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

MMAP $= \smile$

Junpeng Zhu

Greenplum, VMware, Inc.

Apr, 28, 2022

Outline

Outline

Authors

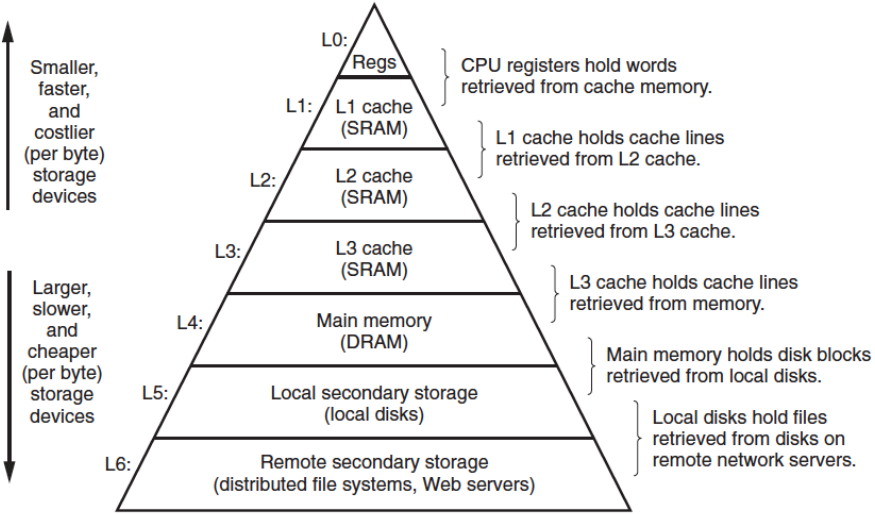
Andrew Crotty
Carnegie Mellon University

Viktor Leis
Friedrich-Alexander-Universität

Andy Pavlo
Carnegie Mellon University

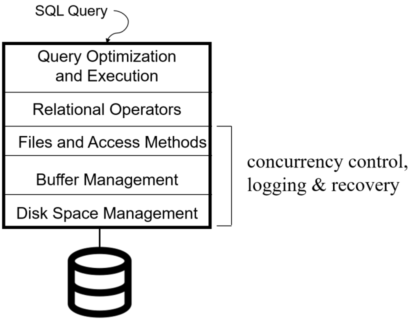
- Andrew Crotty
  - ✓ Andrew Crotty's Bio
  - ✓ Ph.D at Brown, in 2019. Post-doctoral at CMU.
- Viktor Leis
  - ✓ Viktor Leis Bio
  - ✓ Ph.D at TUM, full professor at Friedrich Schiller University Jena.
- Andy Pavlo
  - ✓ Andy Pavlo Bio
  - ✓ Ph.D at Brown, associate professor at CMU.
  - ✓ Never use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

Storage hierarchy, Cont.



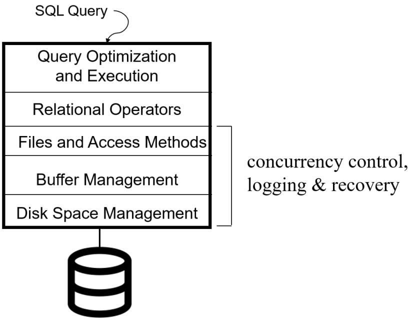
Architecture of RDBMS, Cont.

- 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
- Disk space management



- 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.

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.
- 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).

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.
- 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).

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.

- 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.
- 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.

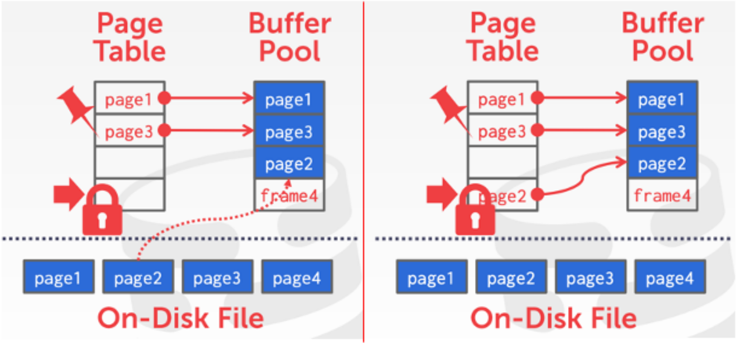
	No Steal	Steal
No Force		Fastest
Force	Slowest	

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. [1]



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

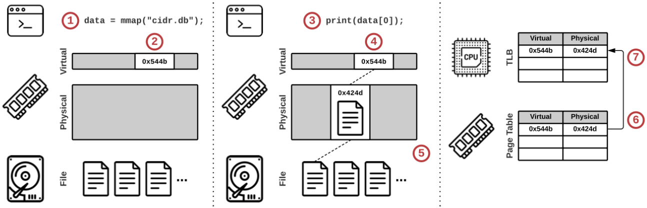
MMAP as Buffer Pool, Cont. [2]

- 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.

2. Ethanzjp MMAP Gendata Demo

MMAP as Buffer Pool, Cont. [2]

- 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.
  - ✓ The program then accesses pages via pointers as if the file resided entirely in memory.

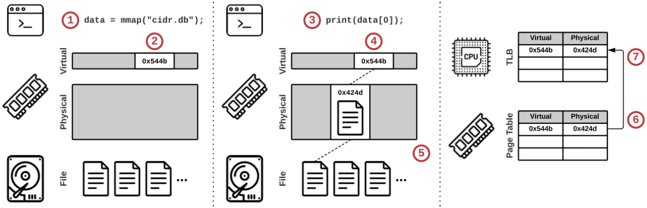


Step-by-step illustration of how a program accesses a file using mmap.

2. Ethanzjp MMAP Gendata Demo

MMAP as Buffer Pool, Cont. [2]

- 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.
  - ✓ 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.

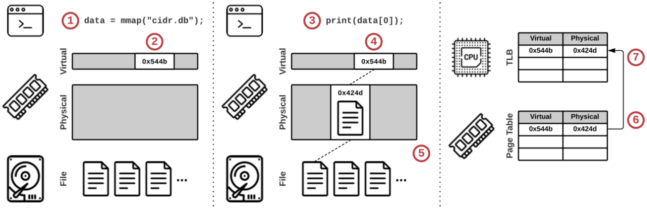


Step-by-step illustration of how a program accesses a file using mmap.

2. Ethanzjp MMAP Gendata Demo

MMAP as Buffer Pool, Cont. [2]

- 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.
  - ✓ 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.

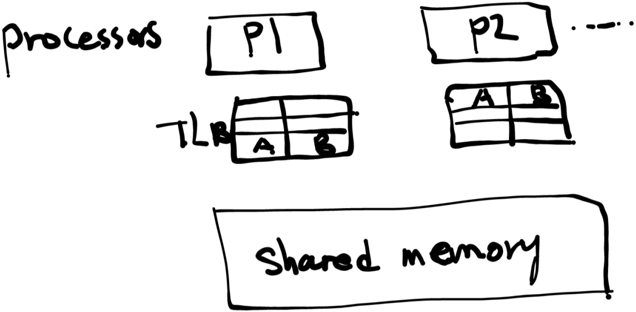


Step-by-step illustration of how a program accesses a file using mmap.

2. Ethanzjp MMAP Gendata Demo

TLB shootdown

- Shared Memory Model [3]



3. Ethanzjp Shared Memory Demo

Comparsion of Buffer Pool and MMAP

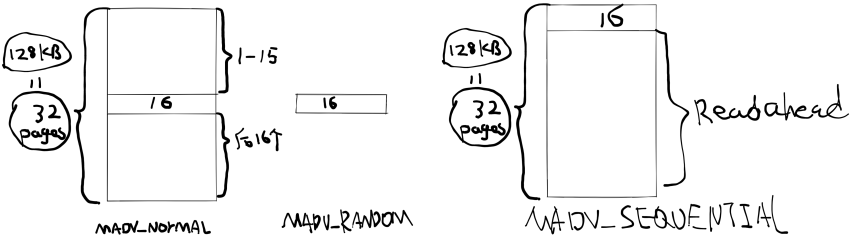
- Buffer Pool
  - ✓ The DBMS maintaining complete control over how and when it transfers pages.
- MMAP
  - ✓ The OS handles all necessary paging behind the scenes rather than the DBMS's buffer pool.
- Stonebraker 1981 opinion [4]

> 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.

4. 1981 Stonebraker's Paper

POSIX API, Cont.

- mmap [5]
- madvise hints to the OS about expected data access patterns [6]



- mlock [7] 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 [8] explicitly flushes the specified memory range to secondary storage.

5. mmap man7 page
6. madvise man7 page
7. mlock man7 page
8. 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]
RavenDB	2014–	[4]
InfluxDB	2015–2020	[8, 1]
WiredTiger	2020–	[17]

9. LevelDB Snapshot Demo

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]
RavenDB	2014–	[4]
InfluxDB	2015–2020	[8, 1]
WiredTiger	2020–	[17]

- 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.

9. LevelDB Snapshot Demo

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]
RavenDB	2014–	[4]
InfluxDB	2015–2020	[8, 1]
WiredTiger	2020–	[17]

- 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.
- SingleStore removed mmap-based file I/O after encountering poor performance on simple sequential scan queries.

9. LevelDB Snapshot Demo

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]
RavenDB	2014–	[4]
InfluxDB	2015–2020	[8, 1]
WiredTiger	2020–	[17]

- 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.
- 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].

9. 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.

Outline

Transactional Safety

GREENPLUM DATABASE

- 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

ß

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.

ß

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.

ß

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.

ß

Transactional Safety

GREENPLUM DATABASE

- 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.

ß

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

ß

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.

ß

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.

ß

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.

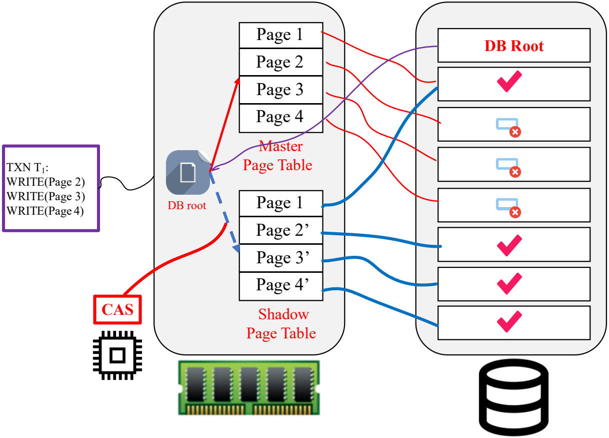
ß

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

ß

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

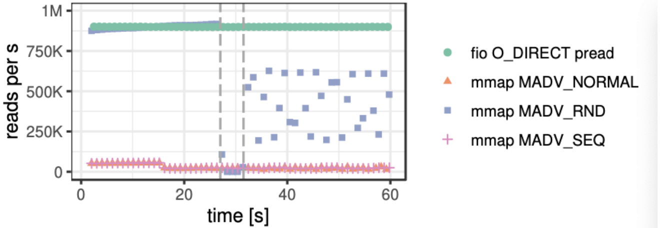
- page-level checksums
- gracefully handling I/O errors

Performance Issues

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

Outline

Random Reads on Bandwidth [10]

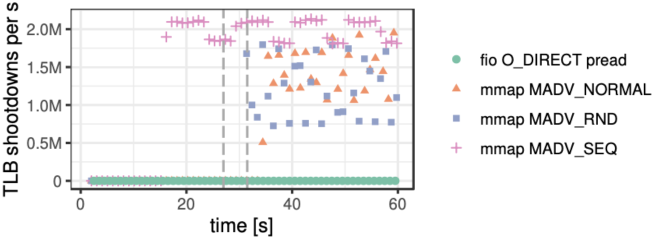


(a) Bandwidth

- 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

10. mmapbenchmark

Random Reads on TLB Shootdown



(b) TLB Shootdowns

- we measured using /proc/interrupt

Sequential Scan on Bandwidth

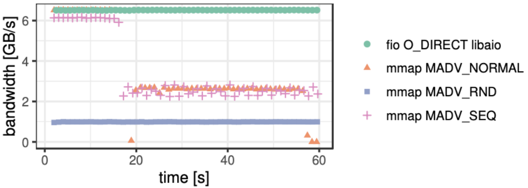


Figure 3: Sequential Scan – 1 SSD (mmap: 20 threads; `fio`: `libaio`, 1 thread, `iodepth 256`)

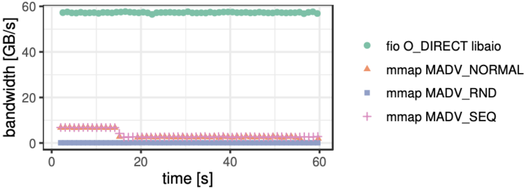


Figure 4: Sequential Scan – 10 SSDs (mmap: 20 threads; `fio`: `libaio`, 4 threads, `iodepth 256`)

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.

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.

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.

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.

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 :

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.

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.

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

- RavenDB Response
- Community Comments

Outline

Thank you !
Welcome for any questions !

Junpeng Zhu
Greenplum, VMware, Inc.