Concurrency on Persistent Memory:
Designing Concurrent Data Structures for Persistent Memory

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Executive Summary

- Challenges of building concurrent data structures for persistent memory
- Two approaches to design concurrent data structures for persistent memory
Agenda

- Motivation
- Two approaches for data consistency
  - Transaction approach
  - Atomic approach
- Concurrent hash map for persistent memory
- Integration with PMEMKV
- Summary
Goal

- Design concurrent data structures for persistent memory.
  - Data structure resides in persistent memory.
  - Operations are thread-safe.
  - Operations are fault-tolerant.
    - Data survive unexpected crashes and power failures
Motivation

- PMDK provides low-level API for persistent memory programmers.
- Developers think in terms of data structures and algorithms.
What’s Done

- Evaluated two approaches to support data consistency in concurrent data structures.
- Redesigned Intel® Threading Building Blocks (Intel TBB) `concurrent_hash_map` for persistent memory.
  - Published as part of PMDK
    [https://github.com/pmem/libpmemobj-cpp/pull/40](https://github.com/pmem/libpmemobj-cpp/pull/40)
- Integrated our data structures into PMEMKV.
Two Approaches for Data Consistency

- Transactions
  - Define a set of operations to be done atomically.
- Atomic approach
  - Atomically switch between consistent states.
Transactions for Data Consistency

- All modifications are done inside a transaction.
- Write-Ahead Log (WAL) is used to track modifications.
- For each uncommitted transaction, consistent state is restored on restart from WAL.

```c++
template<class T>
class list {
    struct node_t {
        T value;
        persistent_ptr<node_t> next;
    }
    persistent_ptr<node_t> head;
    persistent_ptr<node_t> tail;

public:
    void push_back(T v) {
        transaction::manual(pop);
        auto n = make_persistent<node_t>(v, nullptr);
        if (head == nullptr) {
            head = tail = n;
        } else {
            tail->next = n;
            tail = n;
        }
        transaction::commit();
    }
};
```
Concurrent PMDK Transactions

- PMDK transaction does not support isolation.
  - WAL is per-thread.
- Atomic operations cannot be used inside PMDK transactions.
- Possible solutions:
  - Use critical section.
  - Hold lock until transaction completed.

// Variable a is located in persistent memory
std::atomic<int> a = 0;

Thread 1:
```c++
std::atomic<int> a = 0;
tx_begin();
add_to_log(&a);
++a;
...
tx_abort();
```

Thread 2:
```c++
std::atomic<int> a = 0;
tx_begin();
add_to_log(&a);
++a;
...
tx_commit();
```

Incorrect value of the counter is restored from undo log if thread 1 aborts transaction while thread 2 successfully commits its changes.
Mutex in Persistent Memory

- Mutex is a volatile entity.
  - Unexpected termination may leave mutex in the locked state.
  - Mutex must be re-initialized to the unlocked state on each process restart.
- PMDK solves this issue:
  - Persistent mutex
    - Unlocked on each process restart.
  - Volatile field in a persistent data structure
    - Re-initialized on each process restart.

```cpp
class Foo {
    pmem::obj::mutex mtx;
};
```
```cpp
class Bar {
    pmem::obj::v<std::mutex> m;
};
```
Atomic Approach for Data Consistency

- Alternative approach to PMDK transactions
- Custom restore logic
- PMDK atomic allocator
- Manual cache flushes

```cpp
template<class T>
class list {
   struct node_t {
      T value;
      persistent_ptr<node_t> next;
   };
   persistent_ptr<node_t> head;
   persistent_ptr<node_t> tail;
   persistent_ptr<node_t> new_node; // Hold last allocated node

public:
   void push_back(T v) {
      make_persistent_atomic<node_t>(pop, new_node, v, nullptr);
      if (head == nullptr) {
         head = tail = new_node;
         pop.persist(head); // Cache flush
      } else {
         tail->next = new_node;
         pop.persist(tail->next); // Cache flush
         tail = new_node;
      }
      pop.persist(tail); // Cache flush
   }

   void restore() {
      if (new_node) {
         // Restore logic
      }
   }
};
```
PMDK Atomic Memory Allocator

- PMDK atomic allocator atomically does the following:
  - allocates memory;
  - assigns the result to a user-provided persistent pointer.

- Persistent pointer on the stack cannot be used.
  - Persistent memory leak is possible if a process is terminated.

```cpp
int main() {
  pool_base pop = ...;
  persistent_ptr<Foo> p = nullptr;
  make_persistent_atomic<Foo>(pop, p);
  return 0;
}
```
Lock-Free Algorithms on Persistent Memory

- Memory subsystem consists of:
  - **Volatile domain** - registers, caches
  - **Persistent domain** – DIMMs.
- Changes made by one thread are visible to other threads before it is persisted.
  - CMPXCHG + CLWB – not atomic
- Restore after an abnormal termination should take care of such cases.

**Compare-and-swap** is used to insert an element to the tail
# Transactions vs. Atomic Approach

<table>
<thead>
<tr>
<th></th>
<th>Transactions</th>
<th>Atomic approach</th>
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</thead>
<tbody>
<tr>
<td>Data consistency support</td>
<td>• Natural way to support data consistency</td>
<td>• Developer is responsible for data consistency.</td>
</tr>
<tr>
<td></td>
<td>• PMDK is responsible for data consistency and data restore after crash.</td>
<td>• Custom restore logic is required for each particular data structure.</td>
</tr>
<tr>
<td>Performance overhead</td>
<td>• Performance overhead to handle WAL</td>
<td>• Better performance</td>
</tr>
<tr>
<td>Concurrency support</td>
<td>• PMDK transaction does not support isolation</td>
<td>• Suitable for concurrent algorithms</td>
</tr>
<tr>
<td></td>
<td>• Cannot use lock free algorithms</td>
<td></td>
</tr>
</tbody>
</table>
Concurrency Hash Map

- Per-bucket Read-Write lock
  - Find() acquires read lock.
  - Insert() acquires write lock.
- Insert operation:
  - Finds bucket.
  - Allocates new node.
  - Inserts a new node.
- Lazy restore on bucket access
  - Checks new_node pointer first.
PMEMKV

- Embedded Key/Value data store optimized for persistent memory
- An option to create custom storage engines
- Usage of db_bench from RocksDB for benchmarking

https://github.com/pmem/pmemkv
Concurrent Hash Map and PMEMKV

Concurrent hash map is a new storage engine that:

- enables maximum throughput in multithreaded applications;
- keeps P99 latency flat with a growing number of threads.
DB_bench Results

Throughput (Ops/sec) – scales with a number of threads

P99 latency (sec/Op) – flat

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Summary

- Compared two approaches to build concurrent data structures for persistent memory:
  - Transactions vs. Atomic approach.
- Designed a concurrent hash map for persistent memory.
- Enabled concurrency in PMEMKV.
Call to Action

- Try our data structures in your persistent memory workloads:
  https://github.com/pmem/libpmemobj-cpp

- Try PMEMKV in your C/C++, Java*, Python* apps
  - Customizable Key/Value data storage:
    https://github.com/pmem/pmemkv

- Provide your feedback.
Thank You

Questions?