CSE 332 Winter 2024
Lecture 7: $\underbrace{\text{Dictionaries}}_{\text{Map}}$, $\underbrace{\text{BSTs}}$

Nathan Brunelle

http://www.cs.uw.edu/332

Warm Up: Tree Method

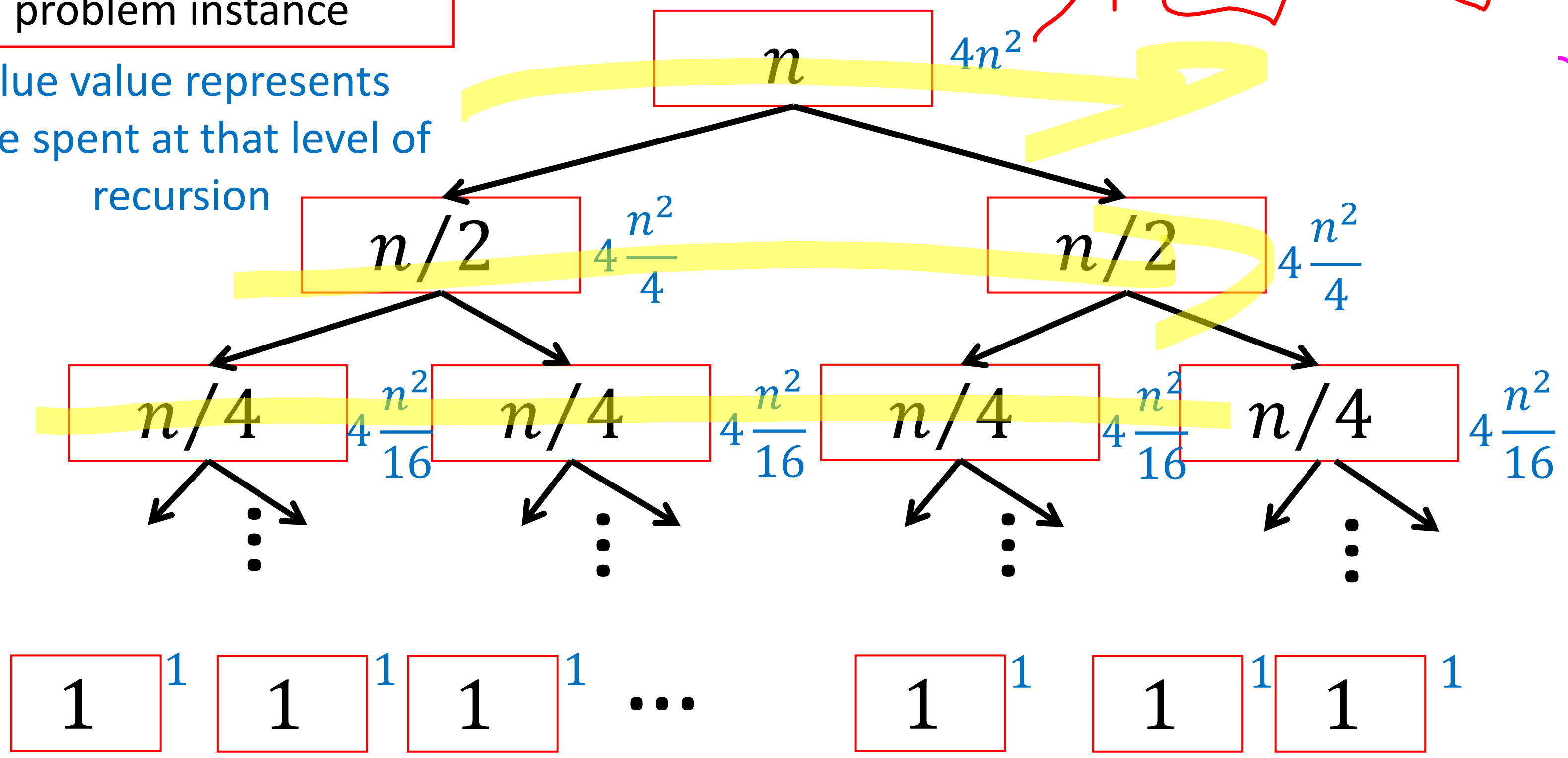
$T(1) = 1$

$\frac{n}{2^i}$

$$T(n) = 2T\left(\frac{n}{2}\right) + 4n^2$$

Red box represents a problem instance

Blue value represents time spent at that level of recursion



$\Rightarrow 4 \cdot 2^i \frac{n^2}{4^i}$ work at level i

$\left(\frac{n}{2^i}\right)^2$

$\log_2 n$ levels of recursion

$$T(n) = \sum_{i=1}^{\log_2 n} 4 \cdot 2^i \frac{n^2}{4^i} = 4n^2 \sum_{i=1}^{\log_2 n} \frac{1}{2^i} = \Theta(n^2)$$

Θ(n)

Warm Up: Which is better?

Floyd's

Both of the following build a binary heap within an unordered array. Which is better?

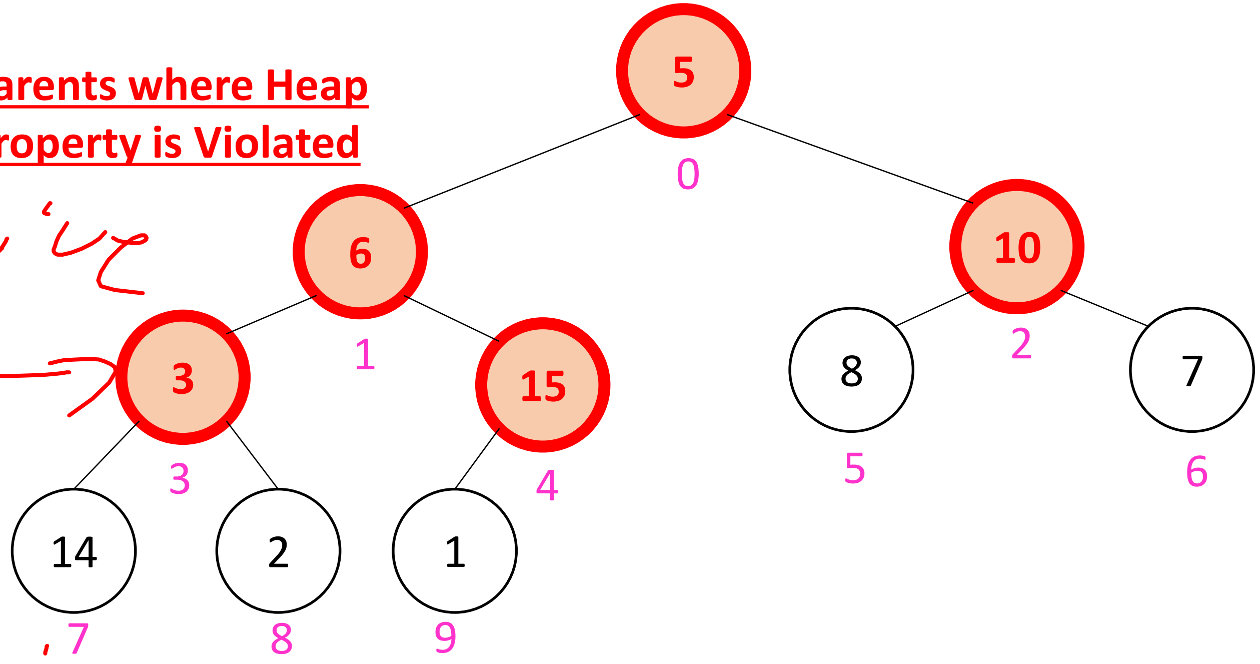
Root expensive

```
buildHeapDown(arr){
  for(int i = arr.length; i>0; i--){
    percolateDown(arr, i);
  }
}
```

leaves are expensive

```
buildHeapUp(arr){
  for(int i = 0; i<arr.length; i++){
    percolateUp(arr, i);
  }
}
```

Parents where Heap Property is Violated



5	6	10	3	15	8	7	14	2	1
0	1	2	3	4	5	6	7	8	9

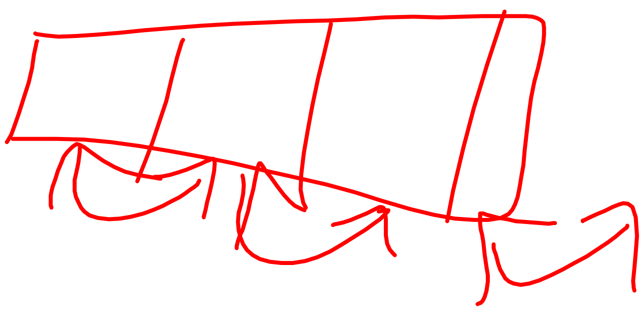
Dictionary (Map) ADT

Key → Value

- Contents:
  - Sets of key+value pairs
  - Keys must be comparable
- Operations:
  - insert(key, value)
    - Adds the (key,value) pair into the dictionary
    - If the key already has a value, overwrite the old value
      - Consequence: Keys cannot be repeated
  - find(key)
    - Returns the value associated with the given key
  - delete(key)
    - Remove the key (and its associated value)

Naïve attempts

Data Structure	Time to insert	Time to find	Time to delete
Unsorted Array	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Unsorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Sorted Array	$\boxed{\Theta(n)}$	$\boxed{\Theta(\log n)}$	$\Theta(n)$
Sorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$



Less Naïve attempts

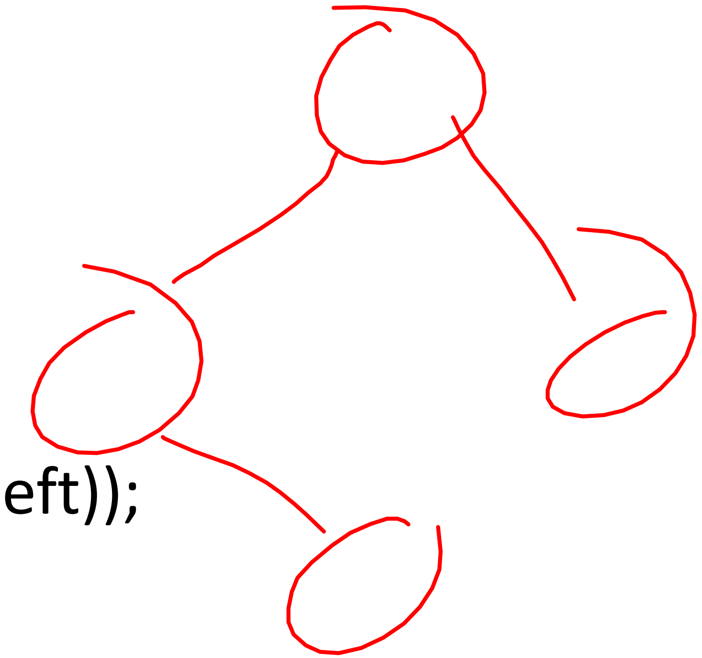
- Binary Search Trees (today)
- Tries (Project 1)
- AVL Trees (next week)
- B-Trees (next week)
- HashTables (week after)
- Red-Black Trees (not included in this course)
- Splay Trees (not included in this course)

Naïve attempts

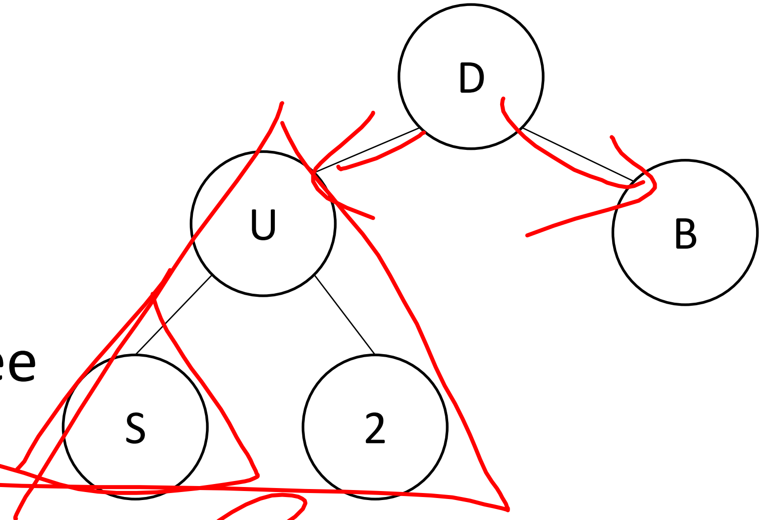
Data Structure	Time to insert	Time to find	Time to delete
Unsorted Array	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Unsorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Sorted Array	$\Theta(n)$	$\Theta(\log n)$	$\Theta(n)$
Sorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Binary Search Tree (W.C.)	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Binary Search Tree (average)	$\Theta(\log n)$	$\Theta(\log n)$	$\Theta(\log n)$

Tree Height

```
treeHeight(root){
        height = 0;
        if (root.left != Null){
                height = max(height, treeHeight(root.left));
        }
        if (root.right != Null){
                height = max(height, treeHeight(root.right));
        }
        return height;
}
```



More Tree "Vocab"



- Traversal:
  - An algorithm for "visiting/processing" every node in a tree
- Pre-Order Traversal:
  - Root, Left Subtree, Right Subtree

DUS2B

- In-Order Traversal:
  - Left Subtree, Root, Right Subtree

SU2DB

- Post-Order Traversal
  - Left Subtree, Right Subtree, Root

S2UBD

Name that Traversal!

```
AorderTraversal(root){
        if (root.left != Null){
                process(root.left);
        }
        if (root.right != Null){
                process(root.right);
        }
        process(root);
}
```

Post

```
BorderTraversal(root){
        process(root);
        if (root.left != Null){
                process(root.left);
        }
        if (root.right != Null){
                process(root.right);
        }
}
```

Pre

```
CorderTraversal(root){
        if (root.left != Null){
                process(root.left);
        }
        process(root)
        if (root.right != Null){
                process(root.right);
        }
}
```

In

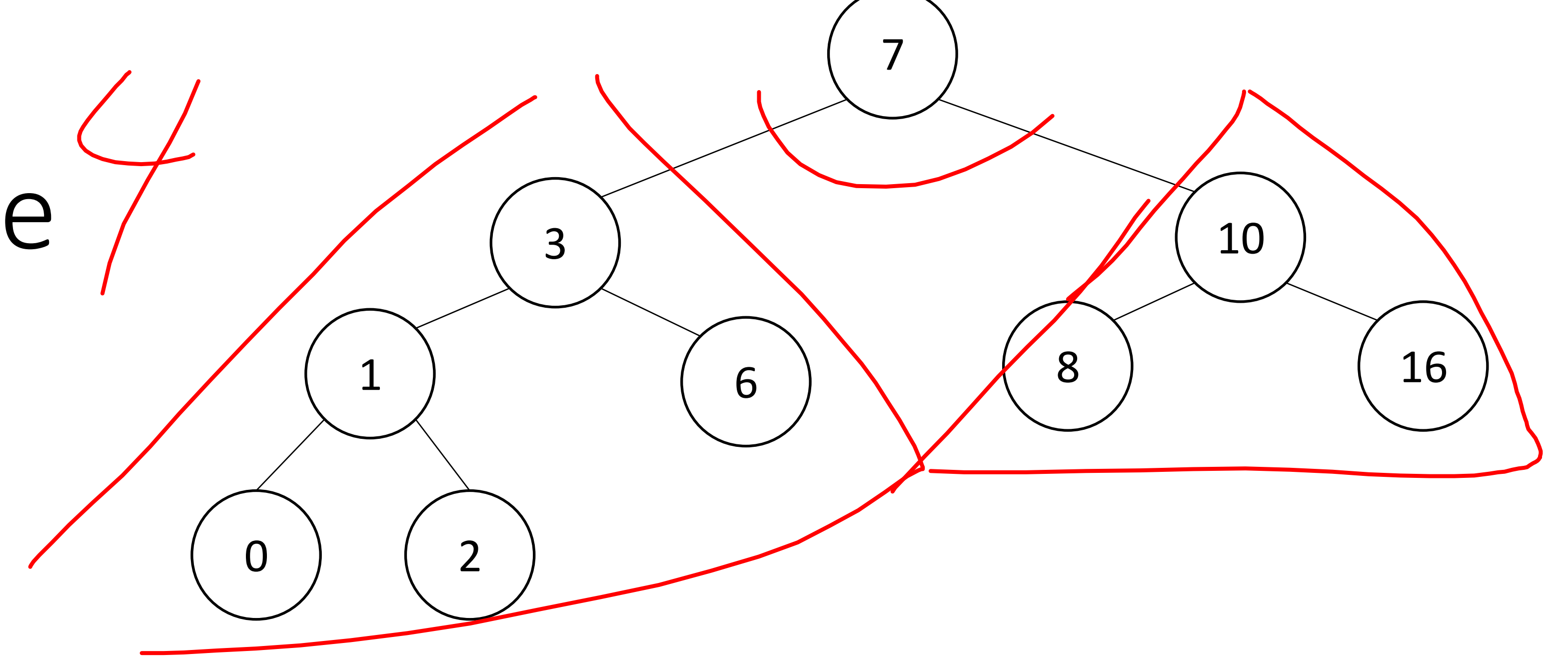
Binary Search Tree

4

- Binary Tree
  - Definition:
- Order Property
  - All keys in the left subtree are smaller than the root
  - All keys in the right subtree are larger than the root

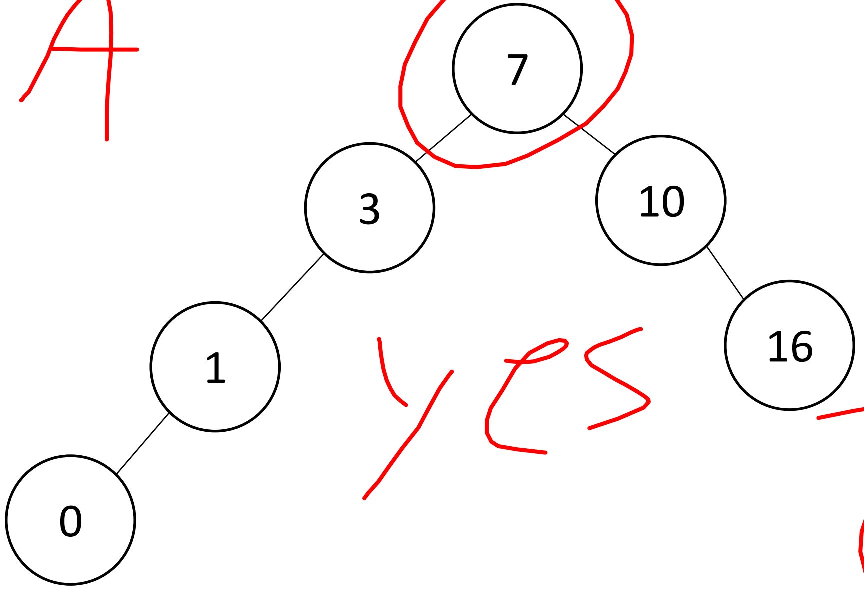
- Shape

- Why?



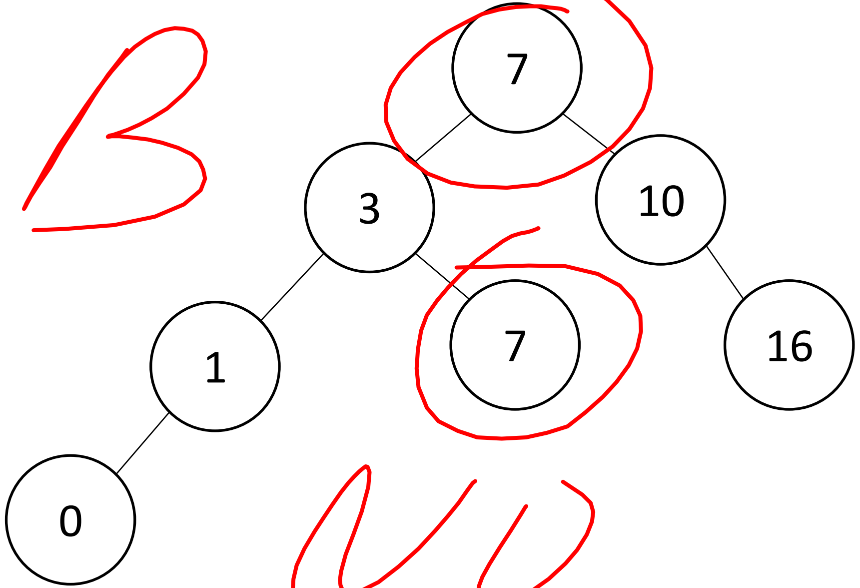
Are these BSTs?

A



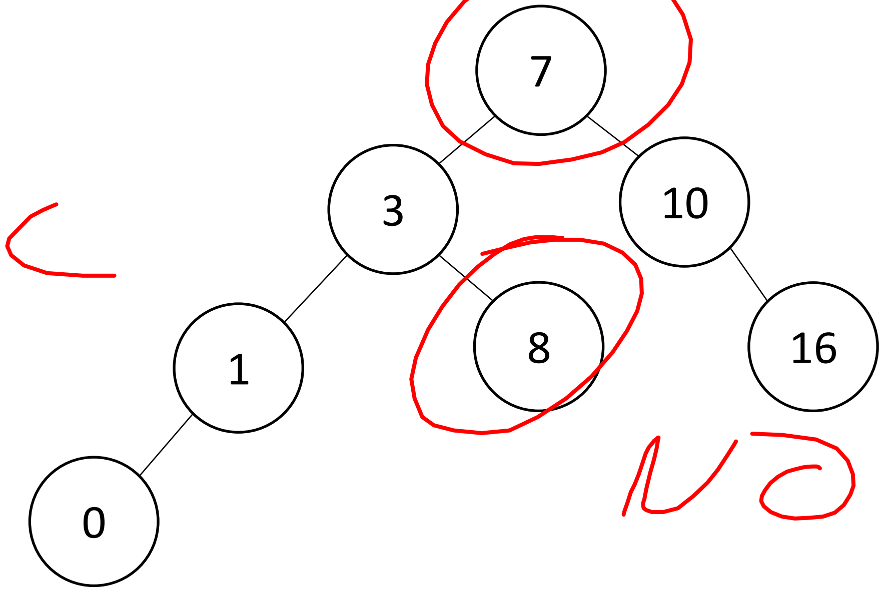
yes

B



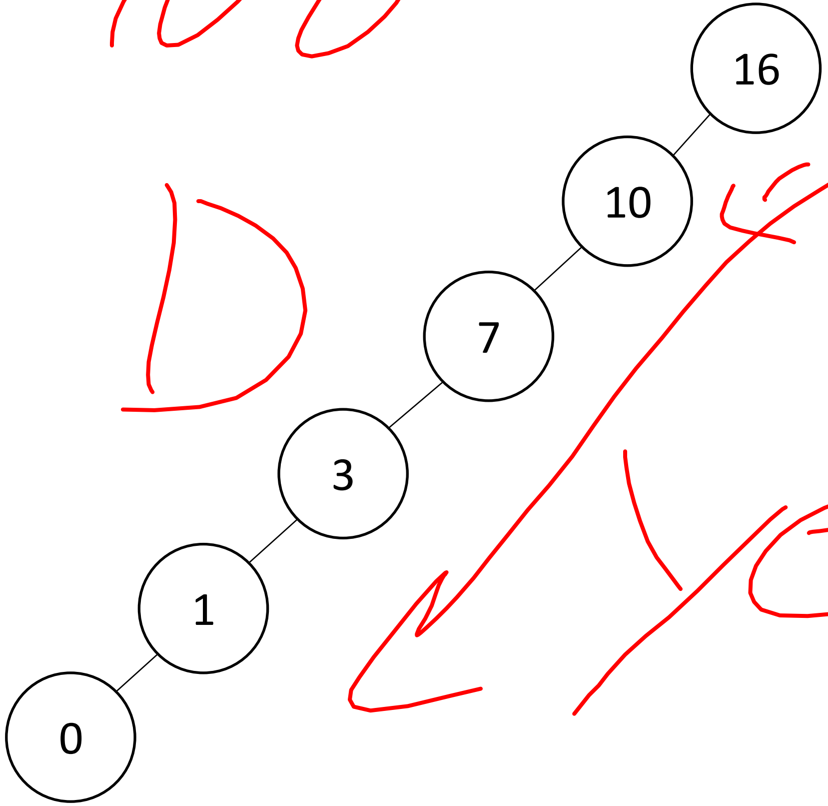
NO

C



No

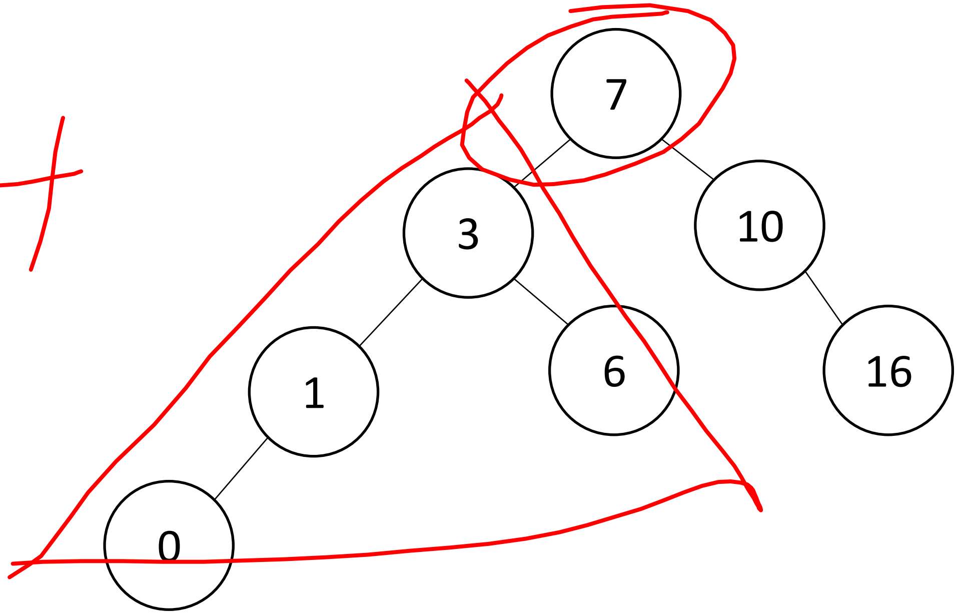
D



yes

Find Operation (recursive)

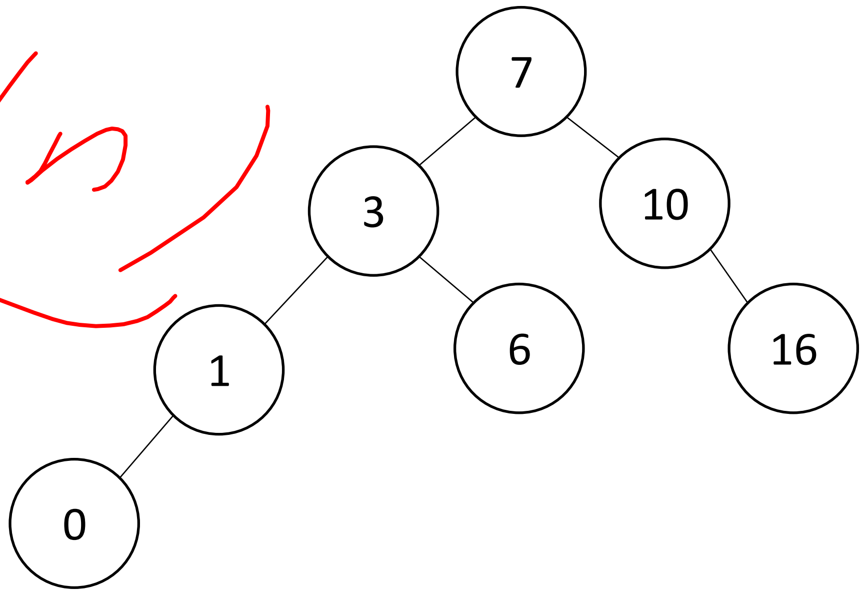
4



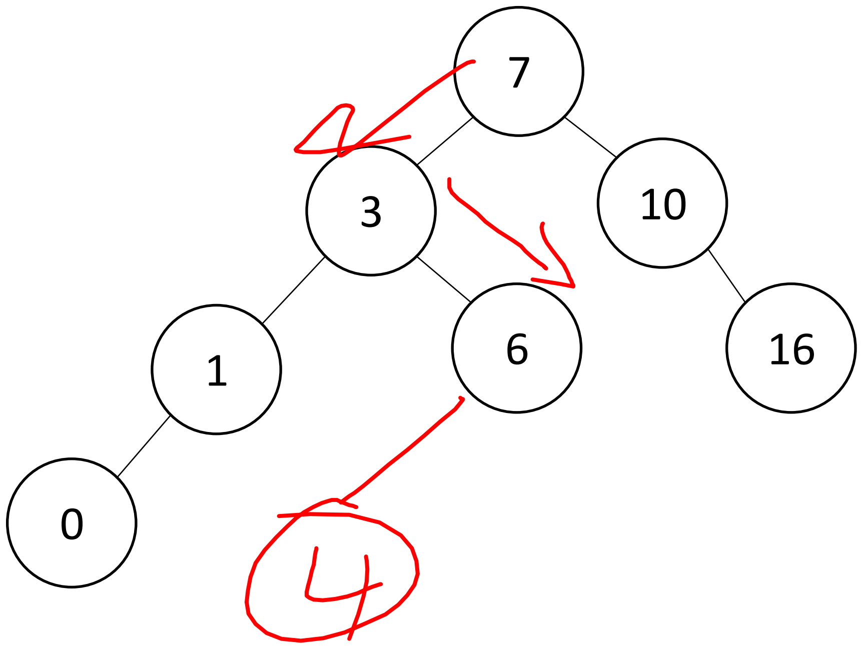

```
find(key, root){
        if (root == Null){
                return Null;
        {
        if (key == root.key){
                return root.value;
        }
        if (key < root.key){
                return find(key, root.left);
        }
        if (key > root.key){
                return find(key, root.right);
        }
        return Null;
}
```

Find Operation (iterative) $O(n)$

```
find(key, root){
        while (root != Null && key != root.key){
                if (key < root.key){
                        root = root.left;
                }
                else if (key > root.key){
                        root = root.right;
                }
        }
        if (root == Null){
                return Null;
        }
        return root.value;
}
```



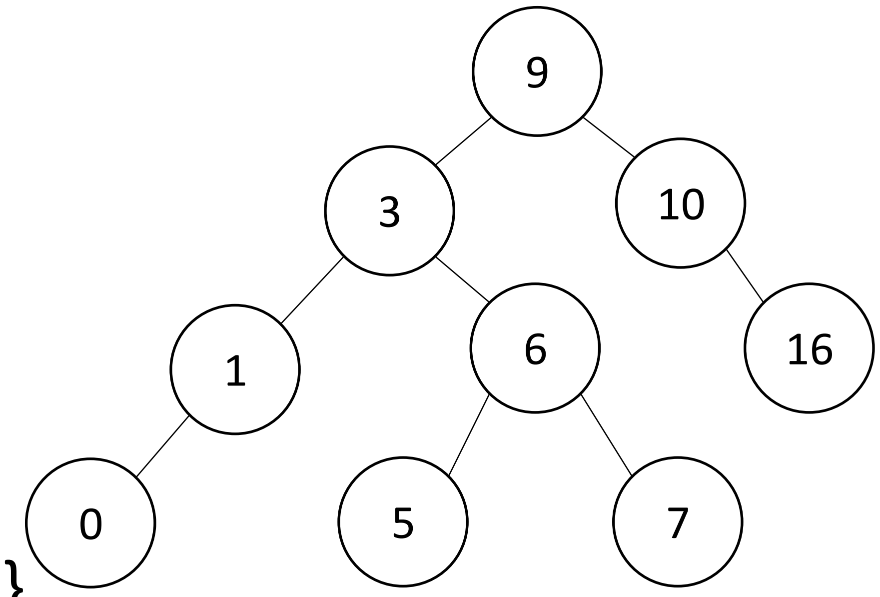
Insert Operation (iterative) 4




```
insert(key, value, root){
    if (root == Null){ this.root = new Node(key, value); }
    parent = Null;
    while (root != Null && key != root.key){
        parent = root;
        if (key < root.key){ root = root.left; }
        else if (key > root.key){ root = root.right; }
    }
    if (root != Null){ root.value = value; }
    else if (key < parent.key){ parent.left = new Node(key, value); }
    else{ parent.right = new Node (key, value); }
}
```

Note: Insert happens only at the leaves!

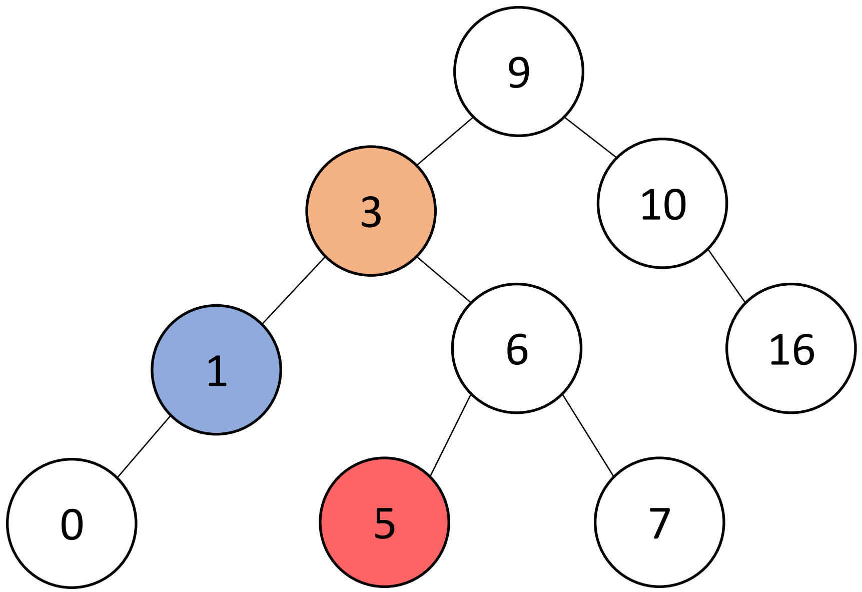
Delete Operation (iterative)




```
delete(key, root){
        while (root != Null && key != root.key){
                if (key < root.key){ root = root.left;      }
                else if (key > root.key){ root = root.right; }
        }
        if (root == Null){ return; }
        // Now root is the node to delete, what happens next?
}
```

Delete – 3 Cases

- 0 Children (i.e. it’s a leaf)
- 1 Child
- 2 Children



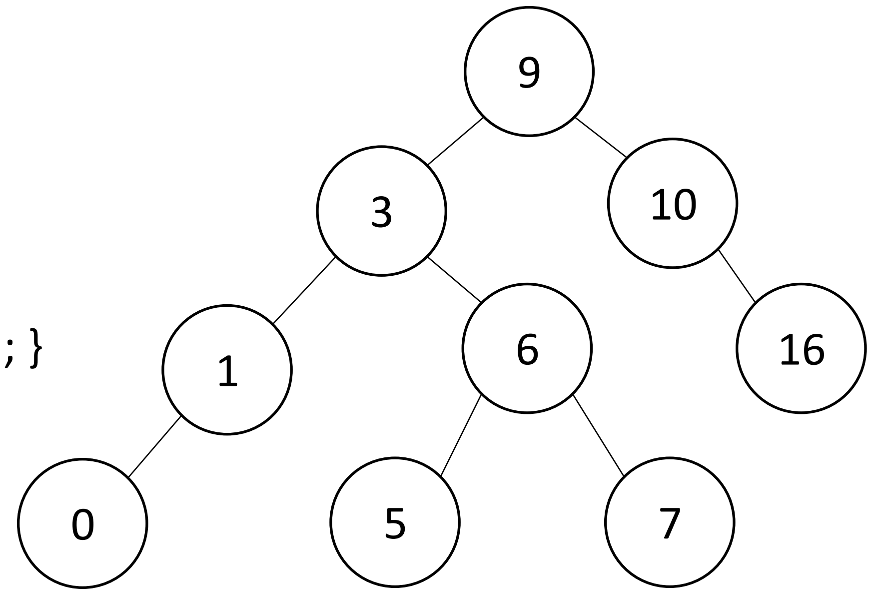
Finding the Max and Min

- Max of a BST:
  - Right-most Thing

```
maxNode(root){
        if (root == Null){ return Null; }
        while (root.right != Null){
                root = root.right;
        }
        return root;
}
```

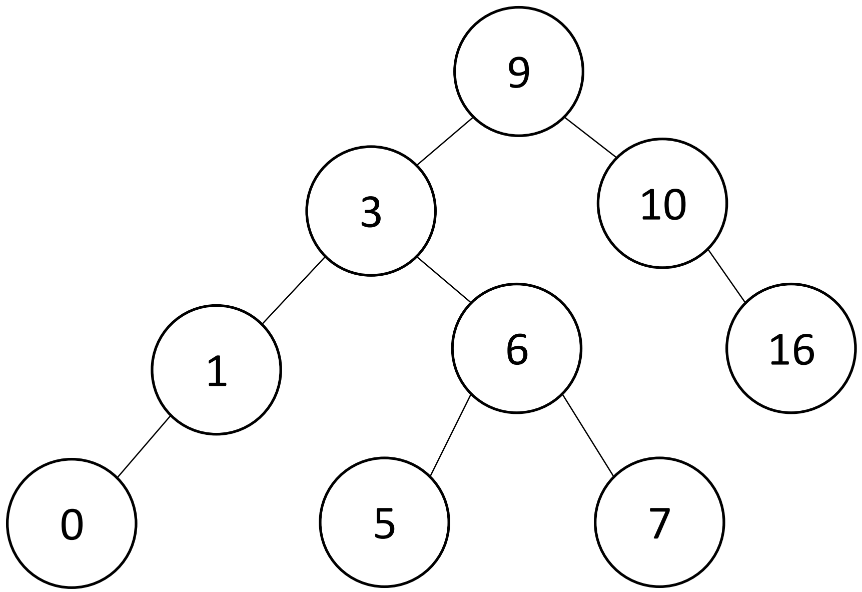
- Min of a BST:
  - Left-most Thing

```
minNode(root){
        if (root == Null){ return Null; }
        while (root.left != Null){
                root = root.left;
        }
        return root;
}
```



Delete Operation (iterative)

```
delete(key, root){
        while (root != Null && key != root.key){
                if (key < root.key){ root = root.left;  }
                else if (key > root.key){ root = root.right; }
        }
        if (root == Null){ return; }
        if (root has no children){
                make parent point to Null Instead;
        }
        if (root has one child){
                make parent point to that child instead;
        }
        if (root has two children){
                make parent point to either the max from the left or min from the right
        }
}
```



Worst Case Analysis

- For each of Find, insert, Delete:
  - Worst case running time matches height of the tree
- What is the maximum height of a BST with n nodes?

Improving the worst case

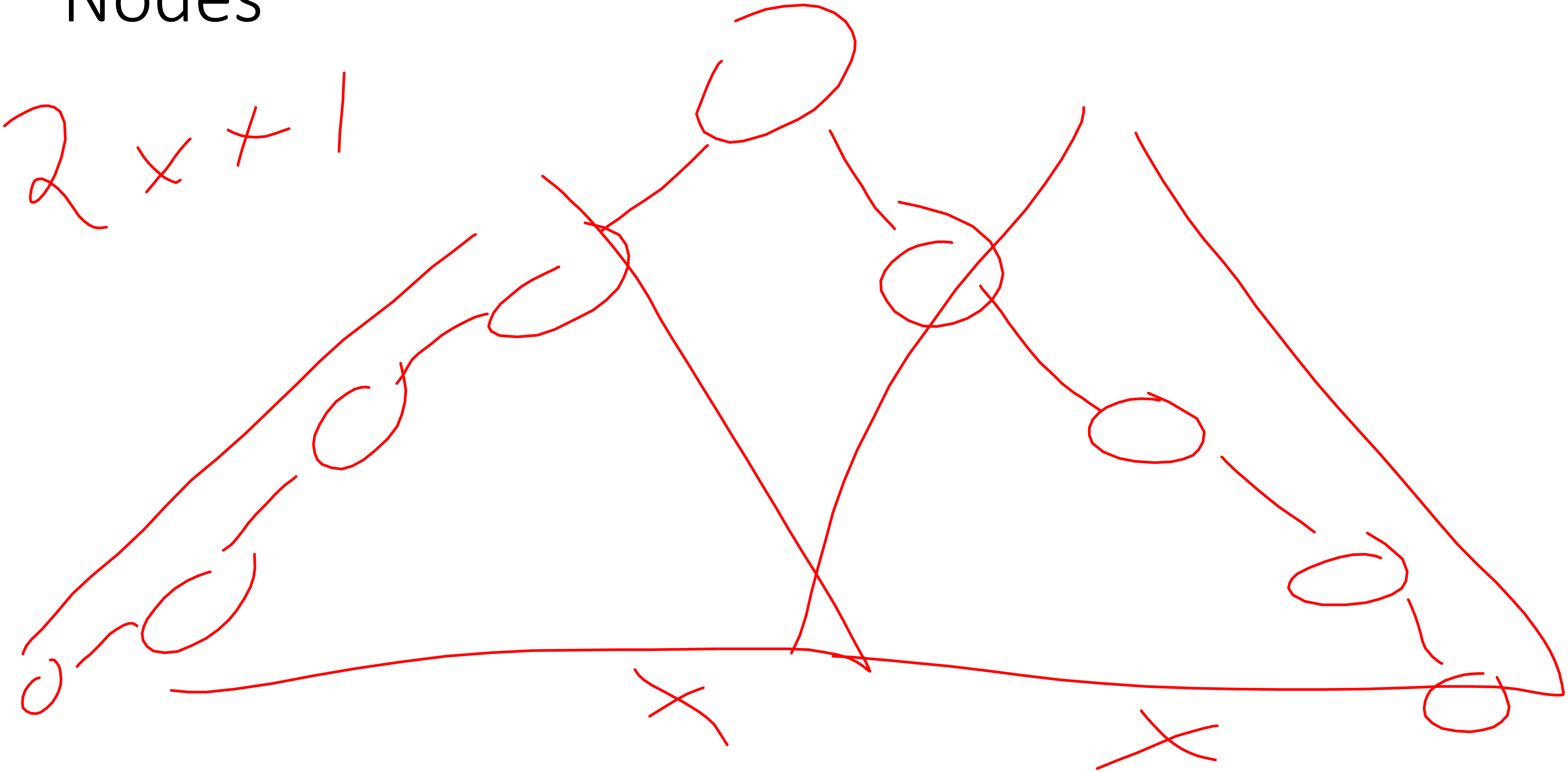
- How can we get a better worst case running time?

add shape rules
to keep tree short

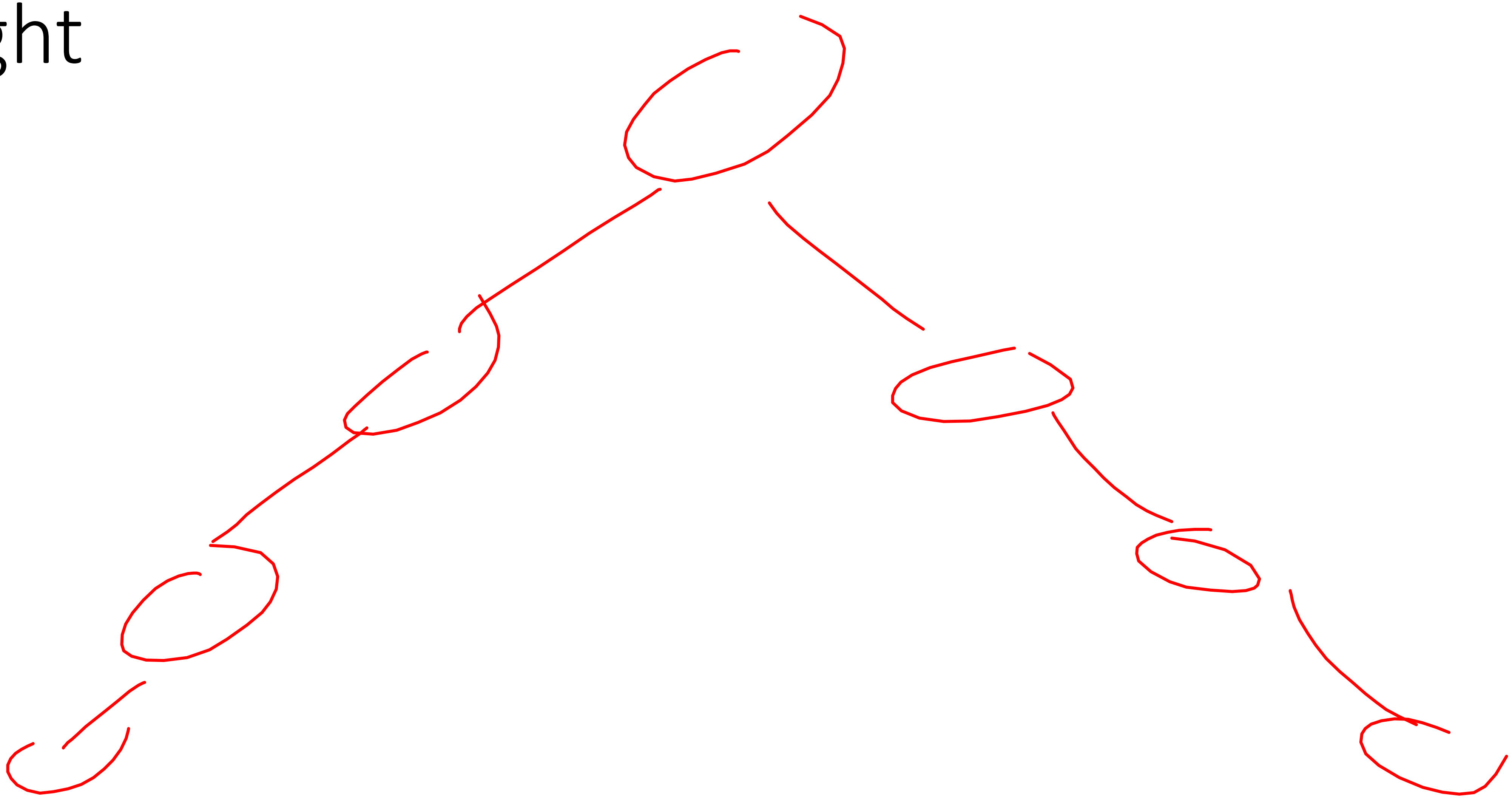
“Balanced” Binary Search Trees

- We get better running times by having “shorter” trees
- Trees get tall due to them being “sparse” (many one-child nodes)
- Idea: modify how we insert/delete to keep the tree more “full”

Idea 1: Both Subtrees of Root have same # Nodes



Idea 2: Both Subtrees of Root have same height



Idea 3: Both Subtrees of every Node have same # Nodes

Idea 4: Both Subtrees of every Node have same height

Teaser: AVL Tree

- A Binary Search tree that maintains that the left and right subtrees of every node have heights that differ by at most one.
  - Not too weak (ensures trees are short)
  - Not too strong (works for any number of nodes)