

## 1 The Concurrent Binary Search Tree Algorithm

### 1.1 Abstract

This algorithm is an implementation of the set ADT. That includes:

- The *insert*( $x$ ) method adds  $x$  to the tree, returning *true* if and only if  $x$  wasn't already in the tree.
- The *remove*( $x$ ) method removes  $x$  to the tree, returning *true* if and only if  $x$  was in the tree.
- The *contains*( $x$ ) method returns *true* if and only if  $x$  was in the tree.

Due to a set being represented by such data structure like a binary search tree, there are certain mechanisms which require additional care in comparison to the *Lazy List*. Such additional care, is induced merely due to the fact that when *remove*-ing *binary nodes* from the tree (nodes who have both a left and a right child (and thus a left and a right subtree)) – we ought to replace such nodes with their successor in the tree, in order to maintain the *tree invariants*. This mechanism presents the following inconsistency:

Assume we have a tree with keys  $k_1$ ,  $k_2$ , and that  $k_2$  is the successor of  $k_1$ . Moreover, assume that the path between the node holding  $k_1$  and the node holding  $k_2$  is greater than one edge (i.e., there's at least one key in the tree which is in-between  $k_1$  and  $k_2$ 's path). Consequently, assume there is some operation named *op* pending which is traversing through the tree to find if  $k_2$  exists in the tree. Moreover, assume that *op*'s *traversal* has yet to reach the node holding  $k_2$  – and that it has already traversed through the node holding  $k_1$  (i.e., the traversal is currently at a node holding a key in-between  $k_1$  and  $k_2$ ). Subsequently, assume another thread chose to run *remove*( $k_1$ ). We get that this thread will replace the node holding  $k_1$  with the node holding  $k_2$ , since  $k_1$  has a successor and it's  $k_2$ . Assume it has done so. Subsequently, assume *op*'s *traversal* continues running, and that it finds that  $k_2$  doesn't exist in the tree (since the node holding  $k_2$  has moved to the location of the node that held  $k_1$ , and since the *traversal* has already passed the location of the node that held  $k_1$ ). We therefore get a violation, since  $k_2$  is present in the tree, and since no other thread is trying to remove it.

This violation suggests that the naïve way of *traversing* the tree is incorrect for such an algorithm – since a *traversal* can become invalid while it is running. Therefore, we suggest the new following approach to *traversing* the tree – which must end as valid *traversal*.

#### 1.1.1 New Tree Traversal

The following approach recognizes that throughout the *traversal* of some operation, the key that it searches for might have moved to a location higher than where the *traversal* currently resides at. It recognizes so, by rerunning the *traversal* and checking for a repeating result (i.e., the same parent). Only after a repeating result should the *traversal* terminate. Notice: we rerun the *traversal* if and only if the key was not found.

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```
1 public NodePair traverse(int key) {
2     NodePair first = new NodePair(null, null, false);
3
4     while (true) { // break if two consecutive traversals coalesce or if the key is found
5         Node second = findKeyOnce(key);
6         if ( (second.parent == first.parent) or (second.key == key) ) {
7             return second;
8         }
9         first = second;
10    }
```

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**Fig. 1:** Pseudo-code for the traversal logic. We can see that the traversal terminates if and only if two consecutive traversals yield the same result (assuming both found the key to not exist in the tree), or if the key was found in some traversal in the while loop.

## 1.2 The *remove(x)* method

### 1.2.1 Implementation

When removing an element, we first traverse the tree to find the node to remove and its parent node. If the node was found, it and its parent should be locked and validated (a similar validation to the *Lazy List*'s), and then there are three cases: the node can be either binary, unary or a leaf.

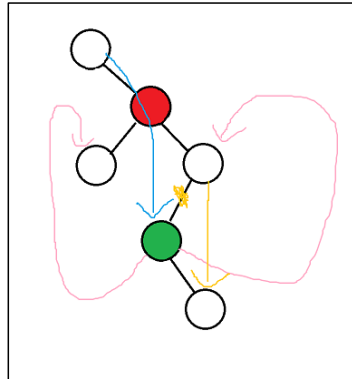
If the node is a leaf, the removal is trivial – just disconnect the node's parent from the node.

If the node is unary, then it's still simple enough – just connect the parent to the single child of the node being removed.

The third case is more complicated – as the “hole” created by the removed node must be filled with its successor. This “filling” must be done without ever disconnecting any node or subtree from the tree, otherwise concurrent calls to *contains* or *insert* might fail. This is done by first finding the node's successor – the leftmost child in the subtree rooted in the removed node's right child. The successor and its parent must be locked, too, to prevent them from changing. Then, again, there are two cases: either the successor is a leaf, or it has a right child.

If the successor is a leaf, it can be connected to the removed node's children, then connected to the removed node's parent, and finally disconnected from its original parent. Note that the order is important – any other order temporarily unlinks some of the nodes from the tree, harming linearizability.

Otherwise, the removal must be more complicated, as demonstrated by Figure 2.



**Fig. 2:** The red node is being removed, and the green node is its successor. No order of setting up the links is correct, as any order temporarily unlinks some nodes.

The pink, orange and blue links should be created for the removal, but:

- Starting with the pink links disconnects the successor's child
- Starting with the orange link disconnects the successor and its children
- Starting with the blue link disconnects the node to remove and its subtree

Any order of modifying the links temporarily unlinks some nodes from the tree, and the removal can't be achieved. Hence, a more complicated removal function is required when the successor has a right child: First, the successor is turned into a leaf by finding its own successor and modifying the tree so that it becomes its left child. Then, once the successor becomes a leaf, it can be removed as previously explained.

Note that similarly to the removal in the *Lazy List*, the removed node is marked before its links are being modified, to prevent other functions from misusing bad nodes.

### 1.2.2 Linearization Point

- For a successful removal, the linearization point is when the node is marked as removed. This happens before the physical removal, but after all the relevant nodes (successor and maybe successor of successor, too) are found.
- For an unsuccessful call, the linearization point is when the parent of the place where the node should be is validated and found to be null.

## 1.3 The *insert(x)* method

### 1.3.1 Implementation

The implementation of *insert(x)* is similar to its implementation in the *Lazy List* algorithm. We first traverse the tree to find the location of the node of where *x* would have been inserted. Notice: this is a regular binary search tree; therefore, all new nodes are inserted as leaves.

**Commented [SC1]:** I might have missed it, but the paragraph says nothing about the fact that all the new nodes are leaves - maybe state it somewhere?

I mentioned it is a regular binary :**Commented [AT2R1]** search tree, and added additional clarifications. I hope it suffices.

Then, we grab locks over *pred* – the parent of the location of the node of where *x* should have been inserted, as well as a lock over *curr* – the location of the node of where *x* should have been inserted. After grabbing the aforesaid locks, we validate that the state of the tree among those two alleged nodes has been maintained (i.e., checking *curr* is still the child of *pred*), as well as assure that *pred* as well as *curr* aren't logically removed (i.e., *marked*).

If such validation/assurance fails – we simply rerun the logic of this method (similarly to the *Lazy List*).

If the validation/assurance succeeds, we continue on with similar mechanisms to the *Lazy List* insertion – that includes: checking if the location of the node of where *x* would have been inserted is an already existing node. In that case, we return **false**, since the traversal would have skipped that node in case it wouldn't have held *x*. The other case, is that the location of the node of where *x* would have resided isn't an already existing node. In such case, we simply create a new Node holding *x*, and set it as a left/right child correspondingly to the parent of the location of the node of where *x* would have resided. As stated above, the inserted node of *x* will always initially be a leaf.

### 1.3.2 Linearization Point

- For a successful *insert(x)* call (i.e., *true* being returned), we linearize the *insert(x)* method at the point of setting the left/right child of the relevant node to be a new node that holds *x*.
- For an unsuccessful *insert(x)* call (i.e., *false* being returned), we linearize the *insert(x)* method at the point of comparing *x* and the key of the node of where *x* would have resided (such comparison would result in them being equal – and therefore no insertion is needed).

## 1.4 The *contains(x)* method

### 1.4.1 Implementation

The implementation of *contains* is as simple as traversing the tree as described in the section describing the new tree traversal. After getting the traversal result, the function reports that the key exists if and only if it is found and unmarked.

Just like in the lazy list, the function doesn't hold any locks – and the linearizability is enforced by the implementation of the other functions.

### 1.4.2 Linearization Point

- For a successful call, the linearization point is when getting a positive traversal result and checking that the resulting node is not marked.
- For an unsuccessful call, we either linearize it at the point of observing a marked node containing the key, or linearize *contains(x)* with any relevant *insert(x)* (similarly to the *Lazy List* description of *contains(x)*'s linearization point).

## 1.5 Deadlock-Prevention

### 1.5.1 Lock Ordering Over Branches

We have ordered the sequence of lock acquisition in such way that locks of nodes in the same branch in the tree, are acquired in a total order. The **branch-specific total order** of node-lock acquisition, is defined by the height of the nodes in the tree. An operation must acquire higher nodes' locks in some branch in the tree, before acquiring lower nodes' locks in the same branch. Such **branch-specific total order** of node-lock acquisition, avoids a *resource-deadlock* in our algorithm, since no operation of our algorithm tries to acquire locks over two nodes from two different branches. Therefore, we are granted a *deadlock-free* algorithm.

### 1.5.2 Enforcing Lock Ordering Over Branches

Enforcing node-lock ordering over same branches in the tree would be done in the naïve way of manually acquiring node-locks in the same branch in a descending manner. Albeit, if there's a possibility of nodes on the same branch being reordered throughout the process of acquiring their locks, it would result in our **branch-specific total order** of node-lock acquisition being breached, which would result in our algorithm not being *deadlock-free*.

Unfortunately, such reordering of nodes on the same branch is possible in our case, due to the *remove(x)* mechanism which might replace a “*to-be-removed*” node with its successor – which could change their order in the branch (assuming the successor resided lower in height in the branch). Therefore, throughout the algorithm, after most node-lock acquisitions (we will soon explain what the exception cases are), we validate that the following “*to-be-acquired*” node-lock is correspondent with our **branch-specific total order** of node-lock acquisition (i.e., we validate that it's lower in height in the branch than the last acquired node-lock). Notice, in cases that we acquire a node-lock over a parent and then acquire a node-lock over its child, the lock order validation is done using the *child* fields of the parent.

We have mentioned that we don't validate the **branch-specific total order** of node-lock acquisition after every node-lock acquisition. Such cases occur in our algorithm only in a scenario where some node  $n_1$  whose right sub-tree isn't empty, has just had its lock acquired, while the “*to-be-acquired*” node-lock is the lock of the parent of the successor of  $n_1$ . We'll now prove that in such case, validating the **branch-specific total order** of node-lock acquisition after  $n_1$ 's lock's acquisition is unnecessary. Let's first call  $n_1$ 's successor *succ*, and *succ*'s parent *succ\_pred*. We'll prove that after  $n_1$ 's lock acquisition, and before *succ\_pred*'s lock acquisition, they can't be reordered in their branch, proving that we don't need to validate lock ordering in this case. Well, in our algorithm, the order between  $n_1$  and *succ\_pred* can be breached only if another node  $n_2$  finds *succ\_pred* to be its successor – otherwise the algorithm won't change *succ\_pred*'s location nor height in the tree. Let's assume on the contrary that when the algorithm operated on  $n_2$ , it reordered  $n_1$  and *succ\_pred*. Let's contradict. We have two options: first, *succ*'s right subtree is empty. In such case, *succ*'s left subtree is also empty (since it is a successor of  $n_1$  and it is found on  $n_1$ 's right subtree), and therefore *succ*'s is a leaf, which means that *succ\_pred* is *succ*'s successor, which means that  $n_2$  is *succ*. The algorithm operating on a leaf won't affect its parent's location nor height in the tree, and therefore the algorithm doesn't

reorder  $n_1$  and  $succ\_pred$ , contradiction. Second,  $succ$ 's right subtree isn't empty. In such case,  $n_2$  must reside in  $succ$ 's right subtree, and therefore the algorithm operating on  $n_2$  will only be able to push  $succ\_pred$  downwards in height in the relevant branch – thus, the algorithm won't reorder  $n_1$  and  $succ\_pred$ , contradiction. To sum up, we've shown that the algorithm won't reorder  $succ\_pred$  and  $n_1$  throughout the acquisition of  $succ\_pred$ 's lock, which proves that such aforementioned cases don't require the validation of the **branch-specific total order** of node-lock acquisition.