CS 106B, Lecture 21
Binary Search Trees

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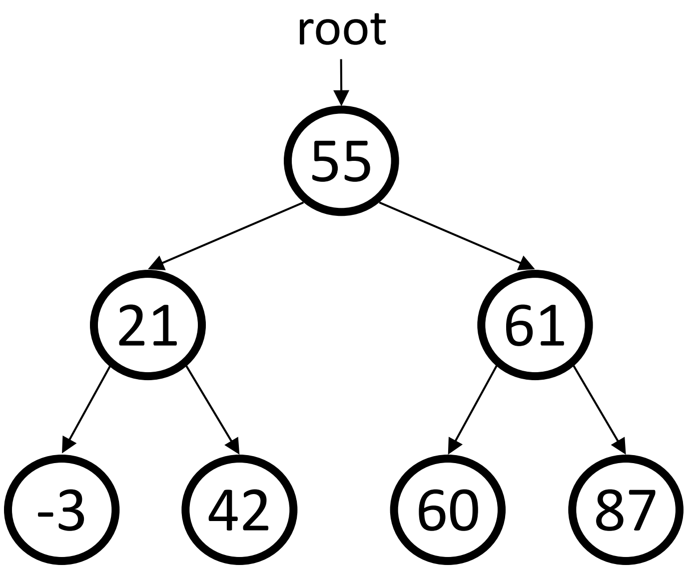
Based on slides created by Marty Stepp, Chris Gregg, Keith Schwarz, Julie Zelenski, Jerry Cain, Eric Roberts, Mehran Sahami, Stuart Reges, Cynthia Lee, and others

Plan for Today

- How to implement a Set
- Modifying Trees
  - Contains
  - getMin/getMax
  - Add
  - FreeTree
  - Removal

Exercise: contains

- Write a function **`contains`** that accepts a tree node pointer as its parameter and searches the tree for a given integer, returning `true` if found and `false` if not.
  - `contains(root, 87)` → `true`
  - `contains(root, 60)` → `true`
  - `contains(root, 63)` → `false`
  - `contains(root, 44)` → `false`

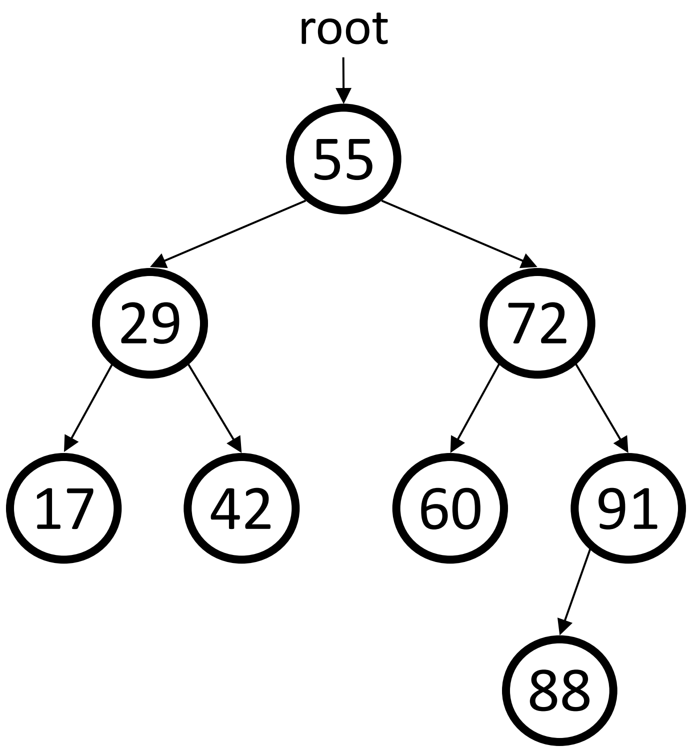


contains solution

```
// Returns whether this BST contains the given integer.
// Assumes that the given tree is in valid BST order.
bool contains(TreeNode* node, int value) {
    if (node == nullptr) {
        return false;   // base case: not found here
    } else if (node->data == value) {
        return true;    // base case: found here
    } else if (node->data > value) {
        return contains(node->left, value);
    } else {            // root->data < value
        return contains(node->right, value);
    }
}
```

getMin/getMax

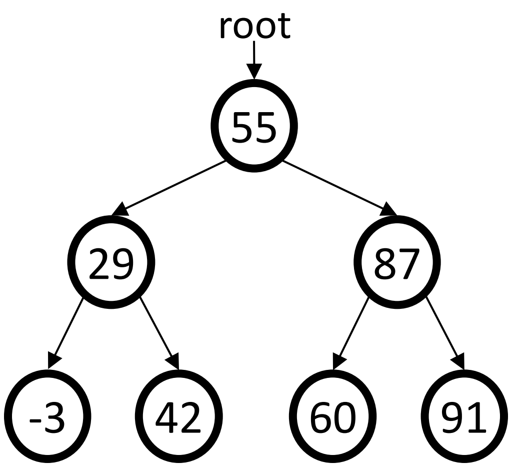
- Sorted arrays can find the smallest or largest element in O(1) time.
- How could we get the same values in a binary search tree?



getMin/Max solution

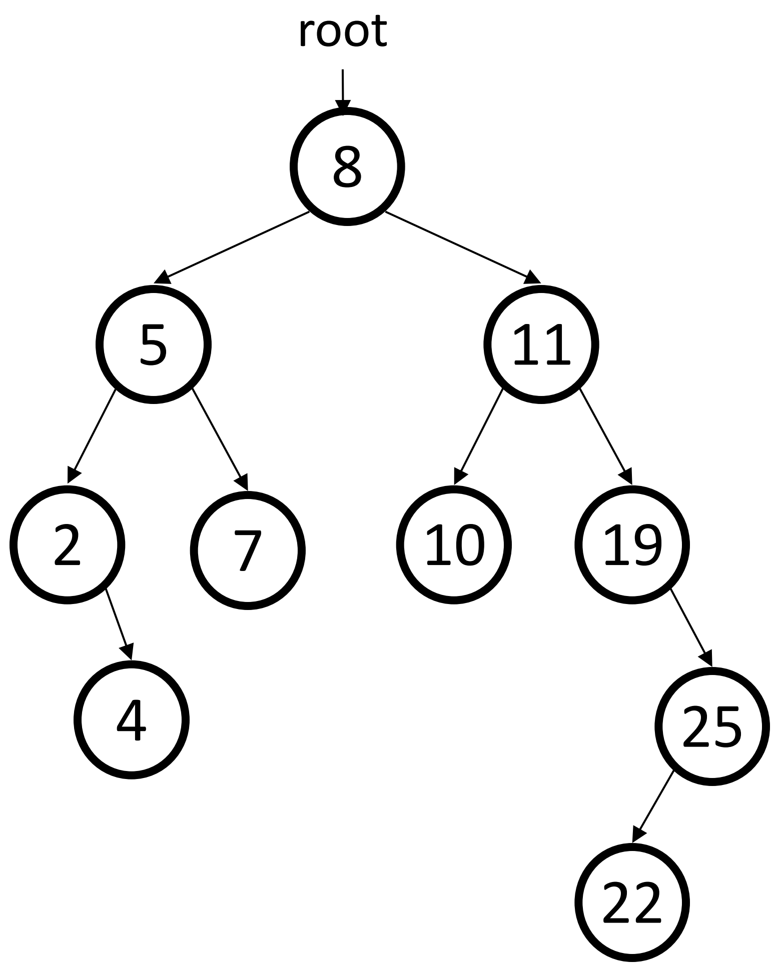
```
// Returns the minimum/maximum value from this BST.
// Assumes that the tree is a nonempty valid BST.
int getMin(TreeNode* root) {
    if (root->left == nullptr) {
        return root->data;
    } else {
        return getMin(root->left);
    }
}

int getMax(TreeNode* root) {
    if (root->left == nullptr) {
        return root->data;
    } else {
        return getMax(root->left);
    }
}
```



Adding to a BST

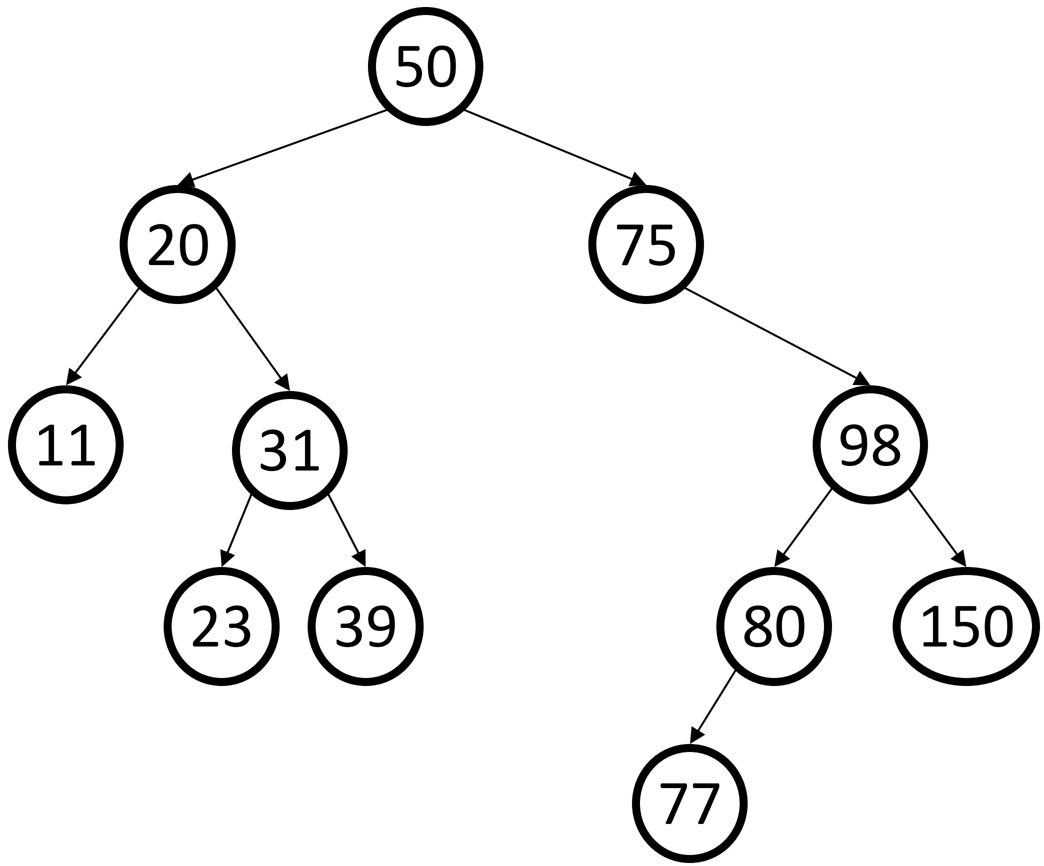
- Suppose we want to add new values to the BST below.
  - Where should the value 14 be added?
  - Where should 3 be added? 7?
  - If the tree is empty, where should a new value be added?



Adding exercise

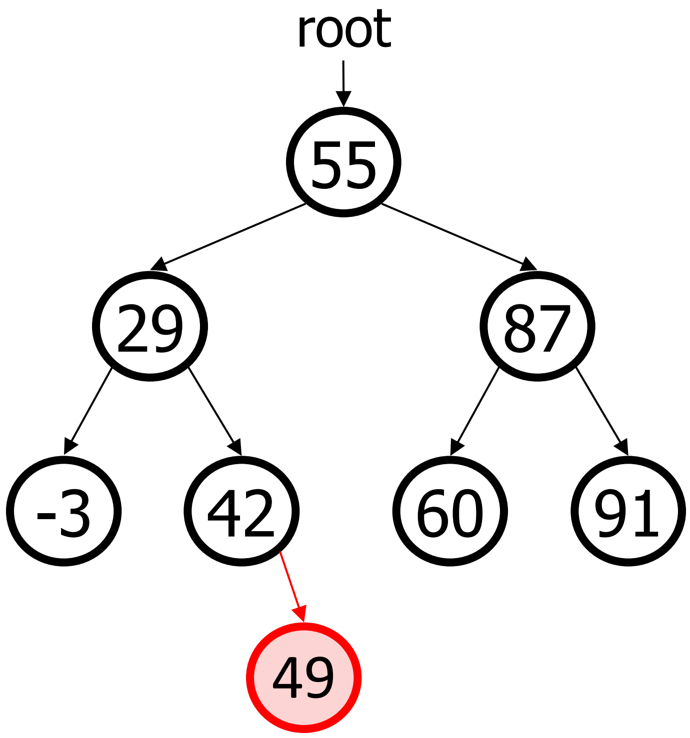
- Draw what a binary search tree would look like if the following values were added to an initially empty tree in this order:

50
20
75
98
80
31
150
39
23
11
77



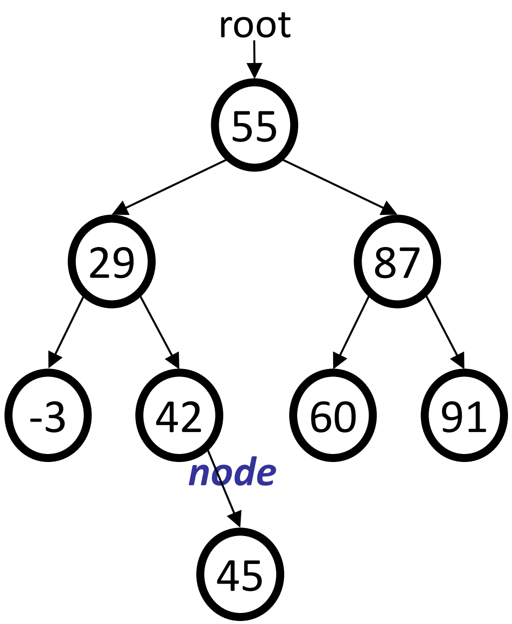
Exercise: add

- Write a function **add** that adds a given integer value to the BST.
  - Add the new value in the proper place to maintain BST ordering.
    - `tree.add(root, 49);`



Add Solution

```
void add(TreeNode*& node, int value) {
    if (node == nullptr) {
        node = new TreeNode(value);
    } else if (node->data > value) {
        add(node->left, value);
    } else if (node->data < value) {
        add(node->right, value);
    }
}
```



- Must pass the current node *by reference* for changes to be seen.

Announcements

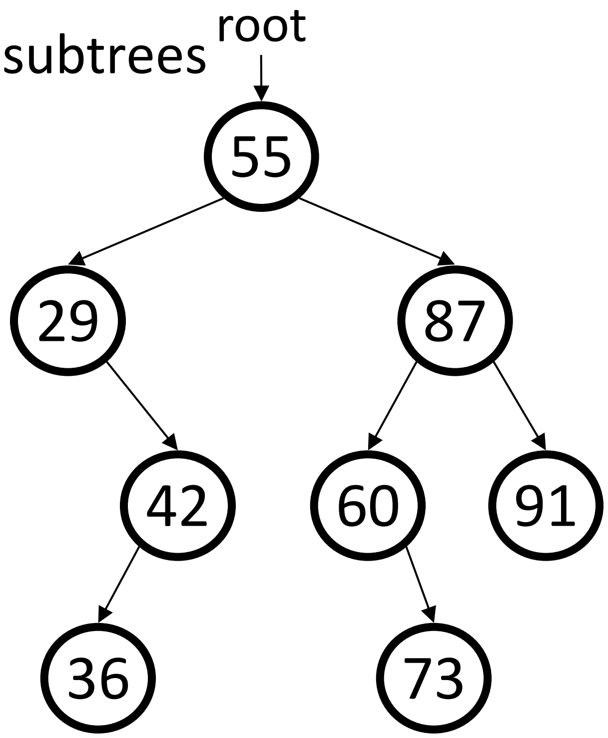
- Assn. 5 is due today

- Assn. 6 goes out today
  - Linked Lists. Give yourself plenty of time!

- One extra free late day for filling out the survey
  - Thanks for the feedback!

Free Tree

- To avoid leaking memory when discarding a tree, we must free the memory for every node.
  - Like most tree problems, often written *recursively*
  - must free the node itself, and its left/right subtrees
  - this is another *traversal* of the tree
    - should it be pre-, in-, or post-order?

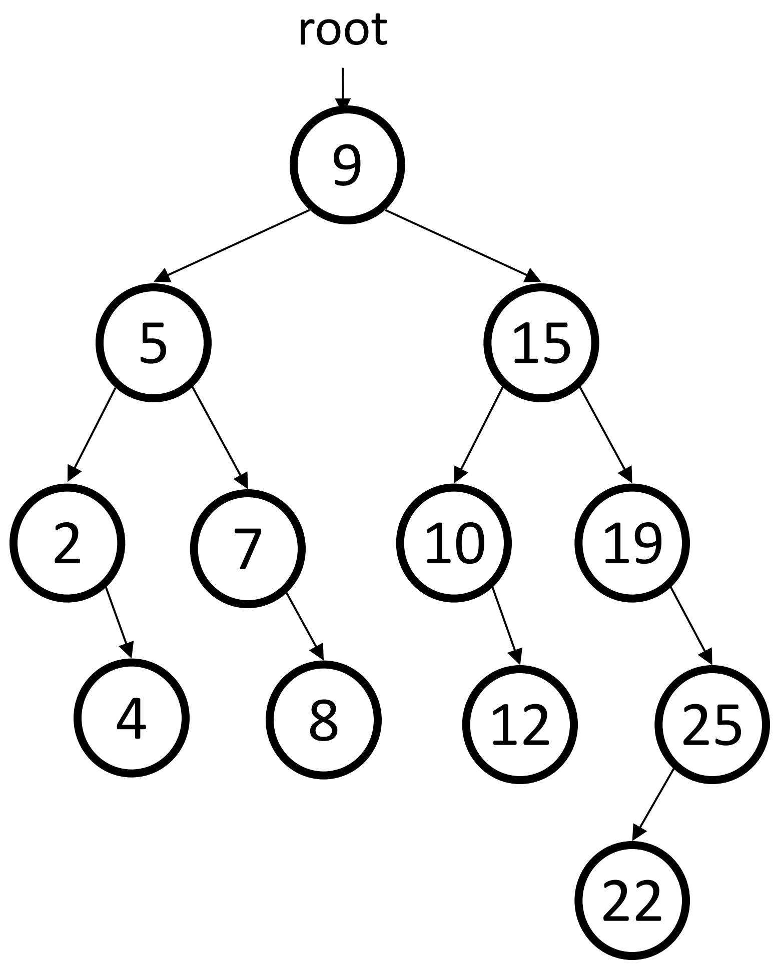


Free tree solution

```
void freeTree(TreeNode* node) {
    if (node == nullptr) {
        return;
    }
    freeTree(node->left);
    freeTree(node->right);
    delete node;
}
```

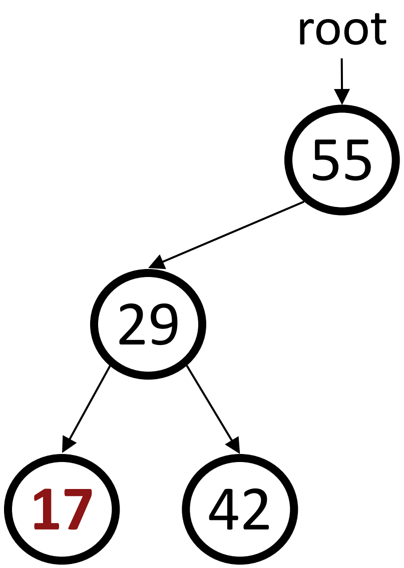
Removing from a BST

- Suppose we want to **remove** values from the BST below.
  - Removing a leaf like 4 or 22 is easy.
  - What about removing 2? 19?
  - How can you remove a node with two large subtrees under it, such as 15 or 9?

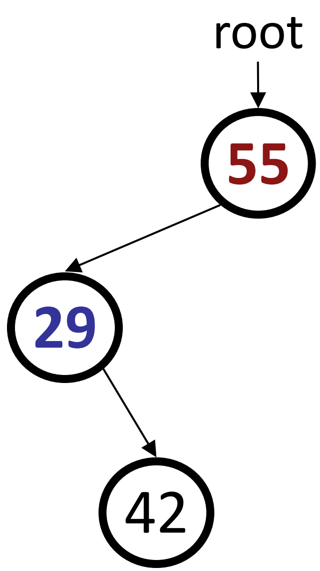


Cases for removal

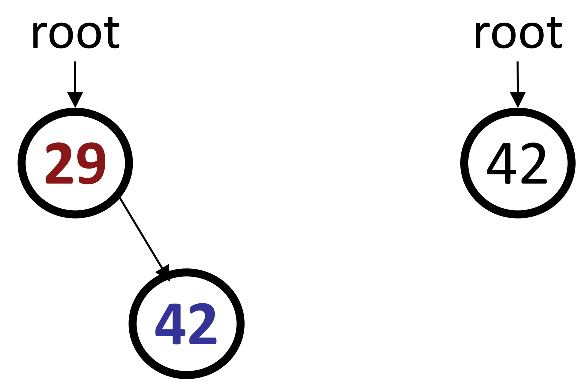
1. a **leaf**: Replace with `nullptr`
2. a node with a **left child only**: Replace with left child
3. a node with a **right child only**: Replace with right child



`remove(root, 17);`



`remove(root, 55);`



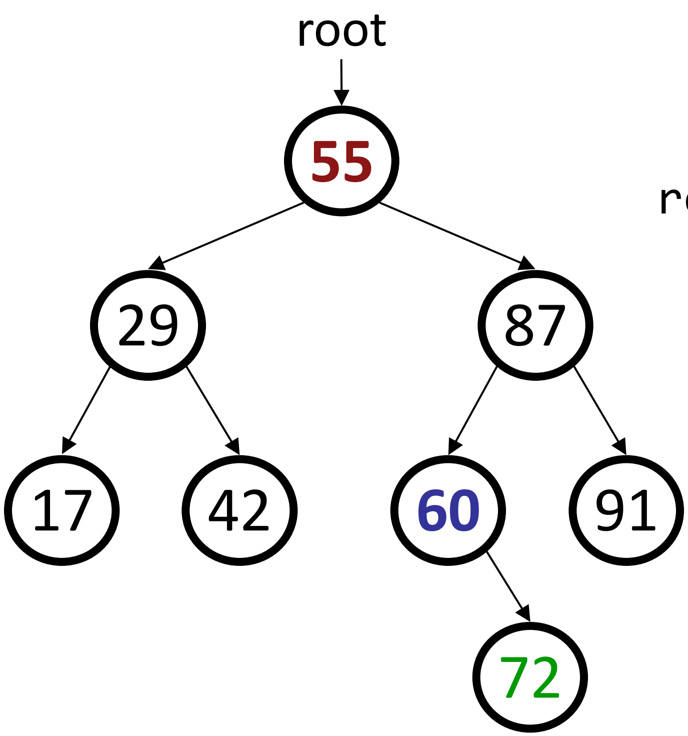
`remove(root, 29);`

Cases for removal

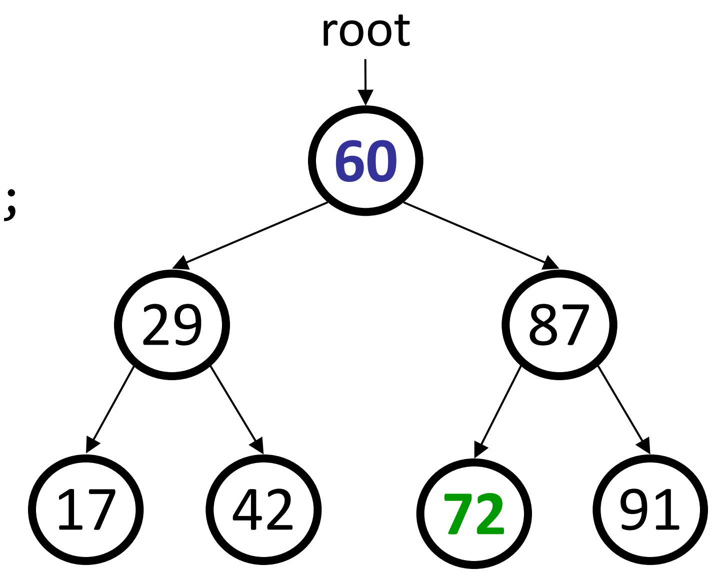
4. a node with **both** children:

   replace with **min from right**

   (replacing with **max from left** would also work)

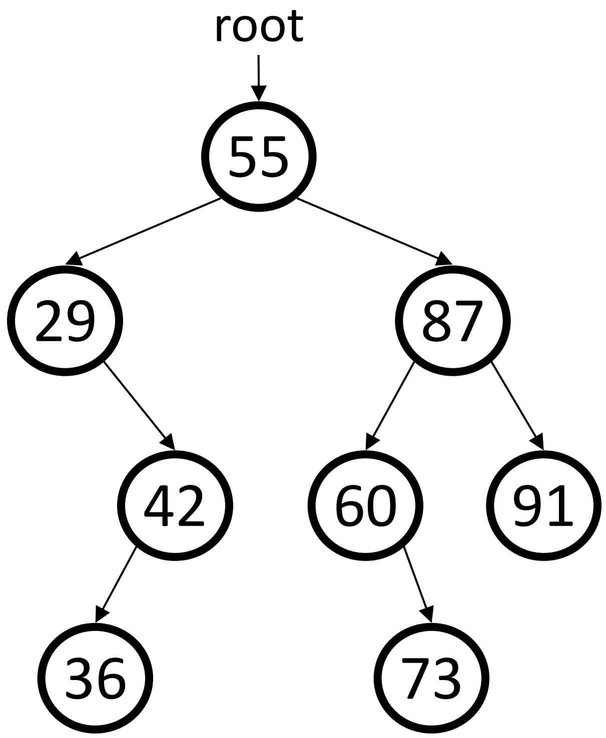



```
remove(root, 55);
```



Exercise: remove

- Add a function **`remove`** that accepts a root pointer and removes a given integer value from the tree, if present. Remove the value in such a way as to maintain BST ordering.
  - `remove(root, 73);`
  - `remove(root, 29);`
  - `remove(root, 87);`
  - `remove(root, 55);`



remove solution

```
// Removes the given value from this BST, if it exists.
// Assumes that the given tree is in valid BST order.
void remove(TreeNode*& node, int value) {
    if (node == nullptr) {
        return;
    } else if (value < node->data) {
        remove(node->left, value);    // too small; go left
    } else if (value > node->data) {
        remove(node->right, value);   // too big; go right
    } else {
        // value == node->data; remove this node!
        // (continued on next slide)
        ...
```

remove solution

```
        // value == node->data; remove this node!
        if (node->right == nullptr) {
            // case 1 or 2: no R child; replace w/ left
            TreeNode* trash = node;
            node = node->left;
            delete trash;
        } else if (node->left == nullptr) {
            // case 3: no L child; replace w/ right
            TreeNode* trash = node;
            node = node->right;
            delete trash;
        } else {
            // case 4: L+R both; replace w/ min from right
            int min = getMin(node->right);
            remove(node->right, min);
            node->data = min;
        }
    }
}
```

Overflow

- We saw how to add to a binary search tree. Does it matter what order we add in?
  - Try adding: 50, 20, 75, 98, 80, 31, 150
  - Now add the same numbers but in sorted order: 20, 31, 50, 75, 80, 98, 150