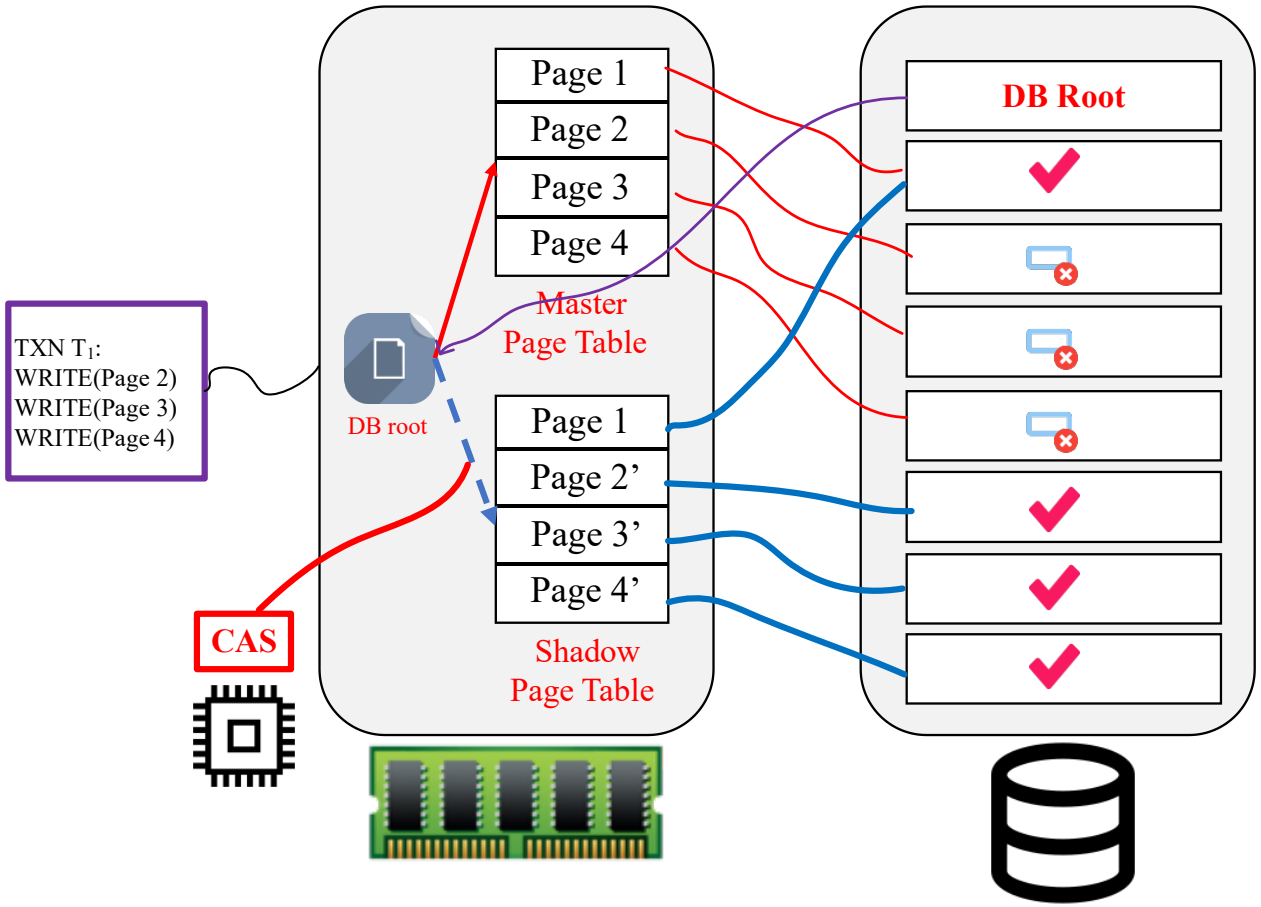
The DBMS seems no longer needs to manage its own buffer pool, as it cedes this responsibility to the OS.

Outline

Transactional Safety

- 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 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
    - MAP_PRIVATE to enable OS CoW.
    - The DBMS modifies the affected pages in the private workspace.
    - To provide durability, the DBMS must use a write-ahead log (WAL) to record changes.
    - DBMS applies the committed changes to the primary copy using msync.
  - User space CoW
    - Copy the mmap-backed memory page to user buffer.
    - Update and recording the WAL logging.
    - Copy the modified pages back to the mmap-backed memory.
  - 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

- 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.

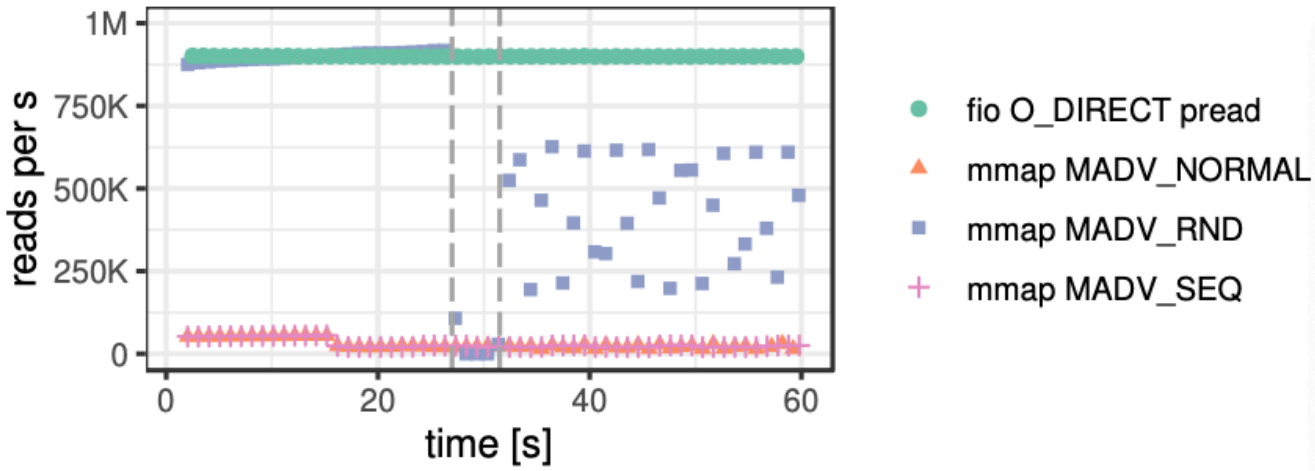
Error Handling

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

Performance Issues

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

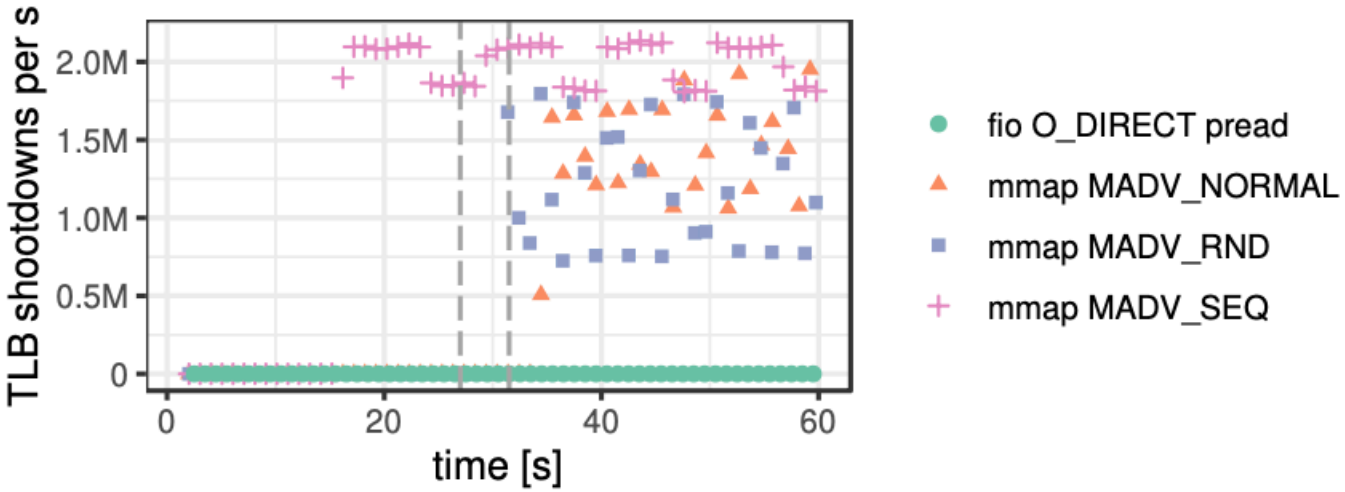
Outline



(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

Random Reads on TLB Shootdown



(b) TLB Shootdowns

- we measured using /proc/interrupt

Sequential Scan on Bandwidth

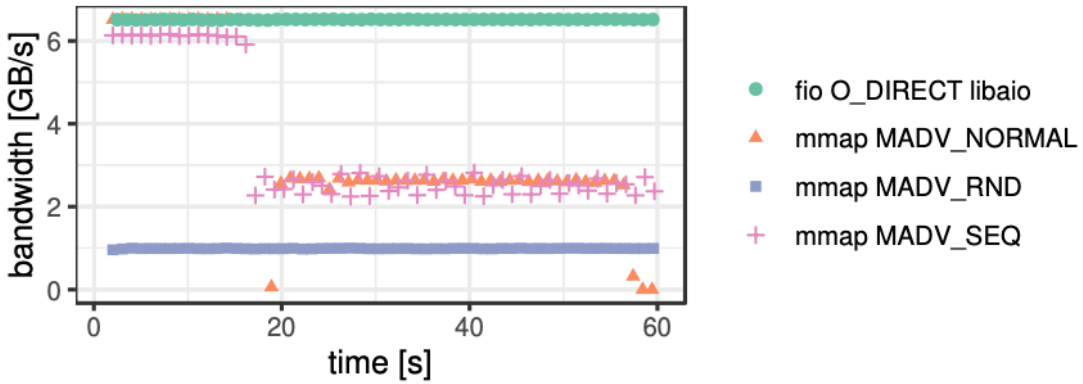


Figure 3: Sequential Scan – 1 SSD (mmap: 20 threads; fio: libaio, 1 thread, iodepth 256)

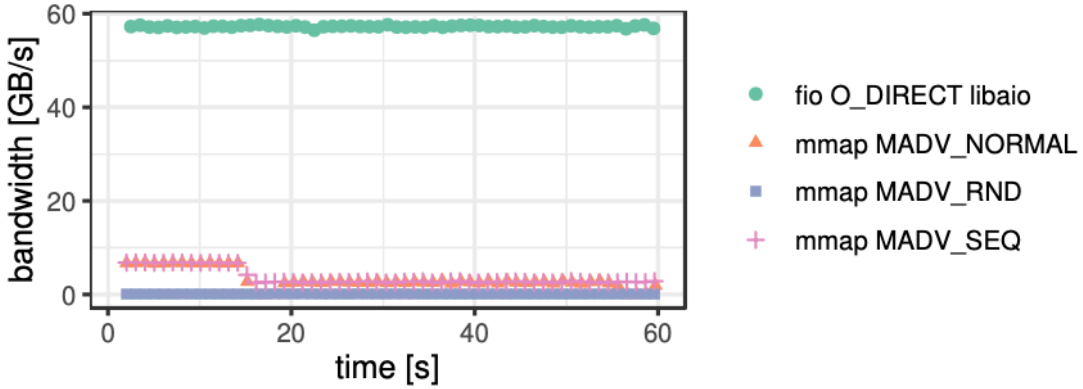


Figure 4: Sequential Scan – 10 SSDs (mmap: 20 threads; fio: libaio, 4 threads, iodepth 256)

Outline

Conclusions

- mmap is not a suitable replacement for a traditional buffer pool.
- When you should not use mmap in your DBMS:
  - You need to perform updates in a transactionally safe fashion.
  - You want to handle page faults without blocking on slow I/O or need explicit control over what data is in memory.
  - You care about error handling and need to return correc results.
  - You require high throughput on fast persistent storage devices.
- When you should maybe use mmap in your DBMS:
  - ✓ Your working set (or the entire database) fits in memory and the workload is read-only.
  - ✓ You need to rush a product to the market and do not care about data consistency or long-term engineering headaches.
  - ✓ Otherwise, never.

Outline

References I

- https://ravendb.net/articles/re-are-you-sure-you-want-to-use-mmap-in-your-database-management-system
- https://news.ycombinator.com/item?id=29936104

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Thank you!
Welcome for any questions!

Junpeng Zhu (朱君鹏)
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