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

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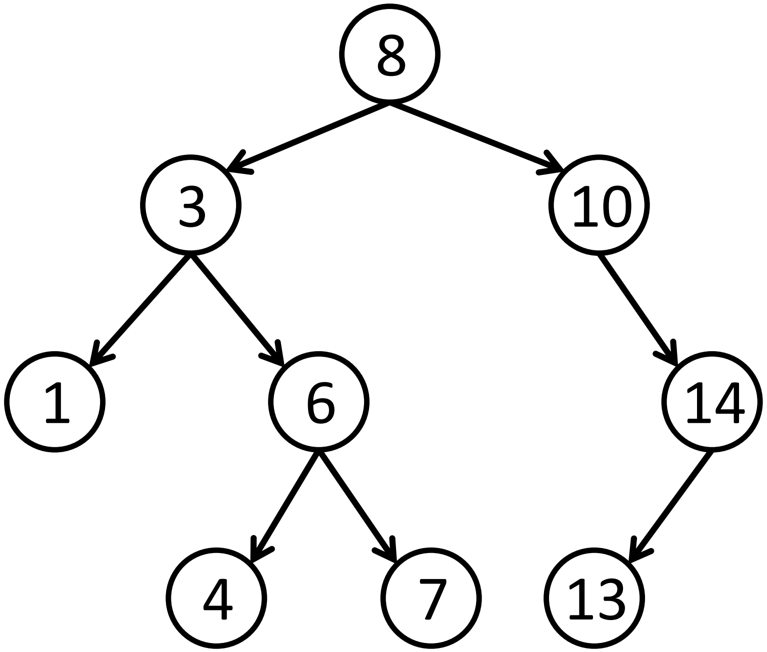
Outline

- 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)*

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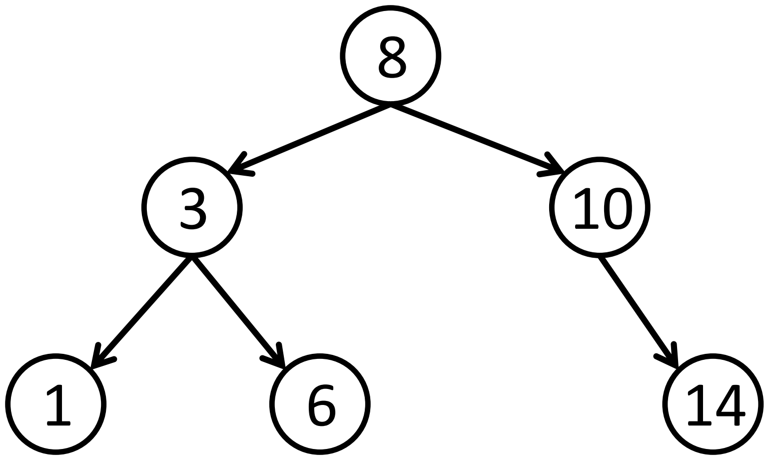
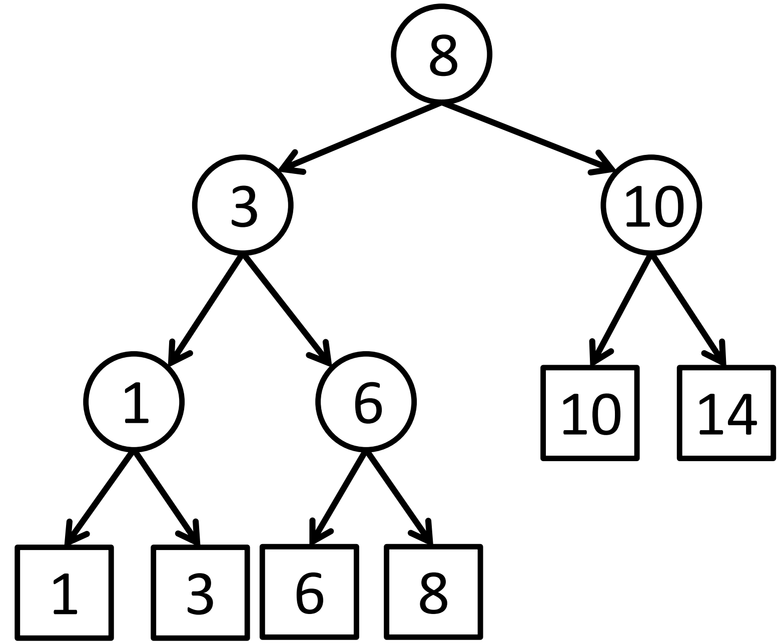
Internal vs. External BSTs



Internal



External

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

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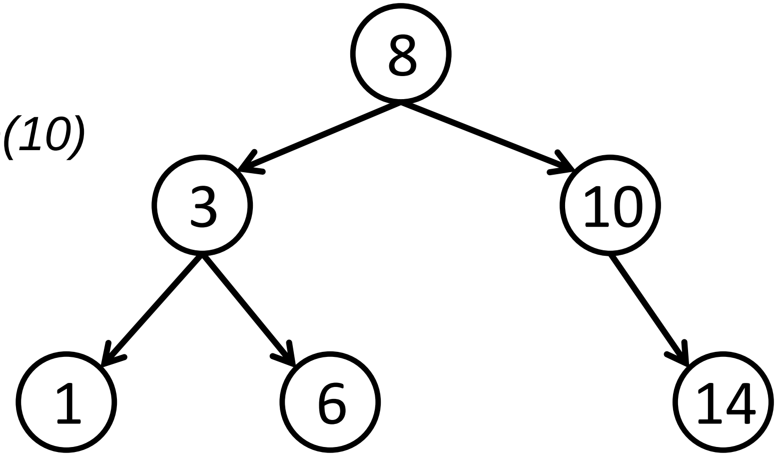

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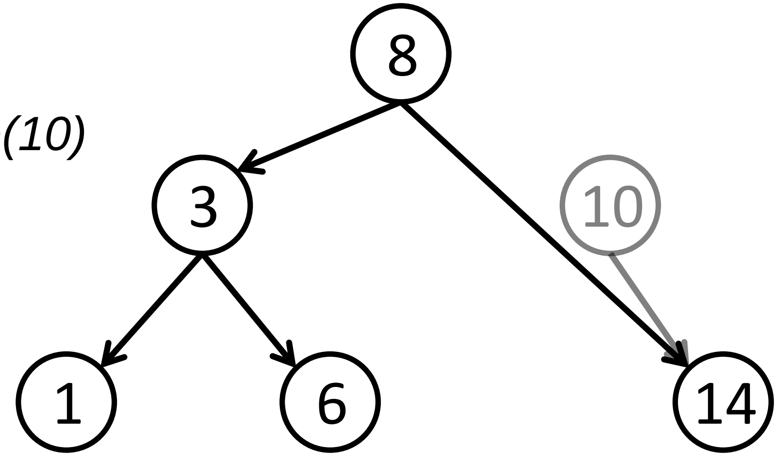

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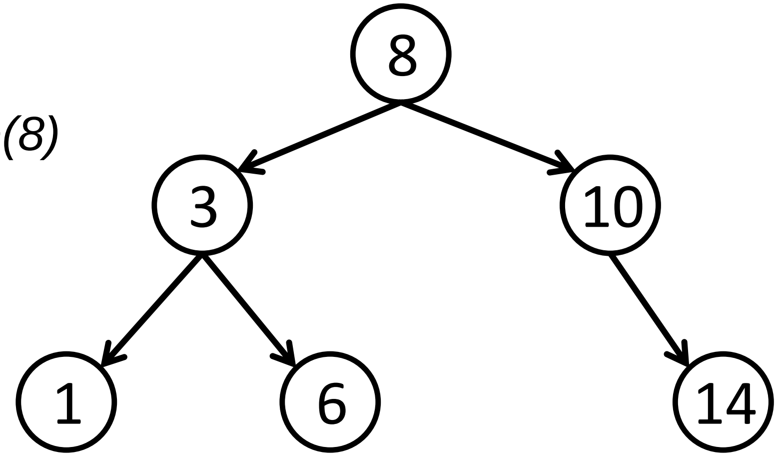

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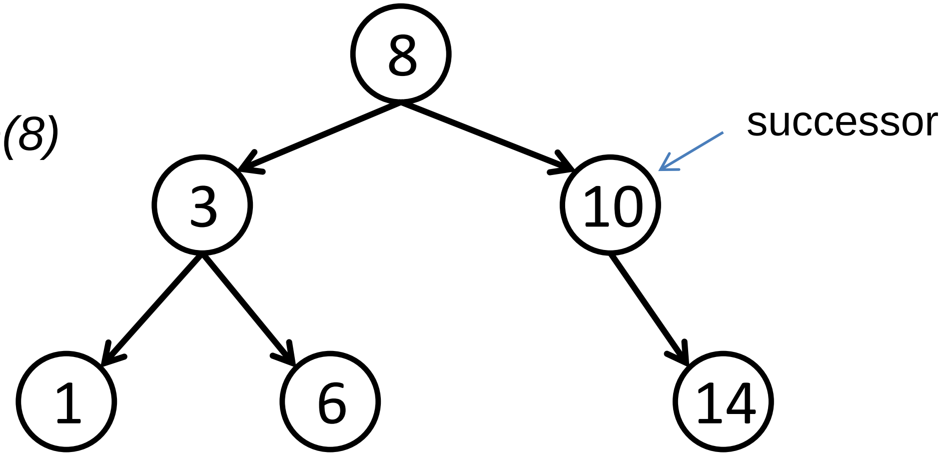

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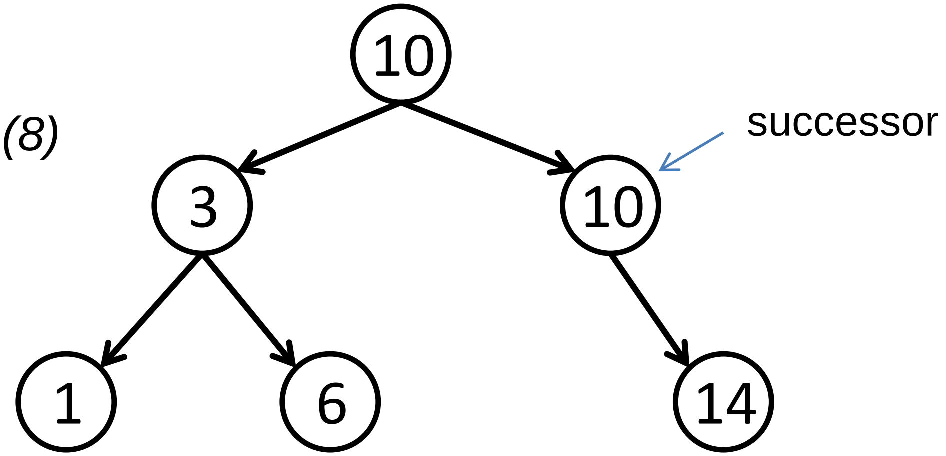

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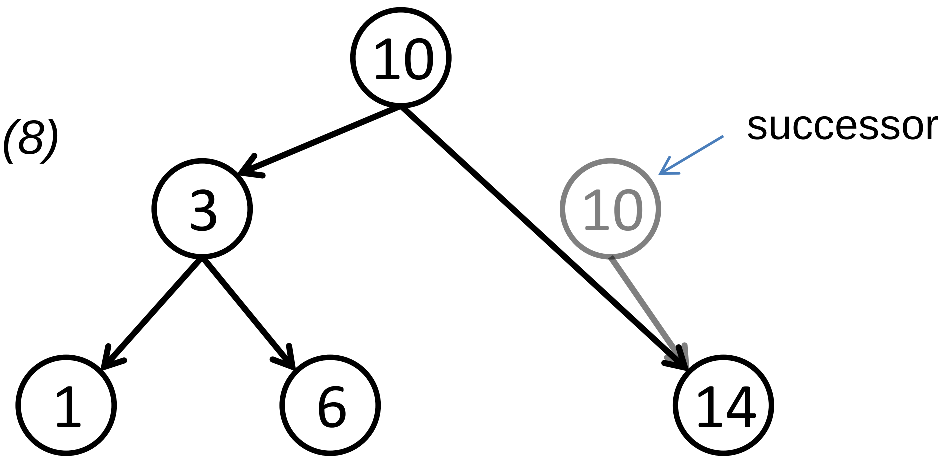

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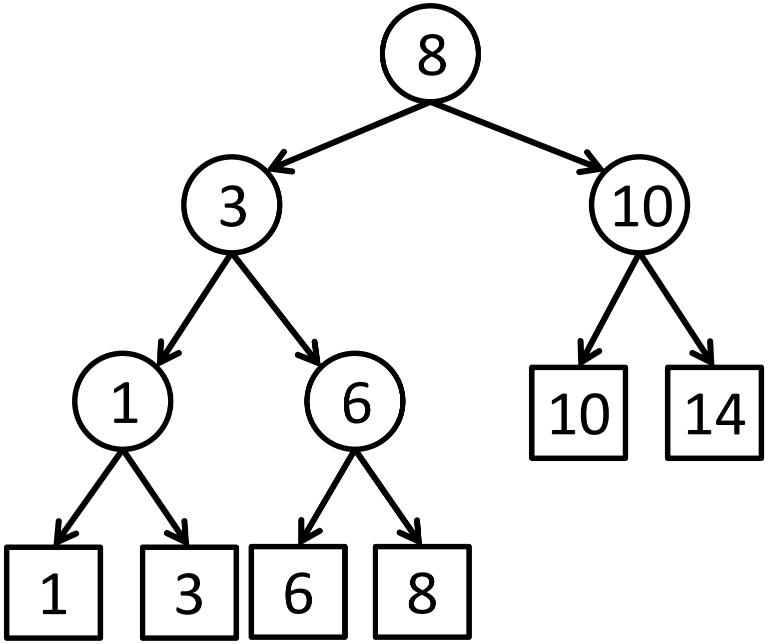

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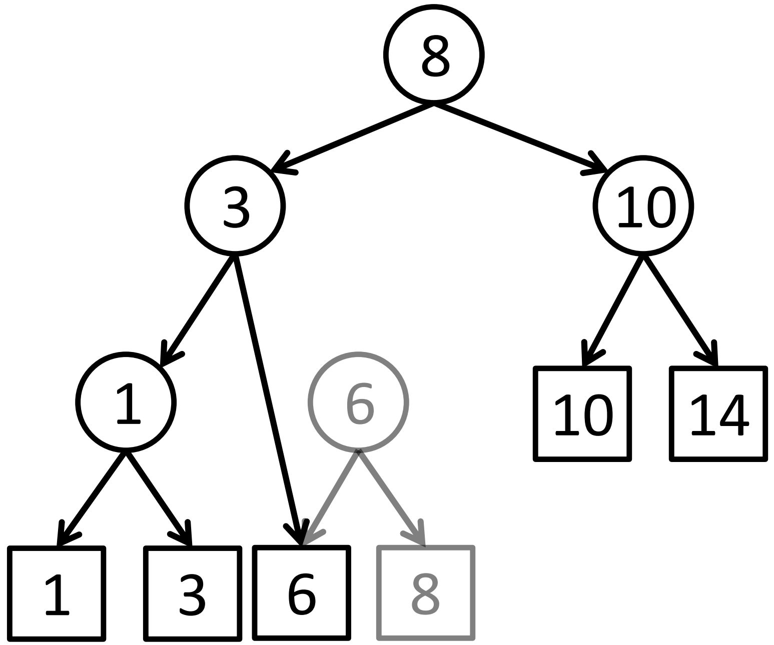
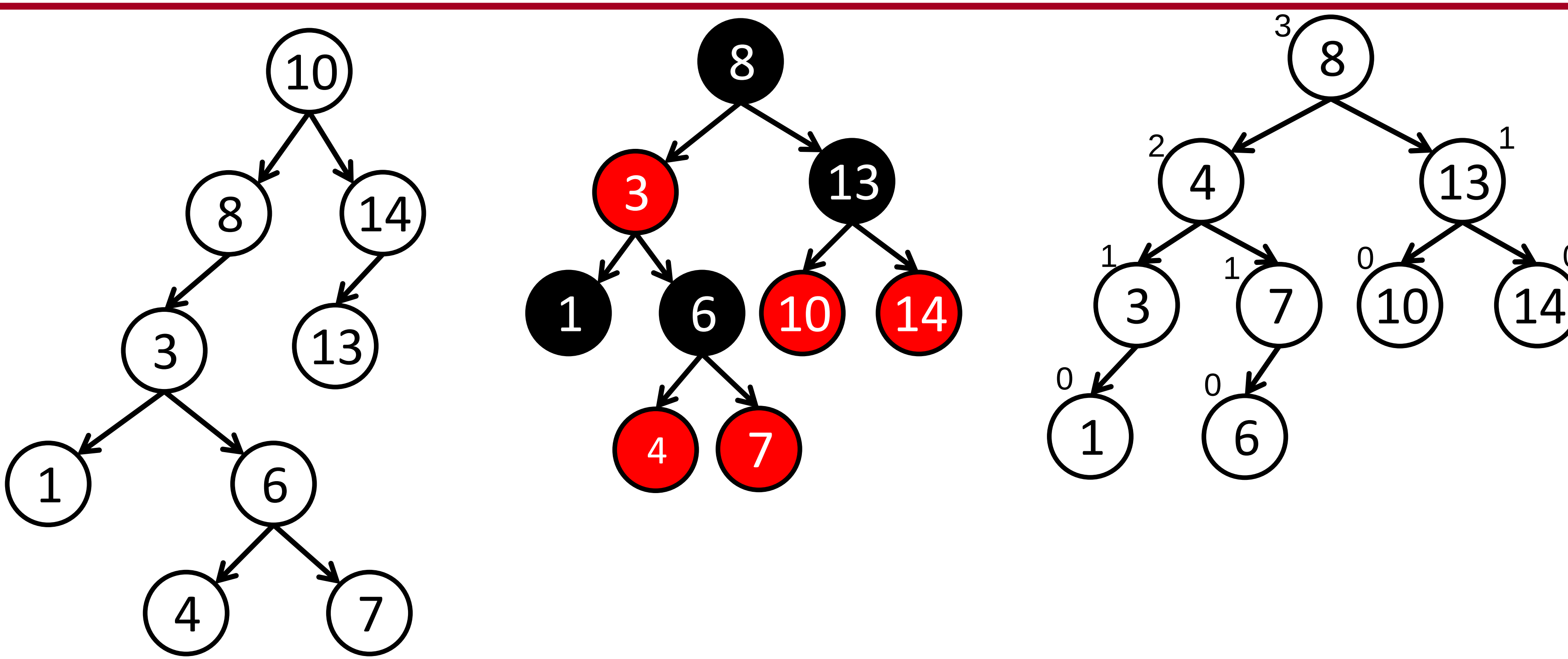


Unbalanced vs. Balanced BSTs



Unbalanced Tree Red-Black Tree AVL Tree

+ 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

Insertion in an Unbalanced BST

```
int bst_insert(bst_t *bst, int key, void *value)
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  traverse_bst(bst, key);
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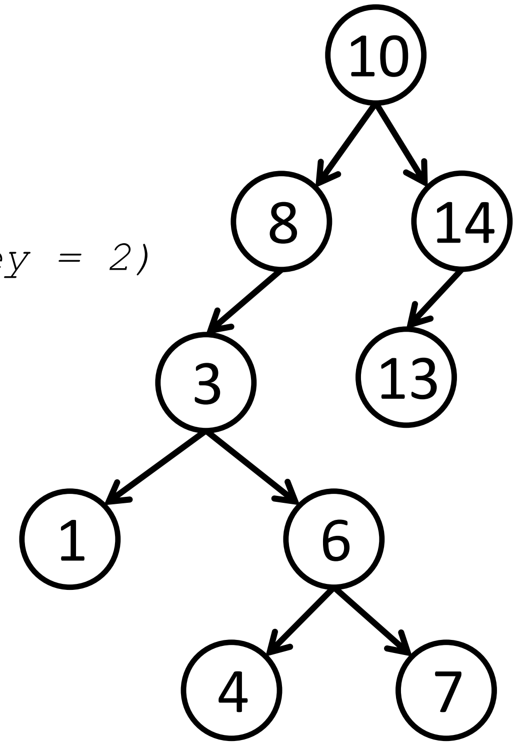

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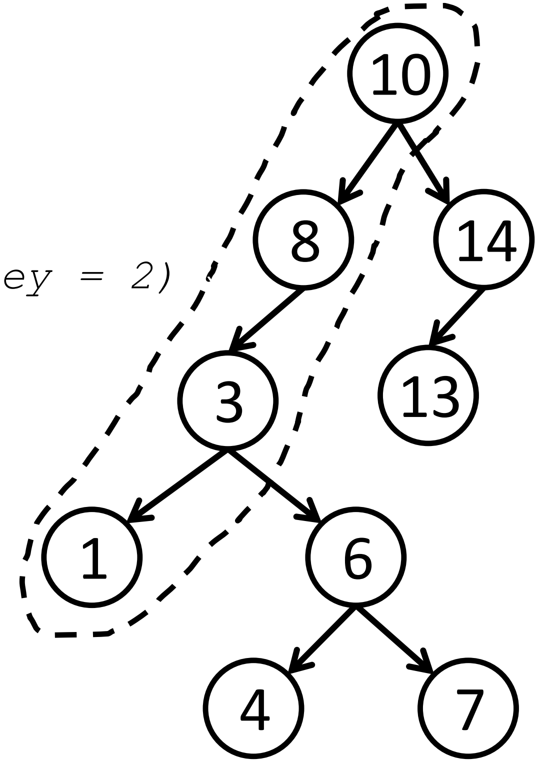

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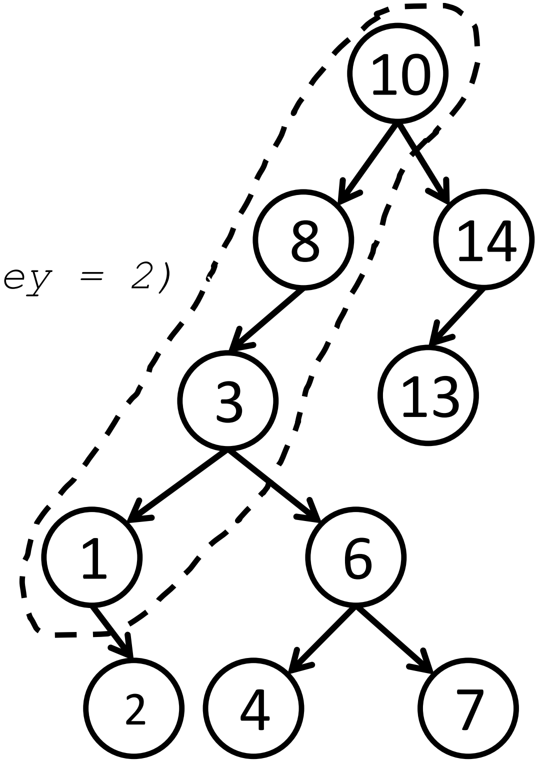

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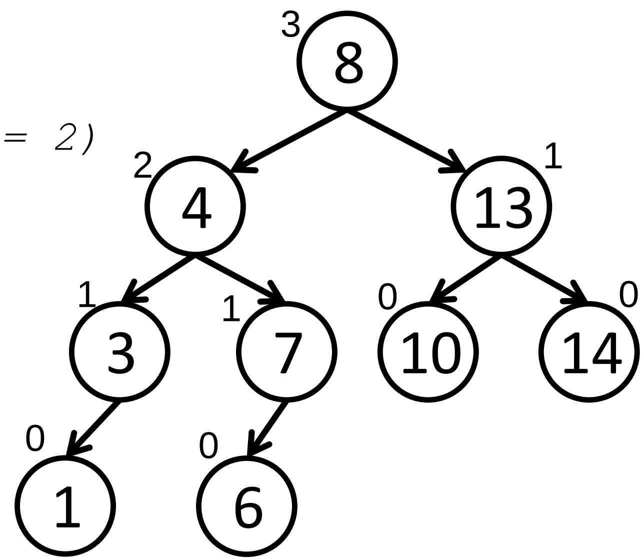

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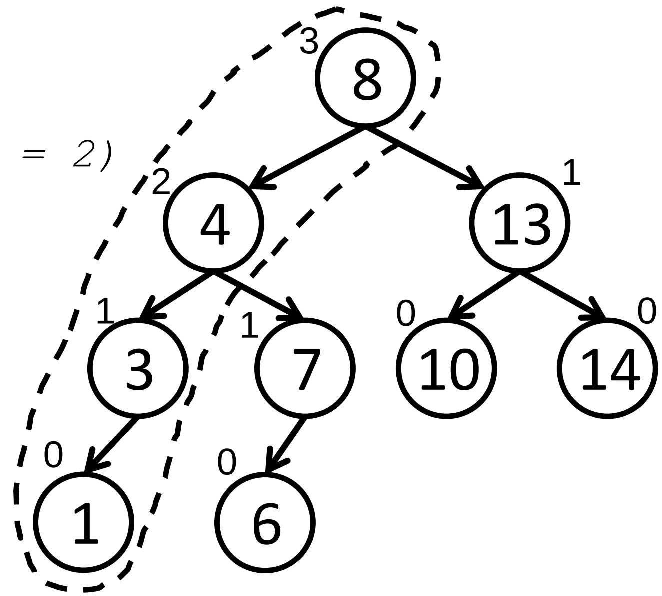

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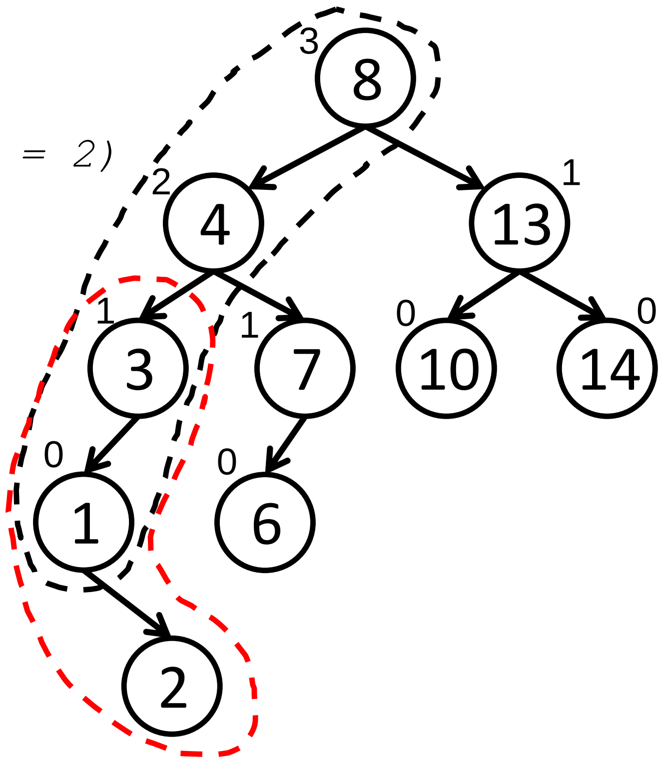

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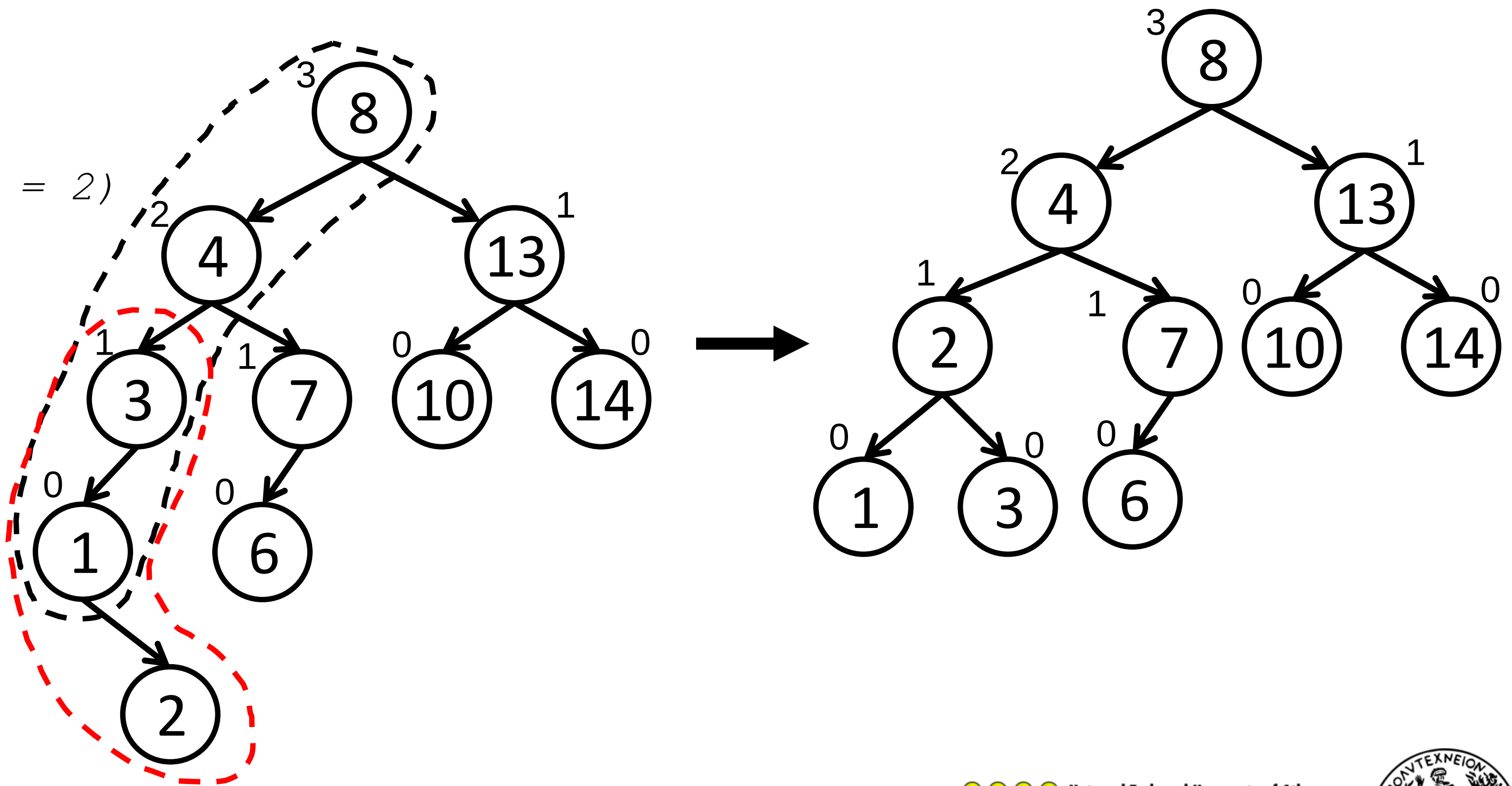

CONCURRENT BINARY SEARCH TREES

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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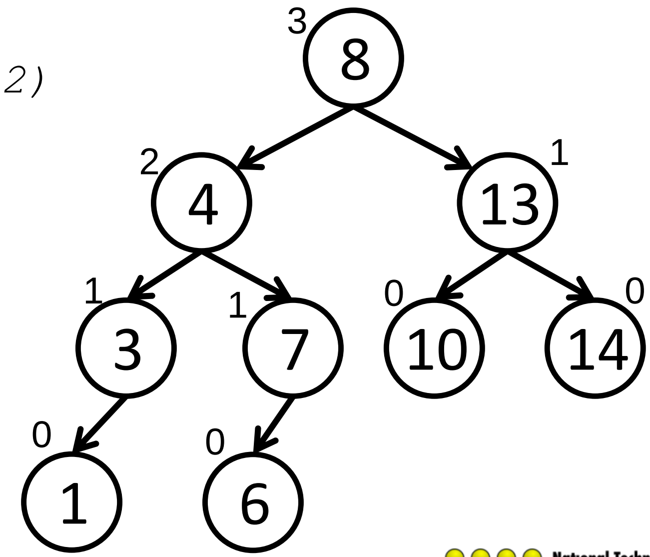

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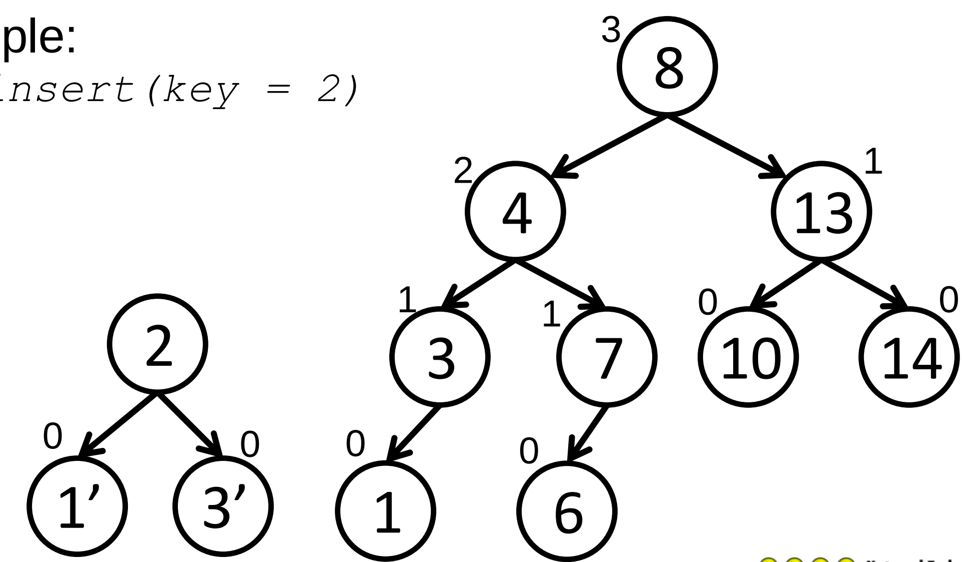

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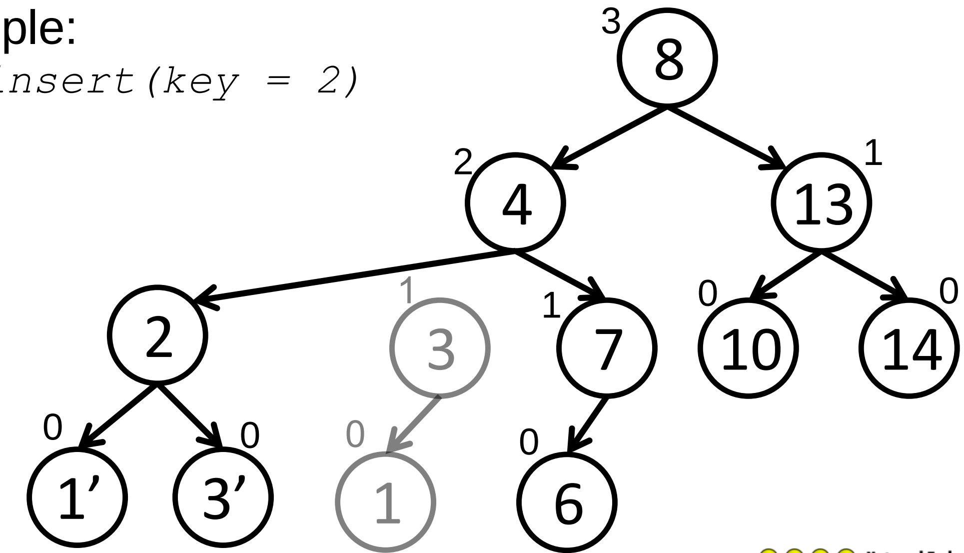

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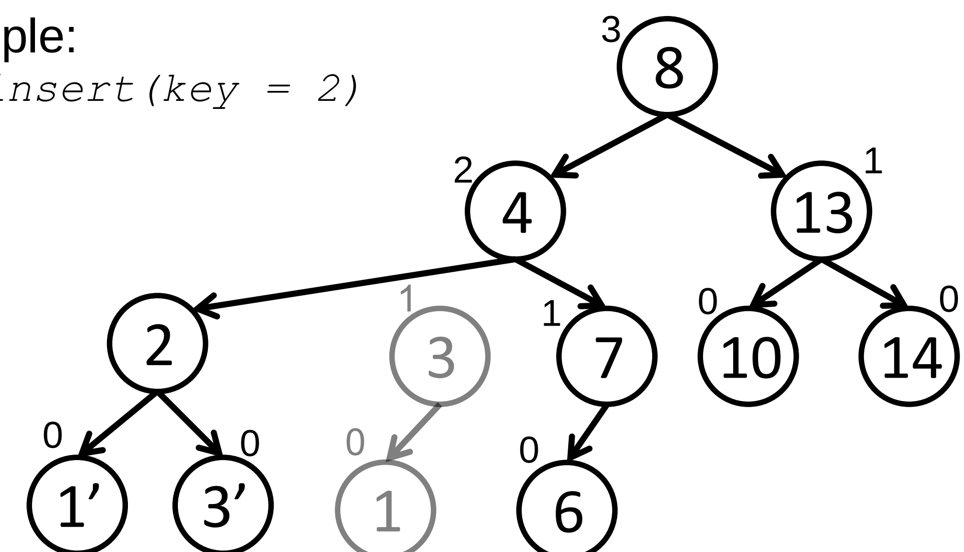

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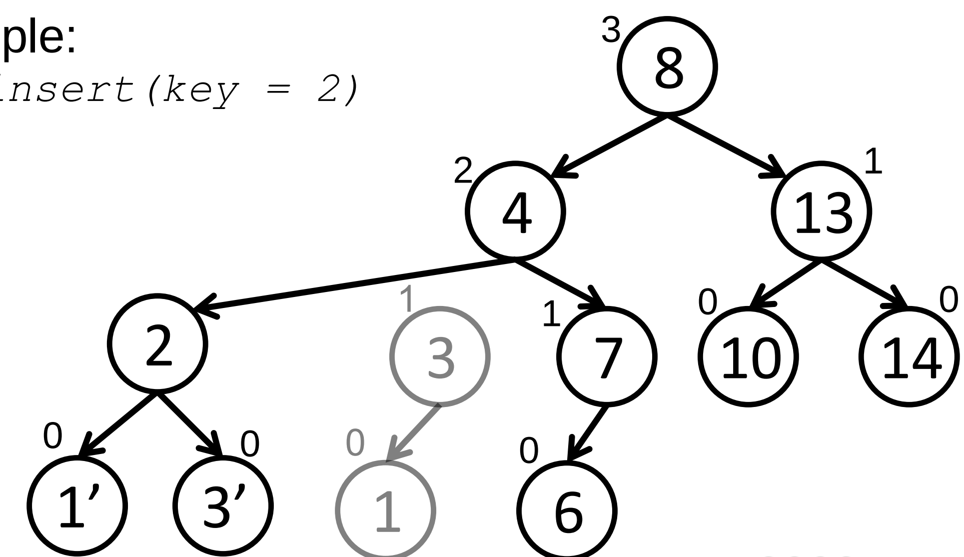

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  - Updat ly only a single

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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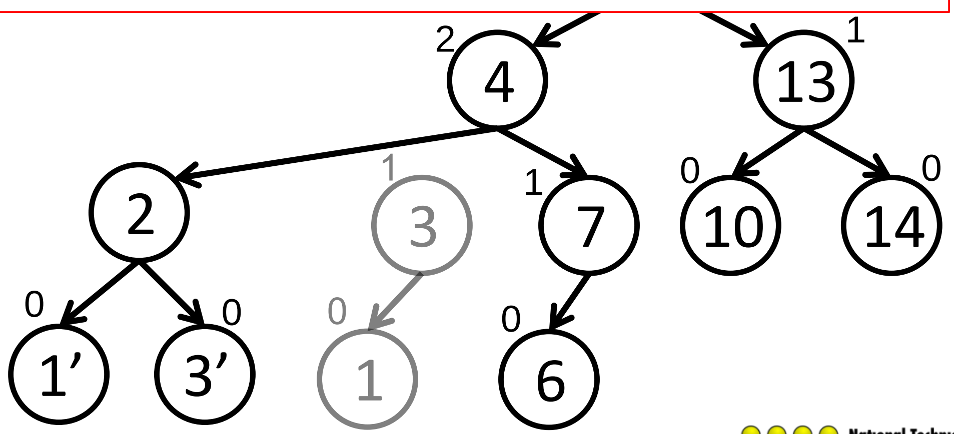

Concurrent HTM-based BSTs

- 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:
      - Validate that the traversal ended at the correct node
      - Insert/Delete the node and rebalance if necessary
    - \+ Shorter transactions than cg-htm
    - \- Traversals (and consequently lookup operations) may need to restart

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RCU-HTM

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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

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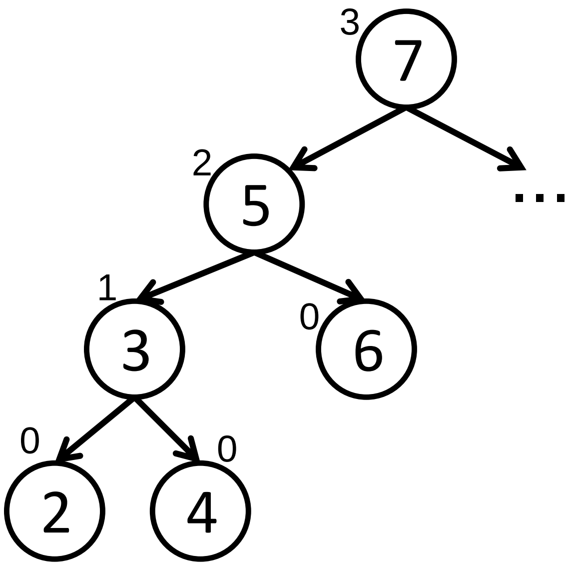
RCU-HTM: insert operation

Example: *insert(key = 1)*



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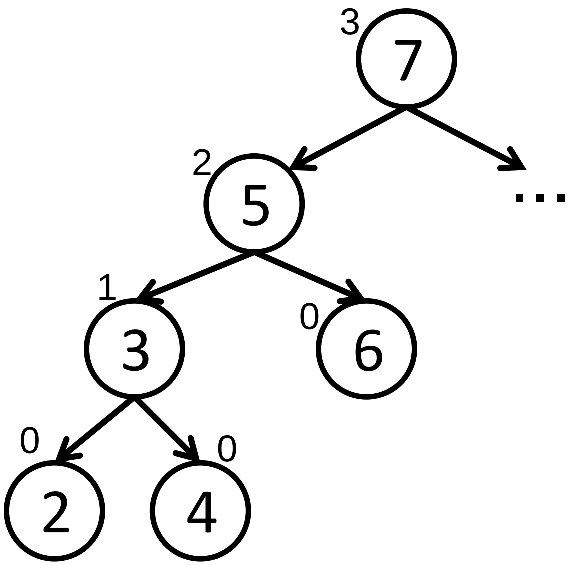

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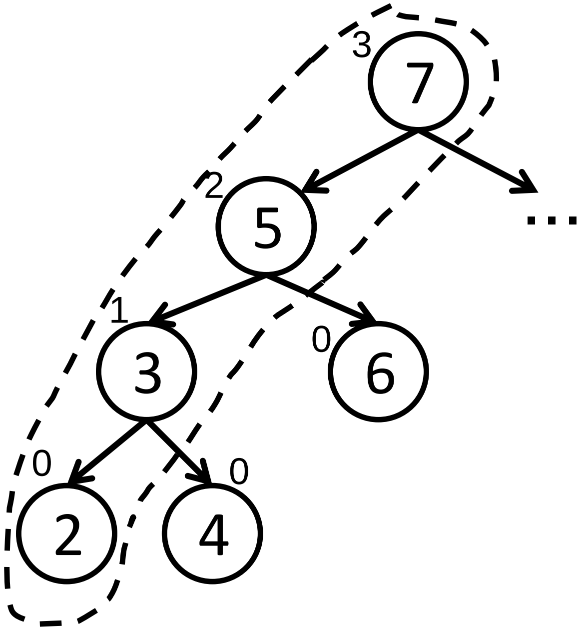

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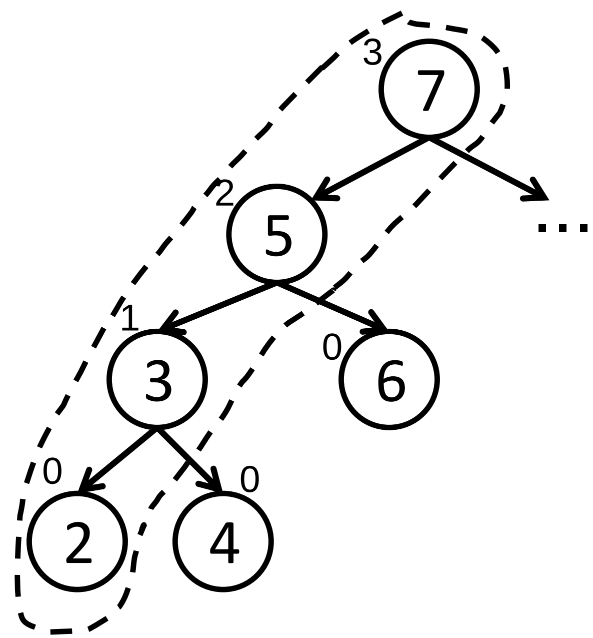

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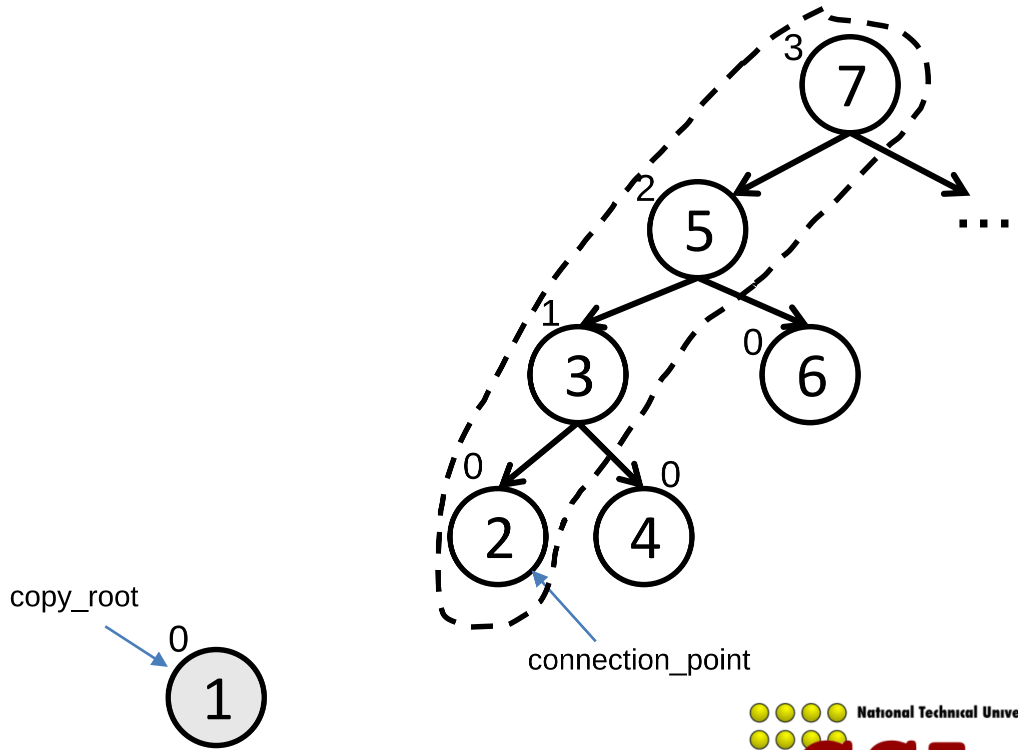

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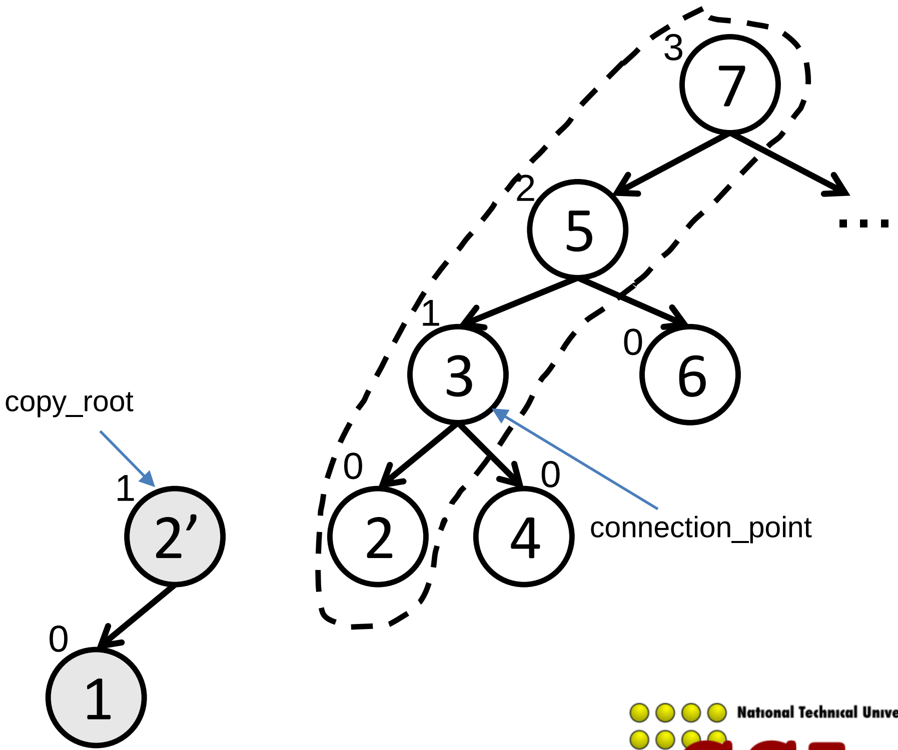

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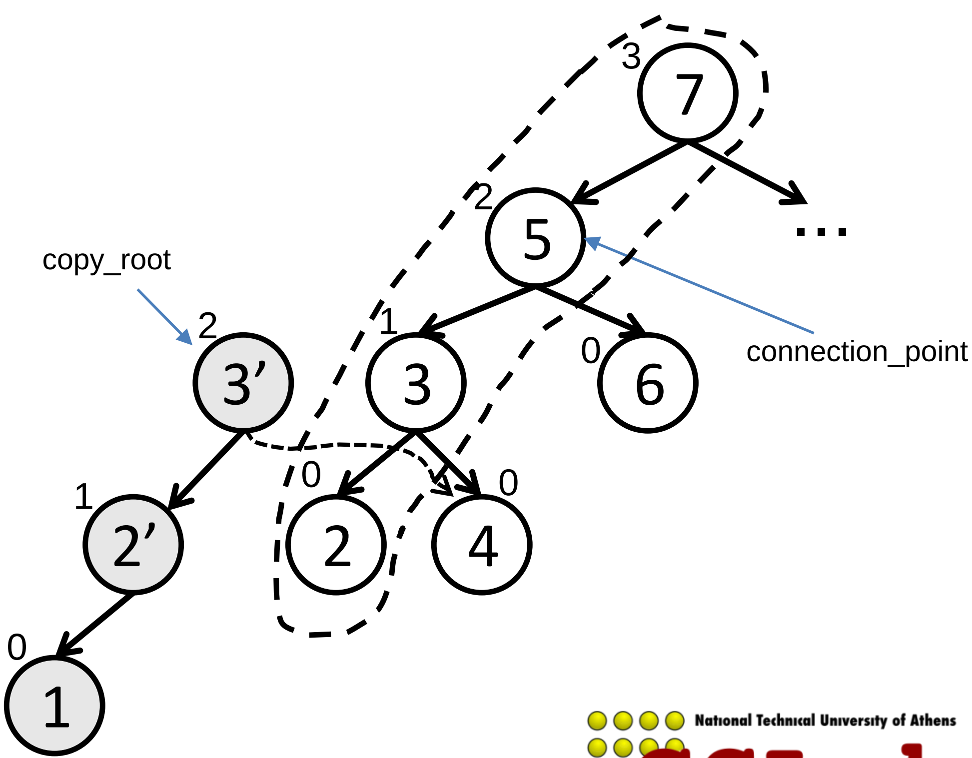

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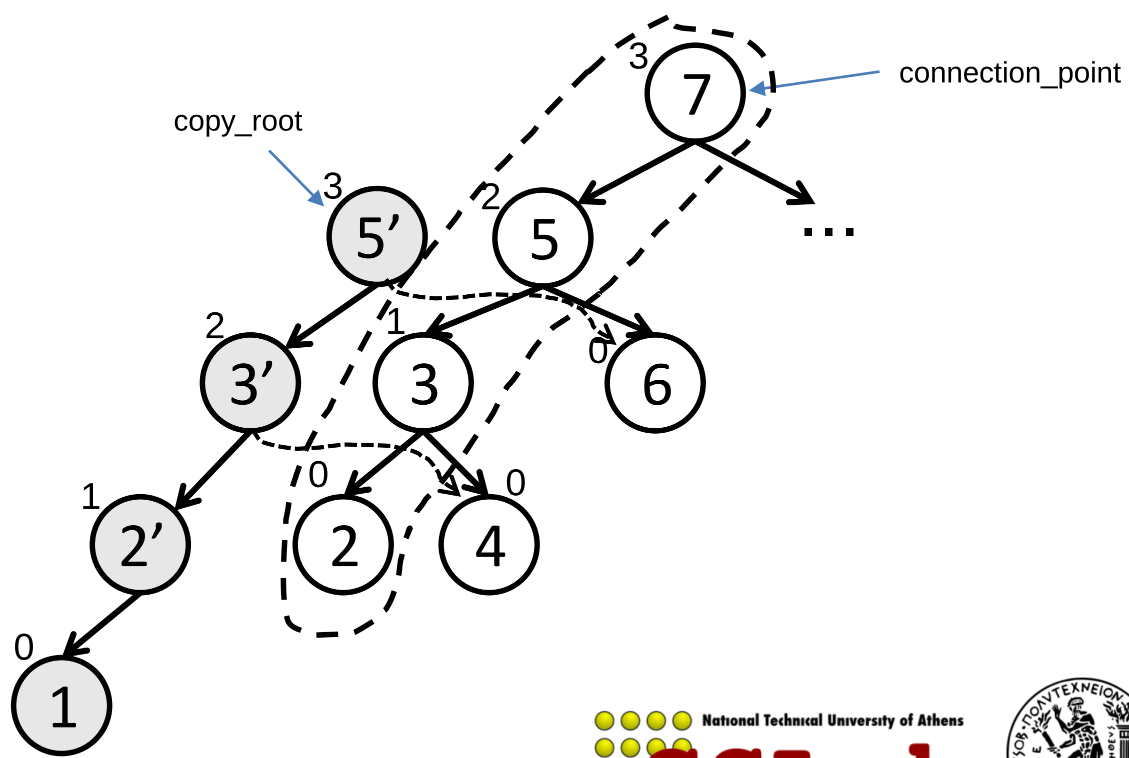

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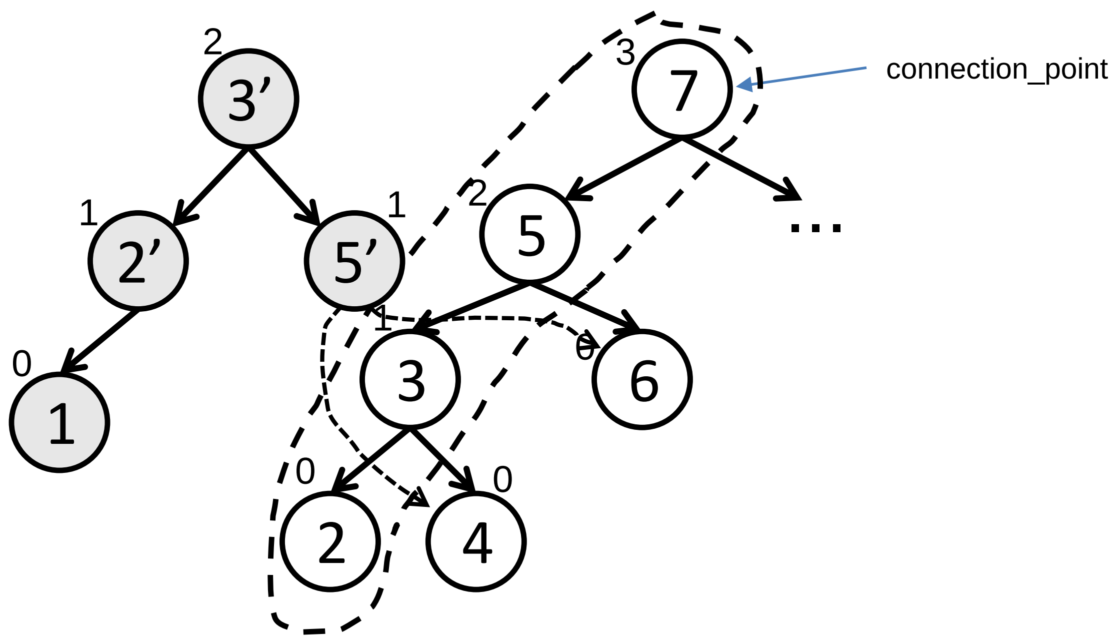

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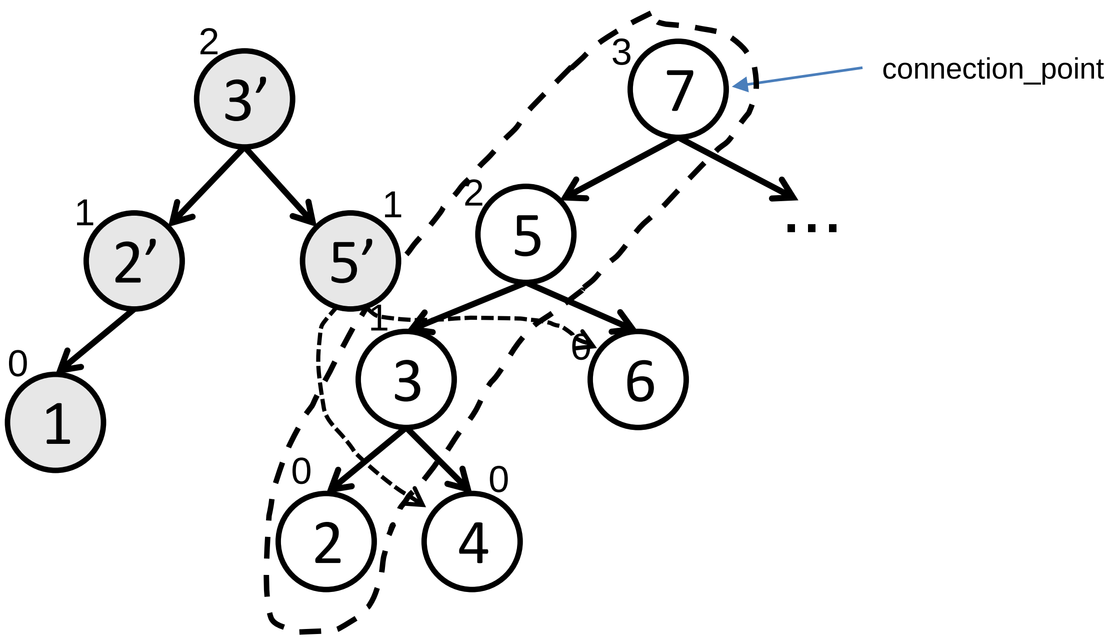

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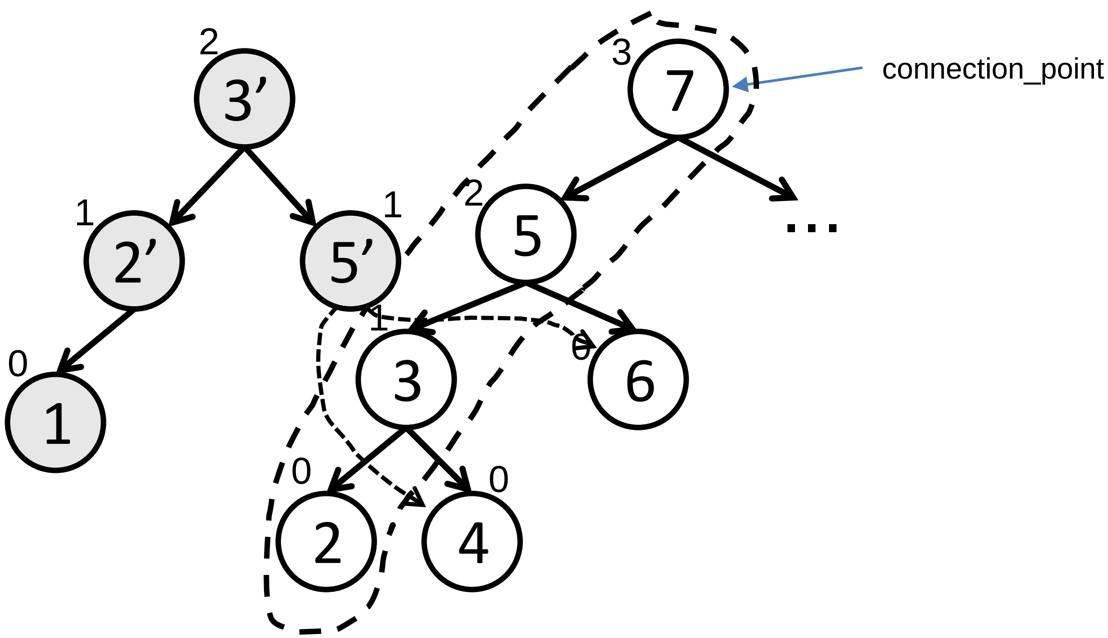
   - Also validate the access path followed during traversal
4. Install the copy
   - Change connection_point's child

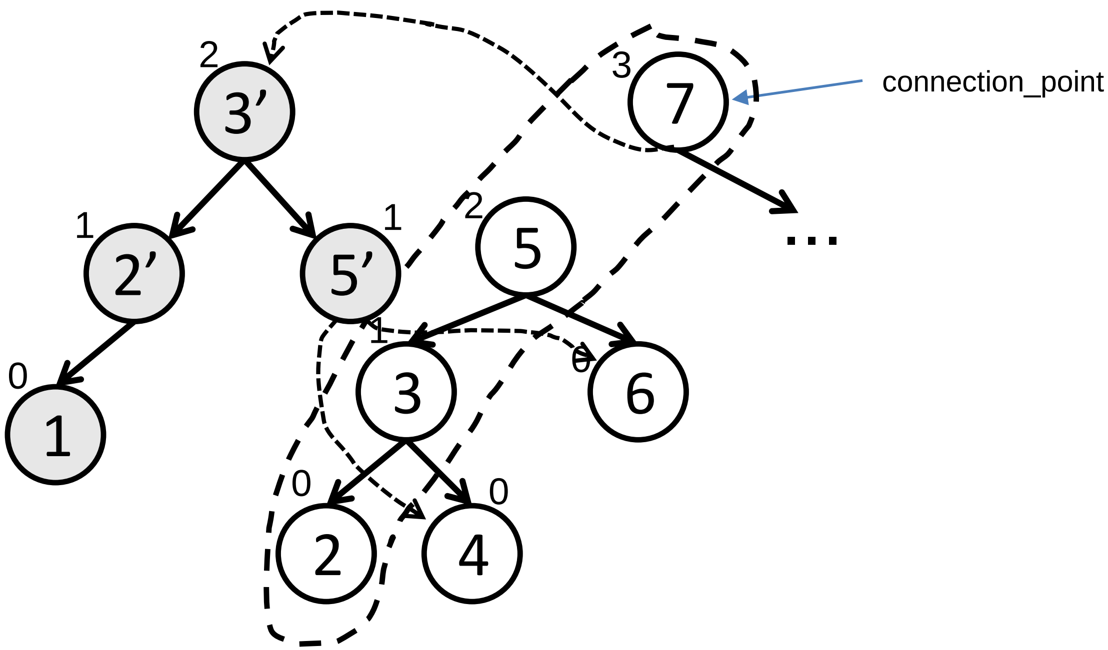
Example: *insert(key = 1)*



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
2. Perform the insertion and rebalance using copies
   - The reverse traversal uses the saved stack of pointers
   - For each copied node we store the observed children pointers
3. Validate the modified copy
   - For each copied node check that children pointers haven't been modified since we copied the node
   - Also validate the access path followed during traversal
4. Install the copy
   - Change connection_point's child

Example: *insert(key = 1)*



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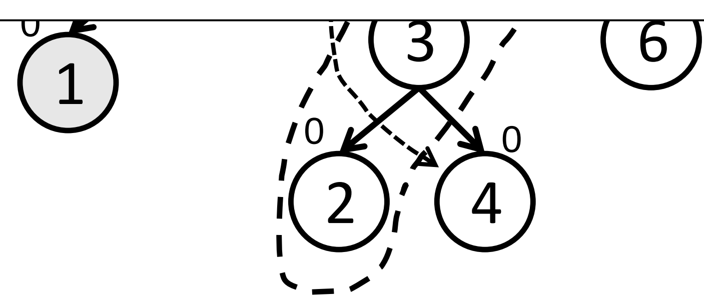
4. Install the copy
   - Change connection_point's child

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: *insert(key = 1)*



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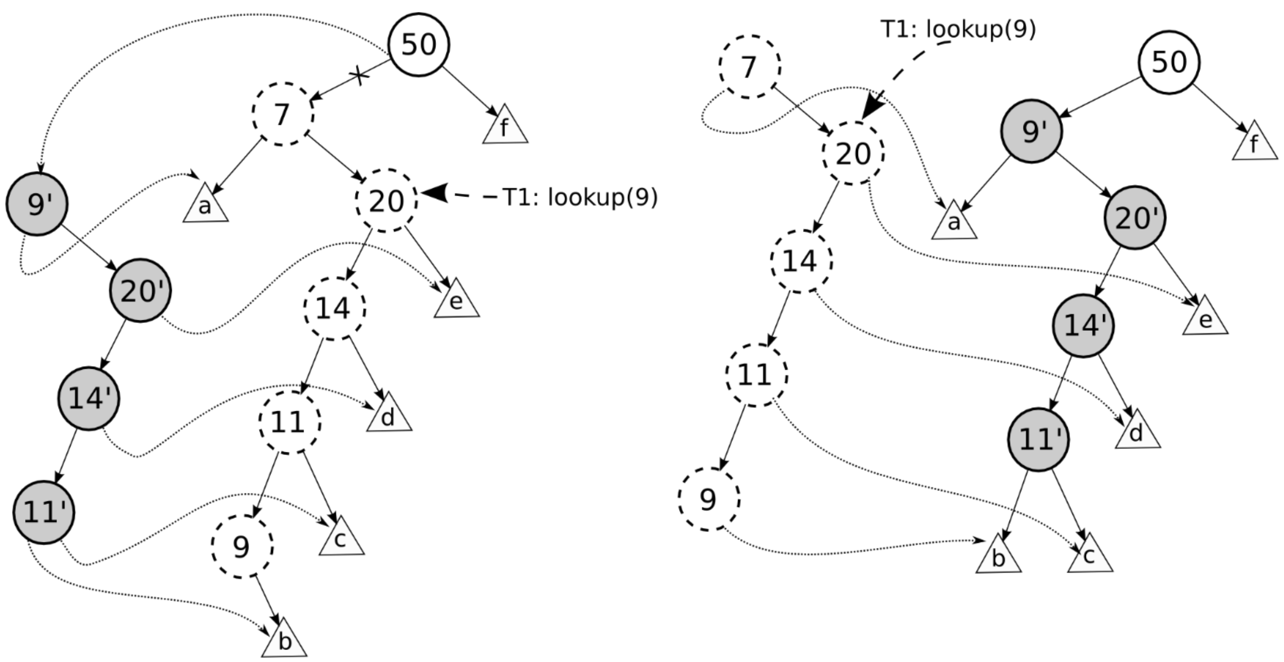
RCU-HTM: delete operation

- Similar to insert
- One difference:
  - When we delete a node with two children we need to copy the whole path to its successor



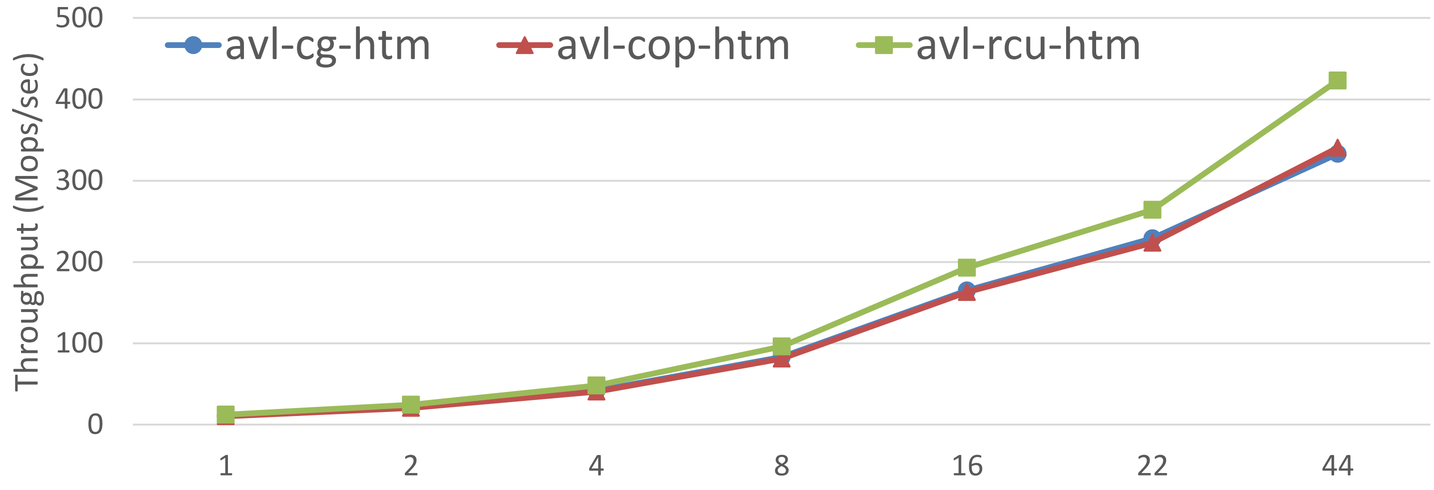
EXPERIMENTAL RESULTS

Experimental Setup

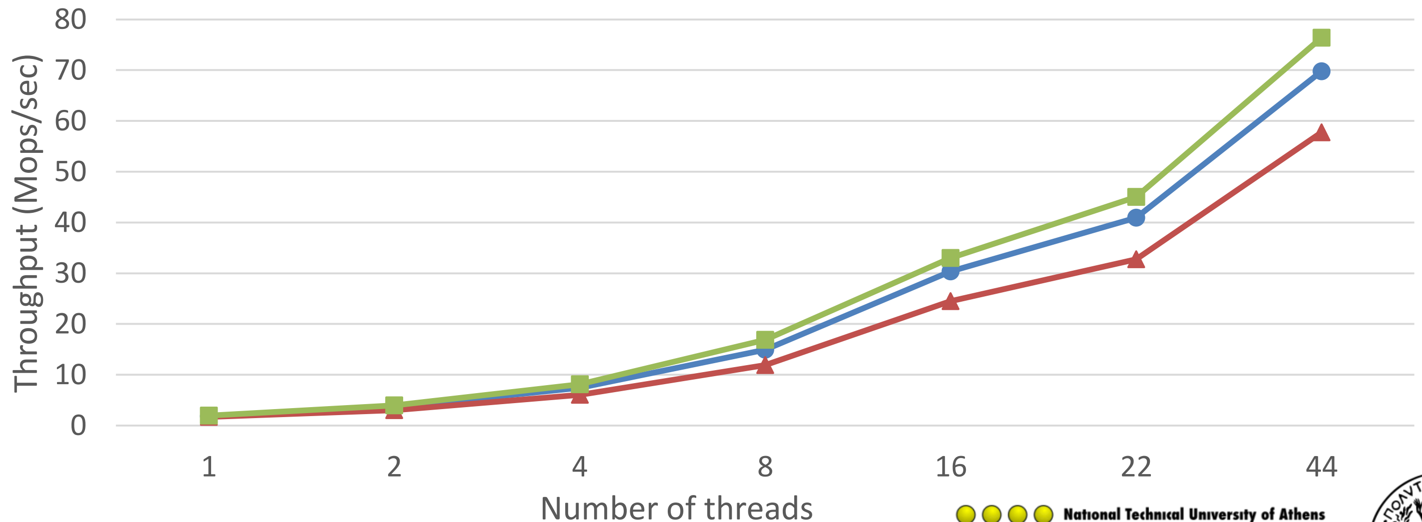
- Intel Broadwell-EP Xeon E5-2699 v4
  - 22 cores / 44 hyperthreads @ 2.2GHz
  - 64 GB of RAM
- GCC 4.9.2, -O3 optimizations enabled
- Scalable memory allocator (jemalloc)
- No memory reclamation
- All threads pinned to hardware threads (hyperthreads enabled only at 44-threaded executions)
- Experiments:
  - 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



2M keys
100% lookups



Comparison with HTM-based approaches

2K keys
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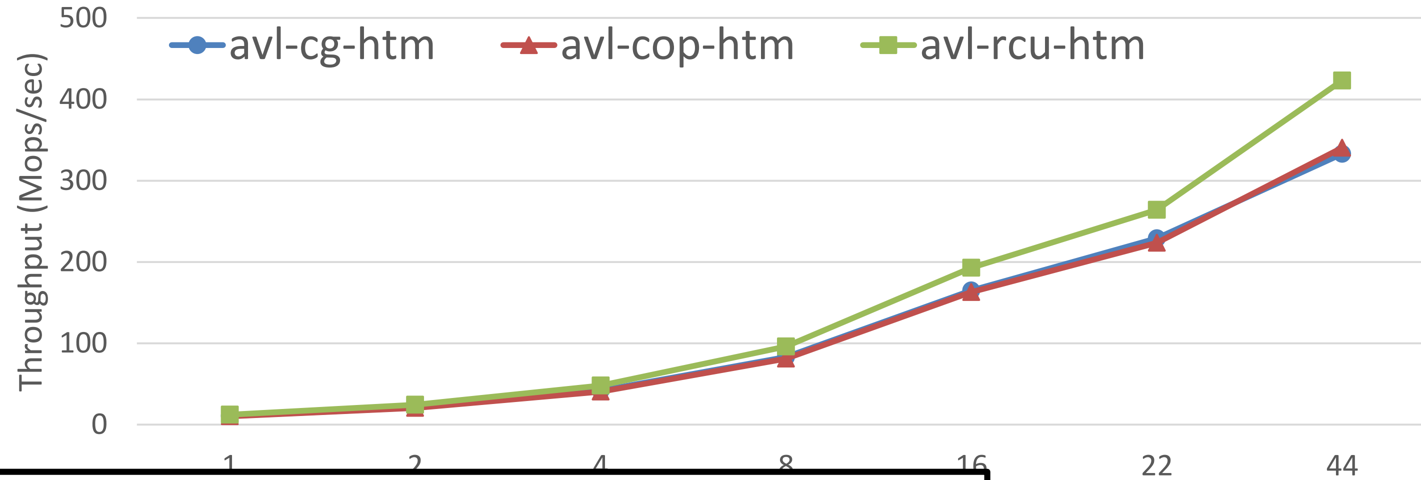
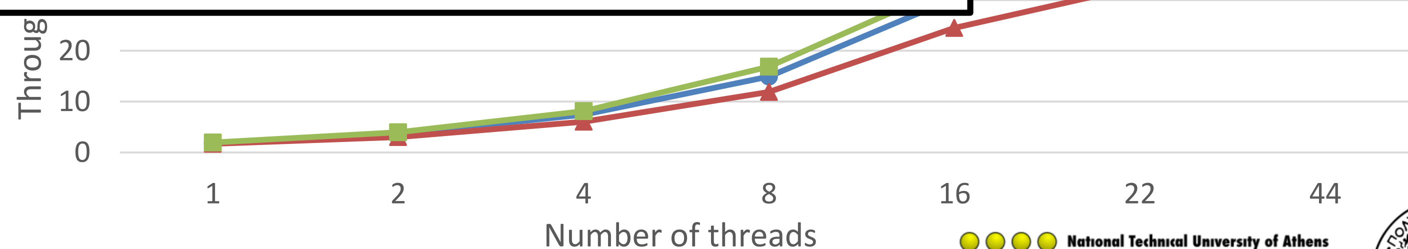


Read-only workloads

- 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)



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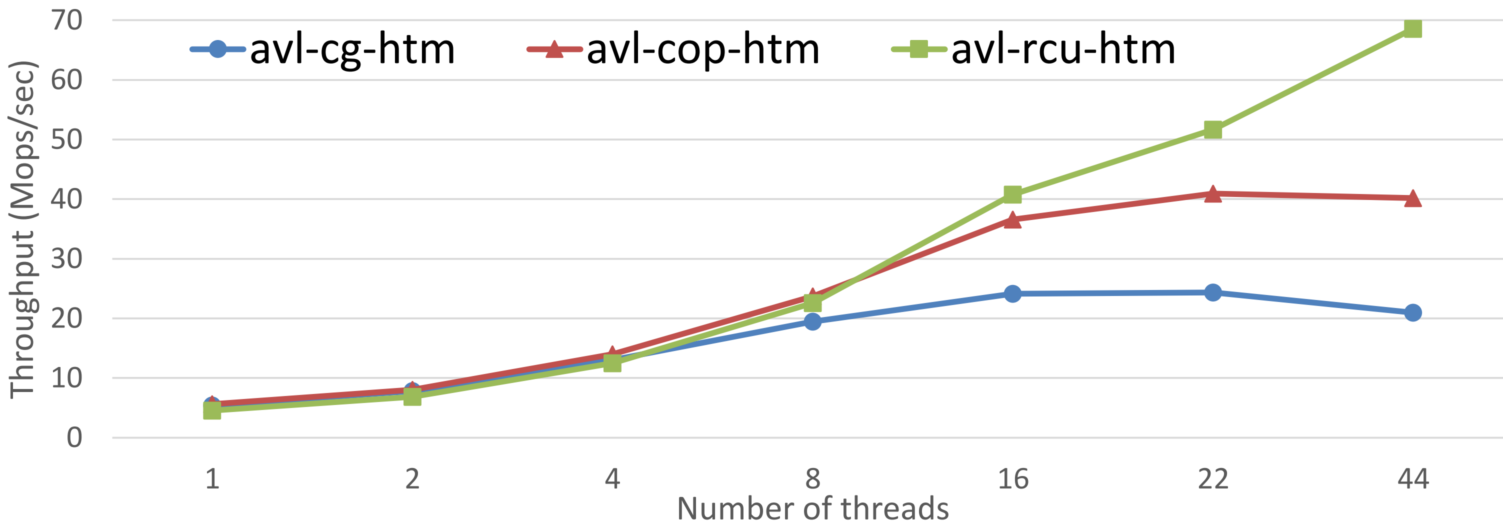
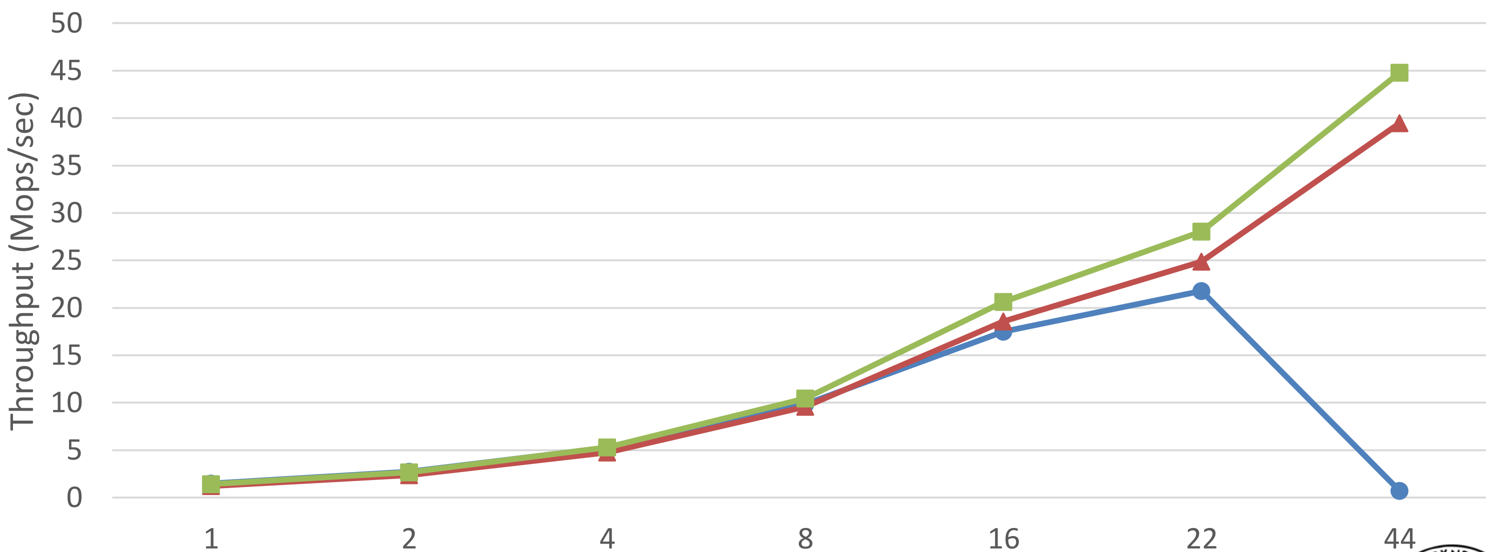
Comparison with HTM-based approaches

2K keys
20% lookups

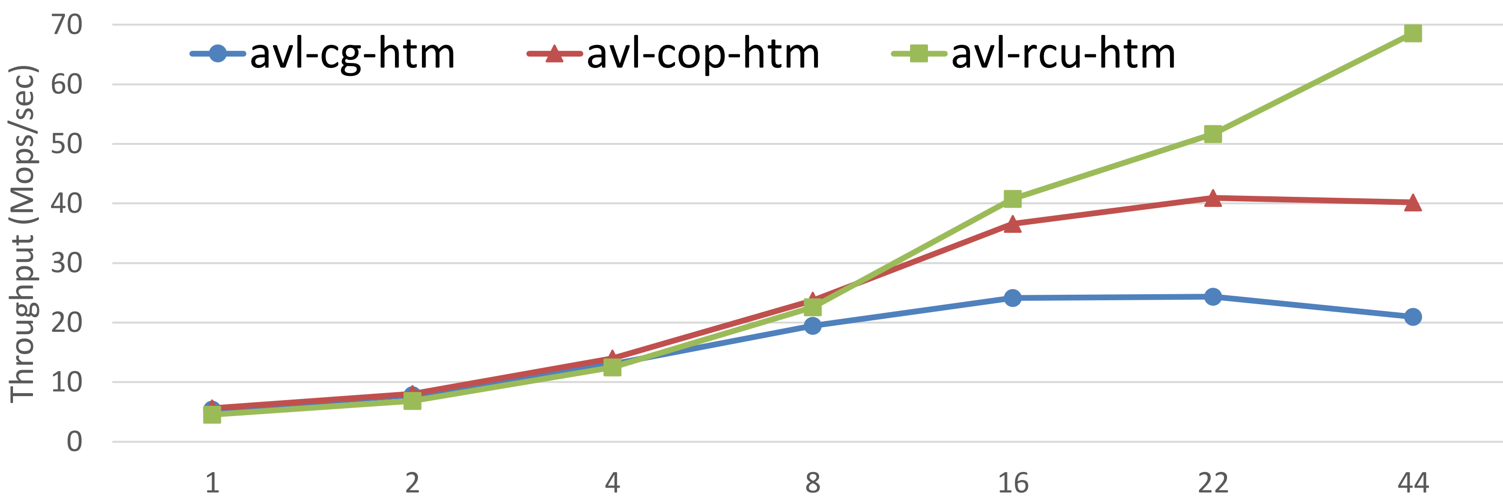


2M keys
20% lookups



Comparison with HTM-based approaches

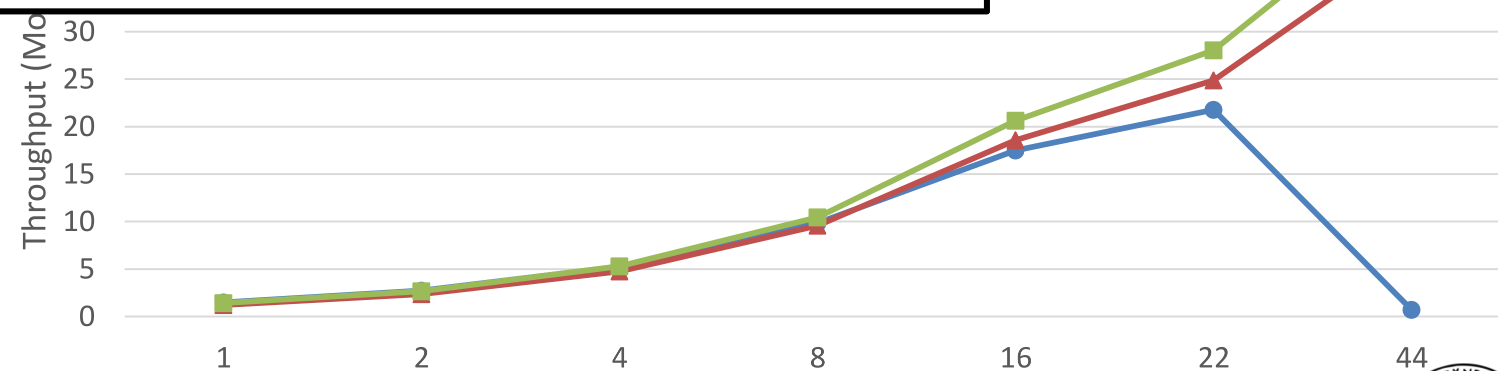
2K keys
20% lookups



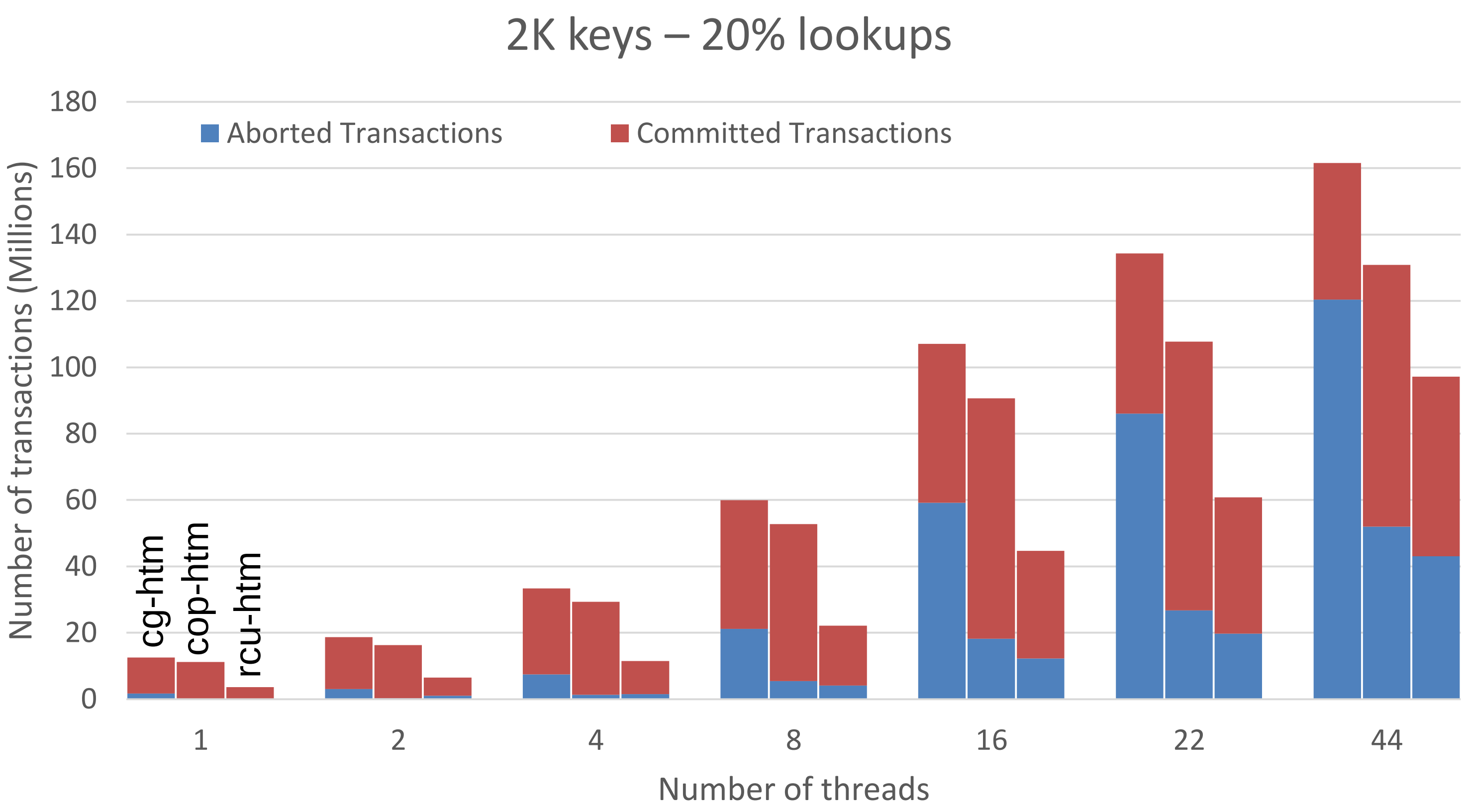
Write-dominated workloads

- 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.

2M keys
20% lookups



Comparison with HTM-based approaches



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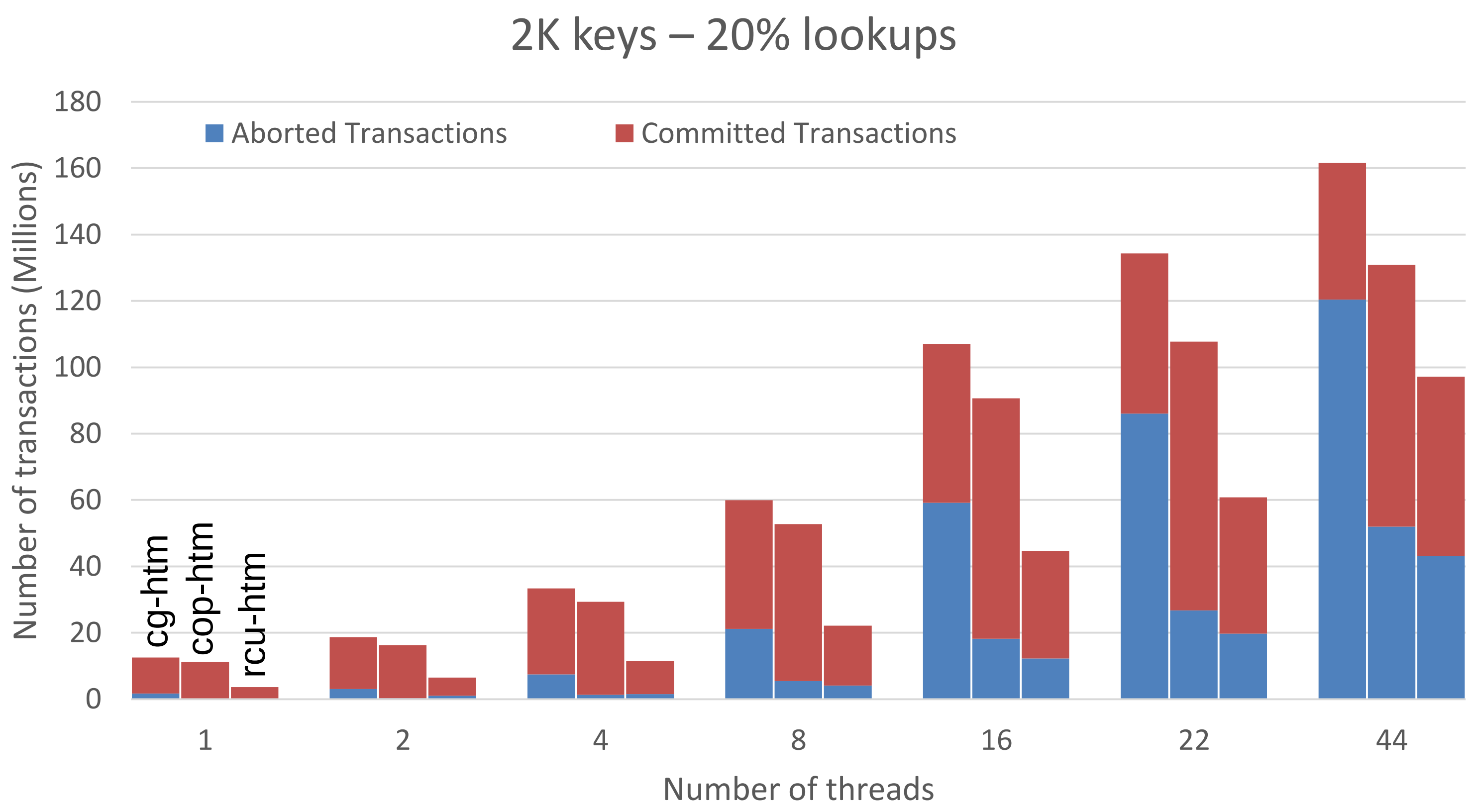
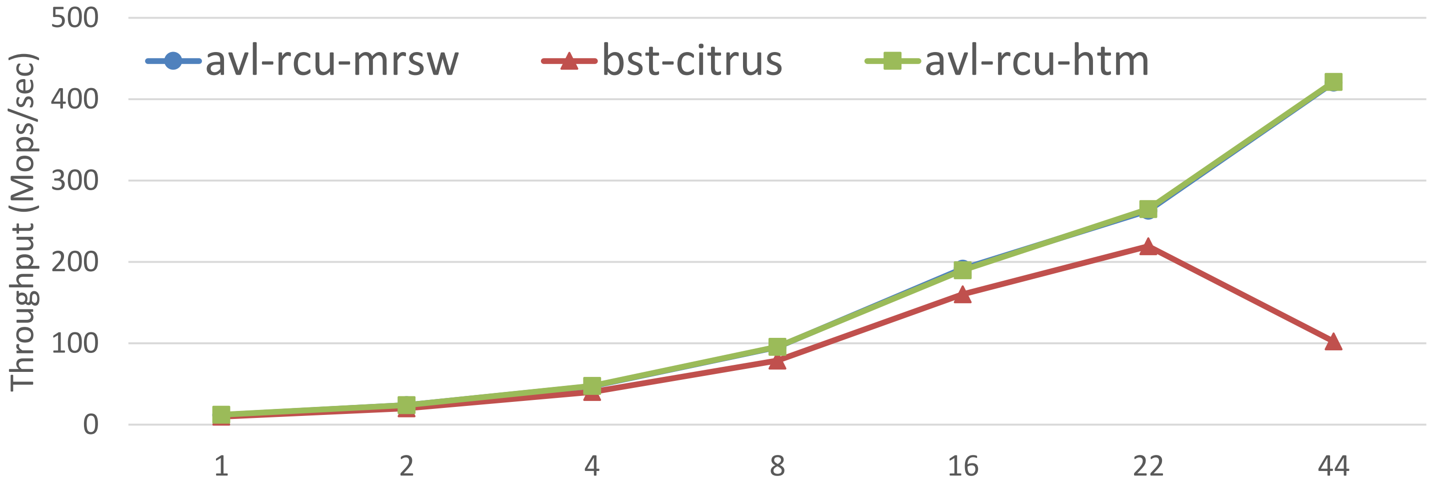
Comparison with HTM-based approaches



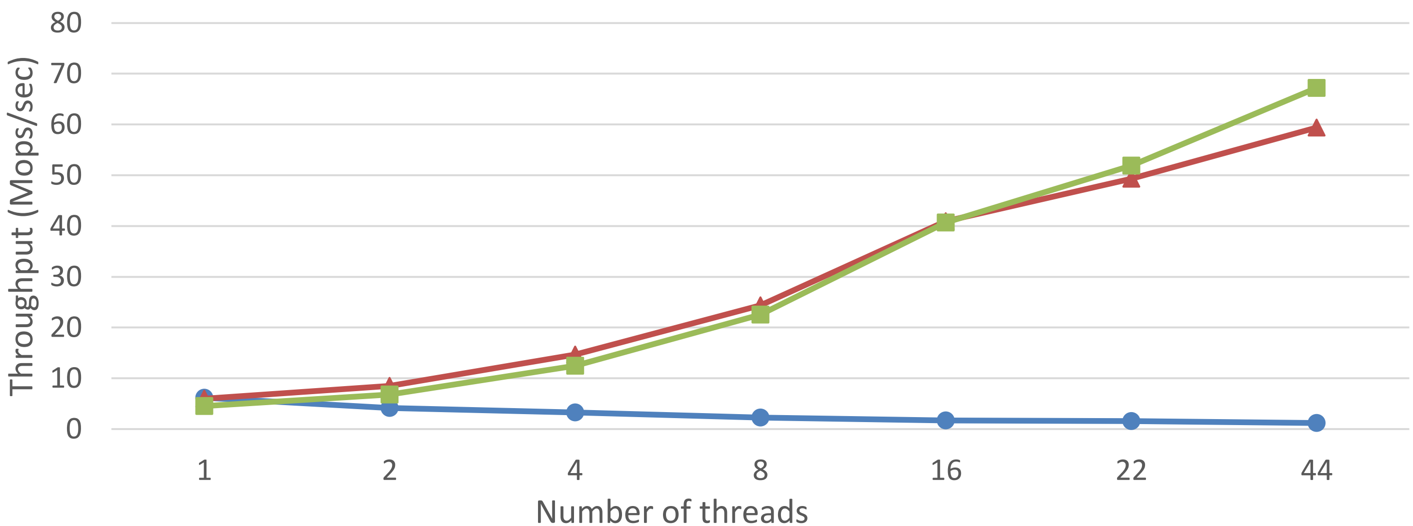
RCU-HTM executes much less transactions and suffers less aborts.

Comparison with RCU-based approaches

2K keys
100% lookups



2K keys
20% lookups



avl-rcu-mrsw: writers synchronized using a single lock
bst-citrus: unbalanced BST, RCU for readers, fine-grain locks for writers [Arbel PODC'14]

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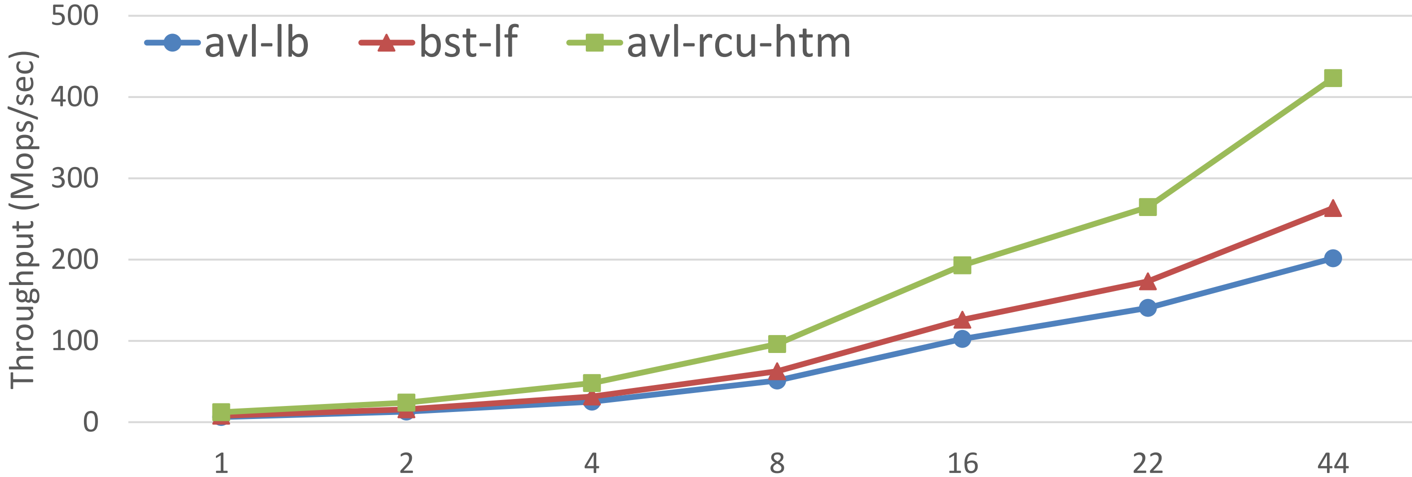
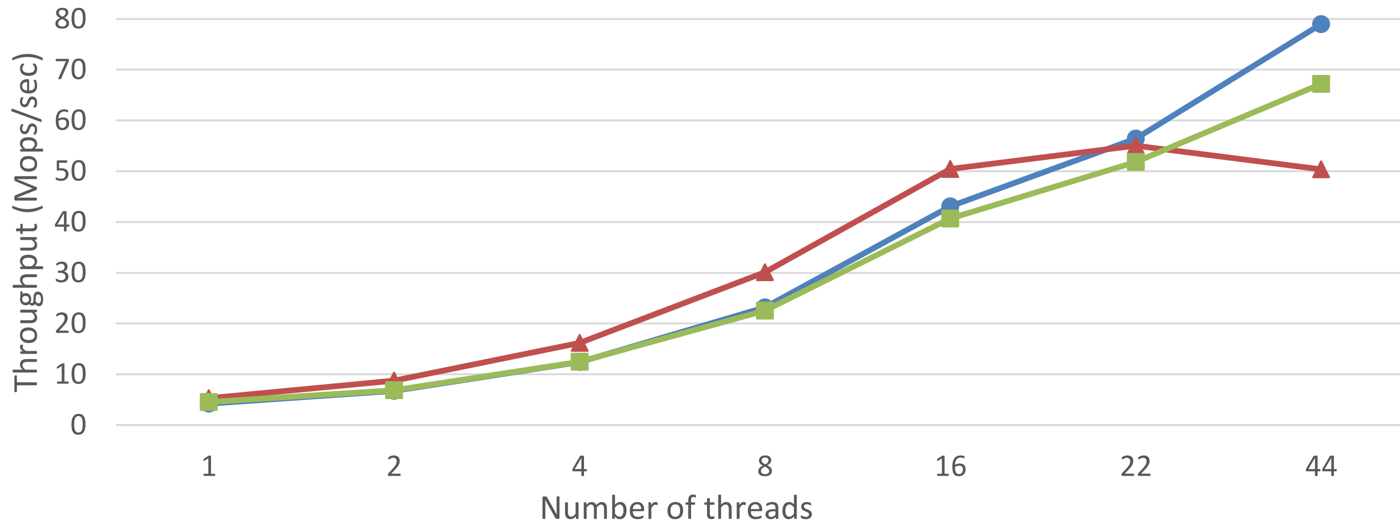
Comparison with state-of-the-art

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]

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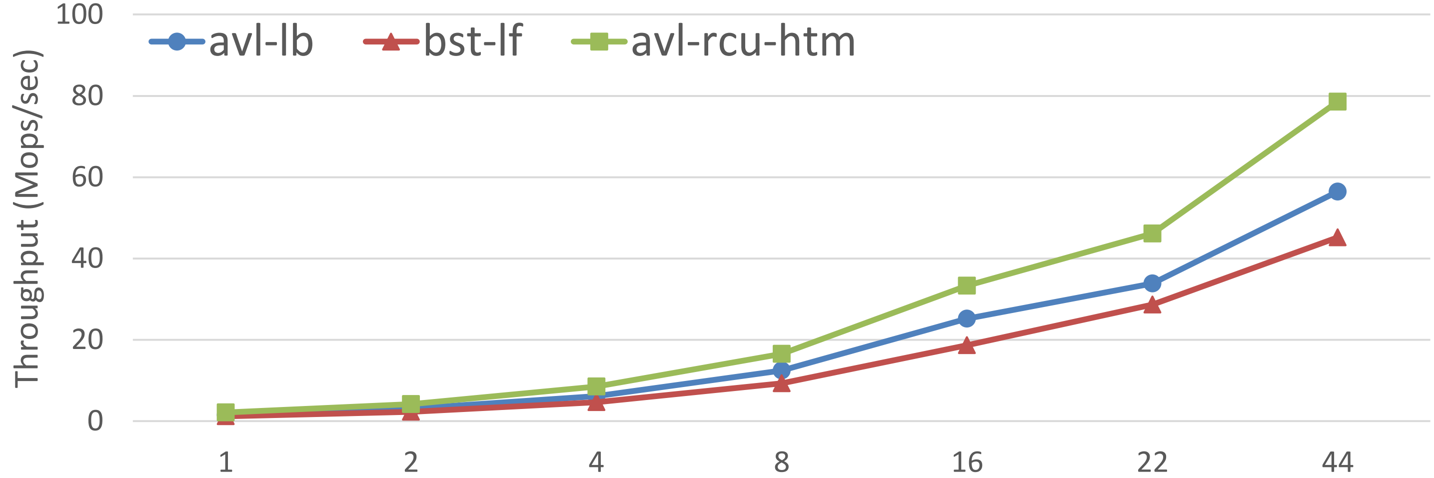
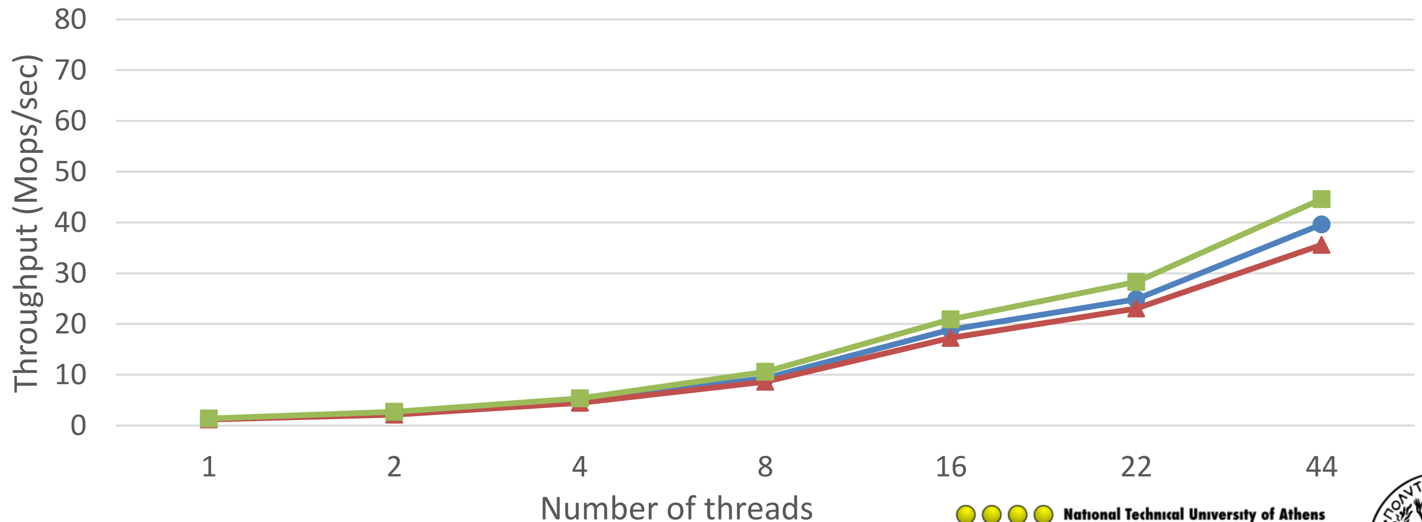
Comparison with state-of-the-art

2M keys
100% lookups



2M keys
20% lookups



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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.)

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THANK YOU!

QUESTIONS?

ACKNOWLEDGMENT

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