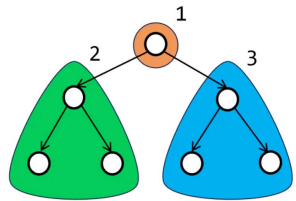


TREE

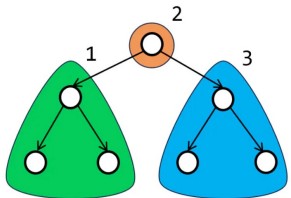
Tree Traversals

Depth-First Traversals

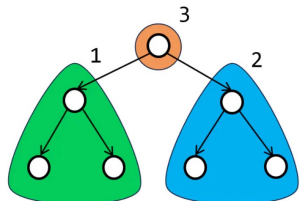
- **Pre-order:** Root - Left - Right



- **In-order:** Left - Root - Right



- **Post-order:** Left - Right - Root



Breadth-First Traversal (Level Order Traversal)

Visit every node on a level before moving to a lower level.

Tree Traversals

Depth-First Traversals

Use a recursive algorithm to traverse according to the order

- **Pre-order:** Root - Left - Right



```
if (!root) return;  
doSomething();  
visit(node->left);  
visit(node->right);
```

- **In-order:** Left - Root - Right



```
if (!root) return;  
visit(node->left);  
doSomething();  
visit(node->right);
```

- **Post-order:** Left - Right - Root



```
if (!root) return;  
visit(node->left);  
visit(node->right);  
doSomething();
```

Tree Traversals

Example of pre-order and in-order

```
struct TreeNode {
    int val;
    TreeNode *left, *right;
    TreeNode(int x) : val(x), left(nullptr), right(nullptr) {}
};

// Pre-order traversal
void preorderTraversal(TreeNode* root) {
    if (root == nullptr) return;
    cout << root->val << " ";
    preorderTraversal(root->left);
    preorderTraversal(root->right);
}

// In-order traversal
void inorderTraversal(TreeNode* root) {
    if (root == nullptr) return;
    inorderTraversal(root->left);
    cout << root->val << " ";
    inorderTraversal(root->right);
}
```

Tree Traversals

Example of post-order and level-order

```
struct TreeNode {
    int val;
    TreeNode *left, *right;
    TreeNode(int x) : val(x), left(nullptr), right(nullptr) {}
};

// Post-order traversal
void postorderTraversal(TreeNode* root) {
    if (root == nullptr) return;
    postorderTraversal(root->left);
    postorderTraversal(root->right);
    cout << root->val << " ";
}

// Level-order traversal using a queue
void levelOrderTraversal(TreeNode* root) {
    if (root == nullptr) return;
    queue<TreeNode*> q;
    q.push(root);
    while (!q.empty()) {
        TreeNode* current = q.front();
        q.pop();
        cout << current->val << " ";
        if (current->left != nullptr) q.push(current->left);
        if (current->right != nullptr) q.push(current->right);
    }
}
```

BFS Using Stack

BFS with std::stack

- This might be useful for problems when you want to return and resume (for example, [872. Leaf-Similar Trees](#))

```
struct TreeNode {
    int val;
    TreeNode *left, *right;
    TreeNode(int x) : val(x), left(nullptr), right(nullptr) {}
};

// Pre-order traversal
void bfs(std::stack<TreeNode*>& tree) {
    while(!tree.empty()) {
        TreeNode* root = tree.top();
        tree.pop();
        // do something ...
        if (root->right) tree.push(root->right);
        if (root->left) tree.push(root->left);
    }
}
```

Problem – 100. Same Tree

Easy



LeetCode

leetcode.com/problems/same-tree

Problem

- You are given the root of two trees
- Write a function to check if they are the same

- **Example:**

$p = [1,2,3]$, $q = [1,2,3]$

Output: true

Problem – 100. Same Tree

Easy



LeetCode

leetcode.com/problems/same-tree

Solution

- Traverse both trees (**p** and **q**) recursively and check if the nodes are the same
- Start by the base case:
are **p** and **q** null? return true
- One of them are null? return false, because they should be the same
- Finally, check if **p->val** is equal to **q->val** and also for both and left, recursively

Problem – 100. Same Tree

Easy



LeetCode

leetcode.com/problems/same-tree

Code Time: $O(n)$ where n is the number of nodes Space: $O(h)$ where h is the height of the tree. Best case is usually $O(\log n)$ for balanced trees, but skewed trees is usually $O(n)$

```
bool isSameTree(TreeNode* p, TreeNode* q) {  
    // base case: leaf is null. If both are null, then return true  
    if (!p && !q) return true;  
    // if both are not NULL, then they must have value.  
    // If one of them doesn't have value, then they're different, return false  
    if (!p || !q) return false;  
    // they must have the same value  
    // as any other nodes in the tree  
    return p->val == q->val &&  
           isSameTree(p->left, q->left) &&  
           isSameTree(p->right, q->right);  
}
```

Problem – 226. Invert Binary Tree

Easy

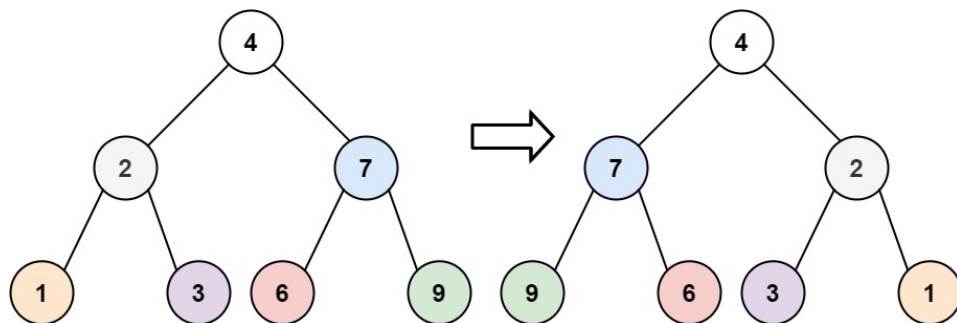


LeetCode

leetcode.com/problems/invert-binary-tree

Problem

- You are given the root of a binary tree
- Invert the tree and return the root
- **Example:**



Problem – 226. Invert Binary Tree

Easy



LeetCode

leetcode.com/problems/invert-binary-tree

Solution

- Recursively traverse the tree
- Create a new pointer **temp** that points to **left** node
- Set **left** node to **right**
- Set **right** node to **temp**
- Call the function recursively for **left** and **right**
- Return root

Problem – 226. Invert Binary Tree

Easy



LeetCode

leetcode.com/problems/invert-binary-tree

Code Time: $O(n)$ Space: $O(h)$ where h is the height of the tree

```
TreeNode* invertTree(TreeNode* root) {  
    // base case  
    if (!root) return nullptr;  
  
    // create a new pointer to left  
    TreeNode* temp = root->left;  
    // invert  
    root->left = root->right;  
    root->right = temp;  
  
    // recursively invert left and right  
    invertTree(root->left);  
    invertTree(root->right);  
  
    return root;  
}
```

Problem – Maximum Depth of Binary Tree

Easy

 LeetCode <https://leetcode.com/problems/maximum-depth-of-binary-tree>

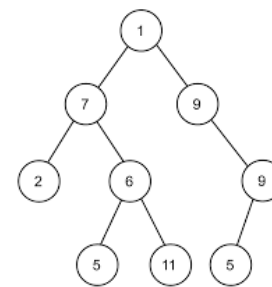
Problem Statement

- Given the root of a binary tree, find the maximum depth

- Example:**

root = [1,7,9,2,6,null,9,null,null,5,11,5,null]

- Output:** 4



Solution – Maximum Depth of Binary Tree

Easy

 LeetCode <https://leetcode.com/problems/maximum-depth-of-binary-tree>

Solution

- Perform **post-order** traversal: left - right - root
- Recursively go left and right to find each value
- Return the max of each one

Code – Maximum Depth of Binary Tree

Easy

 <https://leetcode.com/problems/maximum-depth-of-binary-tree>

```
int maxDepth(TreeNode* root) {  
    if (!root) return 0;  
    // find max left  
    int maxLeft = maxDepth(root->left);  
    // find max right  
    int maxRight = maxDepth(root->right);  
    // return max +1 (account for root)  
    return std::max(maxLeft, maxRight) + 1;  
}
```

Problem – Path Sum

Easy



LeetCode

<https://leetcode.com/problems/path-sum>

Problem Statement

- It is given the **root** of a binary tree and an integer **target sum**

- Example:**

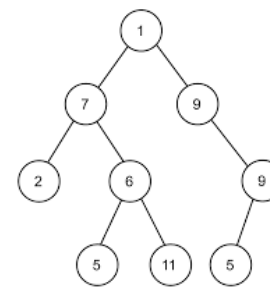
root = [1,7,9,2,6,null,9,null,null,5,11,5,null]

target sum = 10

- Return true if there is a path from root to leaf that adds up to 10

- Output:** true

Node 1 + Node 7 + Node 2 = 10



Solution – Path Sum

Easy

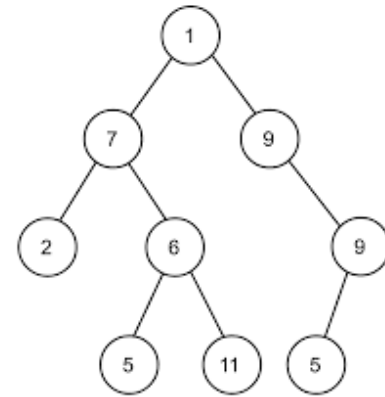


LeetCode

<https://leetcode.com/problems/path-sum>

Solution

- Start from root node (1)
- Subtract from target number (example $10 - 1 = 9$)
- Continue going down the tree, until the target is 0, return true
- After visiting all nodes, if the target is not zero, return false



Code – Path Sum

Easy



LeetCode

<https://leetcode.com/problems/path-sum>

```
bool hasPathSum(TreeNode* root, int targetSum) {
    if (!root) {
        return false;
    }
    // we want targetSum to be zero
    targetSum -= root->val;
    // if there is no left, no right, we've reached the end of the path
    // so if the targetSum is zero, then the nodes summed up to the targetSum
    if (!root->left && !root->right && targetSum == 0) {
        return true;
    }
    // propagate to left and right
    return hasPathSum(root->left, targetSum) || hasPathSum(root->right, targetSum);
}
```

Also, a small performance tweak can be made by avoiding writing *targetSum*: *targetSum -= root->val*

This will avoid a memory write access, making the calculation directly in the CPU, but also at a cost of readability

```
if (!root->left && !root->right && targetSum - root->val == 0) {
    ...
    return hasPathSum(root->left, targetSum - root->val) || hasPathSum(root->right, targetSum - root->val);
}
```

Problem – 297. Serialize and Deserialize Binary Tree

Hard

 LeetCode leetcode.com/problems/serialize-and-deserialize-binary-tree

Problem

- Design an algorithm to serialize and deserialize a binary tree
- You have to build two interfaces: serialize that returns a string, and deserialize that returns the whole tree as `TreeNode` pointer
- The string can be represented at any format (comma-separated, space separated etc)

Solution – 297. Serialize and Deserialize Binary Tree

Hard

 leetcode.com/problems/serialize-and-deserialize-binary-tree

Solution

- **Serialize:** traverse the tree pre-order, and append its value to a string

Null value should also be represented

Example: [1,2,null,null,3 ...]

Call "traverse" to do it recursively

- **Deserialize:** split the string into tokens
read each token and re-build the tree by adding a new node
Call "buildTree" to do it recursively

Code – 297. Serialize and Deserialize Binary Tree

Hard

 LeetCode leetcode.com/problems/serialize-and-deserialize-binary-tree

Code Time: $O()$ Space: $O()$

```
string serialize(TreeNode* root) {
    // traverse the tree in pre-order: root, left, right
    // generate a string with comma separator,
    // example: 1,2,N,N,3 ...
    string result;
    traverse(root, result);
    return result;
}

TreeNode* deserialize(string data) {
    // split the input data
    vector<string> tokens = split(data);
    // index to be used to access the elements from tokens recursively.
    // Hence, we need to create it here to pass by reference.
    // Note that index is bounded by the number of tokens, so it won't overflow
    int index = 0;
    TreeNode* root = buildTree(tokens, index);
    return root;
}
```

continue...

Code – 297. Serialize and Deserialize Binary Tree

Hard

 leetcode.com/problems/serialize-and-deserialize-binary-tree

```
TreeNode* buildTree(vector<string>& tokens, int& index) {
    // read the current token based on the index
    const string& token = tokens[index];
    // increment index before checking for null
    ++index;
    // base case: null node
    if (token == "N") {
        return nullptr;
    }
    // build root
    TreeNode* node = new TreeNode(stoi(token));
    // build left
    node->left = buildTree(tokens, index);
    // build right
    node->right = buildTree(tokens, index);
    return node;
}
```

```
// traverse in pre-order (root, left, right)
// and append the values to the string 's'
// append 'N' if it is NULL
void traverse(TreeNode* root, string& s) {
    if (!s.empty()) s += ",";
    // base case, we need to append null
    if (!root) {
        s += "N";
        return;
    }
    // visit root
    s += to_string(root->val);
    // visit left
    traverse(root->left, s);
    // visit right
    traverse(root->right, s);
}
```

```
// helper function in C++ to split string
vector<string> split(const string& s) {
    vector<string> result;
    stringstream ss(s);
    string token;
    while(getline(ss, token, ',')) {
        result.push_back(token);
    }
    return result;
}
```

Code – 297. Serialize and Deserialize Binary Tree

Hard

 leetcode.com/problems/serialize-and-deserialize-binary-tree

Some interesting alternative to split

- C++ 23 have an interesting way to split using `std::views::split`

```
vector<string> split(string s) {  
    auto result = s |  
        views::split(',') |  
        views::transform([](auto&& subRange) {  
            return string(subRange.start(), subRange.end());  
        });  
}
```

- To understand, this follow a structure similar to unix pipes:

```
echo "123,N,556" | split | transform
```

- `std::views::split` returns ranges, something like:

```
[ range("123"), range("N"), range("556") ]
```

- `std::views::transform` converts each subrange into an actual string

Problem – Kth Smallest Element in a BST

Medium



LeetCode

leetcode.com/problems/kth-smallest-element-in-a-bst

Problem Statement / Solution

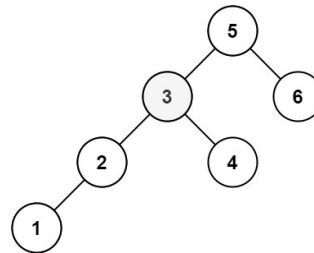
- You are given the **root** of a binary search tree and an **integer k**
- Find the k^{th} smallest value

- **Example**

From all values in the tree: 1,2,3,4,5,6

k = 3 so find the 3th smallest value

Output is 3: 1,2,**3**,4,5,6 (3th)



Solution – Kth Smallest Element in a BST

Medium

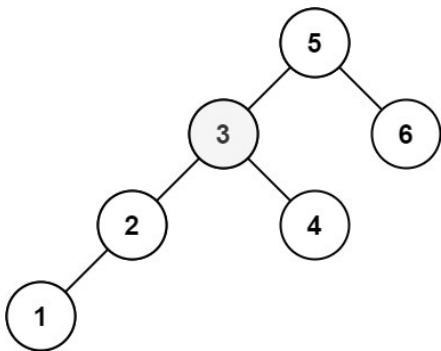


LeetCode

leetcode.com/problems/kth-smallest-element-in-a-bst

Solution

- Note that the smallest element is in the left leaf
- Therefore, there is an order from small \rightarrow big values from left \rightarrow root \rightarrow right
- Perform in-order traversal **k** times and stop in the desired node



Code – Kth Smallest Element in a BST

Medium



LeetCode

leetcode.com/problems/kth-smallest-element-in-a-bst

Code Time: $O(k)$ Space: $O(h)$ where h is the height of the tree

```
// in-order traversal: left, node: right
void traverse(TreeNode* node, int& k, int& result) {
    // base case
    if (!node) return;
    // visit left first
    traverse(node->left, k, result);
    // visit node
    k--;
    if (k == 0) {
        result = node->val;
        return;
    }
    // visit right
    traverse(node->right, k, result);
}

int kthSmallest(TreeNode* root, int k) {
    // perform pre-order traversal
    int result;
    traverse(root, k, result);
    return result;
}
```

Problem – 124. Binary Tree Maximum Path Sum

Hard

 leetcode.com/problems/binary-tree-maximum-path-sum

Problem

- You are given the root node of a binary tree
- Return the **max path sum** of any path
- A path can be linear (from the root all the way down to the leaf) or the three node: root, left and right)
- A path can start at any node

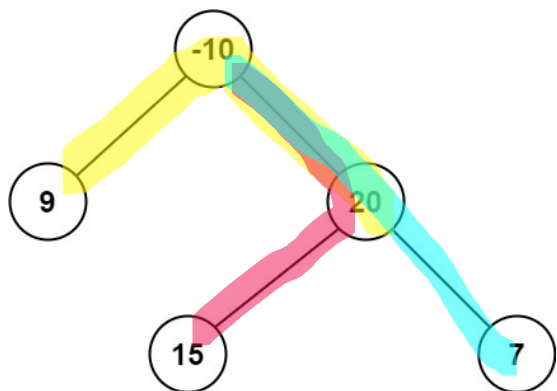
- **Example:**

$9 \rightarrow -10 \rightarrow 20$ is a valid path

$-10 \rightarrow 20 \rightarrow 15$ is a valid path

$9 \rightarrow -10 \rightarrow 20 \rightarrow 7$ is **NOT** a valid path

$20 \rightarrow 7$ is a valid path



Solution – 124. Binary Tree Maximum Path Sum

Hard



LeetCode

leetcode.com/problems/binary-tree-maximum-path-sum

Solution

- Use **post-order** traversal (bottom-up recursion)
- At each node:
 - Recursively compute left and right max path gains
 - Consider all 3 possible paths:
 1. Turn path: left + root + right
 2. Linear path: root + left
 3. Linear path: root + right
 - Also consider just the root (if the children is negative)
- Track the maximum path seen so far
- Only return linear path (root + one child) upward to maintain the valid structure
- Also, prune negative gain before returning

Problem – 124. Binary Tree Maximum Path Sum

Hard

 leetcode.com/problems/binary-tree-maximum-path-sum

Code Time: $O(n)$ Space: $O(h)$ where n is the number of nodes and h is the height of the tree.

```
int findMaxSum(TreeNode* root, int& maxSum) {
    if (!root) return 0;
    int left = findMaxSum(root->left, maxSum);
    int right = findMaxSum(root->right, maxSum);
    // 1st possible path: exactly the only 3 nodes: root, right and left
    int threeNodes = left + right + root->val;
    // 2nd possible path, linear recursive path: root + left
    int secondPath = root->val + left;
    // 3rd possible path, linear recursive path: root + right
    int thirdPath = root->val + right;

    // check if we should consider left, right or only root itself
    int bestPath = max({root->val, secondPath, thirdPath});

    // maxSum can be the accumulated 2nd and 3rd (linear path)
    // or the threeNodes path
    maxSum = max({maxSum, bestPath, threeNodes});

    // Prune subtree: we start from the bottom, so we can set 0
    // to ignore left or right path
    return max(0, bestPath);
}

int maxPathSum(TreeNode* root) {
    int maxSum = INT_MIN;
    findMaxSum(root, maxSum);
    return maxSum;
}
```

Problem – 124. Binary Tree Maximum Path Sum

Hard

 leetcode.com/problems/binary-tree-maximum-path-sum

Code (compact) Time: $O(n)$ Space: $O(h)$ where n is the number of nodes and h is the height of the tree.

```
int find(TreeNode *node, int& totalMax) {
    if (!node) return 0;
    int leftGain = max(0, find(node->left, totalMax));
    int rightGain = max(0, find(node->right, totalMax));
    int currentMax = node->val + leftGain + rightGain;
    totalMax = max(totalMax, currentMax);
    return node->val + max(leftGain, rightGain);
}

int maxPathSum(TreeNode* root) {
    int totalMax = INT_MIN;
    find(root, totalMax);
    return totalMax;
}
```

Problem – 102. Binary Tree Level Order Traversal

Medium



LeetCode

leetcode.com/problems/binary-tree-level-order-traversal

Problem Statement / Solution / Code Time: $O(-)$ Space: $O(-)$

■ ...

Problem – 572. Subtree of Another Tree

Easy

 leetcode.com/problems/subtree-of-another-tree

Problem Statement / Solution / Code Time: $O(-)$ Space: $O(-)$

■ ...

Problem – 872. Leaf-Similar Trees

Easy



LeetCode

leetcode.com/problems/leaf-similar-trees

Problem Statement

- You are given two trees
- The goal is to compare if they have the same leaves
- The leaves should be in the same order
- Example:

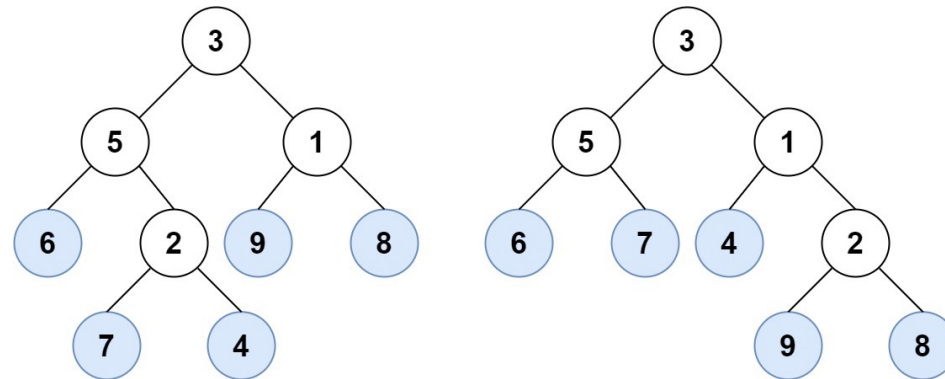
First tree:

leaves = 6,7,4,9,8 (blue nodes)

Second tree:

leaves = 6,7,4,9,8

- Return true if the leaves are the same



Solution – Leaf-Similar Trees

Easy



LeetCode

leetcode.com/problems/leaf-similar-trees

Solution

- Get the first leaf value from tree 1
- Get the first leaf value from tree 2
- Compare, if they are different, return false immediately
- Otherwise, continue finding the next leaf value for tree 1 and 2

Implementation

- Create two stacks **stack<TreeNode*> left** and **stack<TreeNode*> right**
- Add the

Code – Leaf-Similar Trees

Easy



LeetCode

leetcode.com/problems/leaf-similar-trees

Code Time: $O(n + m)$ where n and m are the numbers of nodes for trees 1 and 2 Space: $O(h_1 + h_2)$ where h_1 and h_2 represents the height of the tree

```
// returns the value of the leaf, or -1 if empty
int getLeaf(stack<TreeNode*>& tree) {
    // tree is a reference, we will always pop an element from it
    while(!tree.empty()) {
        // get the top element from the stack
        TreeNode* node = tree.top();
        // already visited, so remove from stack
        tree.pop();
        // is this a leaf?
        if (!node->left && !node->right) {
            // yes, return the value
            return node->val;
        }
        // push the right FIRST to the stack
        if (node->right) tree.push(node->right);
        // left should be on top of the stack
        if (node->left) tree.push(node->left);
    }
    return -1;
}
```

```
bool leafSimilar(TreeNode* root1, TreeNode* root2) {
    // initialize the stacks, add root1 and root2
    std::stack<TreeNode*> leftTree, rightTree;
    leftTree.push(root1);
    rightTree.push(root2);

    while(true) {
        // get the leaves to compare
        int leaf1 = getLeaf(leftTree);
        int leaf2 = getLeaf(rightTree);
        // exit immediately if one leaf is different
        if (leaf1 != leaf2) return false;
        // stop when there are no leaves left
        if (leaf1 == -1 || leaf2 == -1) break;
    }
    return true;
}
```

Problem – 1448. Count Good Nodes in Binary Tree

Medium

 leetcode.com/problems/count-good-nodes-in-binary-tree

Problem Statement

- You are given a binary tree and have to find "**good**" nodes
- A **good node** is a **node** where the values in the path are always less than or equal to the **node**
- The **root node** is always a **good node**
- Example:

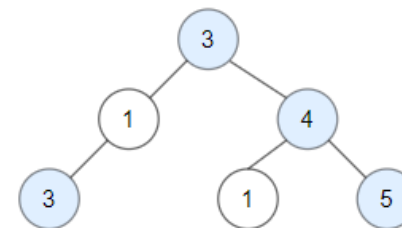
- root 3 is a good node

left side:

- left **leaf 1** is not a good node because $1 < 3$
- **leaf 3** is a good node because $3 > 1$ and $3 == 3$

right side:

- **leaf 4** is a good node because $4 > 3$
- **leaf 1** is not a good node because $1 < 4$
- **leaf 5** is a good node because $5 > 4 > 3$



Solution – 1448. Count Good Nodes in Binary Tree

Medium



LeetCode

leetcode.com/problems/count-good-nodes-in-binary-tree

Solution

- ...

Code – 1448. Count Good Nodes in Binary Tree

Medium

 leetcode.com/problems/count-good-nodes-in-binary-tree

Code Time: $O(n + m)$ where n and m are the numbers of nodes for trees 1 and 2 Space: $O(h_1 + h_2)$ where h_1 and h_2 represents the height of the tree

```
// returns the value of the leaf, or -1 if empty
int getLeaf(stack<TreeNode*>& tree) {
    // tree is a reference, we will always pop an element from it
    while(!tree.empty()) {
        // get the top element from the stack
        TreeNode* node = tree.top();
        // already visited, so remove from stack
        tree.pop();
        // is this a leaf?
        if (!node->left && !node->right) {
            // yes, return the value
            return node->val;
        }
        // push the right FIRST to the stack
        if (node->right) tree.push(node->right);
        // left should be on top of the stack
        if (node->left) tree.push(node->left);
    }
    return -1;
}
```

```
bool leafSimilar(TreeNode* root1, TreeNode* root2) {
    // initialize the stacks, add root1 and root2
    std::stack<TreeNode*> leftTree, rightTree;
    leftTree.push(root1);
    rightTree.push(root2);

    while(true) {
        // get the leaves to compare
        int leaf1 = getLeaf(leftTree);
        int leaf2 = getLeaf(rightTree);
        // exit immediately if one leaf is different
        if (leaf1 != leaf2) return false;
        // stop when there are no leaves left
        if (leaf1 == -1 || leaf2 == -1) break;
    }
    return true;
}
```

Code – Count Good Nodes in Binary Tree

Medium



LeetCode

leetcode.com/problems/count-good-nodes-in-binary-tree

Code (recursive) Time: $O(n + m)$ where n and m are the numbers of nodes for trees 1 and 2 Space: $O(h1 + h2)$ where $h1$ and $h2$ represents the height of the tree