CSE 143

Binary Search Trees

Costliness of *contains*

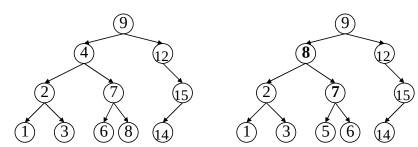
- Review: in a binary tree, *contains* is O(N) (worst case)
- *contains* may be a frequent operation in an application
- Can we do better than O(N)?
- Turn to previous experience for inspiration...
  - Why was binary search so much better than linear search?
  - What did it take to ensure that Quicksort was O(n log n)
  - Can we apply the same idea to trees?

Binary Search Trees

- Idea: order the nodes in the tree so that, given that a node contains a value *v*,
  - All nodes in its left subtree contain values < *v*
  - All nodes in its right subtree contain values > *v*
- A binary tree with these properties is called a *binary search tree* (BST)
- Notes:
  - Can also define a BST using >= and <= instead of >, <
    - This implies there could be duplicate values in the tree
  - In Java, if the values are not primitive types, they must implement interface comparable (i.e., provide compareTo)

Examples(?)

- Are these are binary search trees? Why or why not?



Implementing a Set with a BST

- Can exploit properties of BSTs to have fast, divide-and-conquer implementations of add and contains
  - TreeSet!
- A TreeSet can be represented by a pointer to the root node of a binary search tree, or null of no elements yet

```
public class SimpleTreeSet implements Set {
    private BTNode root;                // root node, or null if none
    public SimpleTreeSet( ) { root = null; }
    // size as for BinTree
    ...
}
```


contains for a BST

- For a general binary tree, contains had to search both subtrees
  - Like linear search
- With BSTs, need to only search one subtree
  - All small elements to the left, all large elements to the right
  - Search either left or right subtree, based on comparison between item and value at the root of the (sub-)tree
  - Like binary search

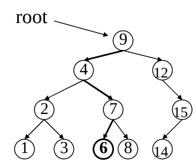
Code for *contains* (in TreeSet)

```
/** Return whether item is in set */
public boolean contains(Object item) {
    return subtreeContains(root, (Comparable) item);
}
// Return whether item is in (sub-)tree with root r
private boolean subtreeContains(BTNode r, Comparable item) {
    if (r == null) {
        return ____________________ ;
    } else {
        int comp = item.compareTo(r.item);
        if (comp == 0) { return ____________________ ; }            // found it!
        else if (comp < 0)   { return ___________________________ ; }  //
search left
        else /* comp > 0 */ { return ___________________________ ; }  //
search right
    }
```

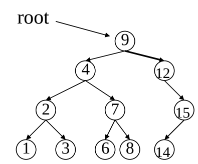
12/5/2004 (c) 2001-4, University of Washington 21-7

Examples

contains(6)



contains(10)



12/5/2004 (c) 2001-4, University of Washington 21-8

Cost of BST *contains*

- Work done at each node:
- Number of nodes visited (depth of recursion):
- Total cost:

12/5/2004 (c) 2001-4, University of Washington 21-9

add

- Must preserve BST invariant: insert new element in correct place in BST
- Two base cases
  - Tree is empty: create new node which becomes the root of the tree
  - If node contains the value, found it; suppress duplicate add
- Recursive case
  - Compare value to current node's value
  - If value < current node's value, add to left subtree recursively
  - Otherwise, add to right subtree recursively

12/5/2004 (c) 2001-4, University of Washington 21-10

Example

- Add 8, 10, 5, 1, 7, 11 to an initially empty BST, in that order:

12/5/2004 (c) 2001-4, University of Washington 21-11

Example (2)

- What if we change the order in which the numbers are added?
- Add 1, 5, 7, 8, 10, 11 to a BST, in that order (following the algorithm):

12/5/2004 (c) 2001-4, University of Washington 21-12

Code for *add* (in TreeSet)

```
/** Ensure that item is in the set. */
public void add(Object item) {
    root = addToSubtree(root, (Comparable) item);    // add item to tree
}
/** Add item to tree rooted at r.  Return (possibly new) tree containing item. */
private BTNode addToSubtree(BTNode r, Comparable item) {
    …
}
```


Code for *addToSubtree*

```
/** Add item to tree rooted at r.  Return (possibly new) tree containing item. */
private BTNode addToSubtree(BTNode r, Comparable item) {
    if (n == null) {                          // adding to empty tree
        return new BTNode(item, null, null);
    }
    int comp = item.compareTo(r.item);
    if (comp == 0) { return; }                // item already in tree
    if (comp < 0) {                           // add to left subtree
        r.left = addToSubtree(r.left, item);
    } else /* comp > 0 */ {                   // add to right subtree
        r.right = addToSubtree(r.right, item);
    }
    return r;    // this tree has been modified to contain item
}
```


Cost of *add*

- Cost at each node:
- How many recursive calls?
  - Proportional to height of tree
  - Best case?
  - Worst case?

A Challenge: iterator

- How to return an iterator that traverses the sorted set in order?
  - Need to iterate through the items in the BST, from smallest to largest
- Problem: how to keep track of position in tree where iteration is currently suspended
  - Need to be able to implement next( ), which advances to the correct next node in the tree
- Solution: keep track of a path from the root to the current node
  - Still some tricky code to find the correct next node in the tree

Another Challenge: *remove*

- Algorithm: find the node containing the element value being removed, and remove that node from the tree
- Removing a leaf node is easy: replace with an empty tree
- Removing a node with only one non-empty subtree is easy: replace with that subtree
- How to remove a node that has two non-empty subtrees?
  - Need to pick a new element to be the new root node, and adjust at least one of the subtrees
  - E.g., remove the largest element of the left subtree (will be one of the easy cases described above), make that the new root

Analysis of Binary Search Tree Operations

- Cost of operations is proportional to height of tree
- Best case: tree is *balanced*
  - Depth of all leaf nodes is roughly the same
  - Height of a balanced tree with *n* nodes is ~log *n*
- If tree is unbalanced, height can be as bad as the number of nodes in the tree
  - Tree becomes just a linear list

Summary

- A binary search tree is a good general implementation of a set, if the elements can be ordered
  - Both contains and add benefit from divide-and-conquer strategy
  - No sliding needed for add
  - Good properties depend on the tree being roughly balanced
- Not covered (or, why take a data structures course?)
  - How are other operations implemented (e.g. iterator, remove)?
  - How do you keep the tree balanced as items are added and removed?

12/5/2004 21-19