Combining HTM and RCU to Implement Highly Efficient Balanced Binary Search Trees

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Outline

• Binary Search Trees (BSTs)
• Concurrent BSTs
• RCU-HTM
• Experimental results
• Conclusions & Future work
BINARY SEARCH TREES
Binary Search Trees (BSTs)

- A classic binary tree with an additional property:
  - Nodes in left subtree have keys less than the key of the root, nodes in right subtree have keys greater than the root.
- Most commonly used to implement dictionaries:
  - <key,value> pairs
  - 3 operations: lookup(key), insert(key, value) delete(key)
Internal vs. External BSTs

**Internal**: <key, value> pairs in every node

**External**: values only in leaves, internal nodes only contain keys.

- External trees simplify the `delete()` operation
- They require twice as much memory
- Longer traversal paths
Deletion in an Internal BST
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• Deleting a node with one or zero children is easy
  – Just change parent’s child pointer
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Example: delete(10)
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• Deleting a node with two children is more complicated
  – Need to find successor, swap keys and remove successor node
  – Successor may be many links away
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Example: delete(8)
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Example: delete(8)
Deletion in an External BST

• Deletion is always simple
Deletion in an External BST

- Deletion is always simple

Example: delete(8)
Deletion in an External BST

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Example: delete(8)
Unbalanced vs. Balanced BSTs

- Balanced trees limit the height of the tree (i.e., the length of maximum path) to provide bounded and predictable traversal times.
- Rebalancing requires additional effort after insertions/deletions.
int bst_insert(bst_t *bst, int key, void *value)
{
    traverse_bst(bst, key);
    if (key was found) return 0;
    insert_node(bst, key, value);
    return 1;
}
int bst_insert(bst_t *bst, int key, void *value)
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Example:
bst_insert(key = 2)
int bst_insert(bst_t *bst, int key, void *value) {
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Insertion in an Unbalanced BST

```c
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    return 1;
}
```

Example:
```
bst_insert(key = 2)
```
int bbst_insert(bbst_t *bst, int key, void *value)
{
    traverse_bbst(bbst, key);
    if (key was found) return 0;
    insert_node_and_rebalance(bbst, key, value);
    return 1;
}
Insertion in a Balanced BST

```c
int bbst_insert(bbst_t *bst, int key, void *value)
{
    traverse_bbst(bbst, key);
    if (key was found) return 0;
    insert_node_and_rebalance(bbst, key, value);
    return 1;
}
```

Example:

```c
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```

![Balanced Binary Search Tree Diagram]

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Insertion in a Balanced BST

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![Balanced BST Diagram](image)
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Example:
`bst_insert(key = 2)`

Before:
```
  8
 / \  
 4   13
 /   /
3    7
|     |
2     10
```

After:
```
  8
 / \  
 4   13
 /   /
3    7
|     |
2     10
```

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CONCURRENT BINARY SEARCH TREES
Concurrent BSTs

There are 2 challenges for concurrent *internal* and *balanced* BSTs:

1. The deletion of a node with 2 children requires exclusive access to the whole path from the node to the successor.
2. Rebalancing requires several modifications that need to be performed in a single atomic step.

Proposed non-blocking and lock-based concurrent BSTs are either:

- Unbalanced [Natarajan PPoPP’14, Howley SPAA’12, Ellen PODC’10]
- Relaxed balanced [Bronson PPoPP’10, Drachsler PPoPP’14, Brown PPoPP’14]
- External [Natarajan PPoPP’14, Ellen PODC’10]
- Partially external [Bronson PPoPP’10]
Concurrent RCU-based BSTs

• Read-Copy-Update (RCU)
  – Modifications are performed in copies and not in place. Copies are atomically installed in the shared data structure.
  – Readers may proceed without any synchronization and without restarting
  – Updaters need to be explicitly synchronized (most commonly only a single updater is allowed to operate)
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Example:
```
bst_insert(key = 2)
```

```
    8
   / \
  4   13
 /     /
3  7    10 14
|     |
1    6
```

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Example:

\[
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\]
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Example:

```
bst_insert(key = 2)
```

Old readers may still traverse old versions of nodes. New readers will see the new nodes.
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Example:

`bst_insert(key = 2)`

Old readers may still traverse old versions of nodes. New readers will see the new nodes.

Updaters can safely replace parts of the tree as only a single updater is allowed to operate.
Concurrent RCU-based BSTs

• Read-Copy-Update (RCU)
  – Modifications are performed in copies and not in place. Copies are atomically *installed* in the shared data structure.
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  – Updateers need to be explicitly synchronized (most commonly only a single updater is allowed).

Single updater RCU tree:
  • Multiple readers
  • Single updater

Citrus RCU tree [Arbel PODC’14]:
  • Multiple updaters using fine-grain locks.
  • Unbalanced tree to enable fine-grain locking

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Updaters can safely replace parts of the tree as only a single updater is allowed.
Concurrent HTM-based BSTs

• Hardware Transactional Memory (HTM)
  – Avoids STM’s huge overheads
  – Allows the modification of multiple locations atomically → good fit for the rebalancing phase in a BBST

• HTM-based BSTs:
  – Coarse-grained HTM (cg-htm):
    • Each operation enclosed in a single transaction
      + Easy to implement
      - Large transactions (increased conflict probability)
  – Consistency-Oblivious-Programming HTM (cop-htm) [Avni TRANSACT’14]:
    • The traversal is performed outside the transaction
    • The executed transaction includes 2 steps:
      o Validate that the traversal ended at the correct node
      o Insert/Delete the node and rebalance if necessary
      + Shorter transactions than cg-htm
      - Traversals (and consequently lookup operations) may need to restart
RCU-HTM
Combines **RCU** with **HTM** in an innovative way and provides trees with:

1. **Asynchronized traversals (thanks to RCU)**
   - Oblivious of concurrent updates in the tree
   - No locks, no transactions or any other synchronization
   - No restarts

2. **Concurrent updaters (thanks to HTM)**
   - All updates are performed in copies
   - Modified copies are first validated and then installed in the tree
   - An HTM transaction is used for the validation+installation phase
   - HTM transaction includes several reads but only a single write → minimized conflict probability
Example: $\text{insert}(\text{key} = 1)$
RCU-HTM: insert operation

1. Traverse the tree to locate the insertion point
   • During traversal we maintain a stack of pointers to the traversed nodes

Example: \textit{insert(key = 1)}
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   • The reverse traversal uses the saved stack of pointers
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   • Also validate the access path followed during traversal

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   • Change connection_point’s child

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Example: \( \text{insert(key = 1)} \)
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Steps 3 and 4 performed atomically inside an HTM transaction
If the validation in step 3 fails we abort the transaction and restart the operation

For the non-transactional fallback path we use a lock that allows only a single updater.

Example: \textit{insert(key = 1)}
RCU-HTM: delete operation

• Similar to insert
• One difference:
  – When we delete a node with two children we need to copy the whole path to its successor
EXPERIMENTAL RESULTS
Experimental Setup

• Intel Broadwell-EP Xeon E5-2699 v4
  – 22 cores / 44 hyperthreads @ 2.2GHz
  – 64 GB of RAM
• GCC 4.9.2, -O3 optimizations enabled
• Scalable memory allocator (jemalloc)
• No memory reclamation
• All threads pinned to hardware threads (hyperthreads enabled only at 44-threaded executions)
• Experiments:
  – Threads run for 2 seconds, executing randomly chosen operations (lookups/inserts/deletes)
  – 3 Workloads: 100%, 80% and 20% lookups, and the rest equally divide between insertions and deletions
  – 3 tree sizes: 2K keys, 20K keys and 2M keys
Comparison with HTM-based approaches

2K keys
100% lookups

Throughput (Mops/sec)

Number of threads

2M keys
100% lookups
Comparison with HTM-based approaches

Read-only workloads
- No conflict/capacity aborts → all HTM-based trees scale
- RCU-HTM is constantly better due to 2 reasons:
  - In small trees the overhead of starting/ending transactions is visible in cg-htm and cop-htm.
  - In large trees the transaction overhead is hidden but rcu-htm is faster because of the smaller size of its nodes (e.g., cop-htm also stores 3 more pointers: parent, prev, succ)
Comparison with HTM-based approaches

2K keys
20% lookups

2M keys
20% lookups
Comparison with HTM-based approaches

Write-dominated workloads
- In small trees both cg-htm and cop-htm suffer from conflict aborts due to their larger transactions (see next slide).
- In large trees cop-htm also manages to avoid conflicts.
Comparison with HTM-based approaches

2K keys – 20% lookups

Aborted Transactions
Committed Transactions

Number of threads

Number of transactions (Millions)

1 2 4 8 16 22 44

cg-htm cop-htm rcu-htm
Comparison with HTM-based approaches

RCU-HTM executes much less transactions and suffers less aborts.
Comparison with RCU-based approaches

2K keys
100% lookups

Throughput (Mops/sec)

avl-rcu-mrsw
bst-citrus
avl-rcu-htm

2K keys
20% lookups

Throughput (Mops/sec)

avl-rcu-mrsw: writers synchronized using a single lock
bst-citrus: unbalanced BST, RCU for readers, fine-grain locks for writers [Arbel PODC’14]
Comparison with state-of-the-art

2K keys 
100% lookups

2K keys 
20% lookups

avl-lb: relaxed balance lock-based AVL tree [Bronson PPOPP’10]
bst-lf: unbalanced lock-free (CAS-based) tree [Natarajan PPoPP’14]
Comparison with state-of-the-art

Throughput (Mops/sec)

Throughput (Mops/sec)

Number of threads

2M keys 100% lookups

2M keys 20% lookups
CONCLUSIONS & FUTURE WORK
Conclusions & Future Work

• RCU-HTM combines RCU with HTM and provides concurrent BSTs that are:
  – Internal
  – Strictly balanced
  – Efficient both for readers and updaters

• Future work
  – Memory reclamation
  – Formal proof of correctness (linearizability)
  – More BSTs (e.g., B+-trees, Splay trees, etc.)
THANK YOU!

QUESTIONS?

ACKNOWLEDGMENT

Intel Corporation for kindly providing the Broadwell-EP server on which we executed our experiments.