Lessons learned from the early performance evaluation of Intel Optane DC Persistent Memory in DBMS

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Abstract

Non-volatile memory (NVM) is an emerging technology, which has the persistence characteristics of large capacity storage devices (e.g., HDDs and SSDs), while providing the low access latency and byte-addressability of traditional DRAM memory. This unique combination of features opens up several new design considerations when building database management systems (DBMSs), such as replacing DRAM (as the main working space memory) or block devices (as the persistent storage), or implementing both at the same time for several DBMS components (such as access methods, storage engine, buffer management, logging/recovery, etc.).

However, interacting with NVM requires changes to application software to best use the device (e.g., mmap and clflush of small cachelines instead of write and fsync of large page buffers). Before introducing (potentially major) code changes to the DBMS for NVM, developers need a clear understanding of NVM performance in various conditions to help make better design choices.

In this paper, we provide extensive performance evaluations conducted with a recently released NVM device, Intel Optane DC Persistent Memory (PMem), under different configurations with several micro-benchmark tools. Further, we evaluate OLTP and OLAP database workloads (i.e., TPC-C and TPC-H) with Microsoft SQL Server 2019 when using the NVM device as an in-memory buffer pool or persistent storage. From the lessons learned, we share some recommendations for future DBMS design with PMem, e.g., simple hardware or software changes are not enough for the best use of PMem in DBMSs.

1 Introduction

Non-volatile memory (NVM) is an emerging technology which forces the database community to revisit various DBMS internals (e.g., access methods, storage engine, buffer management, logging, recovery, etc.) \(^9\) because of its unique device characteristics. For example, one recently released NVM device, Intel Optane DC persistent memory (PMem for short hereafter), provides large capacity and persistence like traditional block storage devices (e.g., HDDs and SSDs), as well as low latency and byte-addressability like DRAM memory.

The focus of this paper is to explore PMem’s characteristics, mainly in the DBMS perspective, under several PMem configurations with micro-benchmark tools. The observations and analysis we gain in this paper help explain more traditional database workload performance results (e.g., impact of writes on OLTP and OLAP workloads) and inform our suggestions for optimal DBMS internal parameters for query processing on PMem. For example, our results show that the small I/O request sizes can best take advantage of PMem’s relatively high performance compared to other traditional storage devices (i.e., SSDs). Additionally, we observe that PMem devices do not exhibit the same concurrent request scaling rules as SSDs.

In addition, we evaluate OLTP and OLAP workloads (i.e., TPC-C and TPC-H) with different PMem device configurations to explore the potential database design choices when integrating PMem in DBMSs. Our OLTP and OLAP evaluations reveal some important design considerations when building DBMSs with PMem: (1) Replacing a traditional DRAM based buffer pool with PMem configured in Memory Mode (e.g., for its increased capacity for working set memory and ability to use directly without software changes) is a suboptimal solution because of its extreme performance asymmetry between reads and writes. This design choice hurts not only the performance of write intensive OLTP workloads, but also that of read intensive OLAP workloads because all intermediate query results are also written to PMem; (2) extending a DRAM buffer pool with PMem requires a PMem enlightened database page to buffer placement policy. For example, our results show that the performance of OLAP workloads can drop significantly if we do not ensure hot pages land on DRAM, despite the high read performance of PMem.

Our device micro-benchmark results and database workload evaluations point out that the solutions introduced so far only provided initial implementations, but there are huge opportunities...
for additional research to properly adopt this new technology for DBMS internals.

In summary, the contributions of our paper are as follows:

- We share some important PMem device characteristics and introduce crucial factors (e.g., degree of parallelism, I/O request size, and impact of frequent writes) for database query processing with PMem.
- We evaluate OLTP and OLAP workloads with different PMem configurations (i.e., replacing DRAM buffer pool, extending DRAM buffer pool, and replacing storage devices with PMem) in a production grade DBMS, and
- Based on our findings, we make design choice recommendations for buffer management and storage engines for DBMSs.

In the remainder of the paper, we present related work and different possible PMem configurations in Section 2 and Section 3 followed by the PMem device performance and database workload evaluations with PMem in Section 4 and 5 respectively. Some future research directions are discussed in Section 6.

2 RELATED WORK

After the recent release of PMem, initial efforts on performance characterization of the device have been started [6, 8, 18, 23, 29, 30], which also motivates the performance evaluations of PMem in different applications, e.g., B-tree performance evaluations [20], scientific benchmark evaluations [22], power usage evaluations [23], hybrid memory system evaluations [17], integer compression schemes [31] and some initial database workload evaluations on PMem [18]. There are also some other initial studies on how to close the latency gap between DRAM and PMem in latency-sensitive operations [24], how to provide efficient I/O primitives with PMem [26], how to design better page replacement policy with PMem [21] and how to efficiently provide replication mechanisms with PMem [32]. However, to our knowledge, no detailed database workload evaluations and DBMS design recommendations on the newly released PMem device exist yet.

Prior to the release of PMem, a series of research works have been motivated by the predicted use of future NVM devices. These efforts focused on how to utilize NVM in database systems for improved performance, recovery, or other lines compared to other storage devices (see [10, 12, 13, 25, 28] and the references herein). However, due to the lack of real NVM devices when those works were published, they were based on NVM emulated in DRAM, typically with an expectation of near DRAM bandwidths, which we now know to be inaccurate assumptions. Hence, the feasibility of those ideas on the real NVM device is still unknown.

3 PMEM CONFIGURATIONS

We use three different modes (shown in Figure 1) of accessing PMem, each of which has its own set of trade-offs and must be chosen in the system’s firmware configuration.

First, in Memory Mode PMem is used as the main memory of a system that leverages DRAM as a high-speed L4 cache, managed by the hardware’s memory controller. This mode can be used as a way to increase the capacity of the working memory for a system, and to use PMem with existing applications without modification.

However, in this mode, PMem is actually still volatile. That is to say, all data written to PMem in Memory Mode is lost upon a system restart (whether the cause of the restart is intentional or not). Thus, in this mode we are not able to take advantage of a key feature of the device. Moreover, the cache (re)placement policy is subject to NUMA and other effects and cannot be managed by software.

In both of the other access mode options, Direct Access (DAX) and File I/O. PMem guarantees persistence of the data it stores.

In DAX mode, applications use PMem via memory semantics (i.e., load and store instructions), after an initial interaction with the OS through the mmap syscall to setup a virtual address space mapping, thus allowing the direct CPU data access to PMem’s address space without further kernel intervention. However, this may involve significant changes to application code to handle things like torn writes due to CPU cacheline flushing semantics that most applications don’t generally need to be concerned with. Instead, application developers have to carefully inject clflush, mfence, and other low level instructions or make use of libraries (e.g., Intel’s PMDK [4]), which are known to introduce other inefficiencies [19], to do it for them.

On the other hand, in File I/O mode, PMem is accessed by applications using standard file system APIs (e.g., read, write, etc.). This has higher latency than DAX mode when the number of data accesses within a region are frequent since each operation must pass through the entire I/O software stack of the OS. Additionally, block I/O typically does not provide byte-addressable semantics.

Table 1 provides a summary of the PMem configurations.

| feature            | configuration | Memory Mode | DAX Mode | File I/O Mode |
|--------------------|---------------|-------------|----------|---------------|
| disk like features | Persistence   | ✓           | ✓        | ✓             |
|                    | Large capacity| ✔           | ✔        |               |
| memory like features| Byte addressability | ✓   | ✓        |               |
|                    | CPU direct access | ✓   | ✓        |               |

Figure 1: Different configurations of PMem. PMem with the orange color (in the PMem and File I/O modes) indicates the use of PMem as persistent storage while the gray color (in the Memory Mode) means its usage as volatile memory.
4 PMEM MICRO-BENCHMARK ANALYSIS

This section presents a comprehensive performance analysis of PMem device characteristics when used as persistent storage (i.e., the DAX or File I/O modes) or as main memory (i.e., Memory Mode), as described in Section 3.

4.1 System configuration

We conduct all experiments on a dual-socket server with Intel Xeon Platinum 8260L CPUs. Each socket has 24 physical cores, each of which has its own 32KB L1 and 1MB L2 caches, and a shared 35.75MB L3 cache. Each socket is also populated with 96GB of DRAM (six 16GB Micron DDR4), and 1 TB PMem (two interleaved 512GB Intel Optane DC Persistent Memory modules installed in memory DIMM slots).

Note that all experiments in this section are performed on the two interleaved PMem modules in one socket accessed by the local CPUs (i.e., no remote NUMA accesses). To compare performance when PMem is used as persistent storage, we use one NVMe 4TB Intel DC P4510 Series SSD (called SSD for short hereafter). Finally, we run Ubuntu 18.10 on the server where hyper-threading is enabled, and the CPU power governor is configured to performance mode, forcing the CPU to use the highest possible (turbo) clock frequency.

4.2 PMem as persistent storage

We first investigate the performance characteristics of PMem when it is used in the DAX or File I/O modes, comparing with SSD, and study their implications when designing DBMSs for PMem. For this evaluation, we use Flexible I/O tester (fio) [1] to issue synchronized I/O requests, varying several parameters, including the I/O request size, access patterns (random/sequential and read/write), and the number of I/O threads, seeking to answer the following questions:

(Q1) How will the different I/O sizes affect the performance of PMem in the DAX and File I/O modes?

(Q2) How is PMem’s performance affected as the number of I/O threads increases?

(Q3) What is the performance difference between read and write requests in PMem?

While previous work [18] has already addressed portions of the above questions (e.g., [18] focuses on single-thread experiments while we vary the number of I/O threads and I/O sizes simultaneously), our main contribution in this analysis is to consider how PMem’s performance characteristics affect when redesigning various DBMS components for PMem. Note that due to space limits, we present bandwidth results measured with only sequential read/write workloads (Figure 2–3). We also measured the latency results, which, however, are less relevant to the database workload experiments and thus not included here.

Observation 1. Figure 2 shows the peak bandwidth of read and write workloads with varied I/O request sizes. When the I/O size is small (i.e., < 4KB), PMem DAX shows significant performance gains compared to PMem File I/O and SSD (e.g., with 512B I/O size, PMem DAX achieves about 5x and 50x higher throughputs than PMem File I/O and SSD, respectively). However, with bigger I/O sizes, there is no distinct performance advantage of PMem DAX compared to PMem File I/O.

Analysis Unlike PMem DAX of which the internal device access size is 256B with 64B cacheline operations from the byte level CPU load/store instructions perspective, PMem File I/O and SSD access data in the sector size granularity exposed to the OS, which is typically configured to 4KB or 512B. Therefore, PMem File I/O and SSD waste I/O bandwidth if the required data size is smaller than the block size. Further PMem File I/O and SSD always need to go through the I/O stack to fetch data, adding extra system call overheads. On the other hand, this overhead can be easily amortized when issuing large I/Os, resulting in no noticeable advantage in PMem DAX over others.

Recommendations The performance improvement achieved by using small I/O sizes in PMem DAX provides an interesting opportunity to speed up the query processing in DBMSs with small page sizes. As an example, let’s consider using a 512B page instead of 8KB for a B-tree node, and further assume that each record has a size of 64B. Then we can fit 8 and 128 records into 512B and 8KB nodes, respectively, and the depth of the B-tree index can be calculated as $\log_8(n)$ for the 512B node, and $\log_{128}(n)$ for the 8KB node, where $n$ is the total number of records in the database. Thus, the depth difference between two node sizes would be $\log_8(n)/\log_{128}(n) \approx 2$. Given the latency of accessing 512B data is about five times faster than 8KB (i.e., on a single-thread measurement, we observed that the access latency in PMem DAX is reduced from 2.6 $\mu$s to 0.5 $\mu$s), we can expect in total about 2.5x faster index lookup time of traversing from the root to a leaf node.
Observation 2. Figure 3 shows how read/write bandwidth changes with the number of I/O threads using a fixed-size I/O size (i.e., 8KB). As can be seen in the figure, the read/write bandwidth of PMem gradually drops after a certain number of threads (i.e., 12 and 4 threads in reads and writes, respectively). Thus, although PMem provides better overall throughput than SSD, it exhibits poor concurrent request scaling compared with it.

Analysis: With more threads, the per-thread sequential access pattern becomes in aggregate more random from a device perspective, thus causing more congestion at the internal PMem device controller. (A similar observation can be found in [18]). The results shown in Figure 3 indicate that, unlike SSD, a large number of outstanding I/Os are not needed to fully exploit the parallelism of PMem for both modes.

Recommendations: The relatively poor scalability of PMem compared to SSD recommends us to limit the maximum degree of parallelism for PMem I/O within a database engine.

Observation 3. The performance of reads and writes of the DAX and File I/O are asymmetric (peak read bandwidth vs. peak write bandwidth for both PMem DAX and File I/O: ~10.6GB/s vs. ~3.5GB/s). In contrast, SSD provides more balanced performance between reads and writes (~2.7GB/s vs. ~2.8GB/s). As mentioned earlier, this performance pattern is also observed by [18].

Recommendations: The read-write asymmetry of PMem implies the necessity of avoiding writes as much as possible for PMem.

4.3 PMem as Memory

In this subsection, we present the performance characteristics of PMem in memory mode by using Memory Latency checker (MLC hereafter) [3], which is compared with the performance of DRAM and the PMem in DAX mode.

Also as observed in [29], performance measurements in Memory Mode require careful attention to data sizes. Too small, and they will fit entirely in the DRAM L4 cache, and thus won’t measure PMem behavior at all. To address this we initialized two different size of data (100GB and 500GB) in PMem each of which is larger than the 96GB DRAM we have allocated to a single socket. Note that during the write performance measurements on 500GB dataset in PMem Memory Mode, MLC crashed due to some internal issues. So, we present the write performance only for 100GB dataset. In this subsection, we wish to address the following questions:

(Q4) How does the number of threads influence PMem Memory Mode performance?

(Q5) How does the dataset size influence PMem Memory Mode performance?

(Q6) What is the relative performance of PMem Memory Mode compared to that of PMem DAX and DRAM?

Note that [7] and [29] have provided initial evaluations on PMem Memory Mode with different dataset sizes under different system configurations, addressing (Q5) and also partially (Q6). But the influence of the thread count against the performance is still missing. Due to the space limit, only the sequential read and write bandwidth are shown in Figure 4, from which we note the following:

Observation 4. As the number of threads increases, the PMem Memory Mode bandwidth increases first before it becomes saturated and drops.

Analysis: This performance pattern also appears in PMem DAX and PMem File I/O, which can thus be explained in the same way.

2Recall that measurements are restricted to a single socket.
as Observation 2 in Section 4.2. Namely, concurrent requests appear as random I/O resulting in increased contention to the device controller.

**Recommendations** Similar to the discussion in Observation 2, to use PMem as the buffer pool in a DBMS via Memory Mode, it is advisable to limit the number of concurrent threads accessing PMem. However, in this context, especially when the working set exceeds the size of DRAM, it means limiting concurrency inside the entire buffer pool as well, since we lack other software control over which pages are in the L4 DRAM cache vs PMem, thus effectively limiting the amount of concurrency on the entire DBMS.

**Observation 5.** PMem Memory Mode read bandwidth drops as the size of data increases (e.g., the peak bandwidth drops from \( \sim 13.9\text{GB/s (100GB)} \) to \( \sim 8.7\text{GB/s (500GB)} \) with four threads)

**Analysis:** Similar performance pattern is also observed in [29]; as the dataset size increases in PMem Memory Mode, a larger proportion of requests miss in the L4 DRAM cache, and have to be serviced by PMem. As noted previously in Observation 2, this will result in a larger number of concurrent accesses to DRAM which may appear more random and result in more contention.

**Observation 6.** Under write workloads with smaller data size (100GB), the PMem Memory Mode performs slightly better than PMem DAX while with larger data size or under highly parallel write workloads with smaller data size, PMem Memory Mode performs worse than PMem DAX. We can also observe a huge gap between the DRAM performance and PMem performance

**Analysis:** As explained above, in PMem Memory Mode, if the data size in PMem is larger, DRAM page misses may happen, thus slowing down the data access speed, which becomes more severe for writes in PMem Memory Mode (see the worse write performance of PMem Memory Mode than that of PMem DAX with 16 threads in Figure 4b). In contrast, DRAM misses do not happen for PMem DAX due to the CPU direct access. Also as expected, the DRAM performance is much better than PMem.

**Recommendations** Through the observation 5 and observation 6, we know that with data size larger than DRAM, especially under write-intensive workloads, PMem DAX performs better than PMem Memory Mode. As we will see in Section 5, under OLAP workloads where many writes for intermediate results are issued, PMem Memory Mode still perform worse than PMem DAX, and even worse than SSD.

5 DATABASE WORKLOAD EVALUATIONS

We will now present our performance evaluations of typical OLTP and OLAP workloads, specifically, TPC-C and TPC-H workloads, with different PMem configurations in Microsoft SQL Server 2019.

**5.1 Experimental design**

As mentioned earlier, we can directly use PMem in SQL Server 2019 either as the persistent storage or in conjunction with the buffer pool. For the former use case, File I/O is currently still issued against PMem. For the latter use case, the DRAM buffer pool in SQL Server 2019 can be extended with Hybrid buffer pool support [2], whereby the warm pages cached in PMem are accessed with DAX without being cached in DRAM buffer pool.

In the following, we continue to use PMem DAX and PMem File I/O to denote the use of PMem as the persistent storage, with the Hybrid buffer pool enabled and disabled respectively. We compare these with the traditional DBMS configuration: SSD as the persistent storage and DRAM as the buffer pool (denoted as SSD). When PMem is used in Memory Mode as the buffer pool in SQL Server, DRAM behaves like an L4 cache and SSD is the persistent storage, which we denote by SSD + PMem Memory Mode. For this case, we denote the traditional DBMS configuration as SSD + DRAM to highlight the difference in the two buffer pool configurations.

Similar to the earlier configurations in Section 4, we use PMem and NVMe SSD in one socket and set the CPU affinity mask in SQL Server such that only the CPUs from the same socket are used [5]. We observed that the location of the tempdb where the intermediate results are stored can influence the performance. Therefore, throughout the experiments, we use the same directory for tempdb which is located in a separate SSD drive not used for persistent data storage.

We study two typical database workloads – TPC-C and TPC-H. For the TPC-C experiments, we use OLTPBench [14, 15] to issue the queries and configure each run to last 30 minutes. To minimize the effect of checkpoints, we also set the checkpointing recovery interval in SQL Server to 60 minutes, which effectively disables checkpoints during the TPC-C experiments. For the TPC-H experiments, we warm up the buffer pool by running each of the 22 queries for multiple times and only consider the runtime for the last execution.

To understand the influence of the dataset size, we use two different scale factors — SF 100 and SF 500 for TPC-H and SF 1300 and SF 6500 for TPC-C. These generate database instances with sizes of approximately 100GB and 500GB respectively.

5.2 TPC-H benchmark

Due to space constraints, we present a subset of the performance results for TPC-H queries in Figures 5–6. We note the following:

**Observation 7.** With smaller scale factor, i.e. SF=100, PMem DAX fails to outperform SSD and PMem File I/O. As Figure 5 shows, when SF=100, the runtime of Query 3 with PMem DAX is \(6X\) slower than PMem File I/O and SSD (\(<5s\) for both). This is alleviated with larger SF, i.e. SF = 500, with which DAX is slightly better than SSD (\(188s\) vs. \(197s\))

**Analysis:** As explained in [2], the use of the Hybrid buffer pool with DAX is to reference the pages in PMem instead of caching them in DRAM buffer pool. This implies that with the Hybrid buffer pool enabled, the hot pages in PMem are fetched by CPUs from PMem repetitively, failing to utilize the benefit of the DRAM buffer pool. In contrast, when SF=100, by using PMem File I/O and SSD, large portions of the hot pages are cached in DRAM buffer pool after their first access, leading to smaller overheads in subsequent page accesses and, thus, shorter query execution times. We confirm this phenomenon by monitoring memory usage that reveals that up to 150GB DRAM buffer pool is used for PMem File I/O and SSD, while only \(20GB\) DRAM is used for PMem DAX.

In case of larger SFs, only a small portion of the hot pages can be cached in the DRAM buffer pool for PMem File I/O and SSD, which means that the I/O overhead will become more prominent. We
observe that Query 3 and Query 18 run slightly faster on PMem due to the smaller I/O overhead compared to SSD. Also note that the performance difference between PMem DAX and PMem File I/O is quite small. The reason is that the page size in SQL Server is 8K, for which there is no performance difference under the read workloads between DAX and File I/O as observed in Section 4.2.

Recommendations This unexpected result indicates the need for further research into good DAX PMem aware page placement policies for the buffer pool in DBMS. One possible way to improve this is to use similar ideas to the buffer pool extension support in SQL Server [16] which prioritizes hot pages in DRAM first, and uses SSD as a second chance tier.

Observation 8. As Figure 6 shows, the performance of SSD + PMem Memory Mode is worse than that of SSD + DRAM. For example, with SF=100, the runtime of Query 3 with SSD + PMem Memory Mode is 60s, far longer than the runtime with SSD + DRAM.

Analysis: Although TPC-H is a read-intensive workload, substantial intermediate results are generated during query execution, especially when the data size is large. These are written to the buffer pool and possibly spill to tempdb files if there is not enough memory, resulting in many write operations. As explained in Section 4.3, write operations on PMem Memory Mode can lead to performance loss, thus longer query processing time.

Recommendations This result indicates that it is not appropriate to directly replace DRAM with PMem in Memory Mode as the buffer pool in DBMS even for (read intensive) TPC-H workloads because of the writes to tempdb for intermediate query results.

5.3 TPC-C benchmark

We show TPC-C performance results in Figure 7 and observe that:

Observation 9. There is no significant performance difference between PMem File I/O, PMem DAX, and SSD under TPC-C workloads.

Analysis: TPC-C is a write-intensive workload. As Figure 2 in Section 4 shows, with the SQL Server page size of 8K, the peak write bandwidth of both PMem DAX and PMem File I/O is only marginally better than that of SSD. But when the device I/Os are fully saturated, the write bandwidth of PMem drops compared to the peak write bandwidth due to congestion, which, however, we do not observe in SSD (see Figure 3 in Section 4.2).

Recommendations The downside of the write operations on PMem has been known by the database community even before the appearance of the real PMem device, which has motivated several related works on limiting the write operations on PMem by redesigning the B-tree index [27], join algorithms [28], query optimizer [11], etc, for PMem-aware DBMSs. It would be valuable to revisit the feasibility of those early works on the real PMem device.

6 CONCLUSION AND FUTURE WORK

In this paper, we explored some missing device characteristics that are closely related to the database query performance. Our results revealed that some DBMS internal configurations should be changed to take advantage of PMem in the system: (1) A different degree of parallelism, (2) optimal I/O request sizes, and (3) a new page placement policy (to avoid frequent writes on PMem) should be considered to optimize the use of PMem in DBMSs.

Our database workload evaluations showed that developers should clearly understand the new device characteristics before introducing software/hardware changes to DBMSs for the best use of PMem in the system. In other words, simple hardware (e.g., replacing DRAM buffer pool with PMem) or software (e.g., extending DRAM buffer pool with PMem without introducing a new page placement policy) changes will not be properly integrating PMem in DBMSs.

We revealed some important aspects of using PMem in DBMSs, which can help make better database design choices. However, there are still many open questions on the best use of PMem in the system for many other DBMS internals (e.g., access methods, logging/recovery, etc.).
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