

CS624 - Analysis of Algorithms

Binary Search Trees

October 3, 2019

Definition (Path)

- A path in a graph is a sequence $v_0, v_1, v_2, \dots, v_n$ where each v_j is a vertex in the graph and where for each i , v_i and v_{i+1} are joined by an edge. To make things simple, we insist that any path contain at least one edge.
- Usually we write $v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_n$ to denote a path.
- A path in a graph is simple iff it contains no vertex more than once.

Definition (Loop)

- A loop in a graph is a path which begins and ends at the same vertex.
- A loop $v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_k$ is simple iff
 - ① $k \geq 3$ (that is, there are at least 4 vertices on the path), and
 - ② it contains no vertex more than once, except of course for the first and last vertices, which are the same, and
 - ③ That (first and last) vertex occurs exactly twice.

Definition (Tree)

- A rooted tree is a tree with a distinguished vertex, which we call the root.
- We will denote the root by r .
- If T is a rooted tree with root r , if x and y are vertices in T (and either or both of them might be r) and there is a simple path from r through x to y , we say that x is an **ancestor** of y and y is a **descendant** of x .
- If the part of the path from x to y consists of exactly one edge, we say that x is the **parent** of y and y is a **child** of x .

Note that a vertex is both an ancestor and a descendant of itself. But a vertex cannot be its own parent.

Definition

A binary search tree is a binary tree with each node containing some data, some of which is a key. For each node x : If y is a node on the left of x , $\text{key}[y] \leq \text{key}[x]$. If y is a node on the right of x , $\text{key}[y] \geq \text{key}[x]$.

Reminder, tree traversal (any binary tree):

- Preorder – Visit the node. Then traverse its children, left-to-right.
- Inorder – Traverse the left child. Then visit the node. Then traverse the right child.
- Postorder – Traverse the children, left-to-right. Then visit the node.

Pre/In/Postorder Walks

Algorithm 1 Preorder-Tree-Walk(x)

```
1: if  $x \neq \text{nil}$  then  
2:   visit( $x$ )  
3:   Preorder-Tree-Walk( $x.$  left)  
4:   Preorder-Tree-Walk( $x.$  right)  
5: end if
```

Algorithm 2 Inorder-Tree-Walk(x)

```
1: if  $x \neq \text{nil}$  then  
2:   Inorder-Tree-Walk( $x.$  left)  
3:   visit( $x$ )  
4:   Inorder-Tree-Walk( $x.$  right)  
5: end if
```

Algorithm 3 Postorder-Tree-Walk(x)

```
1: if  $x \neq \text{nil}$  then  
2:   Postorder-Tree-Walk( $x.$  left)  
3:   Postorder-Tree-Walk( $x.$  right)  
4:   visit( $x$ )  
5: end if
```

Pre/In/Postorder runtime

Theorem

If x is the root of a binary tree with n nodes, then each of the above traversals takes $\Theta(n)$ time.

Proof.

Let us define:

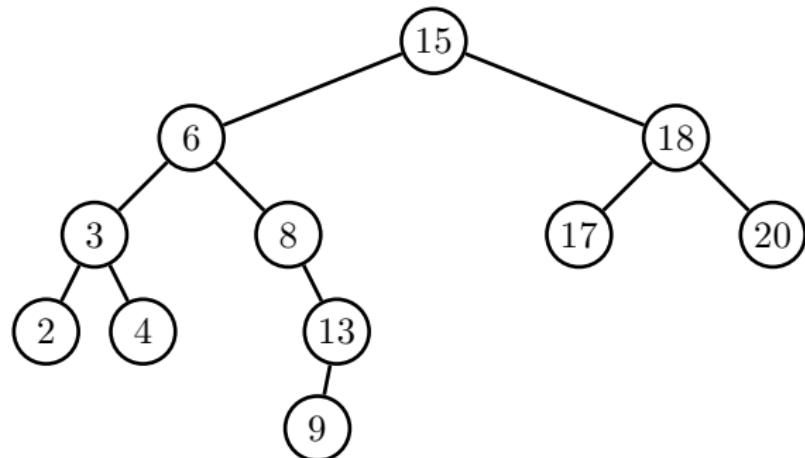
- c = time for the test $x \neq \text{nil}$
- v = time for the call to visit x
- $T(k)$ = time for the call to traverse a tree with k nodes

Then certainly we have

- ① $T(0) = c$ and if the tree with n nodes has a right child with k nodes (so its left child must have $n - k - 1$ nodes), then
- ② $T(n) = c + T(k) + T(n - k - 1) + v$
We can show that $T(n) = (2c + v)n + c$



BST – Example



Operations on BST – Search

Recursive version

Algorithm 4 TreeSearch(x, k)

```
1: if  $x = \text{nil}$  or  $k = \text{key}[x]$  then
2:   return  $x$ 
3: end if
4: if  $k < \text{key}[x]$  then
5:   return TreeSearch(left[ $x$ ],  $k$ )
6: else
7:   return TreeSearch(right[ $x$ ],  $k$ )
8: end if
```

Iterative version

Algorithm 5 TreeSearch(x, k)

```
1: while  $x \neq \text{nil}$  and  $k \neq \text{key}[x]$  do
2:   if  $k < \text{key}[x]$  then
3:      $x \leftarrow \text{left}[x]$ 
4:   else
5:      $x \leftarrow \text{right}[x]$ 
6:   end if
7: end while
8: return  $x$ 
```

The running time is $O(h)$, where h is the height of the tree.

Operations on BST – Minimum and Maximum

Algorithm 6 TreeMinimum(x)

```
1: while  $left[x] \neq nil$  do
2:    $x \leftarrow left[x]$ 
3: end while
4: return  $x$ 
```

Algorithm 7 TreeMaximum(x)

```
1: while  $right[x] \neq nil$  do
2:    $x \leftarrow right[x]$ 
3: end while
4: return  $x$ 
```

The running time is $O(h)$, where h is the height of the tree.

Algorithm 8 TreeSuccessor(x)

```
1: if  $right[x] \neq nil$  then
2:   return TreeMinimum( $right[x]$ )
3: end if
4:  $y \leftarrow p[x]$ 
5: while  $y \neq nil$  and  $x == right[y]$  do
6:    $x \leftarrow y$ 
7:    $y \leftarrow p[x]$ 
8: end while
9: return  $y$ 
```

- The running time of TreeSuccessor on a tree of height h is again $O(h)$, since the algorithm consists on following a path from a node to its successor, and the maximum path length is h .
- What happens when we apply this procedure to the node in the figure above whose key is 20?

TreePredecessor runs in a similar fashion with a similar running time. Therefore we can state the following:

Theorem

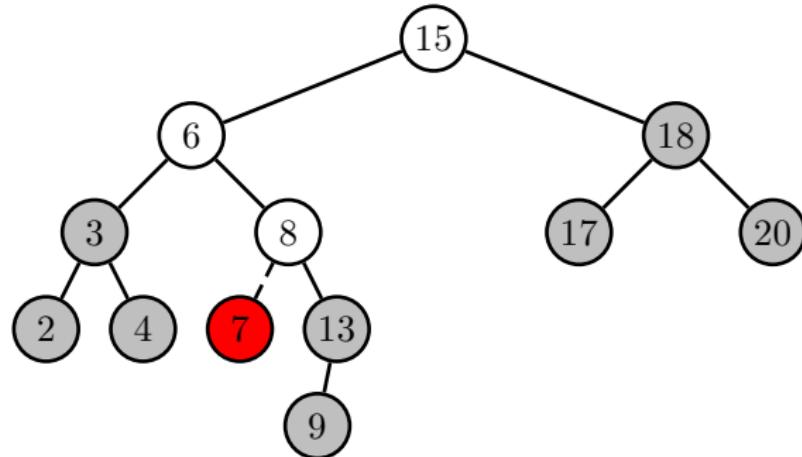
The dynamic-set operations Search, Minimum, Maximum, Successor, and Predecessor can be made to run in $O(h)$ time on a binary search tree of height h .

Operations on BST – Insert

Algorithm 9 TreeInsert(T, z)

```
1:  $y \leftarrow nil$ 
2:  $x \leftarrow Root[T]$ 
3: while  $x \neq nil$  do
4:    $y \leftarrow x$ 
5:   if  $key[z] < key[x]$  then
6:      $x \leftarrow left[x]$ 
7:   else
8:      $x \leftarrow right[x]$ 
9:   end if
10: end while
11:  $p[z] \leftarrow y$ 
12: if  $y == nil$  (This can only happen if the tree  $T$  was empty.) then
13:    $Root[T] \leftarrow z$ 
14: else
15:   if  $key[z] < key[y]$  then
16:      $left[y] \leftarrow z$ 
17:   end if
18: else
19:    $right[y] \leftarrow z$ 
20: end if
```

Insert Example



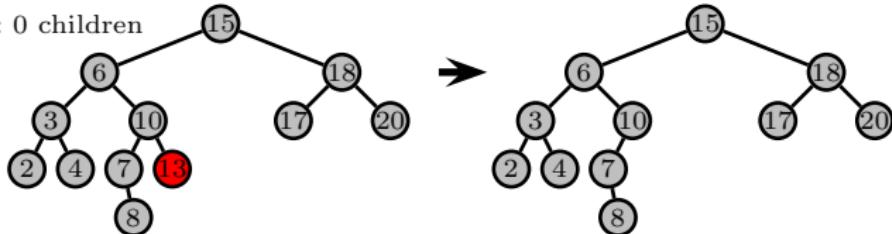
Obviously, Insert runs in $O(h)$ time on a tree of height h

Operations on BST – Delete

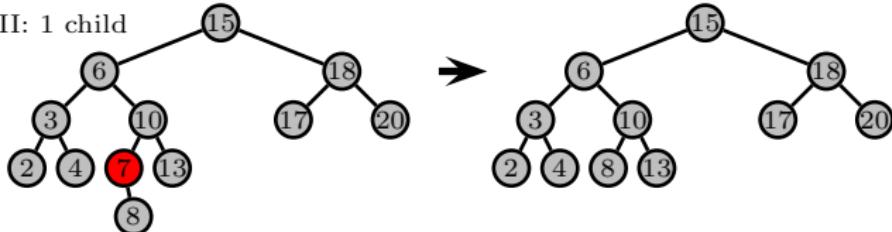
- Deleting a node is somewhat more complicated, since if the node is buried within the tree, we will have to move some of the other nodes around.
- Nevertheless, the idea is quite simple.
- There are three possible cases we need to consider when deleting a node d
 - ① d is a leaf.
 - ② d has one child.
 - ③ d has two children.

Operations on BST – Delete

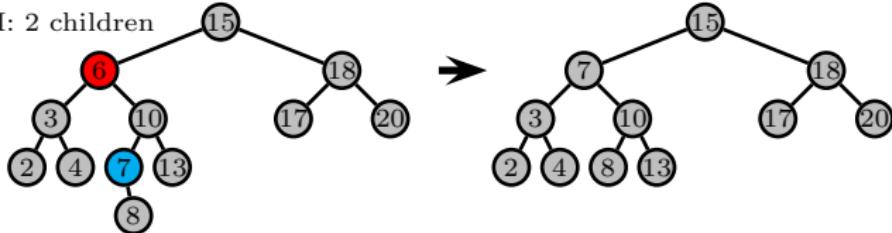
Case I: 0 children



Case II: 1 child



Case III: 2 children



BST Delete Case by Case

- Case I - d is a leaf. This case is trivial. Just delete the node. This amounts to figuring out which child it is of its parent, and making the corresponding child pointer nil.
- Case II: d has one child. In this case, delete d and “splice” its child to its parent – that is, make the parent’s child pointer that formerly pointed to d now point to d ’s child, and make that child’s parent pointer now point to d ’s parent.
- Case III: d has two children. In this case we can’t simply move one of the children of d into the position of d . What we need to do is find d ’s successor and replace d with it. Then delete d ’s successor. Since the successor has at most one child (why?) then we revert to case I or II.

Expected Cost of Building a BST

An algorithm for building a binary search tree from an array $A[1..n]$:

Algorithm 10 BuildBST(A)

- 1: Create Empty Tree
- 2: **for** $i = 1 \dots n$ **do**
- 3: TreeInsert($A[i]$)
- 4: **end for**

- What is the runtime?
- Worst case – array already sorted – quadratic.
- Best case – looks like $O(n \log n)$.
- What does it remind us of?

Modified Version of Partition

- $pivot \leftarrow A[p]$
- Let L be the sequence of elements of $A[p+1..q]$ that are less than pivot in the order they appear in A
- Let U be the sequence of elements of $A[p+1..q]$ that are greater than pivot in the order they appear in A
- Rearrange the elements in $A[p..q]$ so that they appear like this:

$L \ pivot \ U$

- This may require more time than the original partition but not asymptotically more.

- Show that the comparisons needed to build a BST from an array $A[1..n]$ are exactly the same comparisons needed to do quicksort on the array, using ModifiedPartition.
- **Hint:** The comparisons in quicksort are against the pivot elements and the successive pivot elements are the successive elements added to the BST.

- We know that the average runtime for quicksort is $\Theta(n \log n)$.
- What is the “average run time” for building a BST?
- It is the average over running on all possible permutations of the input array.
- This is exactly what we get with randomized quicksort.

Theorem

The average runtime for constructing a BST is $\Theta(n \log n)$.

Runtime for Searching a BST

- The average search time in a BST is h , the height of a tree.
- What is the average height of a BST?
- We know the search time is the depth of a node.
- Which is the number of comparisons we make when inserting the node into the tree.

Runtime for Searching a BST

- We see that the total expected number of comparisons is $O(n \log n)$.
- So the average number of comparisons is $O(\log n)$ per node.
- The average cost for search in a randomly build BST is therefore $O(\log n)$.
- There may be longer paths – in a linear tree the average search time is $O(n)$.
- However, the average height of a randomly build BST is $O(\log n)$.

Runtime for Searching a BST

- Let X_n be a random variable whose value is the height of a binary search tree on n keys
- Let P_n be the set of all permutations of those n keys. (So the number of elements of P_n is $n!$)
- Let π to denote a permutation in P_n . X_n is actually a function on P_n .
- Its value $X_n(\pi)$ when applied to a permutation $\pi \in P_n$ is the height of the binary search tree built from that permutation π .
- We want to find $E(X_n)$, the *expectation* of X_n .
- This is by definition $\sum_{\pi \in P_n} p(\pi)X_n(\pi)$ where $p(\pi)$ denotes the probability of the permutation π .
- Assuming that all permutations have equal probability, $p(\pi) = \frac{1}{n!}$ for all π , and so $E(X_n) = \frac{1}{n!} \sum_{\pi \in P_n} X_n(\pi)$

Note on Distribution

If A and B are two random variables on the same space P_n , then

$$\begin{aligned} E(A + B) &= \sum_{\pi \in P_n} p(\pi)(A(\pi) + B(\pi)) \\ &= \sum_{\pi \in P_n} p(\pi)A(\pi) + \sum_{\pi \in P_n} p(\pi)B(\pi) \\ &= E(A) + E(B) \end{aligned}$$

Note that $\max\{A, B\}$ is also a random variable on P_n – its value at π is just $\max\{A(\pi), B(\pi)\}$. And we have the useful inequality

$$\begin{aligned} E(\max\{A, B\}) &= \sum_{\pi \in P_n} p(\pi) \max\{A(\pi), B(\pi)\} \\ &\leq \sum_{\pi \in P_n} p(\pi)(A(\pi) + B(\pi)) \\ &= E(A + B) = E(A) + E(B) \end{aligned}$$

Expected Height of a BST

- Consider a permutation π . The root of the tree will be the first element of π .
- Suppose the root has position k in the sorted list of keys.
- That means that there will be $k - 1$ keys less than it and $n - k$ keys greater than it.
- So the left subtree will have $k - 1$ elements and the right subtree will have $n - k$ elements.
- Those elements are also chosen randomly from sets of size $k - 1$ and $n - k$ respectively, so we have

$$X_n(\pi) = 1 + \max\{X_{k-1}(\pi), X_{n-k}(\pi)\}$$

- This is our fundamental recursion.

Expected Height of a BST

- Since each value of k is chosen with the same probability (that probability being $\frac{1}{n}$), we have

$$E(X_n) = \sum_{k=1}^n \frac{1}{n} E(1 + \max\{X_{k-1}, X_{n-k}\})$$

- An effective way to estimate it would be to set $Y_n = 2^{X_n}$.
- So Y_n is itself a random variable defined on the set P whose value on the permutation π is $Y_n(\pi) = 2^{X_n(\pi)}$
- At first there is no intuitive significance to the reason for doing this. It's just that we can do better with the mathematics that way.
- Compute $E(Y_n)$ and use this to get a bound on $E(X_n)$.
- This step is also somewhat tricky if you haven't seen it before, but it is a general technique.

Expected Height of a BST

$$\begin{aligned}Y_n(\pi) &= 2^{X_n(\pi)} = 2^{1+\max\{X_{k-1}(\pi), X_{n-k}(\pi)\}} \\&= 2 \cdot 2^{\max\{X_{k-1}(\pi), X_{n-k}(\pi)\}} = 2 \cdot \max\{2^{X_{k-1}(\pi)}, 2^{X_{n-k}(\pi)}\} \\&= 2 \cdot \max\{Y_{k-1}(\pi), Y_{n-k}(\pi)\}\end{aligned}$$

Since each value of k is chosen with probability $\frac{1}{n}$:

$$\begin{aligned}E(Y_n) &= \sum_{k=1}^n \frac{1}{n} \cdot 2E(\max\{Y_{k-1}, Y_{n-k}\}) = \frac{2}{n} \sum_{k=1}^n E(\max\{Y_{k-1}, Y_{n-k}\}) \\&\leq \frac{2}{n} \sum_{k=1}^n (E(Y_{k-1}) + E(Y_{n-k}))\end{aligned}$$

Each term is counted twice so we can simplify to get this:

$$E(Y_n) \leq \frac{4}{n} \sum_{k=1}^n E(Y_{k-1}) = \frac{4}{n} \sum_{k=0}^{n-1} E(Y_k)$$

Expected Height of a BST

It is more convenient to use a strict equality, rather than an inequality. It turns out that we can assume this to be the case since we're really only concerned with an upper bound.

Lemma

If f and g are two functions such that

$$f(0) = g(0) \tag{1}$$

$$f(n) \leq \frac{4}{n} \sum_{k=0}^{n-1} f(k) \tag{2}$$

$$g(n) = \frac{4}{n} \sum_{k=0}^{n-1} g(k) \tag{3}$$

then $f(k) \leq g(k)$ for all $k \geq 1$.

Expected Height of a BST

Proof.

We'll prove this by induction. The inductive hypothesis is that $f(k) \leq g(k)$ for all $k < n$. We know that this statement is true for $n = 1$ by the equation above. The inductive step is then to show that this statement remains true for $k = n$. To show this, we just compute as follows:

$$\begin{aligned} f(n) &\leq \frac{4}{n} \sum_{k=0}^{n-1} f(k) \\ &\leq \frac{4}{n} \sum_{k=0}^{n-1} g(k) = g(n) \end{aligned}$$



Expected Height of a BST

- Based on this, we can assume that $E(Y_n) = \frac{4}{n} \sum_{k=0}^{n-1} E(Y_k)$.
- because any upper bound we obtain for $E(Y_n)$ from this identity will also be an upper bound for the “real” $E(Y_n)$.
- This is a similar trick to the one we used in deriving the average case running time of Quicksort.
- We can do something very similar here, although it is a little more complicated:

- $E(Y_{n+1}) = \frac{4}{n+1} \sum_{k=0}^n E(Y_k)$ and $E(Y_n) = \frac{4}{n} \sum_{k=0}^{n-1} E(Y_k)$

- We get rid of the denominators:

- $(n+1)E(Y_{n+1}) = 4 \sum_{k=0}^n E(Y_k)$

- $nE(Y_n) = 4 \sum_{k=0}^{n-1} E(Y_k)$

Expected Height of a BST

- Now let us subtract and get:

$$(n+1)E(Y_{n+1}) - nE(Y_n) = 4E(Y_n)$$

- $(n+1)E(Y_{n+1}) = (n+4)E(Y_n)$

- Divide both sides by $(n+1)(n+4)$. We get $\frac{E(Y_{n+1})}{n+4} = \frac{E(Y_n)}{n+1}$.

- If you look at it closely for a little while, you will see that if we now divide each side by $(n+2)(n+3)$, we will get something nice: $\frac{E(Y_{n+1})}{(n+4)(n+3)(n+2)} = \frac{E(Y_n)}{(n+3)(n+2)(n+1)}$.

Expected Height of a BST

- And so if we define $g(n) = \frac{E(Y_n)}{(n+3)(n+2)(n+1)}$
- Then we have just derived the fact that $g(n+1) = g(n)$
- In other words, $g(n)$ is some constant. Call it c .
- Then we have $E(Y_n) = c(n + 3)(n + 2)(n + 1) = O(n^3)$
- We are not done yet! We have to find $E(X_n)$

Expected Height of a BST

- We know that there is a constant $C > 0$ and a number $n_0 \geq 0$ such that for all $n \geq n_0$, $E(Y_n) \leq Cn^3$. Hence for all $n \geq n_0$, $2^{E(X_n)} \leq E(2^{X_n}) = E(Y_n) \leq Cn^3$
- Taking the logarithm of both sides we get
$$E(X_n) \leq \log_2 C + 3 \log_2 n = O(\log n)$$
- In other words – the expected height of a randomly build binary search tree is $O(\log n)$.