Designing a User-Friendly Java NVM Framework

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Programming NVM – The Good

- Non-Volatile Memory (NVM) offers an enticing combination of performance, capacity, and persistency
- Programs will no longer have to serialize data out to secondary storage for durability
- Now have access to persistent memory at a byte-level granularity

Programming NVM – The Bad

Leveraging NVM to create persistent applications is tricky:

- Entire memory hierarchy is not durable
  - Processor caches are volatile
- Data must be written back from caches to achieve persistency
  - Perform combination of non-temporal stores, cacheline writebacks (CLWBs), and fences
- Software measures must be taken to ensure failure-atomicity for a collection of writes
  - Hardware only guarantees atomicity at cacheline level granularity
- To simply this process, frameworks for developing persistent applications have been introduced

Outline

1. Describe current NVM framework landscape
   - Current NVM framework features
   - Drawbacks of current frameworks
2. Present some of my work on creating a new high-level Java NVM framework
   - New NVM programming model
   - How we implement our model
   - Creating a high-performance model implementation

Current Techniques for Persistent Applications

- Manual – add explicit assembly instructions and system calls
- Industrial Libraries and Frameworks
  - Persistent Memory Development Kit (PMDK)
- Academic Frameworks
  - Atlas, NVL-C, Espresso, Mnemosyne, ARP, NVThreads, NV-Heaps, more

Current NVM Frameworks – Traits

In current NVM frameworks the user must perform some combination of the following:

- Manually identifying persistent objects
- Wrapping stores needing persistent or transactional support
- Using previously persistently-marked data structures or libraries

Current NVM Frameworks – Drawbacks

Drawbacks of current NVM frameworks:

- Need many markings to identify persistent objects and direct persistent store mechanisms
- Easy to introduce bugs
  - Correctness bugs – markings are missing
  - Performance bugs – too many markings
- Difficult for the compiler to perform optimizations
  - Programmer's intention is not visible to the compiler

Misalignment with High-Level Languages

Most NVM frameworks are designed for C/C++, not managed languages like Java, $C^{\#}$, Scala, etc.

- Cannot use existing built-in libraries
  - Built-ins do not contain necessary persistent markings
- Expose low-level features to programmer
  - Does not abstract away enough details
- Do not perform runtime checks
  - Catch problems before more damage is done

Contribution: Create a New NVM Framework

- Solution to existing shortcomings: Design a new NVM framework
- Focus on programmability first
  - Rely on compiler optimizations to get high performance
- Make framework tailored to managed-languages
  - Build upon their automatic memory management support and transparent object representation

Desirable Traits

Three important programmability goals for our NVM framework's programming model:

1. Require minimal markings by programmer
2. Making libraries and other pre-existing codes persistent should be simple
3. Failure-atomic support should be provided and need only minimal markings

New NVM Framework Highlights

❶ Require minimal markings by programmer

- In our model the user must identify only a ***durable root set*** and failure-atomic regions
- Durable Root Set: the set of objects directly referred to at recovery time
- The runtime then ensures all objects reachable from the durable root set are in NVM
  - *Transitive closure* of the durable root set is placed in NVM automatically
  - Requires dynamically moving objects to NVM throughout execution
- Durable roots should be program's container/parent objects. (E.g. the `DATABASES` map object in H2's Engine.java)

New NVM Framework Highlights

❷ Making libraries and other pre-existing codes persistent should be simple

- Extend the semantics of existing JVM bytecodes
  - E.g. `putfield`, `aastore`, others
- Existing code can now be persistently handled if reachable from a durable root

New NVM Framework Highlights

❸ Failure-atomic support should be provided and need only minimal markings

- Label only failure-atomic regions' start and finish
- The runtime then ensures all persistent objects within the region are properly logged

Runtime Responsibilities

Our programming model requires the framework to:

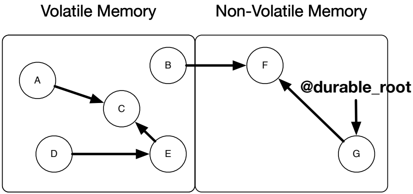
❶ Dynamically detect and monitor the transitive closure of durable roots

- Must ensure everything reachable from a durable root is in NVM

❷ Ensure stores to persistent objects are performed correctly

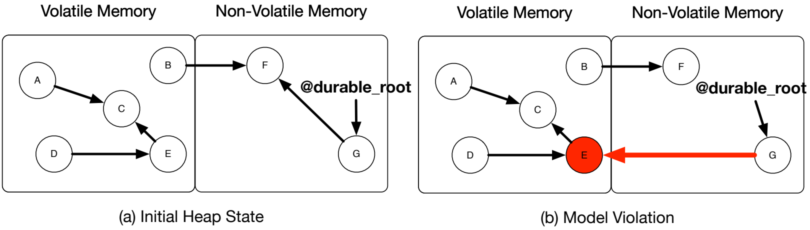
- Behavior is dependent on whether the store is in an failure-atomic region or not

Dynamically Moving Objects to NVM

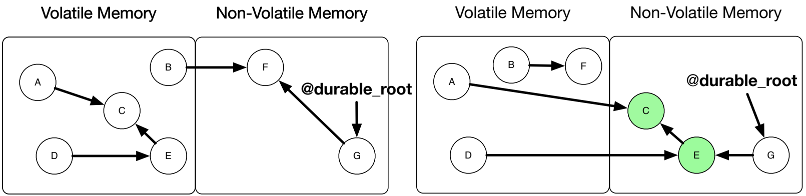


(a) Initial Heap State

Dynamically Moving Objects to NVM



Dynamically Moving Objects to NVM



(a) Initial Heap State (b) Runtime Maintaining Correct Heap State

Ensuring Persistent Stores

Two cases: outside and inside failure-atomic regions

- Outside failure-atomic region - enforce sequential persist order
  - after each store perform CLWB and FENCE
- Inside failure-atomic region - enforce atomic commit at end
  - Epoch Persistency – stores within region can be reordered
  - Logging should be performed to create appearance of atomicity

Recovery Procedure

At recovery time we expect the program to:

1. Check if data from previous execution exists
2. Load previous data if available
   - Checking and Loading is performed by interacting with `@durable_roots`
3. Jump to proper execution point
   - E.g. Server-side event loop

Implementing New Model

- Model requires many guarded actions before accesses
  - Storing to `@durable_root`?
  - Storing to an object reachable from a `@durable_root`?
  - In a failure-atomic region?

Solution:

1. Add extra object header word to contain persistent state and metadata
2. Extend the semantics of several JVM bytecodes to perform the necessary checks and guarded actions
   - More details in papers

JVM Semantic Extension Example

Modified store operation

```
procedure storeField(Object holder, Field f, Value v)
    writeField(holder, f, v)
end procedure
```

JVM Semantic Extension Example

Modified store operation

```
procedure storeField(Object holder, Field f, Value v)
    [Start Added Code]
    if isPersistent(holder) then
        Move value to NVM if necesssary
        Log (object, field, value) tuple if in failure-atomic region
    end if
    [End Added Code]
    writeField(holder, f, v)
    [Start Added Code]
    if isPersistent(holder) then
        Add a cacheline writeback for the store
        Add fence if not in failure-atomic region
    end if
    [End Added Code]
end procedure
```

Optimizing Implementation

Our implementation collects profiling information to limit the performance overhead:

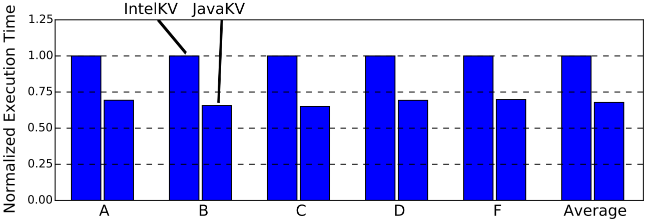
- Limit check overhead
  - Predict whether a given object access site usually handles persistent or volatile objects
  - Can reduce check overhead for sites predicted to handle volatile objects
- Preallocate objects in NVM
  - Predict whether a given allocation site usually allocates objects which become reachable from a `@durable_root`
  - Can originally allocate these objects in NVM to limit object movement

Evaluation Environment

- Modify Maxine 2.0.5
  - Research JVM originally developed by Oracle
- Run on system containing two 24-core Intel® second generation Xeon® Scalable processors (codenamed Cascade Lake)
- System has 128GB Intel Optane DC persistent memory modules

Performance Results

- IntelKV: Intel's pmemkv library (kvtree3 engine) using its Java API
- JavaKV: Implementing same data structure used in pmemkv in our framework
- Use Quickcached (Java KV-Store) and run YCSB



- JavaKV reduces execution time by 32%
- Have more (& fairer) results and comparisons in papers

Papers About Our Model & Framework

Motivating the need for new Java-specific NVM programming model – **ManLang'18**: Defining a High-level Programming Model for Emerging NVRAM Technologies

How to limit our framework's runtime check overhead on volatile objects – **VEE'19**: QuickCheck: Using Speculation to Reduce the Overhead of Checks in NVM Frameworks

How our framework dynamically moves objects between DRAM and NVM – **PLDI'19**: AutoPersist: An Easy-To-Use Java NVM Framework Based on Reachability

Thank You!

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Questions?