Redesigning LSMs for Nonvolatile Memory with NoveLSM

Sudarsun Kannan, Nitish Bhat*, Ada Gavrilovska*, Andrea Arpaci-Dusseau, Remzi Arpaci-Dusseau

University of Wisconsin-Madison, Georgia Institute of Technology*
Key-Value Stores

Key-Value Stores

Keys

100

200

Arbitrary Value

{red car, honda, john}

Widely used

Google
facebook
Quora
Pinterest
mongoDB
Lawrence Livermore National Laboratory
redhat
ethereum
LSM-based Key-Value Stores

Log-structured Merge Tree (LSM)

- Write optimized data structure used in key-value stores

Originally designed for slow hard drives

- In memory buffering, batched, and sequential writes to disk
- High write amplification

Several LSM implementations

- LevelDB (Google), RocksDB (Facebook), Cassandra
- SSD optimized LSMs WiscKey (FAST ‘16), VT-tree (FAST ‘13)
Moving Towards NVM Era

Fast byte-addressable and persistent NVM technologies expected soon

<table>
<thead>
<tr>
<th>Hard Drives</th>
<th>SSD</th>
<th>NVM</th>
<th>DRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW:</td>
<td>2.6 MB/s</td>
<td>250 MB/s</td>
<td>5-10 GB/s</td>
</tr>
<tr>
<td>H/W Lat:</td>
<td>7.1 ms</td>
<td>68 us</td>
<td>500ns - 2us</td>
</tr>
<tr>
<td>Persistence:</td>
<td>Blocks</td>
<td>Blocks</td>
<td>Cache-line</td>
</tr>
</tbody>
</table>
Adding NVM makes LSMs faster?

Why use LSMs in NVM?

- Expected to co-exist with block storage
- **Rewriting production-level LSMs not easy!**

Current LSMs are not designed to exploit storage byte-addressability

Our study shows significant software overheads

1. Serialization and deserialization cost
2. Compaction cost
3. Logging cost
4. Lack of read parallelism
Our Solution: NoveLSM

Use existing LSM and…

1. Reduce serialization – Persistent Skip List
2. Reduce compaction – Direct NVM mutability
3. Reduce logging cost – In-place commits
4. Improve parallelism – Read parallelism across levels

Evaluation Summary:

Evaluation with emulated NVM using benchmarks and application traces
NoveLSM reduces write latency by up to 3.8x and read latency by 2x
Orders of magnitude faster recovery
Outline

Introduction

Background on LevelDB

Motivation
- High serialization, compaction, and logging cost
- Lack of parallelism

NoveLSM Design
- Persistent memtable, NVM mutability, In-place commits
- Read parallelism

Evaluation

Conclusion
LSM-based LevelDB

We study (and extend) LevelDB due to its wider use and simplicity

Put(37, val)

Application

Storage Log

Head

Tail

On-disk log for recovering from failure

In-memory skip list to buffer updates in memory

DRAM Memtable

DRAM Immutable

When buffer full, writes compacted to storage and written sequentially

String Sorted Tables (SST)

Level 0

Level 1

Level 2

Each level is 10x larger than previous level

When a level is full, data moved to next level by merging

When a level is full, data moved to next level by merging
Write Operation

Put(23, val)

Application

DRAM Memtable

DRAM Immutable

Level 0

Level 1

Storage Log

Head

Tail

+$\infty$

+$\infty$

+$\infty$
Write Operation

Put(45, val)

Application

DRAM Memtable

DRAM Immutable

Level 0

Level 1

Storage Log

<table>
<thead>
<tr>
<th>Head</th>
<th>23, value</th>
<th>C</th>
<th>Tail</th>
</tr>
</thead>
</table>
Write Operation

Put(37, val)

Storage Log

<table>
<thead>
<tr>
<th></th>
<th>23,value</th>
<th></th>
<th>45,value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>C</td>
<td>Tail</td>
<td></td>
</tr>
</tbody>
</table>

DRAM Memtable (FULL)

DRAM Immutable

Level 0

Level 1
Write Operation

Put(37, val)

Storage Log
Head | 23,value | C | 45,value | C | Tail

Initiate background compaction

Level 0

Level 1
Write Operation

Storage Log
Head 23,value | C 45,value | C 37,value | C Tail

Initiate background compaction
Read Operation

Get ("107")

Application

DRAM Memtable

Search memtable

DRAM Immutable

Search Immutable memtable

Level 0

0 1 2 3 ....

Level 1

0 1 2 3 4 5 6 7

Range

Blocks

d 12
a 5-6

Range

Blocks

a 0 – 3
r 4 – 8
...

Level 1

0 1 2 3 ... ... ... 100 101 ...
Read Operation

Get ("107")

Application

DRAM Memtable

Search memtable

DRAM Immutable

Search Immutable memtable

Index lookup

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>12</td>
</tr>
<tr>
<td>a</td>
<td>5-6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0-3</td>
</tr>
<tr>
<td>r</td>
<td>4-8</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Index lookup

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0-10</td>
</tr>
<tr>
<td>b</td>
<td>11-15</td>
</tr>
<tr>
<td>...</td>
<td>17</td>
</tr>
<tr>
<td>k</td>
<td>100</td>
</tr>
</tbody>
</table>
Read Operation

Get ("107")

Application

DRAM Memtable

Search memtable

DRAM Immutable

Search Immutable memtable

Deserialize

Index lookup

Index lookup

Index lookup

Index lookup

Range | Blocks
---|---
d | 12
a | 5-6

Range | Blocks
---|---
a | 0-3
r | 4-8
... | ...

Range | Blocks
---|---
a | 0-10
b | 11-15
... | 17
k | 100
Outline

Introduction

Background on LevelDB

Motivation

- High serialization, compaction, and logging cost
- Lack of parallelism

NoveLSM Design

- Persistent memtable, NVM mutability, In-place commits
- Read parallelism

Evaluation

Conclusion
How do LSMs perform on NVM?

LevelDB: Use NVM instead of SSD for storing on-disk SSTable
How do LSMs perform on NVM?

LevelDB: Use NVM instead of SSD for storing on-disk SSTable

Problem: No byte addressable commercial NVM
- Use DRAM and increase latency by 5x (delay writes)
- Use thermal throttling to reduce NVM bandwidth

![Diagram of LSM levels and NVM organization](attachment:image.png)
NVM Gains when Replacing SSD

Analyze with 4 KB value size and 16 GB total data size

Random write gains only 4x even with 80x faster NVM

Read latency gains less than 1.5x
1. High (De)Serialization Cost

Put(37, val)

Application

DRAM Memtable (FULL)

DRAM Immutable

Initiate background compaction

Level 0

Level 1
1. High (De)Serialization Cost

Put(37, val)

Application

DRAM Memtable (FULL)

DRAM Immutable (FULL)

Initiate background compaction

Level 0

Level 1
I. High (De)Serialization Cost

Put(37, val)

Application

DRAM Memtable (FULL)

DRAM Immutable (FULL)

Initiate background compaction

Block 0 | Block 1

Level 1

Serialization of in-memory data to SSTable storage blocks
1. High (De)Serialization Cost

Serialization of in-memory data to SSTable storage blocks
Deserialization of block data to in-memory data during read
1. Deserialization Cost – Read Operation

Deserialization and its related data copy cost increases with value size.
2. High Write Compaction Cost

Compaction time consuming and high overhead
- In-memory structures must be serialized to block format
- Can trigger chain compactions across lower levels
2. High Write Compaction Cost

Compaction cost increases with value size

50% - 88% spent just waiting on compaction stall
3. High Write Logging Cost

Put(23, val)

Application

Storage Log

DRAM Memtable

DRAM Immutable

Level 0

Level 1
3. High Write Logging Cost

Amplification: LSM updates are written to log, memtable, and SSTable
- LevelDB does not sync log updates for performance
- Log updates are appended with a checksum
3. High Write Logging Cost

![Bar Chart]

- **Latency (micros/op)**
- **Log Write**

- **4K**
- **8K**
- **16K**
4. Lack of Parallelism – Sequential Reads

Get ("107")

Application

DRAM Memtable

Search memtable

DRAM Immutable

Search Immutable memtable

Level 0

0 1 2 3 ....

Level 1

0 1 2 3 4 5 6 7

Level 1

0 1 2 3 ... ... ... ... 100 101 ...
4. Lack of Parallelism – Sequential Reads

Get (“107”)

Application → DRAM Memtable → Search memtable

→ DRAM Immutable → Search Immutable memtable

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>12</td>
</tr>
<tr>
<td>a</td>
<td>5-6</td>
</tr>
</tbody>
</table>

Level 0: 0 1 2 3 ....

Level 1: 0 1 2 3 4 5 6 7

Level 1: 0 1 2 3 ... 100 101 ...

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0-3</td>
</tr>
<tr>
<td>r</td>
<td>4-8</td>
</tr>
<tr>
<td>...</td>
<td>....</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0-10</td>
</tr>
<tr>
<td>b</td>
<td>11-15</td>
</tr>
<tr>
<td>...</td>
<td>17</td>
</tr>
<tr>
<td>k</td>
<td>100</td>
</tr>
</tbody>
</table>
4. Lack of Parallelism – Sequential Reads

Get (“107”)

Application

DRAM Memtable

Search memtable

DRAM Immutable

Search Immutable memtable

Level 0

0 1 2 3 ....

Level 1

0 1 2 3 4 5 6 7

Level 1

0 1 2 3 ... ...

Range | Blocks
--|---
d | 12
a | 5-6

Index lookup

Index lookup

Index lookup

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
</table>
a | 0 – 3
r | 4 – 8
... | ... |

<table>
<thead>
<tr>
<th>Range</th>
<th>Blocks</th>
</tr>
</thead>
</table>
a | 0 – 10
b | 11 – 15
... | 17
k | 100

Huge S/W cost
Outline

Introduction

Background on LevelDB

Motivation
  - High serialization, compaction, and logging cost
  - Lack of parallelism

NoveLSM Design
  - Persistent memtable, NVM mutability, In-place commits
  - Read parallelism

Evaluation

Conclusion
NonVolatile Memory LSM (NoveLSM)

Reduce serialization – NVM memtable designed with persistent skip list

Reduce compaction – Enable direct mutability on NVM

Reduce logging cost – In-place transactional commits to NVM memtable

Improve read parallelism – Read LSM levels in parallel
I. Reduce Serialization: Immutable NVM

High DRAM memtable to storage SSTable serialization cost

Idea: Introduce byte-addressable persistent NVM skip list

Diagram:
- Application
  - DRAM Memtable
    - DRAM Immutable
      - NVM Immutable Memtable

Levels:
- Level 0
- Level 1
Immutable Memtable: Persistent Skip List

Skip lists - non-persistent structures with fast probabilistic writes and read

Our goal: make skip lists persistent for exploiting NVM byte-addressability

Insert ("64", val)

Addr: 0x1000

In-memory Skip List

Insert ("64", val)
Designing Persistent Skip List

Persistent skip list created by mapping memory from NVM

Uses offset in the mapped memory instead of virtual address

To read/recover, simply get the root offset and traverse using offsets

Insert ("64", val)

Addr: 0x1000, Offset: 0

Memory-mapped region in a file
Immutable NVM Design

Reduce serialization with a immutable persistent skip list

Put(37, val)

Application

DRAM Memtable (FULL)

DRAM Immutable

NVM Immutable Memtable

Level 0

Level 1
Immutable NVM Design

Reduce serialization with a immutable persistent skip list

\textbf{Put(37, val)}

\begin{itemize}
  \item Application
  \item DRAM Memtable (FULL)
  \item DRAM Immutable (FULL)
  \item NVM Immutable Memtable
\end{itemize}

Level 0

Level 1
Immutable NVM Design

Reduce serialization with a immutable persistent skip list

Put(37, val)

Application

DRAM Memtable (FULL)

DRAM Immutable (FULL)

NVM Immutable Memtable

Copy data to large NVM memtable w/o serialization

Reads avoid deserialization
Immutable NVM Design

Reduce serialization with a immutable persistent skip list

**Put(37, val)**

Application

DRAM Memtable (FULL)

DRAM Immutable (FULL)

NVM Immutable Memtable

Copy data to large NVM memtable w/o serialization

Reads avoid deserialization

Compaction frequency dependent on DRAM memtable size

Increasing DRAM buffer increases memory use by 2x

Recovery cost increases

Log not committed - data loss!
2. Reducing Compaction: NVM Mutability

High compaction cost even with immutable memtable design
2. Reducing Compaction: NVM Mutability

High compaction cost even with immutable memtable design

Application

- DRAM Memtable (FULL)
- DRAM Immutable (FULL)

Level 0

- Level 1

- NVM Memtable
- NVM Immutable
2. Reducing Compaction: NVM Mutability

High compaction cost even with immutable memtable design

Idea: Exploit byte addressability and directly update NVM memtable
2. Reducing Compaction: NVM Mutability

High compaction cost even with immutable memtable design

Idea: Exploit byte addressability and directly update NVM memtable

Application

\text{Put}(100, \text{val})

\text{DRAM Memtable (FULL)} \quad \text{NVM Memtable}

\text{DRAM Immutable (FULL)} \quad \text{NVM Immutable}

Level 0

Level 1
2. Reducing Compaction: NVM Mutability

High compaction cost even with immutable memtable design

Idea: Exploit byte addressability and directly update NVM memtable

Direct NVM mutability provides sufficient time for DRAM compaction
- Reduces foreground stall

NVM memtable persistent – data not lost after failure
3. Reducing Logging Cost: In-place Commits

Problem: Writing to log before memtable has high overhead

<table>
<thead>
<tr>
<th>Storage Log</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
</tr>
</tbody>
</table>

**Put(37, val)**

Application

- **DRAM Memtable**
- **DRAM Immutable (FULL)**
- **NVM Memtable**
3. Reducing Logging Cost: In-place Commits

Problem: Writing to log before memtable has high overhead

Storage Log

| Head | 23, value | C | 45, value | C | 37, value | C | Tail |

- DRAM Memtable (FULL)
- DRAM Immutable (FULL)
- NVM Memtable
3. Reducing Logging Cost: In-place Commits

Problem: Writing to log before memtable has high overhead

Idea: Avoid logging for NVM memtable with in-place commits

Storage Log

| Head | 23, value | C | 45, value | C | 37, value | C | Tail |

DRAM Memtable

DRAM Immutable (FULL)

NVM Memtable

begin_trans()

skiplist.insert(100, val)

dend_trans()
3. Reducing Logging Cost: In-place Commits

Problem: Writing to log before memtable has high overhead

Idea: Avoid logging for NVM memtable with in-place commits

Storage Log

| Head | 23,value | C | 45,value | C | 37,value | C | Tail |

Application

Put(100, val)

NVM Memtable

begin_trans()

skiplist.insert(100, val)

end_trans()

NVM memtable recovery – remap map file and find root pointer
## 4. Increase Parallelism: Read Threading

Solution: Parallelize search using dedicated threads

![Diagram showing parallel read threads]

- Thread management overhead can be expensive
- Bloom filters to launch threading only if DRAM memtable is a miss
Outline

Introduction

Background on LevelDB

Motivation
  - High serialization, compaction, and logging cost
  - Lack of parallelism

Novel LSM Design
  - Persistent memtable, NVM mutability, In-place commits
  - Read parallelism

Evaluation

Conclusion
Evaluation

Benchmarks and application traces
- Dbbench – Widely used LSM benchmark
- YCSB cloud benchmark (see paper)

Evaluation Goals
- Immutable memtable reduce (de)serialization cost?
- Mutable memtable reduce compaction cost?
- When read parallelism is effective?
- Reducing logging improves restart performance?

Evaluation Methodology
- 16 GB database size and vary values sizes
- SSTables always placed in NVM for all approaches
Immutable Memtable: Serialization Impact

LevelDB-NVM – Vanilla LevelDB using NVM for SSTables

NoveLSM [immut-small] – 2GB NVM memtable

NoveLSM [immut-large] – 4GB NVM memtable
Immutable memtable provides marginal gains for writes
- Compaction cost limits benefits

Reduces read deserialization reducing latency by 2x
Reducing Compaction: Mutable Memtable

RocksDB – Facebook’s implementation, optimized for SSD
- Provides parallel compaction
- SSTable uses plain table (cuckoo hashmap) for random access

NoveLSM [mutable] – Direct mutable 4 GB NVM memtable

NoveLSM [mutable +para] – Mutable NVM + read parallelism

NoveLSM [mutable+para +NoSST] – All mutable memtable without SST
Reducing Compaction: Mutable Memtable

Mutable NVM memtable provides up to 3.8x gains over LevelDB

RocksDB parallel compaction and plain table storage effective

NoveLSM [mutable+para +NoSST] – upto 50% gain even over RocksDB
Mutable NVM memtable improves read performance even over RocksDB

Read parallelism (mutable+para) provides gains for larger value sizes
- NoveLSM provides 73% gains even over RocksDB
For LevelDB and RocksDB, we increase DRAM memtable size

For NoveLSM, we increase persistent NVM memtable size

NoveLSM reduces log recovery cost by more than 99%
Summary

Motivation
- Simply adding NVMs to existing LSMs for storage not sufficient
- Eliminating S/W overhead (e.g., serialization, compaction) is critical

Solution
- NoveLSM - byte-addressable and persistent data structures
- Reduce serialization, compaction, and logging cost
- Improve read parallelism

Evaluation
- NoveLSM reduces write latency by up to 3.8x and read latency by 2x
- Makes restarts significantly fast
Conclusion

We are moving towards a storage era with microsecond latency

Eliminating software overhead is critical
- We take first step towards redesigning existing LSMs for NVM

Future work
- Rethink LSMs from scratch for NVM hardware-level performance

More opportunities!
Thanks!

Questions?