Storing STL Containers on NVM

Persistent Programming in Real Life (PIRL) 2019
Topics Covered

• Data Characteristics in In-Memory Databases
  • The Importance of Write-Once Data

• Using PMR and Representation-Aware Containers for NVM

• Performance Evaluation
Background

- Hyrise is a Research Database developed at HPI in Potsdam, Germany

- Relational, in-memory, HTAP, open-source, C++2a

- Research topics: Self-Driving, NVM, Heterogeneous Replication, Footprint Reduction
  - Note that not everyone is working on NVM

- Similar in many concepts to SAP HANA
Data Characteristics in In-Memory Databases

Original value proposition of NVM:
Persistency closer to CPU, fast recovery
BUT: Performance hits for random access

Current value proposition of NVM:
Higher capacity and lower cost than DRAM, less performance impact than SSDs, faster recovery

Base data
(needed after a restart)

Heavily accessed, many writes

Log Buffer
Dyn. Indexes
Hot table data

Join Hashmaps
Position lists

Traditional DRAM territory

Scratch data
(worthless after a restart)

Result Cache
Statistics
Stat. Indexes
Cold table data

Join Spill-Over

Few reads, few writes

NVM as high-capacity scratch space
Goals

• Allow an existing code base to benefit from NVM; minimize the necessary changes
  • Avoid making more code than necessary NVM-aware
  • Make it easy for non-NVM people
• Enable the use of data structures that do not yet have an NVM-aware equivalent

• Limitations that make our live easier:
  • We only write this data once
  • We do not have to care about atomicity
Disclaimer

• Casting memory that came from somewhere into a C++ object is undefined behavior

• ... but it works.

• This might break if the program is recompiled using a different compiler or a different STL

• ... and you won't even notice it.

• For this to be used in a product, more work needs to be done

• ... but we are researchers.
Let’s take a simplified in-memory table with two columns:

```cpp
std::vector<std::tuple<double, int>> table{
    {4.2, 5},
    {1.4, 7},
    {3.5, 2}
};
```

... and build a static (immutable) index on the first column:

```cpp
using Value = double;
using Position = std::size_t;
using InvertedIndex = std::map<Value, Position>;

for (size_t position = 0; position < table.size(); ++position) {
    index->emplace(std::get<0>(table[position]), position);
}
Code Example

• So far so good. But what if we want to store that index on NVM?

• For an immutable chunk, the index is created but never updated

• Surely, libpmemobj++ can help?

• No tree-based map in libpmemobj++, but in libpmemobj:

  * four implementations of tree maps:
  ** ctree - Crit-Bit using tx API of libpmemobj
  ** btree - B-tree using tx API of libpmemobj
  ** rtree - Radix-tree using tx API of libpmemobj
  ** rbtree - red-black tree using tx API of libpmemobj
First attempt with pmemobj

```c
mapc = map_ctx_init(&rbtree_map_ops, pop);
if (!mapc) { /* [...] */ }
TX_BEGIN(pop) {
    map_create(mapc, &D_RW(root)->map, NULL);
    for (size_t position = 0; position < table.size(); ++position) {
        map_insert(mapc, D_RW(root)->map, std::get<0>(table[position]), new_store_item(position).oid);
    }
} TX_ONABORT { /* [...] */ }
} TX_END
```

Observations:

- We might be able to write a C++ wrapper for this
- However, we do not have a nice std::map anymore that we can pass around
- The rbtree implementation is limited to uint64_t keys – what if we want strings?
- This gives us more consistency guarantees that we care for
The path to STL containers on NVM

• Can we simply allocate our std::map on NVM?

```cpp
template <class T>
class nvm_allocator {
    nvm_allocator() {
        // create or load pool
    }

    [[nodiscard]] T* allocate(std::size_t n) {
        return &pmem::obj::make_persistent
            <char[]>(n * sizeof(T))[0];
    }
}
```

using InvertedIndex = std::map<.../>,
    nvm_allocator<.../>;

Issues:

• Data in map is not flushed
• Early crashes lead to persistent leaks
• The nvm_allocator is all over the place
• Remapping invalidates pointers
The path to STL containers on NVM

• Let’s track the allocations and use them to flush:

```cpp
def nvm_allocator() {
    root.inflight_allocations =
        pmem::obj::make_persistent<pmem::obj::
            experimental::vector</*[...]*/>>()();
}

[[nodiscard]] T* allocate(size_t n) {
    T* pointer;
    pmem::obj::transaction::run(pool, [&] {
        pointer = static_cast<T*>(
            resource()->allocate(n * sizeof(T)));
        root.inflight_allocations.emplace_back(pointer, n);
    });
    return pointer;
}

void persist() {
    for (auto& [p, n] : *root.inflight_allocations) {
        pmemobj_persist(pool.handle(), p, n);
    }
    root.inflight_allocations->clear();
}
```

Issues:

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The path to STL containers on NVM

- If instead of T*, we store PMEMoids in the list, we can also use it to free incomplete data:

```cpp
// When reopening the pool:
for (const auto& pmemoid : *root().inflight_allocations) {
    auto ret = pmemobj_tx_free(pmemoid)
    Assert(!ret, "free failed");
}
```

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The path to STL containers on NVM

- Currently, the nvm_allocator is part of the type definition:
  ```cpp
  using InvertedIndex = std::map</*[...]*/,
  nvm_allocator</*[...]*/>;
  ```
- We do not want to drag it through the code base
- Also, we want to be able to store some indexes on DRAM and some on NVM while using the same code

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Polymorphic Memory Resources

- PMR to the rescue

```cpp
using InvertedIndex = std::map</*[...]*///, std::pmr::polymorphic_allocator</*[...]*///>
```

- Instead of making the nvm_allocator a type parameter, we pass in an
  nvm_memory_resource that supports methods such as allocate and deallocate

- For the same type, we can pass nvm_memory_resources or default_memory_resources
  into the constructor of the object

- The nvm_memory_resource holds the information about the pools

- In Hyrise, we use PMR for NUMA-aware allocations anyway, so there is no change needed
Polymorphic Memory Resources

using InvertedIndex = std::map</*[...]*/,
polymorphic_allocator</*[...]*/>>;

auto allocator = polymorphic_allocator</*[...]*/>{
 &nvm_memory_resource::get()};

auto index = InvertedIndex {allocator};

• For simplicity, we limit the example to a single memory resource (i.e., a single pool)

Issues:

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• Remapping invalidates pointers
Polymorphic Memory Resources

- One more thing: Because PMRs propagate into PMR-aware child containers, we get support for nested STL containers for free

```
using Value = std::basic_string<char, /*[...]*/,
polymorphic_allocator<char>>;

using InvertedIndex = std::map<Value, /*[...]*/,
polymorphic_allocator</*[...]*/>>;

auto allocator = polymorphic_allocator</*[...]*/>{
  &nvm_memory_resource::get()};

auto index = InvertedIndex {allocator};
```

Issues:

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Representation-Aware Containers

- Currently, all pointers become invalid after remapping the pool somewhere else
- Easy to verify with –pie
- Internally, the std::map uses T* to reference other nodes in the tree
- We will never get T* to be NVM-aware

Issues:
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Representation-Aware Containers

• Instead of native pointers, the containers should use "fancy pointers“ that can deal with different positions after remapping

• O’Dwyer and Steagall [1] call this requirement *representation awareness*

• Previous uses are in IPC, where two processes might share the same memory, mapped at different locations
  • A tree written by one process should be readable by the other
  • *The benefit of boost::interprocess::offset_ptr is that if a memory region is mapped into the address space of two different processes, then every offset_ptr residing in the mapped region will identify the same object no matter which process is asking — as long as the identified object also resides in the mapped region.*

Representation-Aware Containers

- By simply adding pointer traits to our allocator, we make sure that the reference to a tree’s child nodes is stored as an offset to the position of the pointer:

```cpp
template <class T>
class polymorphic_offset_allocator {
public:
    typedef T value_type;
    typedef boost::interprocess::offset_ptr<T> pointer;
    typedef const boost::interprocess::offset_ptr<T> const_pointer;
    // [...]
};
```

- The index is now readable after remapping

Issues:

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Representation-Aware Containers

- Why don’t we use persistent_ptr?
- Remember that the polymorphic allocator is used for both, objects stored on DRAM and objects stored on NVM
- We cannot get a persistent_ptr for a DRAM object
Representation-Aware Containers

• Limitation: This currently only works in libc++

• In libstdc++, "node-based containers don't use allocator's pointer type internally“ [1]
  
  • Supporting representation-aware containers would be a breaking ABI change
  
  • Issue is unchanged since 2016

It's a bug. It is hard to fix without breaking the ABI, and not breaking the ABI is higher priority than supporting fancy pointers. I hoped to get time to finish the work for GCC 8, and for GCC 9, but now maybe it will happen next year for GCC 10.

Of course if somebody wants it badly enough they could fix the bug themselves, or contract somebody to do it. GCC is free software after all. I'd be happy to share my work-in-progress patches if somebody else wanted to fix it instead of waiting for me to do the other 100 things on my TODO list first.

Screenshot from: https://www.reddit.com/r/cpp/comments/b1fyc9/does_anyone_know_when_libstdc_will_stop_using_raw/
Performance Analysis: Creation

Creating a map (rb-tree) with 5M random entries

Potential for new allocators

Trees are one of the harder examples, as they include a high number of individual allocations. For hash maps, which can be pre-allocated, the overhead of our approach is lower.

Using clang 7.0.1-6.fc29, libcxx 7.0.0-1.fc29, boost 1.70.0 (built with libc++), Fedora 29, max RSS for baseline 393680 kB
Performance Analysis: Read Access

Reading 100k entries from map with 1M entries

- STL Baseline (1)
- (1) + PMR Allocator + Offset Pointers (2)
- Non-Persistent NVM (memkind) (3)
- Our Approach (4)
- nvm/map_rbtree (5)

Can’t explain this yet

Is this required overhead?
Topics NOT Covered

Migrations

• Multiple pools

• We can only migrate entire pools – how to balance flexibility and fragmentation?

Integration into Hyrise, our research database

• How to decide which part of the data should be migrated from DRAM to NVM and back?

• How to selectively skip recovery for chunks that are already stored on NVM?
Future Work

• We spend a lot of time in tracking allocations
  • Using a simpler allocation algorithm could make this cheaper
  • Easiest example: a monotonic_buffer_resource would mean that we don’t have to track anything anymore
  • This also makes migration easier
  • How to balance anti-fragmentation and performance?
• Make this usable
  • Right now, this is a prototype to understand feasibility and performance implications
  • Clean up code, verify implementation
Addenda

Based on the discussions during and after the talk, this slide was added to the published version

• If polymorphic objects are stored, the vtable might move due to ASLR or changes in the code. This will cause the vptr to point to an invalid address.
  • This is the same with interprocess mapping (offset_ptrs original use case)
  • Most NVM-aware data structures likely suffer from a similar problem
  • I am not aware of a solution to this other than not to store polymorphic objects
  • Solving this would be a great step towards persistency as a first-class citizen
Summary / Take Aways

• You do not need new data structures to benefit from NVM if you write data once
• Sometimes, using NVM-aware implementations might even hurt your performance

• We showed how you can adapt STL containers to be stored on and recovered from NVM
• The performance is dominated by the cost of persistent NVM allocations

• Currently, this is (a) libc++ only, and (b) illegal
• If you know anyone from libstdc++, please pitch representation-aware containers
• If you know someone in the committee, please bug them about std::bless (and don't rat me out)