RECIPE : Converting Concurrent DRAM Indexes to Persistent-Memory Indexes

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*On the job market
Persistent Memory (PM)

- New storage class memory technology
- Performance similar to DRAM
- Non-volatile & high-capacity
  - Up-to 6TB on a single machine
Indexing on PM

• PM has high capacity and low latency
  • 6TB on a single machine $\rightarrow$ 100 billion 64-byte key-value pairs
• Indexing data on PM is crucial for efficient data access
PM Indexes

PM Indexes need to achieve three goals simultaneously:

- **Cache Efficiency**
- **Concurrency**
- **Crash Consistency**
PM Indexes

• Cache Efficiency
  • Persistent memory is attached to the memory bus
  • 3x higher latency than DRAM → More cache-sensitive
PM Indexes

• Concurrency
  • High concurrency is necessary for scalability on any modern multicore platform
PM Indexes

• Crash Consistency
  • CPU cache is still volatile
  • Arbitrarily-evicted cache lines $\rightarrow$ Persistence reordering
PM Indexes

• Crash Consistency
  • CPU cache is still volatile
  • Arbitrarily-evicted cache lines $\rightarrow$ Persistence reordering

Program order
write (log);
write (commit);
PM Indexes

• Crash Consistency
  • CPU cache is still volatile
  • Arbitrarily-evicted cache lines → Persistence reordering

Persistence reordering:
write (log);
write (commit);
Reordered
PM Indexes

- Crash Consistency
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  - Arbitrarily-evicted cache lines $\rightarrow$ Persistence reordering
**PM Indexes**

- **Crash Consistency**
  - CPU cache is still volatile
  - Arbitrarily-evicted cache lines $\rightarrow$ Persistence reordering
    - **Flush**: persist writes to PM
    - **Fence**: ensure one write prior another to be persisted first

Consistent persistence ordering:
- write (log)
- flush (log)
- fence ()
- write (commit)
- flush (commit)
- fence ()
Challenge in building PM indexes

Correctness condition: return previously inserted data without data loss or corruption
Challenge in building PM indexes

Concurrency and crash consistency interact with each other, a bug in either can lead to data loss
Bug in Concurrent PM Index

• We found bugs in FAST&FAIR [FAST’18] and CCEH [FAST’19]

• FAST&FAIR: Concurrent PM-based B+Tree
  • One bug in concurrency mechanism
  • Two bugs in recovery mechanism

• CCEH: Concurrent PM-based dynamic hash table
  • One bug in concurrency mechanism
  • One bug in recovery mechanism
How can we reduce the effort involved in building concurrent, crash-consistent PM indexes?

Insight: Isolation and Crash Consistency are similar
How can we reduce the effort involved in building concurrent, crash-consistent PM indexes?

Approach: Convert concurrent DRAM indexes to PM indexes with low effort

Insight: Isolation and Crash Consistency are similar
Already designed for cache efficiency and concurrency
DRAM Index

- Volatile
- Concurrency
- Cache Efficiency

CRASH

Vulnerable

Cache Efficiency
Challenge in Conversion

- Require minimal changes to DRAM index
  - Without modifying the original design principles of DRAM index
Insight for Conversion

- Similar semantics between isolation and consistency\(^1\)
- Isolation
  - Return consistent data while multiple active threads are running
- Crash consistency
  - Return consistent data even after a crash happens at any point

1. Steven Pelley et al., Memory Persistency, ISCA’14
Insight for Conversion

• Similar semantics between isolation and consistency

Approach: reuse mechanisms for isolation in DRAM indexes to obtain crash consistency

1. Steven Pelley et al., Memory Persistency, ISCA’14
• Principled approach to convert DRAM indexes into PM indexes

• Case study of changing five popular DRAM indexes

• Conversion involves different data structures such as Hash Tables, B+ Trees, and Radix Trees

• Conversion required modifying $\leq 200$ LOC

• Up-to 5.2x better performance in multi-threaded evaluation

https://github.com/utsaslab/RECIPE
Outline

• Overall Intuition
• Conversion Conditions
• Conversion Example: Masstree
• Assumptions & Limitations
• Evaluation
Outline

• **Overall Intuition**
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Overall Intuition for Conversion

• Blocking algorithms
  • Use explicit locks to prevent the conflicts of threads to shared data

• Non-blocking algorithms
  • Use well-defined invariants and ordering constraints without locks
  • Employed by most high-performance DRAM indexes
Overall Intuition for Conversion

- Non-blocking algorithms
  - Readers **Detect** and **Tolerate** inconsistencies
    - E.g., Ignore duplicated keys
Overall Intuition for Conversion

• Non-blocking algorithms
  • Readers Detect and Tolerate inconsistencies
    • E.g., Ignore duplicated keys
  • Writers also Detect, but Fix inconsistencies
    • E.g., Eliminate duplicated keys
Overall Intuition for Conversion

- Non-blocking algorithms
  - Readers Detect and Tolerate inconsistencies
  - Writers also Detect, but Fix inconsistencies
  - Helping mechanism\(^1\) \approx Crash Recovery\(^2\)
  - Such indexes are *inherently* crash consistent

1. Keren Censor-Hillel et al., Help!, PODC’15
2. Ryan Berryhill et al., Robust shared objects for non-volatile main memory, OPODIS’15
• Not all DRAM indexes can be converted with **low effort**

• Exploit **inherent crash recovery** in the index

• Provide **specific conditions** that must hold for a DRAM index to be converted

• Provide a matching **conversion actions** for each condition
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Three Conversion Conditions

• Condition 1: Updates via Single Atomic Store
• Condition 2: Writers fix inconsistencies
• Condition 3: Writers don’t fix inconsistencies
• Conditions are not exhaustive!
Three Conversion Conditions

• Condition 1: Updates via Single Atomic Store
• Condition 2: Writers fix inconsistencies
• Condition 3: Writers don’t fix inconsistencies
Condition 1: Updates via Single Atomic Store

- Non-blocking readers, (Non-blocking or Blocking) writers
- Updates become visible to other threads via single atomic commit store
Condition 1: Updates via Single Atomic Store

- Updates become visible to other threads via single atomic commit store
- Conversion: Add flushes after each store and bind final atomic store using fences
Three Conversion Conditions

• Condition 1: Updates via Single Atomic Store
• **Condition 2: Writers fix inconsistencies**
• Condition 3: Writers don’t fix inconsistencies
Condition 2: Writers fix inconsistencies

- Non-blocking readers and writers (don’t hold locks)
- Readers & Writers $\rightarrow$ Detect (✔), Tolerate (✔), Fix (✔)

A sequence of ordered deterministic steps

Writer 1 $\rightarrow$ Step 1 $\rightarrow$ Step 2 $\rightarrow$ Step 3 $\rightarrow$ Commit Step
Condition 2: Writers fix inconsistencies

- Non-blocking readers and writers (don’t hold locks)
- Readers & Writers → Detect (✓), Tolerate (✓), Fix (✓)
Condition 2: Writers fix inconsistencies

- Non-blocking readers and writers (don’t hold locks)
- Readers & Writers $\rightarrow$ Detect (✓), Tolerate (✓), Fix (✓)
Condition 2: Writers fix inconsistencies

- Readers & Writers $\rightarrow$ Detect (✓), Tolerate (✓), Fix (✓)
  - Inherently crash recoverable
Condition 2: Writers fix inconsistencies

- Readers & Writers $\rightarrow$ Detect (✅), Tolerate (✅), Fix (✅)
  - Inherently crash recoverable

Diagram:
- Writer 1
  - Step 1
  - Step 2
  - Crash
- PM
- Step 3
  - Commit Step
Condition 2: Writers fix inconsistencies

• Readers & Writers $\rightarrow$ Detect (✓), Tolerate (✓), Fix (✓)
  • Inherently crash recoverable
Condition 2: Writers fix inconsistencies

- Readers & Writers $\rightarrow$ Detect (✓), Tolerate (✓), Fix (✓)
  - Inherently crash recoverable
  - Conversion: Adding **flushes** and **fences** after each store and specific loads

![Diagram showing the process of thread steps with flushes and fences.]
Three Conversion Conditions

• Condition 1: Updates via Single Atomic Store
• Condition 2: Writers fix inconsistencies
• **Condition 3: Writers don’t fix inconsistencies**
**Condition 3: Writers don’t fix inconsistencies**

- Non-blocking readers, Blocking writers (hold locks)
- Readers & Writers → Detect (✓), Tolerate (✓), Fix (✗)

A sequence of ordered deterministic steps:

Writer 1:
1. Step 1
2. Step 2
3. Step 3
Commit Step

Writer 2:
1. Step 1
2. Step 2
3. Step 3
Commit Step

Update
Condition 3: Writers don’t fix inconsistencies

- Non-blocking readers, Blocking writers (hold locks)
- Readers & Writers → Detect (✓), Tolerate (✓), Fix (X)
Condition 3: Writers don’t fix inconsistencies

- Non-blocking readers, Blocking writers (hold locks)
- Readers & Writers → Detect (√), Tolerate (√), Fix (X)
Condition 3: Writers don’t fix inconsistencies

- Readers & Writers → Detect (✔), Tolerate (✔), Fix (✔)
- Conversion: **Add helping mechanism**
  - *Reuse* existing algorithm handling each step
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Conversion of Masstree

• Example: B-link Tree (Masstree)
Conversion of Masstree

- Example: B-link Tree (Masstree)

1. Installing new sibling

2. Insert middle key to parent
Conversion of Masstree

• Example: B-link Tree (Masstree)

![Diagram of B-link Tree conversion]

Insert 26

Intermediate state
Conversion of Masstree

- Example: B-link Tree (Masstree)
Conversion of Masstree

- Example: B-link Tree (Masstree)

 Lookup 25

 Insert 26

 Detect (25 > 15)

 Tolerate
Conversion of Masstree

• Example: B-link Tree (Masstree)
Conversion of Masstree

• Example: B-link Tree (Masstree)
  • Add helping mechanism to resume split

Insert 30

![Diagram of Masstree conversion]

Resume split (recovery)
Detect
## Conversion Results of Five DRAM Indexes

<table>
<thead>
<tr>
<th>DRAM Index</th>
<th>DS Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CLHT</strong> (Cache-Line Hash Table) [ASPLOS’15]</td>
<td>Hash table</td>
</tr>
<tr>
<td><strong>HOT</strong> (Height Optimized Trie) [SIGMOD’18]</td>
<td>Trie</td>
</tr>
<tr>
<td><strong>BwTree</strong> [ICDE’13]</td>
<td>B+Tree</td>
</tr>
<tr>
<td><strong>ART</strong> (Adaptive Radix Tree) [ICDE’13]</td>
<td>Radix Tree</td>
</tr>
<tr>
<td><strong>Masstree</strong> [Eurosys’12]</td>
<td>Hybrid (B+Tree &amp; Trie)</td>
</tr>
</tbody>
</table>
## Conversion Results of Five DRAM Indexes

- We produce the P-* family of PM indexes

<table>
<thead>
<tr>
<th>DRAM Index</th>
<th>PM Index</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLHT</td>
<td>$P$-CLHT</td>
<td>#1</td>
</tr>
<tr>
<td>HOT</td>
<td>$P$-HOT</td>
<td>#1</td>
</tr>
<tr>
<td>BwTree</td>
<td>$P$-BwTree</td>
<td>#1, #2</td>
</tr>
<tr>
<td>ART</td>
<td>$P$-ART</td>
<td>#1, #3</td>
</tr>
<tr>
<td>Masstree</td>
<td>$P$-Masstree</td>
<td>#1, #3</td>
</tr>
</tbody>
</table>
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Assumptions & Limitations

• Assume garbage collection in memory allocator
• Assume locks are volatile or re-initialized after a crash
• Provide low level of isolation: Read Uncommitted
• RECIPE applies only to individual data structures
Outline

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Evaluation

• How much effort is involved in converting indexes?
• What is the performance of converted indexes?
• Are the converted indexes crash consistent?
Evaluation

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Evaluation

• How much effort is involved in converting indexes?
• What is the performance of converted indexes?
Modified Lines of Code

• Conversion for all indexes $\rightarrow \leq 200$ LoC changes

<table>
<thead>
<tr>
<th>RECIPE-converted Indexes</th>
<th>Lines of Code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index Core</td>
</tr>
<tr>
<td>P-CLHT</td>
<td>2.8K</td>
</tr>
<tr>
<td>P-HOT</td>
<td>2K</td>
</tr>
<tr>
<td>P-BwTree</td>
<td>5.2K</td>
</tr>
<tr>
<td>P-ART</td>
<td>1.5K</td>
</tr>
<tr>
<td>P-Masstree</td>
<td>2.2K</td>
</tr>
</tbody>
</table>
Modified Lines of Code

• Conversion for all indexes $\rightarrow \leq 200$ LoC changes

Conversion for all indexes: $\leq 200$ LoC changes $\leq 9\%$ from core code base

<table>
<thead>
<tr>
<th>Index</th>
<th>LoC</th>
<th>LoC Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-HOT</td>
<td>2K</td>
<td>38 (2%)</td>
</tr>
<tr>
<td>P-BwTree</td>
<td>5.2K</td>
<td>85 (1.6%)</td>
</tr>
<tr>
<td>P-ART</td>
<td>1.5K</td>
<td>52 (3.4%)</td>
</tr>
<tr>
<td>P-Masstree</td>
<td>2.2K</td>
<td>200 (9%)</td>
</tr>
</tbody>
</table>
Evaluation

• How much effort is involved in converting indexes?
• What is the performance of converted indexes?
Performance Evaluation

- 2-socket 96-core machine with 32MB LLC
- 768 GB Intel Optane DC PMM, 378 GB DRAM
- YCSB with 16 threads
- Ordered/Unordered indexes, Integer/String keys

<table>
<thead>
<tr>
<th>Load</th>
<th>Workload A</th>
<th>Workload B</th>
<th>Workload C</th>
<th>Workload E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion 100%</td>
<td>Insertion 50%</td>
<td>Insertion 5%</td>
<td>Point Lookup 100%</td>
<td>Insertion 5%</td>
</tr>
<tr>
<td></td>
<td>Point Lookup 50%</td>
<td>Point Lookup 95%</td>
<td></td>
<td>Range Scan 95%</td>
</tr>
</tbody>
</table>
Ordered Index

• Support both point and range operations
• P-HOT
  • Persistent Height-Optimized Trie converted by RECIPE
• FAST & FAIR [FAST’18]
  • Hand-crafted PM-based concurrent B+Tree
Ordered Index

- P-HOT produced by RECIPE conversion
- P-HOT performs up-to 5.2x better in point operations
- Cache-efficient designs of P-HOT \(\rightarrow\) Low cache misses
RECIPE

• Principled approach to convert concurrent DRAM indexes into PM indexes
• Case study of changing five DRAM indexes
• Evaluations with YCSB show RECIPE indexes have better performance than hand-crafted PM indexes
• Try our indexes: https://github.com/utsaslab/RECIPE