A Fast Contention-Friendly Binary Search Tree*

Tyler Crain
INRIA

Vincent Gramoli
NICTA and University of Sydney

Michel Raynal
Institut Universitaire de France and Université de Rennes

Abstract

This paper presents a fast concurrent binary search tree algorithm. To achieve high performance under contention, the algorithm divides update operations within an *eager abstract access* that returns rapidly for efficiency reason and a *lazy structural adaptation* that may be postponed to diminish contention. To achieve high performance under read-only workloads, it features a rebalancing mechanism and guarantees that read-only operations searching for an element execute lock-free.

We evaluate the contention-friendly binary search tree using Synchrobench, a benchmark suite to compare synchronization techniques. More specifically, we compare its performance against five state-of-the-art binary search trees that use locks, transactions or compare-and-swap for synchronization on Intel Xeon, AMD Opteron and Oracle SPARC. Our results show that our tree is more efficient than other trees and double the throughput of existing lock-based trees under high contention.

Keywords: Binary tree, Concurrent data structures, Efficient implementation.

1 Introduction

Today's processors tend to embed more and more cores. Concurrent data structures, which implement popular abstractions such as key-value stores [28], are thus becoming a bottleneck building block of a wide variety of concurrent applications. Maintaining the invariants of such structures, like the balance of a tree, induces contention. This is especially visible when using speculative synchronization techniques as it boils down to restarting operations [10]. In this paper we describe how to cope with the contention problem when it affects a non-speculative technique.

As a widely used and studied data structure in the sequential context, binary trees provide logarithmic access time complexity given that they are balanced, meaning that among all downward paths from the root to a leaf, the length of the shortest path is not far apart the length of the longest path. Upon tree update, if the height difference exceeds a given threshold, the structural invariant is broken and a rebalancing is triggered to restructure accordingly. This threshold depends on the considered algorithm: AVL trees [1] do not tolerate the longest length to exceed the shortest by 2 whereas red-black trees [2] tolerate the longest to be twice the shortest, thus restructuring less frequently. Yet in both cases the restructuring is triggered immediately when the threshold is reached to hide the imbalance from further operations. In a concurrent context, slightly weakened balance requirements have been suggested [4], but they still require immediate restructuring as part of update operations to the abstractions.

We introduce the *contention-friendly* tree as a tree that transiently breaks its balance structural invariant without hampering the abstraction consistency in order to reduce contention and speed up concurrent operations that access (or modify) the abstraction. More specifically, we propose a partially internal binary search tree data structure decoupling the operations that modify the abstraction (we call these *abstract operations*) from operations that modify the tree structure itself but not the abstraction (we call these *structural operations*). An abstract operation either searches for, logically deletes, or inserts an element from the abstraction where in certain cases the insertion might also modify the tree structure. Separately, some structural operations rebalance the tree by executing a distributed rotation mechanism as well as physically removing nodes that have been logically deleted.

We evaluate the performance of our algorithm against various data structures on three multicore platforms using Synchrobench [17]. First, we compare the

*This paper is an extended version of a draft paper that appeared at the International Conference on Parallel Processing (Euro-Par 2013) [11] Among other improvements, it presents an experimental evaluation on two other platforms and a comparison with four other concurrent binary search trees algorithms from the literature.

performance against the previous practical binary search tree [7]. Although both algorithms are lock-based binary search trees, ours speeds up the other by 2.2×. Second, we evaluate the performance of a lock-free binary search tree [14] that uses exclusively compare-and-swap and the performance of a more recent binary search tree that offers lock-free contains operations (just like ours) and decouples similarly but without logically deleting nodes. Finally, we tested the transaction-based trees: the concurrent red-black tree from Oracle and a port in Java of the speculation-friendly tree [10]. In various settings the contention-friendly tree outperforms the five other trees.

More specifically, we evaluated our algorithm on AMD Opteron, Oracle SPARC and Intel Xeon, against state-of-the-art binary search tree implementations. The former architecture is a machine of 8 processors each running 8 hardware threads at 1.2GHz while the latter is an AMD machine running 64 cores at 1.4GHz. On both architectures, the contention-friendly binary search tree outperforms other trees at only 10% updates.

Roadmap. We present the related work in Section 2. We describe our methodology in Section 3 and the contention-friendly tree in Section 4, and discuss our algorithm correctness in Section 5. We compare the performance of the contention-friendly tree against five other tree data structures synchronised with locks, compare-and-swap and transactions in Section 6. Finally, we conclude in Section 7.

2 Related Work

On the one hand, the decoupling of update and rebalancing dates back from the 70's [19] and was exclusively applied to trees, including B-trees [3], {2,3}-trees [25], AVL trees [26] and red-black trees [32] (resulting in largely studied chromatic trees [5, 33] whose operations cannot return before reaching a leaf) and more recently to skip lists [12, 13]. On the other hand, the decoupling of the removals in logical and physical phases is more recent [30] but was applied to various structures: various linked lists [18, 20, 21, 30], hash tables [29], skip lists [16], binary search trees [6, 10, 14] and lazy lists [23]. Our solution generalizes both kinds of decoupling by distinguishing an abstract update from a structural modification.

We have recently observed the performance benefit of decoupling accesses while preserving atomicity. Our recent speculation-friendly tree splits updates into separate transactions to avoid a conflict with a rotation from rolling back the preceding insertion/removal [10]. While it benefits from the reusability and efficiency of elastic transactions [15], it suffers from the overhead of bookkeeping accesses with software transactional memory. The goal was to bound the asymptotic step complexity of speculative accesses to make it comparable to the complexity of pessimistic lock-based ones. Although this complexity is low in pessimistic executions, our result shows that the performance of a lock-based binary search tree greatly benefits from this decoupling. In Section 6, we show that a Java port of our speculation-friendly tree is significantly slower than the contention-friendly tree.

There exist several tree data structures that exploit locks for synchronization. The practical lock-based tree exploits features of relaxed transactional memory models to achieve high concurrency [7]. The implementation of this algorithm is written in Scala, which allowed us to use it as the baseline in our experiments. A key optimization of this tree distinguishes whether a modification at some node i grows or shrinks the subtree rooted in i. A conflict involving a growth could be ignored as no descendants are removed and a search preempted at node i will safely resume in the resulting subtree. We compare the performance of the original implementation to our tree in Section 6.

Lock-free trees are interesting to make sure that the system always makes progress whereas lock-based trees do not prevent threads from blocking, which can be problematic in a model where cores can fail. A lock-free binary search tree was proposed [14] by using exclusively single-word compare-and-swap (CAS) for synchronization. Unfortunately, this tree cannot be rotated. Section 6 depicts its performance under balanced workloads. A more recent lock-free binary search trees was proposed [31], unfortunately, we are not aware of any Java-based implementation.

3 Overview

In this section, we give an overview of the Contention-Friendly (CF) methodology by describing how to write contention-friendly data structures as we did to design a lock-free CF skip-list [9, 12]. The next section describes how this is done for the binary search tree.

The CF methodology aims at modifying the implementation of existing data structures using two simple rules without relaxing their correctness. The correctness criterion ensured here is linearizability [24]. The data structures considered are *search structures* because they organize a set of items, referred to as *elements*, in a way that allows to retrieve the unique position of an element in the structure given its value. The typical abstraction implemented by such structures is a collection of elements that can be specialized into various sub-abstractions like a set (without duplicates) or a map (that

maps each element to some value). We consider insert, delete and contains operations that, respectively, inserts a new element associated to a given value, removes the element associated to a given value or leaves the structure unchanged if no such element is present, and returns the element associated to a given value or $\perp$ if such an element is absent. Both inserts and deletes are considered *updates*, even though they may not modify the structure.

The key rule of our methodology is to decouple each update into an *eager abstract modification* and a *lazy structural adaptation*. The secondary rule is to make the removal of nodes selective and tentatively affect the less loaded nodes of the data structure. These rules induce slight changes to the original data structures. that result in a corresponding data structure that we denote using the *contention-friendly* adjective to differentiate them from their original counterpart.

3.1 Eager abstract modification

Existing search structures rely on strict invariants to guarantee their big-oh (asymptotic) complexity. Each time the structure gets updated, the invariant is checked and the structure is accordingly adapted as part of the same operation. While the update may affect a small sub-part of the abstraction, its associated restructuring can be a global modification that potentially conflicts with any concurrent update, thus increasing contention.

The CF methodology aims at minimizing such contention by returning eagerly the modifications of the update operation that make the changes to the abstraction visible. By returning eagerly, each individual process can move on to the next operation prior to adapting the structure. It is noteworthy that executing multiple abstract modifications without adapting the structure does no longer guarantee the asymptotic complexity of the accesses, yet, as mentioned in the Introduction, such complexity may not be the predominant factor in contended executions.

A second advantage is that removing the structural adaption from the abstract modification makes the cost of each operation more predictable as operations share similar costs and create similar amount of contention. More importantly the completion of the abstract operation does not depend on the structural adaptation (like they do in existing algorithms), so the structural adaptation can be performed differently, for example, using global information or being performed by separate, unused resources of the system.

3.2 Lazy structural adaptation

The purpose of decoupling the structural adaptation from the preceding abstract modification is to enable its postponing (by, for example, dedicating a separate thread to this task, performing adaptations when observed to be necessary), hence the term "lazy" structural adaptation. The main intuition here is that this structural adaptation is intended to ensure the big-oh complexity rather than to ensure correctness of the state of the abstraction. Therefore the linearization point of the update operation belongs to the execution of the abstract modification and not the structural adaptation and postponing the structural adaptation does not change the effectiveness of operations.

This postponing has several advantages whose prominent one is to enable merging of multiple adaptations in one simplified step. Only one adaptation might be necessary for several abstract modifications and minimizing the number of adaptations decreases accordingly the induced contention. Furthermore, several adaptations can compensate each other as the combination of two restructuring can be idempotent. For example, a left rotation executing before a right rotation at the same node may lead back to the initial state and executing the left rotation lazily makes it possible to identify that executing these rotations is useless. Following this, instead of performing rotations as a string of updates as part of a single abstract operation, each rotation is performed separately as a single local operation, using the most up to date balance information.

Although the structural adaptation might be executed in a distributed fashion, by each individual updater thread, one can consider centralizing it at one dedicated thread. Since these data structures are designed for architectures that use many cores, performing the structural adaptation on a dedicated single separate thread leverages hardware resources that might otherwise be left idle.

Selective removal. In addition to decoupling level adjustments, removals are preformed selectively. A node that is deleted is not removed instantaneously but is marked as deleted. The structural adaptation then selects among these marked nodes those that are suitable for removal, i.e., whose removal would not induce high contention. This selection is important to limit contention. Removing a frequently accessed node requires locking or invalidating a larger portion of the structure. Removing such a node is likely to cause much more contention than removing a less frequently accessed one. In order to prevent this, only nodes that are marked as deleted and have at least one of their children as an empty subtree are removed. Marked deleted nodes can

then be added back into the abstraction by simply unmarking them during an *insert* operation. This leads to less contention, but also means that certain nodes that are marked as deleted may not be removed. In similar, partially external/internal trees, it has already been observed that only removing such nodes [10], [7] results in a similar sized structure as existing algorithms. However, it is difficult to bound the number of marked nodes under peak contention: we could imagine a large number of threads marking all elements simultaneously, resulting in an abstraction of size 0 while the structure contains some logically deleted nodes.

4 The Contention-Friendly Tree

The CF tree is a lock-based concurrent binary search tree implementing classic insert/delete/contains operations. Its structure is similar to an AVL tree except that it violates the depth invariant of the AVL tree under contention. Each of its nodes contains the following fields: a key k, pointers ℓ and r to the left and right child nodes, a *lock* field, a *del* flag indicating if the node has been logically deleted, a *rem* flag indicating if the node has been physically removed, and the integers *left-h*, *right-h* and *local-h* storing the estimated height of the node and its subtrees used in order to decide when to perform rotations.

This section will now describe the CF tree algorithm by first describing three specific CF modifications that reduce contention during traversal, followed by a description of the CF abstract operations.

4.1 Avoiding contention during traversal

Each abstract operation of a tree is expected to traverse $O(\log n)$ nodes when there is no contention. During an update operation, once the traversal is finished a single node is then modified in order to update the abstraction. In the case of delete, this means setting the *del* flag to true, or in the case of insert changing the child pointer of a node to point to a newly allocated node (or unmarking the *del* flag in case the node exists in the tree). Given then, that the traversal is the longest part of the operation, the CF tree algorithm tries to avoid here, as often as possible, producing contention. Many concurrent data structures use synchronization during traversal even when the traversal does not update the structure. For example, performing hand-over-hand locking in a tree helps ensure that the traversal remains on track during a concurrent rotation [7], or, using optimistic strategy (such as transactional memory), validation is done during the traversal, risking the operation to restart in the case of concurrent modifications [22, 23, 34].

4.2 Physical removal

As previously mentioned, the algorithm attempts to remove only nodes whose removal incurs the least contention. Specifically, removing a node n with a subtree at each child requires finding its successor node s in one of its subtrees, then replacing n with s. Therefore precautions must be taken (such as locking all the nodes) in order to ensure any concurrent traversal taking place on the path from n to s does not violate linearizability. Instead of creating contention by removing such nodes, they are left as logically deleted in the CF tree; to be removed later if one of their subtrees becomes empty, or to be unmarked if a later insert operation on the same node occurs.

In the CF tree, nodes that are logically deleted and have less than two child subtrees are physically removed lazily (cf. Algorithm 1). Since we do not want to use synchronization during traversal these removals are done slightly differently than by just unlinking the node. The operation starts by locking the node n to be removed and its parent p (line 6). Following this, the appropriate child pointer of p is then updated (lines 12-13), effectively removing n from the tree. Additionally, before the locks are released, both of n's left and right pointers are modified to point back to p and the *rem* flag of n is set to true (lines 14-15). These additional modifications allow concurrent abstract operations to keep traversing safely as they will then travel back to p before continuing their traversal, much like would be done in a solution that uses backtracking.

4.3 Rotations

Rotations are performed to rebalance the tree so that traversals execute in logarithmic time in the number of elements present in the abstraction once contention decreases. As described in Section 3, the CF tree uses localized rotations in order to minimize conflicts. Methods for performing localized rotation operations in the binary trees have already been examined and proposed in several works such as [4]. The main concept used here is to propagate the balance information from a leaf to the root. When a node has a $\perp$ child pointer then the node must know that this subtree has height 0 (the estimated heights of a node's subtrees are stored in the integers *left-h* and *right-h*). This information is then propagated upwards by sending the height of the child to the parent, where the value is then increased by 1 and stored in the parent's *local-h* integer. Once an imbalance of height more than 1 is discovered, a rotation is performed. Higher up in the tree the balance information might become out of date due to concurrent structural modifications, but, importantly, performing these local

Algorithm 1 Remove and rotate operations executed by process p

```
1:  remove(parent, left-child)_p:
2:    if parent.rem then return false
3:    if left-child then n ← parent.ℓ
4:    else n ← parent.r
5:    if n = ⊥ then return false
6:    lock(parent); lock(n);
7:    if ¬n.del then release-locks(); return false
8:    if (child ← n.ℓ) ≠ ⊥ then
9:      if n.r ≠ ⊥ then
10:       release-locks(); return false
11:   else child ← n.r
12:   if left-child then parent.ℓ ← child
13:   else parent.r ← child
14:   n.ℓ ← parent; n.r ← parent;
15:   n.rem ← true;
16:   release-locks()
17:   update-node-heights();
18:   return true.

19: right-rotate(parent, left-child)_p:
20:   if parent.rem then return false
21:   if left-child then n ← parent.ℓ
22:   else n ← parent.r
23:   if n = ⊥ then return false
24:   ℓ ← n.ℓ;
25:   if ℓ = ⊥ then return false
26:   lock(parent); lock(n); lock(ℓ);
27:   ℓr ← ℓ.r; r ← n.r;
28:   // allocate a node called new
29:   new.k ← n.k; new.ℓ ← ℓr;
30:   new.r ← r; ℓ.r ← new;
31:   if left-child then parent.ℓ ← ℓ
32:   else parent.r ← ℓ
33:   n.rem ← true; // by-left-rot if left rotation
34:   release-locks()
35:   update-node-heights();
36:   return true
```

rotations will eventually result in a balanced tree [4].

Apart from performing rotations locally as unique operations, the specific CF rotation procedure is done differently in order to avoid using locks and aborts/rollbacks during traversals. Let us consider specifically the typical tree right-rotation operation procedure. Here we have three nodes modified during the rotation: a parent node p, its child n who will be rotated downward to the right, as well as n's left child ℓ who will be rotated upwards, thus becoming the child of p and the parent of n. Consider a concurrent traversal that is preempted on n during the rotation. Before the rotation, ℓ and its left subtree exist below n as nodes in the path of the traversal, while afterwards (given that n is rotated downwards) these are no longer in the traversal path, thus violating correctness if these nodes are in the correct path. In order to avoid this, mechanisms such as hand over hand locking [7] or keeping count of the number of operations currently traversing a node [4] have been suggested, but these solutions require traversals to make themselves visible at each node, creating contention. Instead, in the CF tree, the rotation operation is slightly modified, allowing for safe, concurrent, invisible traversals.

The rotation procedure is then performed as follows as shown in Algorithm 1: The parent p, the node to be rotated n, and n's left child ℓ are locked in order to prevent conflicts with concurrent insert and delete operations. Next, instead of modifying n like would be done in a traditional rotation, a new node *new* is allocated to take n's place in the tree. The key, value, and *del* fields of *new* are set to be the same as n's. The left child of *new* is set to $\ell.r$ and the right child is set to $n.r$ (these are the nodes that would become the children of n after a traditional rotation). Next $\ell.r$ is set to point to *new* and p's child pointer is updated to point to ℓ (effectively removing n from the tree), completing the structural modifications of the rotation. To finish the operation $n.rem$ is set to true (or by-left-rot, in the case of a left-rotation) and the locks are released. There are two important things to notice about this rotation procedure: First, *new* is the exact copy of n and, as a result, the effect of the rotation is the same as a traditional rotation, with *new* taking n's place in the tree. Second, the child pointers of n are not modified, thus all nodes that were reachable from n before the rotation are still reachable from n after the rotation, thus, any current traversal preempted on n will still be able to reach any node that was reachable before the rotation.

4.4 Structural adaptation

As mentioned earlier, one of the advantages of performing structural adaptation lazily is that it does not need to be executed immediately as part of the abstract operations. In a highly concurrent system this gives us the possibility to use processor cores that might otherwise be idle to perform the structural adaptation, which is exactly what is done in the CF tree. A fixed structural adaption thread is then assigned the task of running the background-struct-adaptation operation which repeatably calls the restructure-node procedure on the root node, as shown in Algorithm 2, taking care of balance and physical removal. restructure-node is simply a recursive depth-first procedure that traverses the entire tree. At each node, first the operation attempts to physically remove its children if they are logically deleted. Following this, it propagates balance values from its children and if an imbalance is found, a rotation is per-

Algorithm 2 Restructuring operations executed by process p

```
1:  background-struct-adaptation()_p:
2:    while true do
3:      // continuous background restructuring
4:      restructure-node(root).

5:  propagate(n)_p:
6:    if n.ℓ ≠ ⊥ then n.left-h ← n.ℓ.local-h
7:    else n.left-h ← 0
8:    if n.r ≠ ⊥ then n.right-h ← n.r.local-h
9:    else n.right-h ← 0
10:   n.local-h ← max(n.left-h, n.right-h) + 1.

11: restructure-node(node)_p:
12:   if node = ⊥ then return
13:   restructure-node(node.ℓ);
14:   restructure-node(node.r);
15:   if node.ℓ ≠ ⊥ ∧ node.ℓ.del then
16:     remove(node, false)
17:   if node.r ≠ ⊥ ∧ node.r.del then
18:     remove(node, true)
19:   propagate(node);
20:   if |node.left-h − node.right-h| > 1 then
21:     // Perform appropriate rotations.
```

formed.

A single thread is constantly running, but having several structural adaptations threads, or distributing the work among application threads is also possible. It should be noted that, in a case where there can be multiple threads performing structural adaptation, we would need to be more careful on when and how the locks are obtained.

4.5 Abstract operations

The abstract operations are shown in Algorithm 3. Each of the abstract operations begin by starting their traversal from the *root* node. The traversal is then performed, without using locks, from within a while loop where each iteration of the loop calls the get-next procedure, which returns either the next node in the traversal, or $\perp$ in the case that the traversal is finished.

The get-next procedure starts by reading the *rem* flag of *node*. If the flag was set to by-left-rotate then the node was concurrently removed by a left-rotation. As we saw in the previous section, a node that is removed during rotation is the node that would be rotated downwards in a traditional rotation. Specifically, in the case of the left rotation, the removed node's right child is the node rotated upwards, therefore in this case, the get-next operation can safely travel to the right child as it contains at least as many nodes in its path that were in the path of the *node* before the rotation. If the flag was set to true then the node was either removed by a physical removal or a right-rotation, in either case the operation can safely travel to the left child, this is because the remove operation changes both of the removed node's child pointers to point to the parent and the right-rotation is the mirror of the left-rotation. If the rem flag is false then the key of *node* is checked, if it is found to be equal to k then the traversal is finished and $\perp$ is returned. Otherwise the traversal is performed as expected, traversing to the right if the *node.k* is bigger than k or to the left if smaller.

Given that the insert and delete operations might modify *node*, they lock it for safety once $\perp$ is returned from get-next. Before the node is locked, a concurrent modification to the tree might mean that the traversal is not yet finished (for example the node might have been physically removed before the lock was taken), thus the validate operation is called. If false is returned by validate, then the traversal must continue, otherwise the traversal is finished. Differently, given that it makes no modifications, the contains operation exits the while loop immediately when $\perp$ is returned from get-next.

The validate operation performs three checks on *node* to ensure that the traversal is finished. First it ensures that *rem* = false, meaning that the node has not been physically removed from the tree. Then it checks if the key of the node is equal to k, in such a case the traversal is finished and true is returned immediately. If the key is different from k then the traversal is finished only if *node* has $\perp$ for the child where a node with key k would exist. In such a case true is returned, otherwise *false* is returned.

The code after the traversal is straightforward. For the contains operation, true is returned if *node.k* = k and *node.del* = false, false is returned otherwise. For the insert operation, if *node.k* = k then the *del* flag is checked, if it is false then false is returned; otherwise if the flag is true it is set to false, and true is returned. In the case that *node.k* ≠ k, a new node is allocated with key k and is set to be the child of *node*. For the delete operation, if *node.k* ≠ k, then false is returned. Otherwise, the *del* flag is checked, if it is true then false is returned, otherwise if the flag is false, it is set to true and true is returned.

5 Correctness

The contention-friendly tree is linearizable [24] in that in any of its potentially concurrent executions, each of its insert, delete and contains operations executes as if it was executed at some indivisible point, called its *linearization point*, between its invocation and response. We

Algorithm 3 Abstract operations

```
1:  contains(k)_p:
2:    node ← root;
3:    while true do
4:      next ← get_next(node,k);
5:      if next = ⊥ then break
6:      node ← next;
7:    result ← false;
8:    if node.k = k then
9:      if ¬node.del then result ← true
10:   return result.

11: insert(k)_p:
12:   node ← root;
13:   while true do
14:     next ← get_next(node,k);
15:     if next = ⊥ then
16:       lock(node);
17:       if validate(node,k) then break
18:       unlock(node);
19:     else node ← next
20:   result ← false;
21:   if node.k = k then
22:     if node.del then
23:       node.del ← false; result ← true
24:   else // allocate a node called new
25:     new.key ← k;
26:     if node.k > k then node.r ← new
27:     else node.ℓ ← new
28:     result ← true;
29:   unlock(node);
30:   return result.

31: delete(k)_p:
32:   node ← root
33:   while true do
34:     next ← get_next(node,k);
35:     if next = ⊥ then
36:       lock(node);
37:       if validate(node,k) then break
38:       unlock(node);
39:     else node ← next
40:   result ← false;
41:   if node.k = k then
42:     if ¬node.del then
43:       node.del ← true; result ← true
44:   unlock(node);
45:   return result.

46: get-next(node,k)_s:
47:   rem ← node.rem;
48:   if rem = by-left-rot then next ← node.r
49:   else if rem then next ← node.ℓ
50:   else if node.k > k then next ← node.r
51:   else if node.k = k then next ← ⊥
52:   else next ← node.ℓ
53:   return next.

54: validate(node,k)_s:
55:   if node.rem then return false
56:   else if node.k = k then return true
57:   else if node.k > k then next ← node.r
58:   else next ← node.ℓ
59:   if next = ⊥ then return true
60:   return false.
```

proceed by showing that the execution of each operation has a linearization point between its invocation and response, where this operation appears to execute atomically.

Given that the insert and delete operations that return false do not modify the tree and that all other operations that modify nodes only do so while owning the node's locks, these failed insert and delete operations can be linearized at any point during the time that they own the lock of the node that was successfully validated.

The successful insert (i.e., the one that returns true) operation is linearized either at the instant it changes *node.del* to false, or when it changes the child pointer of *node* to point to *new*. In either case, k exists in the abstraction immediately after the modification. The successful delete operation is linearized at the instant it changes *node.del* to true, resulting in k no longer being in the abstraction.

The contains operation is a bit more difficult as it does not use locks. To give an intuition of how it is linearized, first consider a system where neither rotations nor physical removals are performed. In this system, if $node.k = k$ on line 8 is true, then the linearization point is when *node.del* is read (line 9). Otherwise if $node.k \neq k$, then the linearization point is either on line 50 or 52 of the get-next operation where $\perp$ is read as the next node (meaning at the time of this read k does not exist in the abstraction).

Now, if rotations and physical removals are performed in the system, then a contains operation who has finished its traversal might get preempted on a node that is removed from the tree. First consider the case where $node.k = k$, since neither rotations nor removals will modify the *del* flag of a node, then in this case the linearization point is simply either on line 50 or 52 of the get-next operation where the pointer to *node* was read.

Finally, consider the case where $node.k \neq k$. First notice that when false is not read from node.rem (line 47 of get-next) then the traversal will always continue to another node. This is due to the facts that after a right (resp. left) rotation, the node removed from the tree will always have a non-$\perp$ left (resp. right) child (this is the child rotated upwards by the rotation) and that a node removed by a remove operation will never have a $\perp$ child pointer. Therefore if the traversal finishes on a node that has been removed from the tree, it must have read that node's *rem* flag before the rotation or removal had completed. This read will then be the linearization point of the operation. In this case, for the contains operation to complete, the next node in the traversal must be read as $\perp$ from the

child pointer of *node*, meaning that the removal/rotation has not made any structural modifications to this pointer at the time of the read (this is because rotations make no modifications to the child pointers of the node they remove, and removals point the removed node's pointers towards its parent). Thus, given that removals and rotations will lock the node removed meaning no concurrent modifications will take place, effectively the contains operation has observed the state of the abstraction immediately before the removal took place.

6 Experimental Evaluation

We implemented the contention-friendly binary search tree in Java and tested it on two different architectures using the publicly available Synchrobench benchmark suite [17]:

- A 64-way UltraSPARC T2 with 8 processors with up to 8 hardware threads running at 1.2GHz with Solaris 10 (kernel architecture sun4v) and Java 1.7.0_05-b05 HotSpot Server VM.
- A 64-way x86-64 AMD machine with 4 sockets with 16 cores each running at 1.4GHz running Fedora 18 and Java 1.7.0_09-icedtea OpenJDK 64-Bit Server VM.
- A 32-way x86-64 Intel machine with 2 sockets with 8 hyperthreaded cores running at 2.1GHz running Ubuntu 12.04.5 LTS and Java 1.8.0_74 HotSpot 64-Bit Server VM.

For each run, we present the maximum, minimum, and averaged numbers of operations per microsecond over 5 runs of 5 seconds executed successively as part the same JVM for the sake of warmup. As recommended by Synchrobench [17] we kept the range of possible values twice as large as the initial size to keep the structure size constant in expectation during the entire benchmark run.

6.1 Lock-based binary search trees

First, we compare the performance of the contention-friendly tree (CF-tree) against the practical lock-based binary search tree (BCCO-tree [7]) on an UltraSPARC T2 with 64 hardware threads, using the original code of the authors.

Figure 1 compares the performance of the practical BCCO tree against performance of our binary search tree with 2^{12} (left) and 2^{16} elements (right) and on a read-only workload (top) and workloads comprising up to 20% updates (bottom). The variance of our results is quite low as illustrated by the relatively short error bars we have. While both trees scale well with the number of threads, the BCCO tree is slower than its contention-friendly counterpart in all the various settings.

In particular, our CF tree is up to 2.2× faster than its BCCO counterpart. As expected, the performance benefit of our contention-friendly tree increases generally with the level of contention. (We observed this phenomenon at higher update ratios but omitted these graphs for the sake of space.) First, the performance improvement increases with the level of concurrency on Figures 1(c), 1(d), 1(e) and 1(f). As each thread updates the memory with the same (non-null) probability the contention increases with the number of concurrent threads running. Second, the performance improvement increases with the update ratio. This is not surprising as our tree relaxes the balance invariant during contention peaks whereas the BCCO tree induces more contention to maintain the balance invariant.

6.2 Transaction-based binary search trees

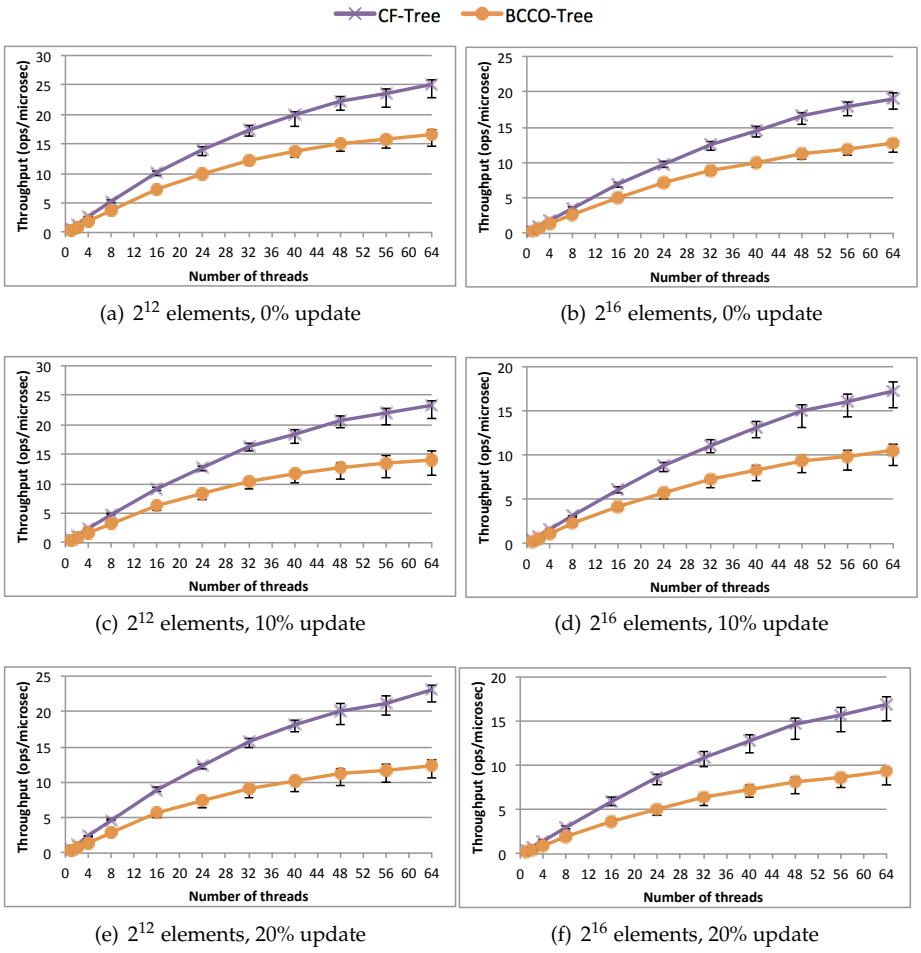
We also compare the contention-friendly tree against two binary search trees using Software Transactional Memories. Note that hardware transactional memory can only be used on small data structures and that transactional instructions are not available in Java, so we decided to use DeuceSTM [27] in its default mode to test the performance of two transaction-based binary search trees.

The first transaction-based binary search tree is the red-black tree developed by Oracle and others that get rid of sentinel nodes to diminish aborts due to false conflicts. Its code was used to implement database tables in the STAMP vacation benchmark [8] that are accessed through transactions and it is publicly available in JSTAMP and as part of Synchrobench[1]. The second is the speculation-friendly binary search tree algorithm [10] especially tuned to reduce the size of transactions by decoupling rotations from the insertion and removal of nodes. We ported the existing implementation from C that is publicly available online[2] to Java and used the DeuceSTM bytecode instrumentation framework as well.

Figure 2 depicts the performance of the transaction-based binary search tree with 10% updates on both our AMD platform (x86-64) and our Niagara 2 (SPARC) platform. To have a clearer view of the shape of the transaction-based BST curves, we used a logarithmic scale on the y-axis. The difference in performance between the transaction-based binary search trees and our contention-friendly binary search tree is substantial. The reason is mainly explained by the overhead induced by

[1] https://sites.google.com/site/synchrobench

[2] https://github.com/gramoli/synchrobench/tree/master/src/sftree.



(a) 2^{12} elements, 0% update (b) 2^{16} elements, 0% update

(c) 2^{12} elements, 10% update (d) 2^{16} elements, 10% update

(e) 2^{12} elements, 20% update (f) 2^{16} elements, 20% update

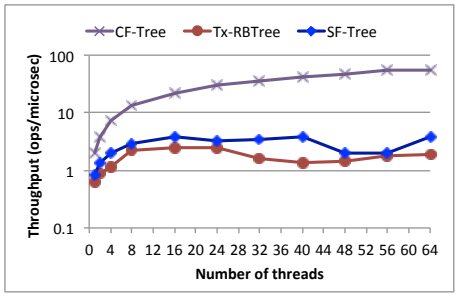
Figure 1: Performance of our contention-friendly tree and the practical concurrent tree [7]

DeuceSTM that instruments the bytecode to produce a transactional version that uses metadata, like read-set and write-set to check the consistency of executions. Interestingly, the curves of the transaction-based binary search trees is smoother on the SPARC architecture, probably due to operating system and architectural optimisations for the JVM.

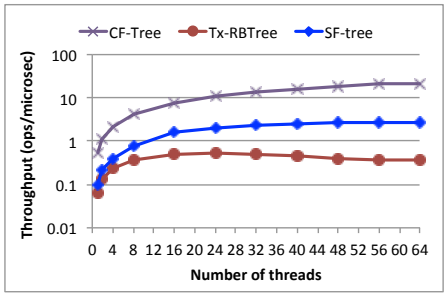
6.3 Lock-free binary search trees

Finally, we compare the contention-friendly tree against trees providing lock-free operations. Similar to our tree, the logical ordering binary search thee (DVY) [11] provides lock-free contains operations and separate the physical structure from the abstract representation. As opposed to our tree though, it does not have transient states where nodes are logically deleted without being physically removed from the tree. The non-blocking binary search tree (EFRB) [14] uses exclusively single-word compare-and-swap for synchronization. Its contains operation never updates the structure and the tree is not balanced. The code of both algorithms is available online.

Figure 3 depicts the results obtained with the existing lock-free binary search tree (EFRB) and the logical ordering binary search tree (DVY). We can see that the DVY-tree is slower than the contention-friendly binary search tree at all thread counts on both architectures. While the DVY-tree uses a similar decoupling technique, it immediately physically remove node from the structure hence affecting the structure each time a remove occur. By contrast, the contention-friendly tree does not immediately remove a node from the structure but simply marks it as logically deleted, hence minimising the contention even with only 10% updates. Finally the EFRB tree presents performance on SPARC that are similar to the contention-friendly tree as it only uses single-word compare-and-swap to synchronise threads and because the workload is uniformly distributed. Even though the

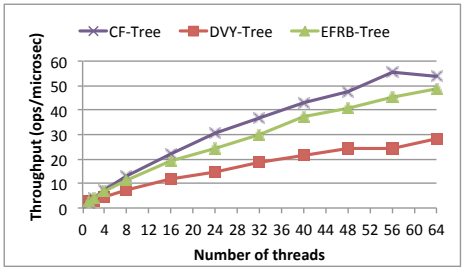


(a) AMD platform

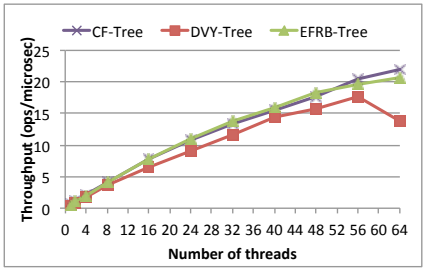


(b) SPARC platform

Figure 2: Transaction-based binary search trees vs. the contention-friendly tree (2^{14} elements and 10% updates)

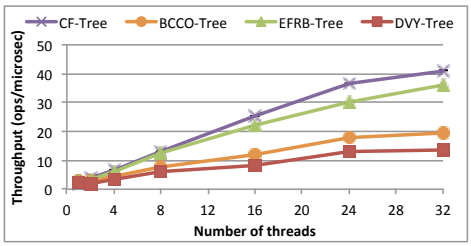


(a) AMD platform

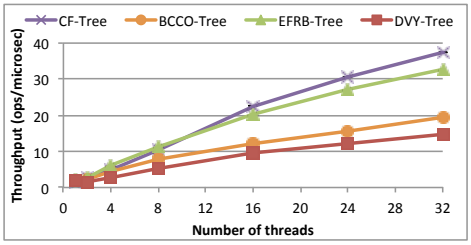


(b) SPARC platform

Figure 3: Lock-free binary search trees vs. the contention-friendly tree (2^{14} elements and 10% updates)



(a) Intel platform - 2^{12} elements - 100% update



(b) Intel platform - 2^{14} elements - 100% update

Figure 4: The lock-free and lock-based trees under heavy contention

workload is also uniformly distributed on x86-64, we can see that the contention-friendly tree remains faster than the EFRB tree. This result is particularly remarkable given that the workload is balanced which should not penalise the performance of the EFRB tree that cannot rotate.

6.4 Performance under high contention

To further stress test the contention-friendly tree, we compared the performance of the lock-free and lock-based trees on smaller data structures with a higher update ratio. The results are depicted in Figure 4. Note that the update are attempted as Synchrobench cannot run 100% updates without becoming deterministic. We can clearly observe that the performance of the EFRB and the DVY trees is more impacted by the contention than the performance of the contention-friendly tree, as the performance gain of the contention-friendly tree is even higher than on Figure 3. The BCCO performance is slightly better than the DVY tree but remains significantly lower than the contention-friendly tree. In particular the performance of the BCCO tree is twice slower than the contention-friendly at 32 threads.

7 Conclusion

The contention-friendly methodology is promising for increasing performance of data structure on multicore

architectures where the number of cores potentially updating the structure continues to grow. It achieves this goal by decoupling the abstraction modifications from the structural modifications, hence limiting the induced contention. We illustrated our methodology with a lock-based binary search tree that we implemented in Java. The comparison of its performance against five state-of-the-art tree structures and on two different multicore architectures indicates that our tree is efficient even under reasonable contention.

Availability

The source code of all the data structures tested in this paper were made publicly available online at `https://github.com/gramoli/synchrobench/tree/master/java/src/trees/` with the BCCO-Tree located at `lockbased/LockBasedStanfordTree.java`, the EFRB-Tree at `lockfree/NonBlockingTorontoBSTMap.java`, the DVY-Tree at `lockbased/LogicalOrderingAVL.java`, the CF-Tree at `lockbased/LockBasedFriendlyTreeMap.java`, the SF-Tree at `transactional/TransactionalFriendlyTreeSet.java` and the Tx-RBTree at `transactional/TransactionalRBTreeSet.java`.

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