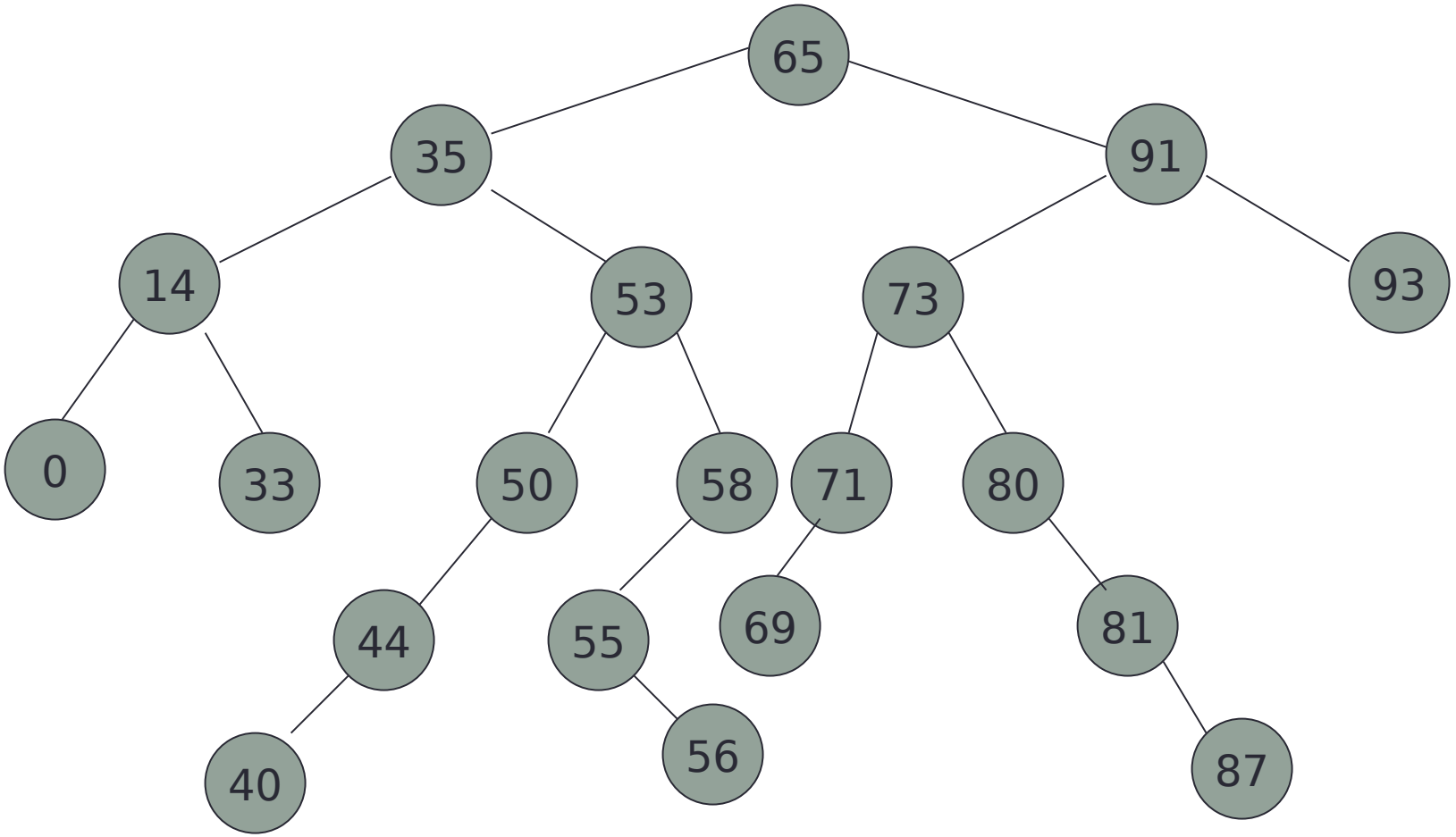
BINARY SEARCH TREES (BSTS)

CSC212: Data Structures

Binary Search Trees (BSTs)

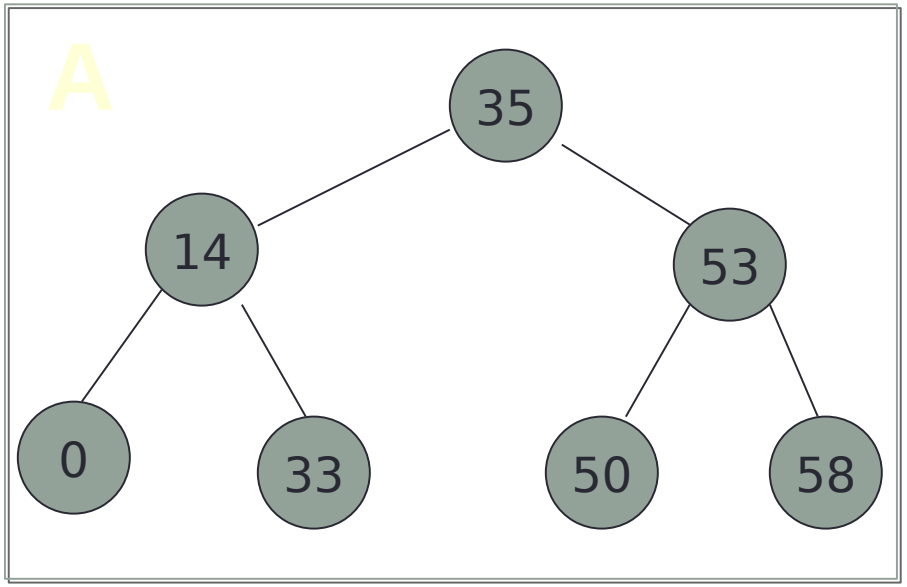
- A Binary Search Tree (BST) is a binary tree such that for each node, say N, the following statements are true:
  1. If L is any node in the left subtree of N, then **L** is **less** than N.
  2. If R is any node in the right subtree of N, then **R** is **greater** than N.

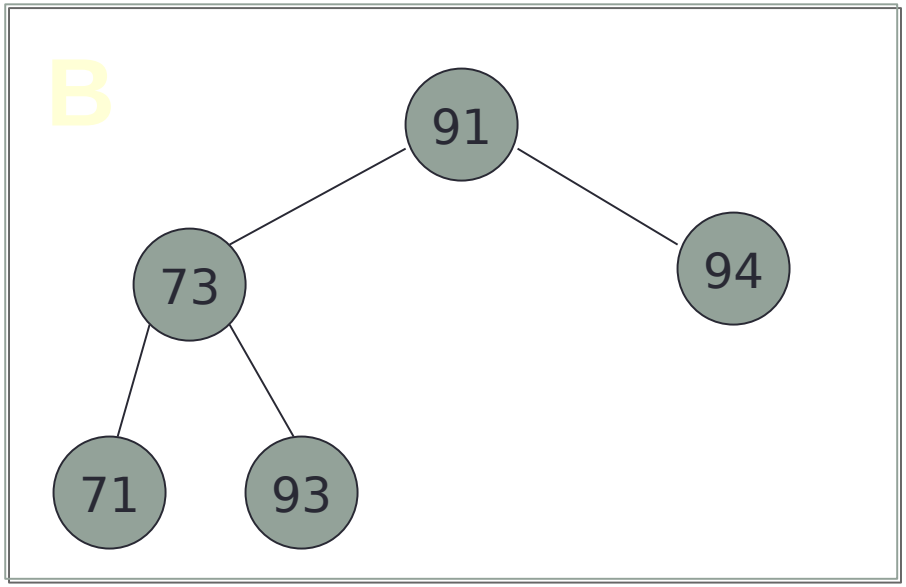
Binary Search Tree (BST): Example

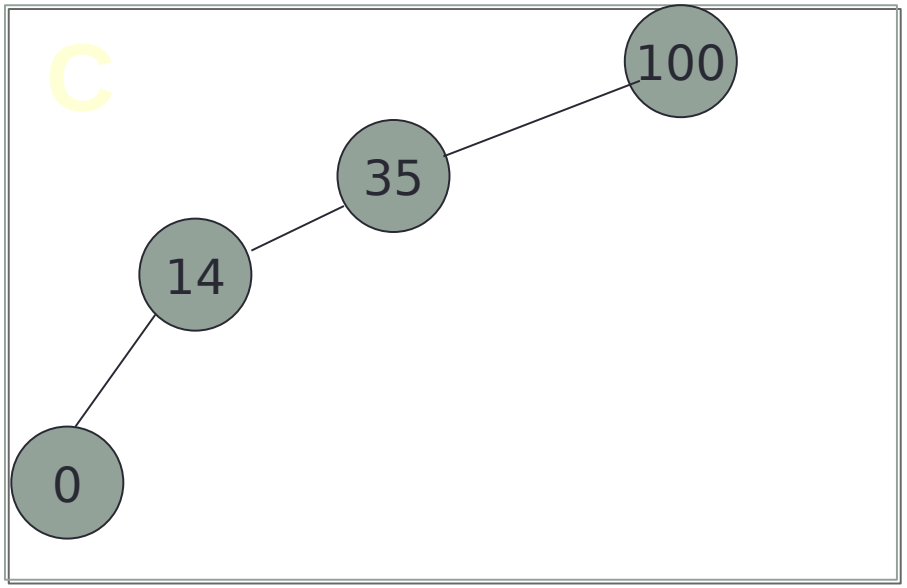


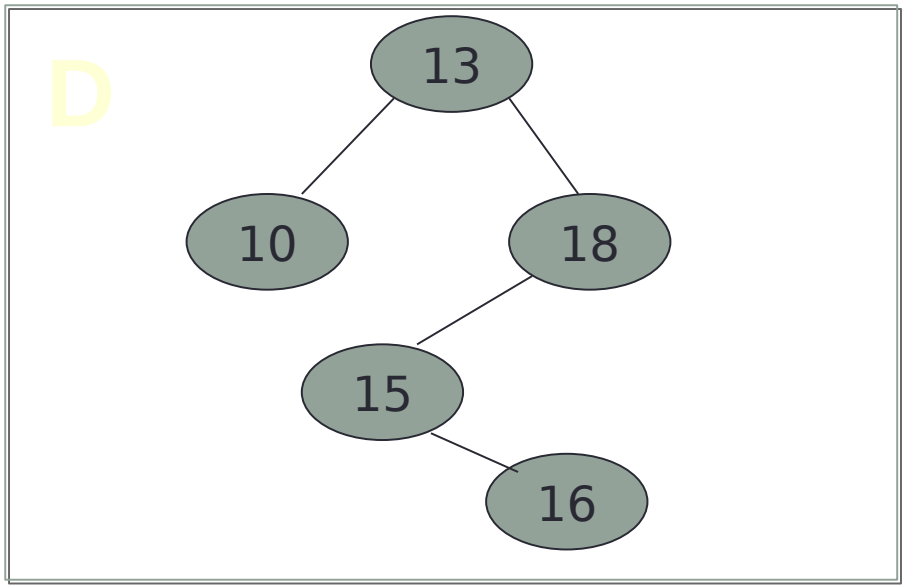
Binary Search Trees (BSTs)

- Consider the search operation **FindKey**: find an element of a particular key value in a binary tree.
  - **In binary tree this operation is O(n).**
    - In a binary tree of 10^6 nodes 10^6 steps required.
  - **In a Binary Search Tree (BST) this operation can be performed very efficiently: $O(\log_2 n)$.**
    - A binary search tree of 10^6 nodes $\log_2(10^6)$ 20 steps only are required.
    - In average case









Which of the above Trees is not BST ?

ADT Binary Search Tree

Elements: the elements are nodes (BSTNode), each node contains the following data type: Type,Key and has LeftChild and RightChild references. .

Structure: hierarchical structure; each node can have two children: left or right child; there is a root node and a current node. If N is any node in the tree, nodes in the left subtree < N and nodes in the right subtree > N.

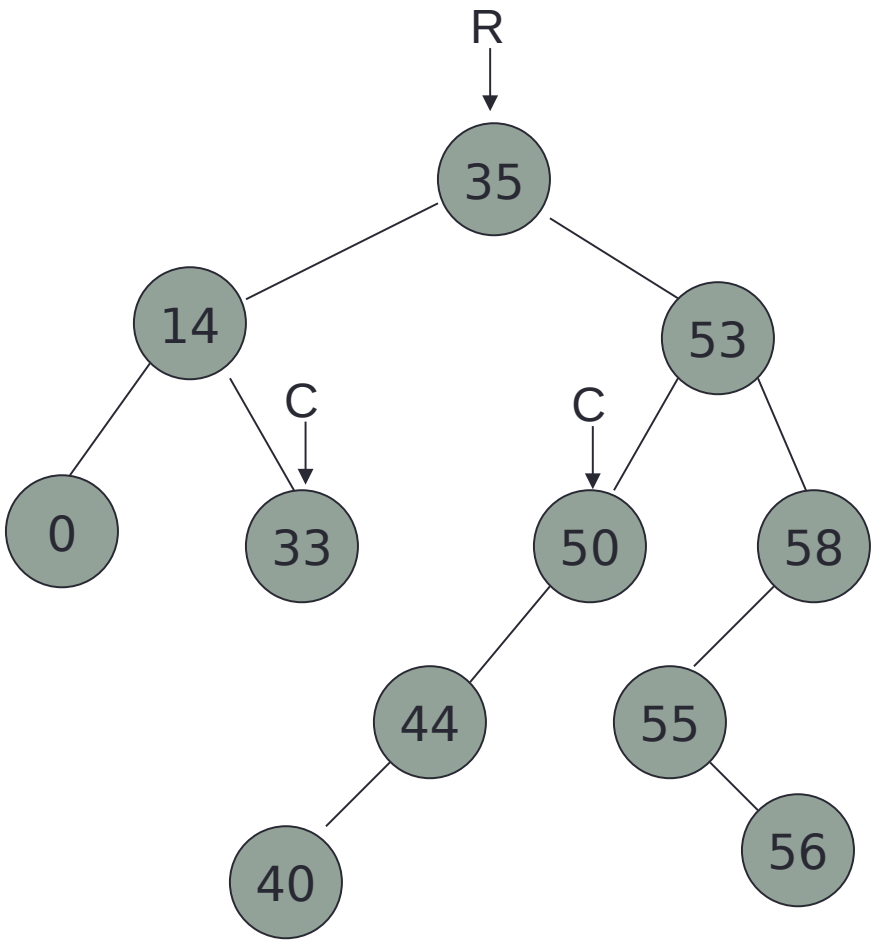
Domain: the number of nodes in a BST is bounded; type/class name is BST

ADT Binary Search Tree

Operations:

1. **Method** FindKey (int tkey, boolean found).
   requires: none.
   input: tkey.
   results: If bst contains a node whose key value is tkey, then that node is made the current node and found is set to true; otherwise found is set to false and either the tree is empty or the current node is the node to which the node with key = tkey would be attached as a child if it were added to the BST.
   output: found.

Find



find (50)

find (30)

ADT Binary Search Tree

2. **Method** Insert (int k, Type e, boolean inserted)

   requires: Full (bst) is false. **input**: key, e.

   results: if bst does not contain k then inserted is set to true and node with k and e is inserted and made the current element; otherwise inserted is set to false and current value does not change. **output**: inserted.

3. **Method** Remove_Key (int tkey, boolean removed)
   input: tkey

   results: Node with key value tkey is removed from the bst and removed set to true. If BST is not empty then root is made the current. **output**: removed

ADT Binary Search Tree

4. **Method** Update(int key, Type e, boolean updated)

   requires: Empty(bst) is false. **input:** key, e. **results:** current node's element is replaced with e. **Output:** updated.

ADT Binary Search Tree

These operations have the same specification as ADT Binary Tree.

5. **Method** Traverse (Order ord)
6. **Method** DeleteSub ( )
7. **Method** Retrieve (Type e)
8. **Method** Empty (boolean empty).
9. **Method** Full (boolean full)

ADT Binary Search Tree: Element

```
public class BSTNode <T> {
  public int key;
  public T data;
  public BSTNode<T> left, right;

  /** Creates a new instance of BSTNode */
  public BSTNode(int k, T val) {
  key = k;
  data = val;
  left = right = null;
  }

  public BSTNode(int k, T val, BSTNode<T> l, BSTNode<T> r) {
  key = k;
  data = val;
  left = l;
  right = r;
  }
}
```

ADT Binary Search Tree: Implementation

```
public class BST <T> {
  BSTNode<T> root, current;

  /** Creates a new instance of BST */
  public BST() {
  root = current = null;
  }

  public boolean empty() {
  return root == null;
  }

  public boolean full() {
  return false;
  }

  public T retrieve () {
  return current.data;
  }
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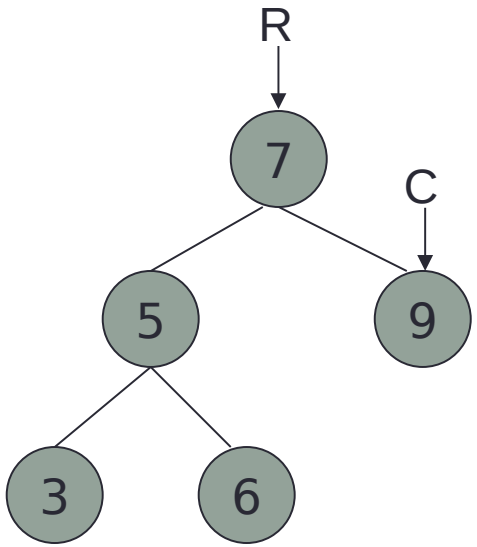
true



false

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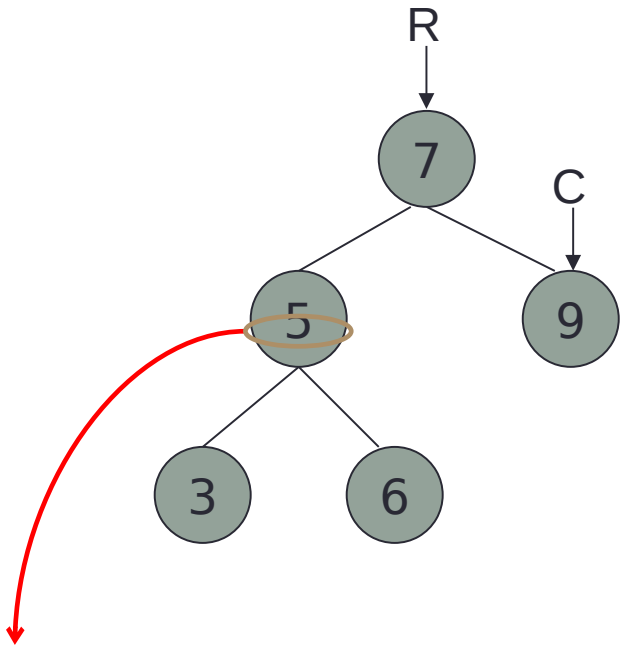

BST: Searching

- The search operation in a binary search tree can be carried out as:

  While (the target element is not found and there is more tree to search) do

  if the target element is “less than” the current element then search the left subtree else search the right subtree.

ADT Binary Search Tree: Implementation

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BSTNode<T> p = root.q = root;

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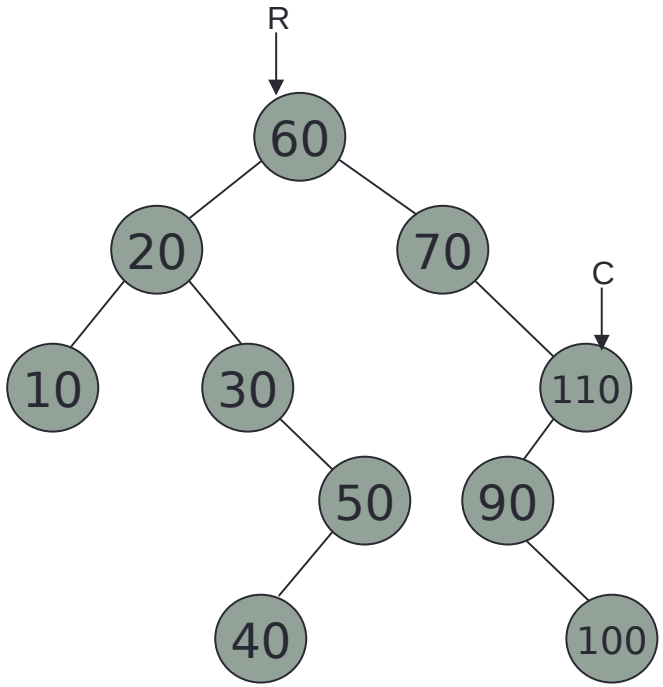
tkey = 60



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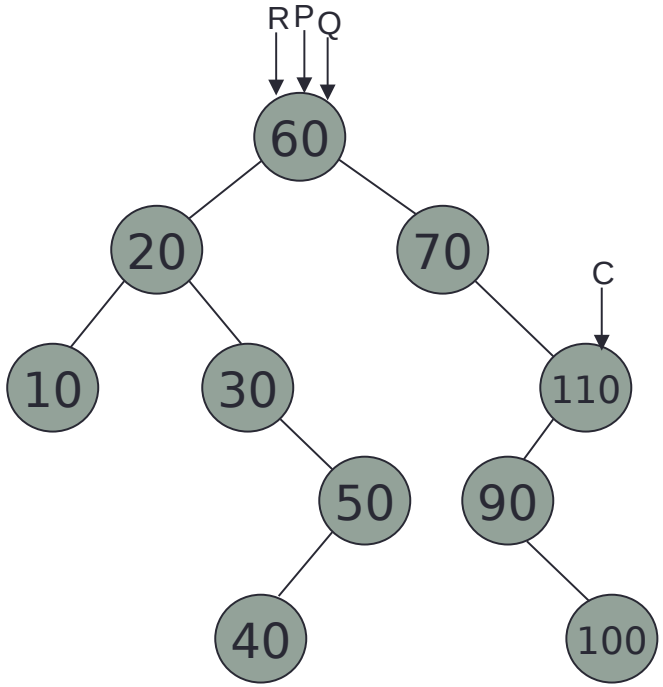

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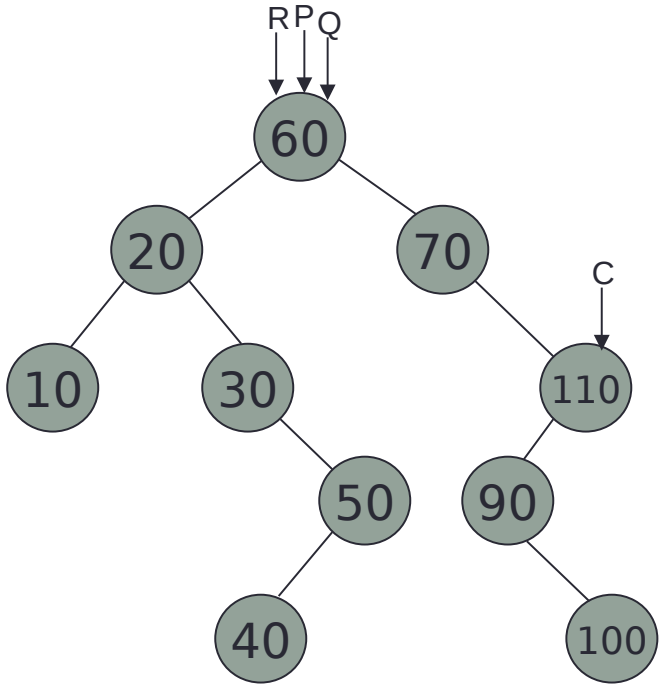

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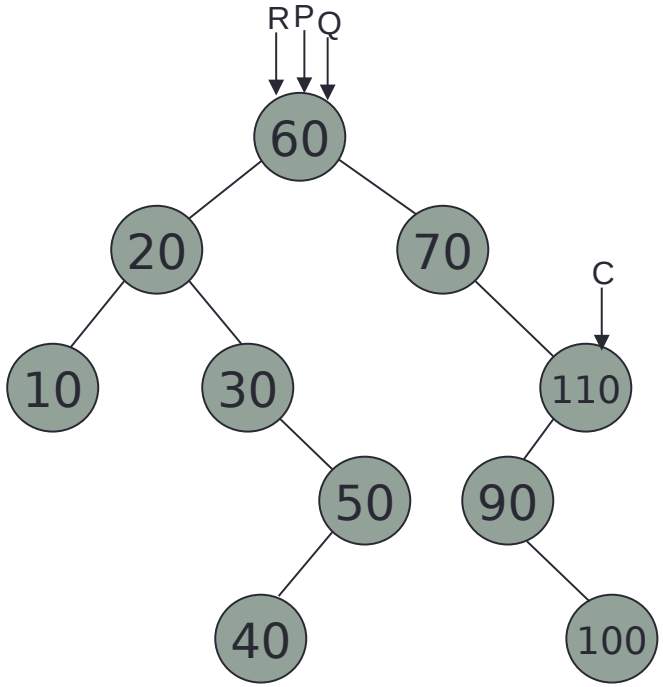

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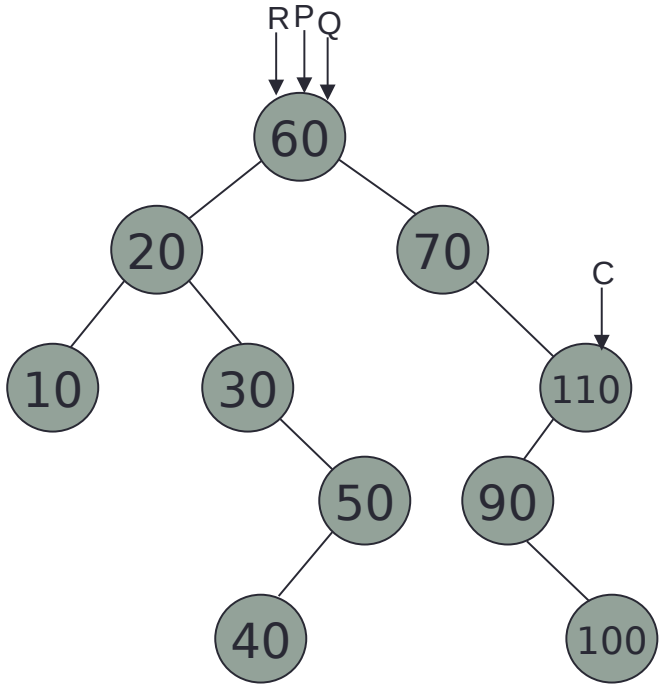

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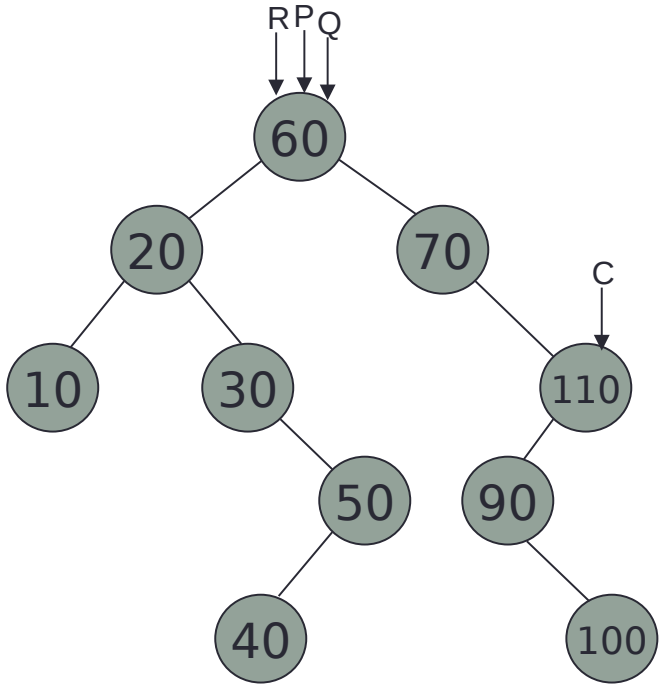

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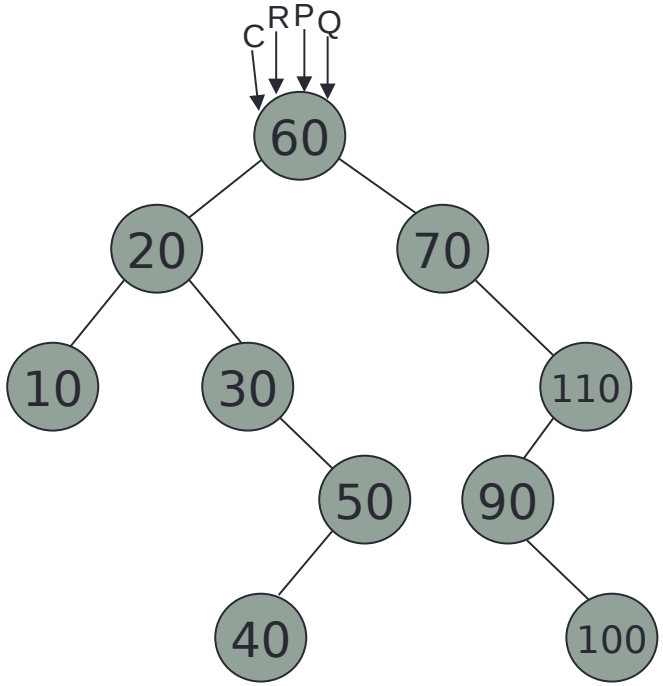

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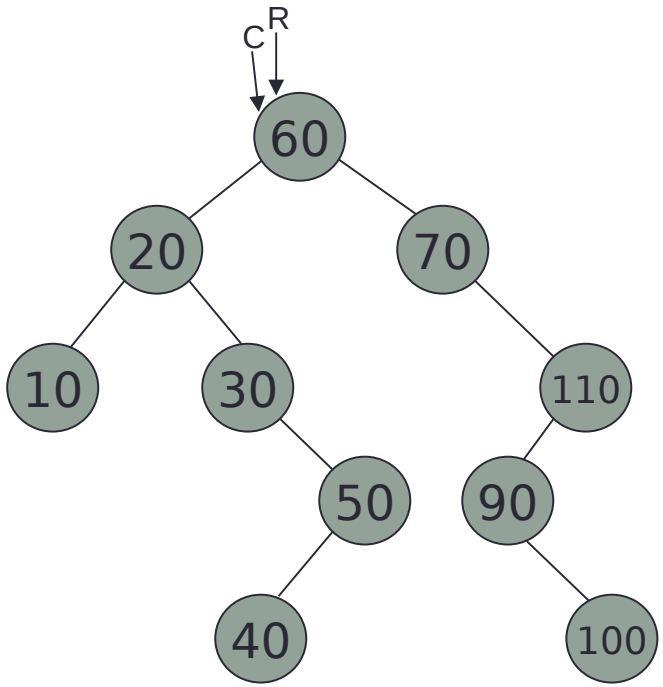

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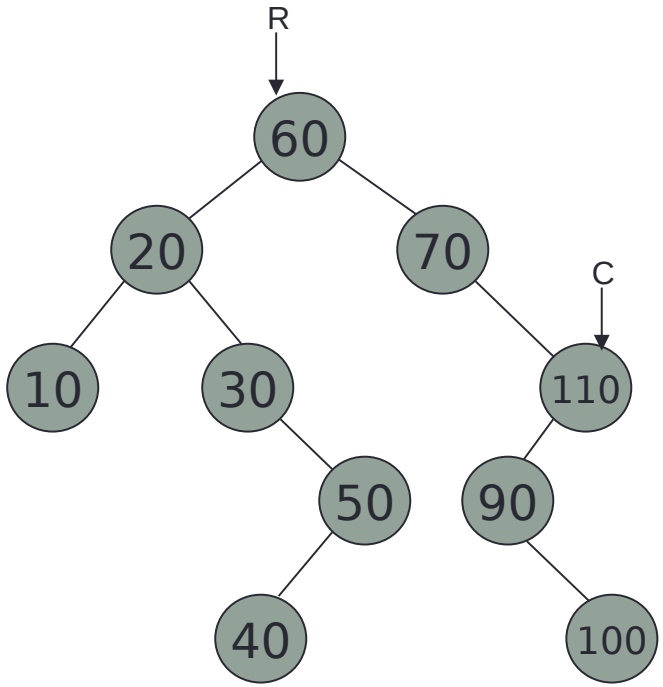

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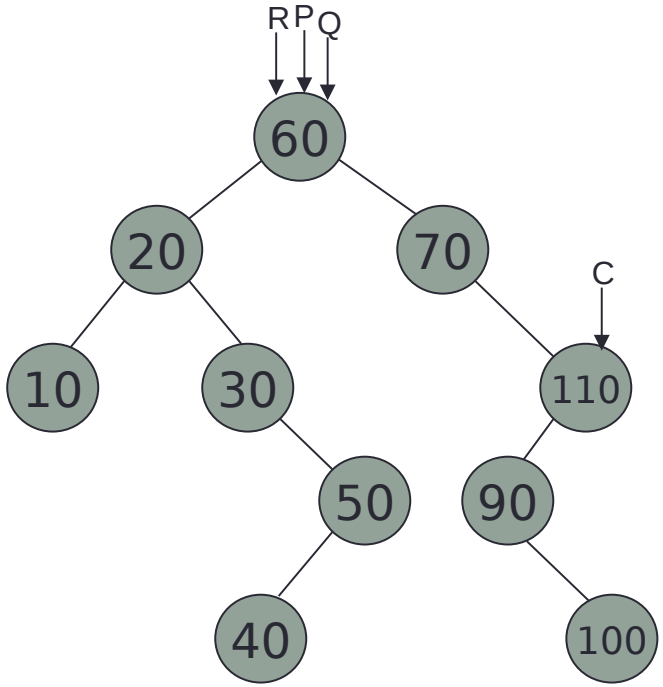

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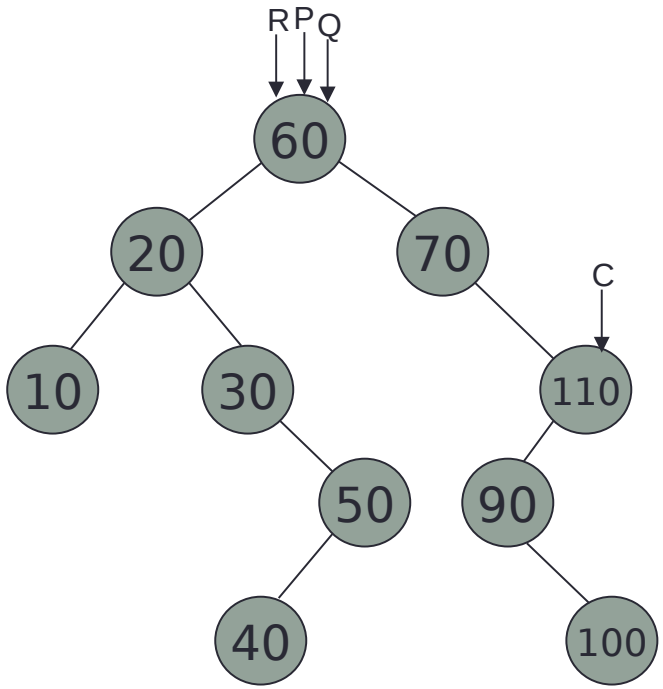

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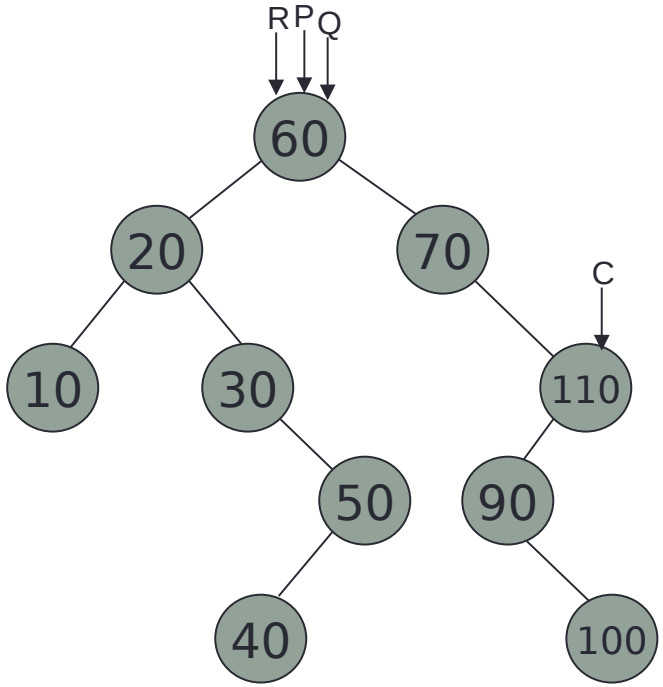

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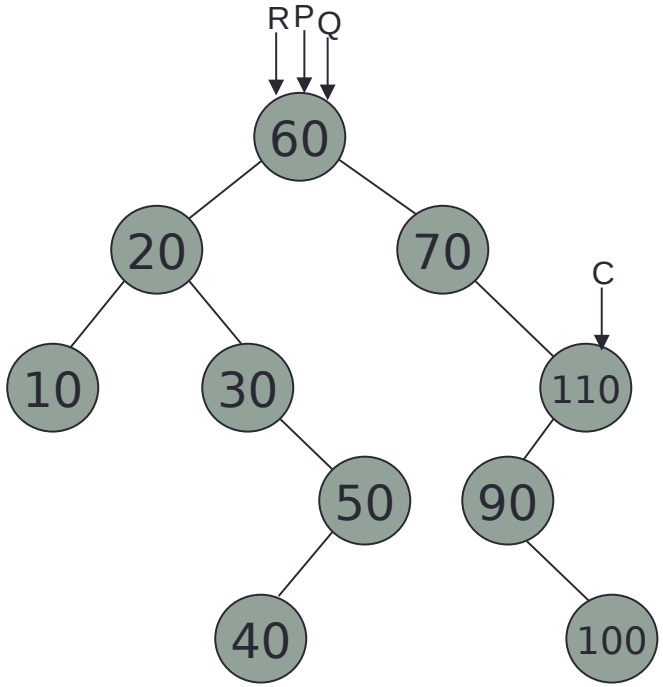

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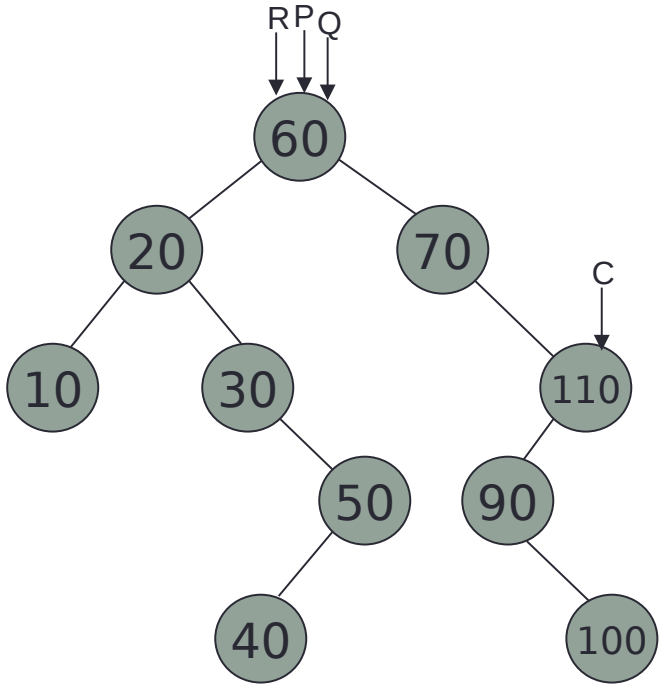

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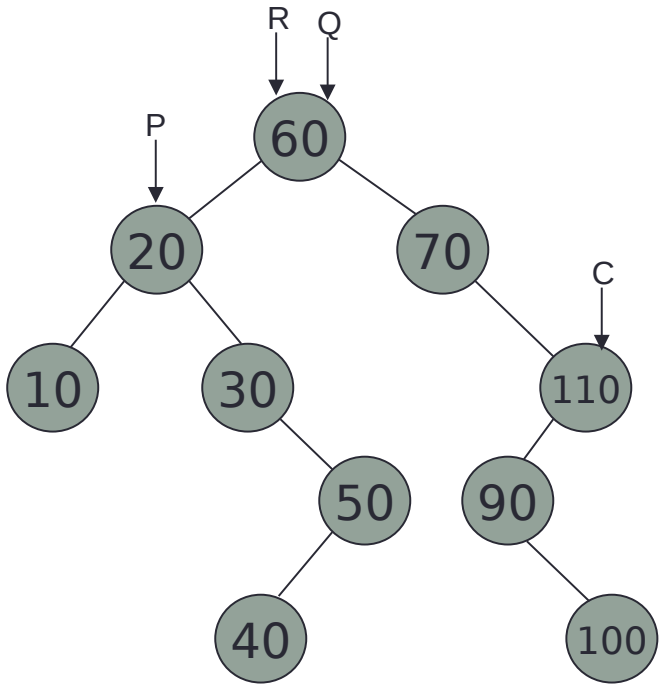

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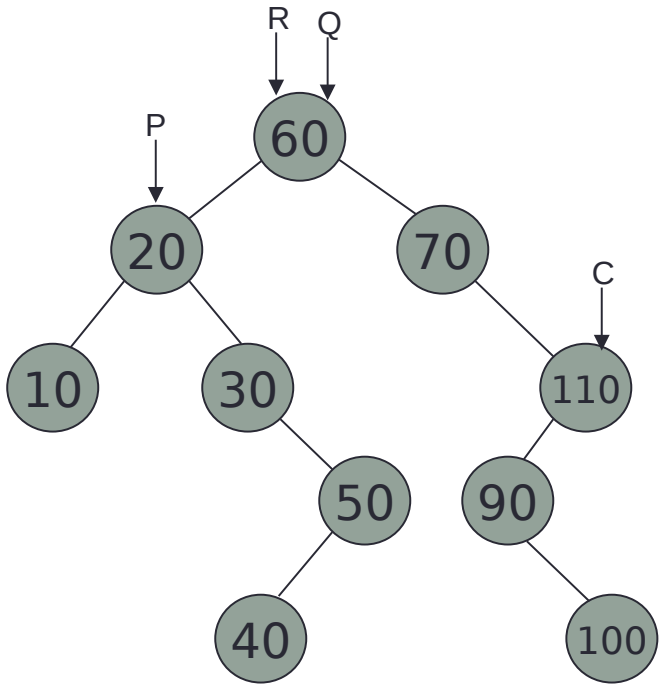

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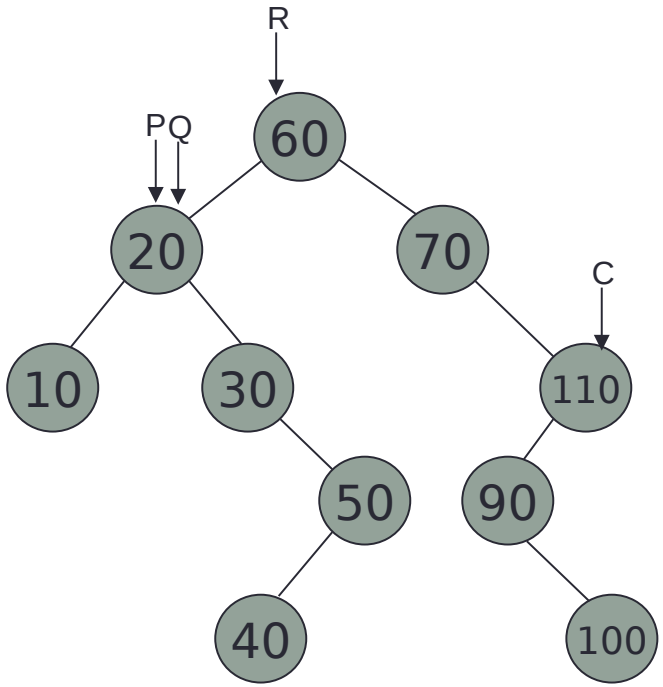

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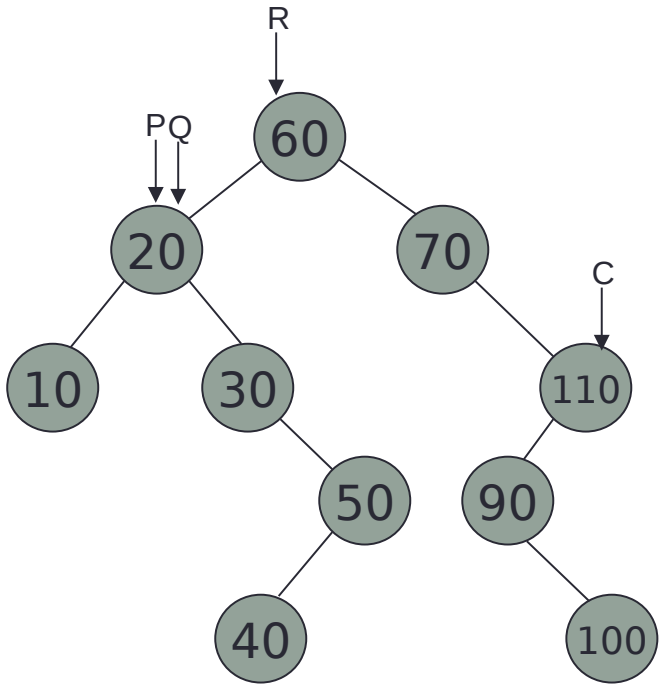

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}
```
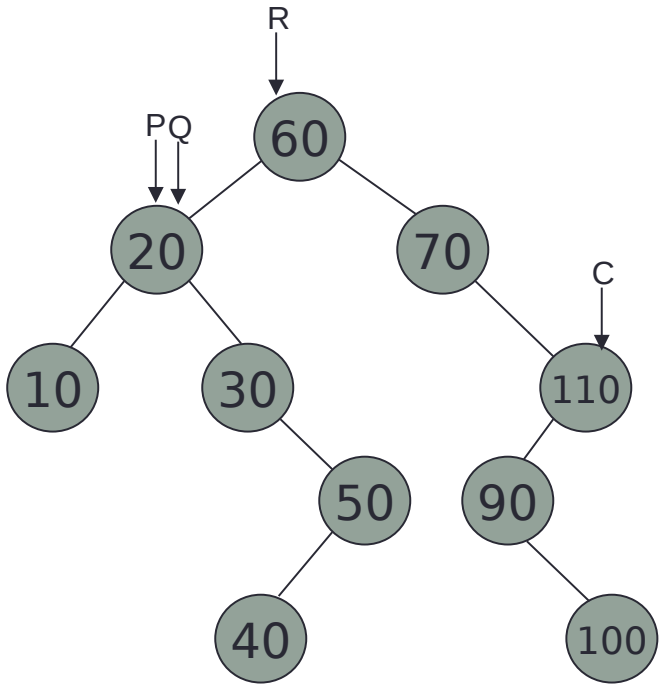

Example #2

tkey = 30

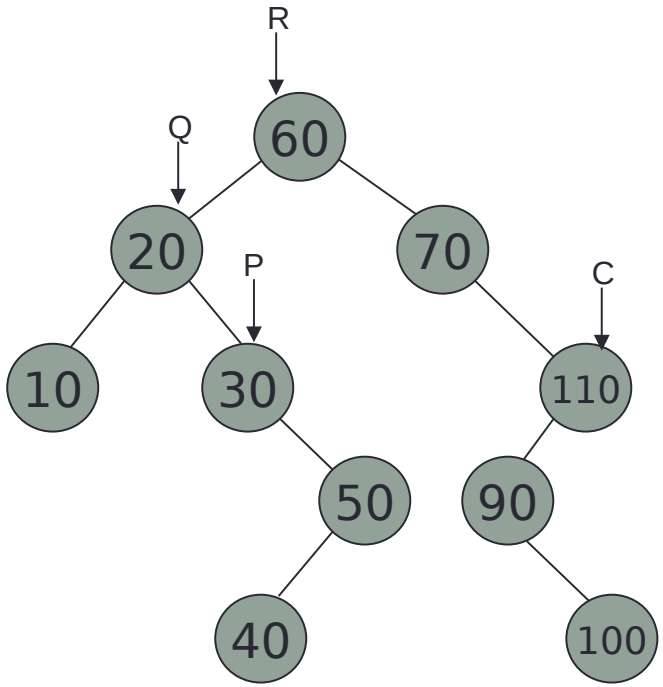


ADT Binary Search Tree: Implementation

```
public boolean findkey(int tkey) {
BSTNode<T> p = root,q = root;

if(empty())
return false;

while(p != null) {
q = p;
if(p.key == tkey) {
current = p;
return true;
}
else if(tkey < p.key)
p = p.left;
else
p = p.right;
}

current = q;
return false;
}
```

Example #2

tkey = 30



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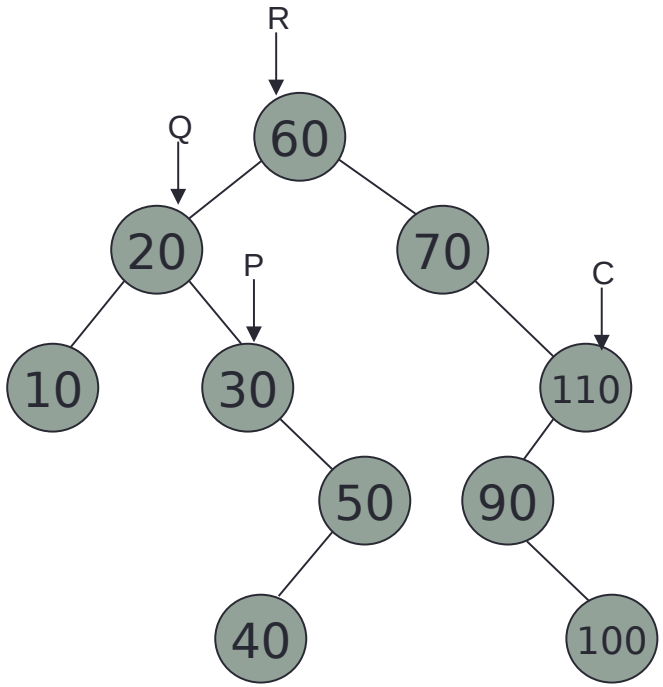
Example #2

tkey = 30



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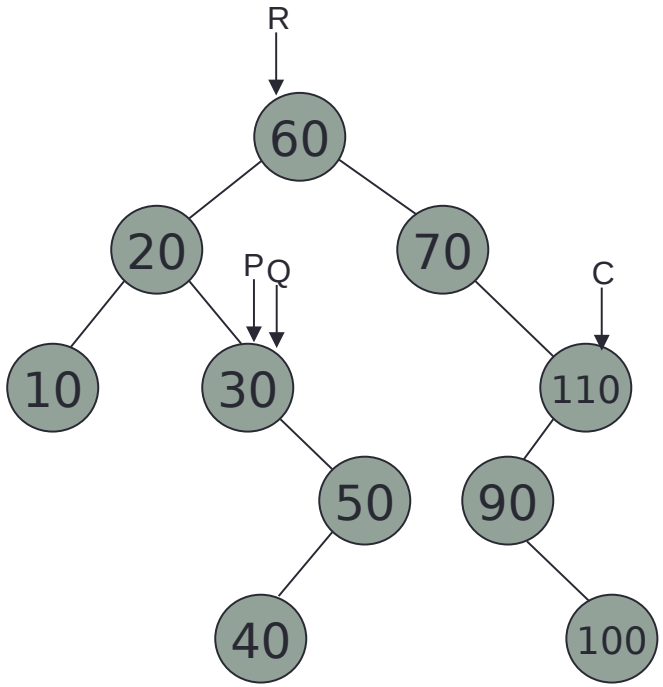
tkey = 30



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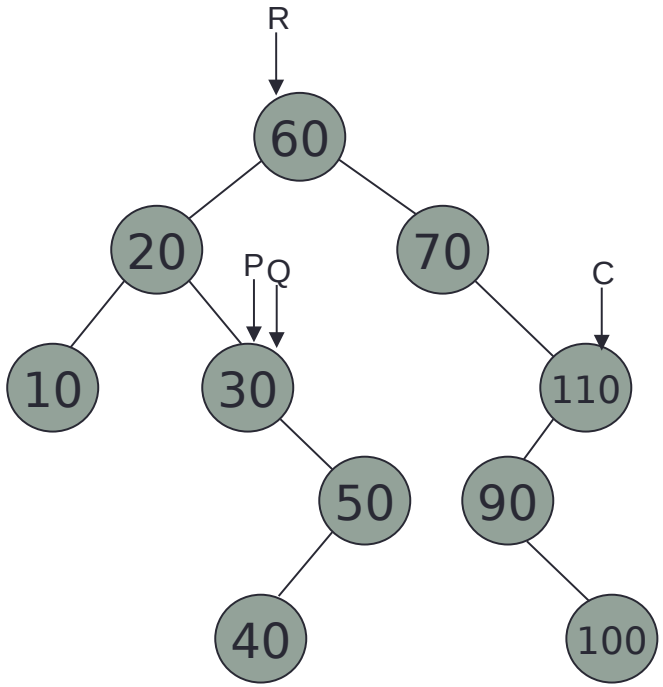
tkey = 30



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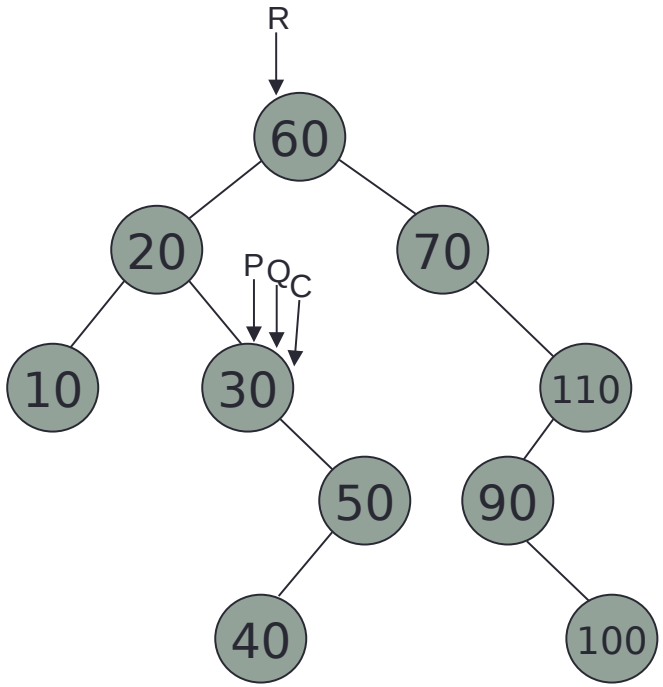
Example #2

tkey = 30



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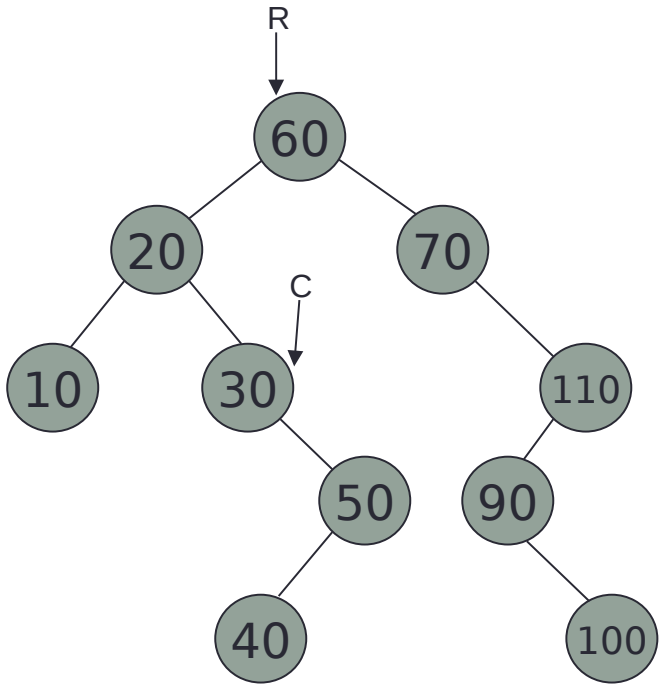

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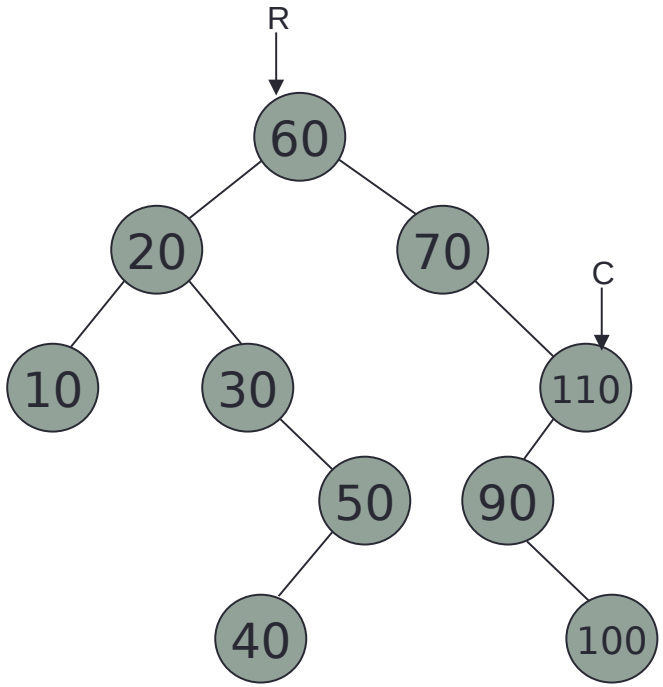
```

Example #3

tkey = 90



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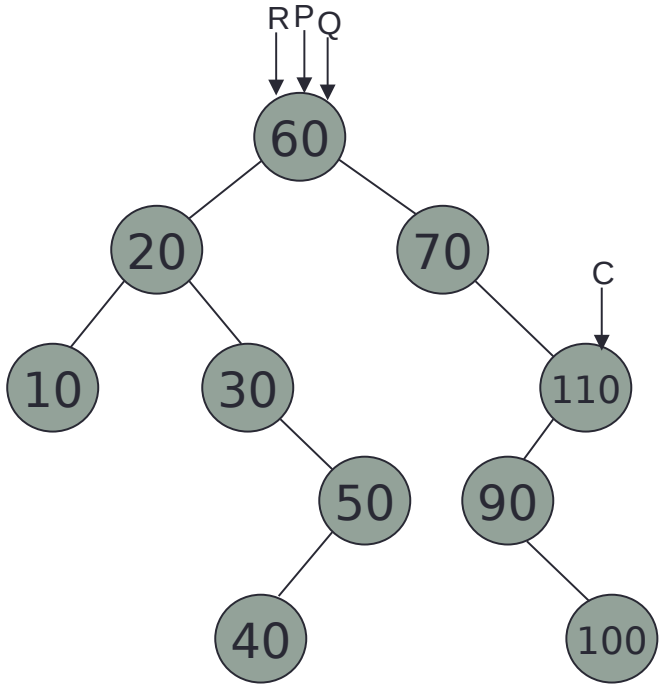
Example #3

tkey = 90



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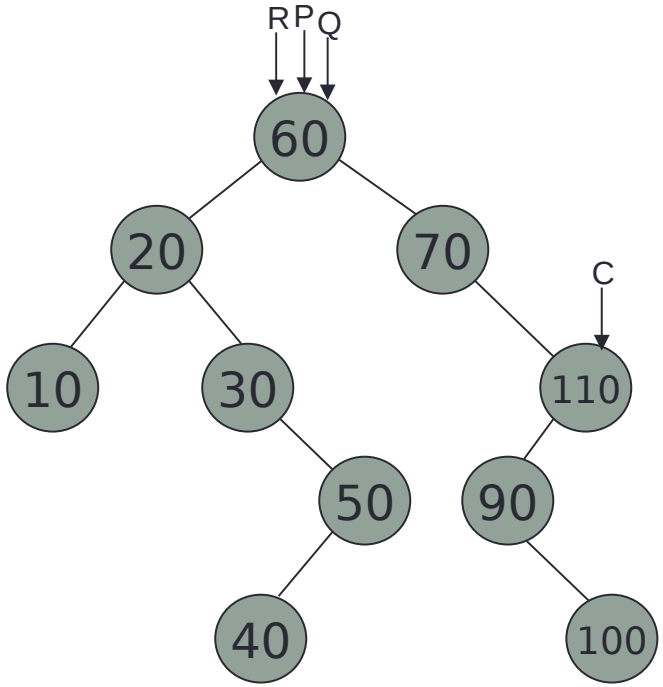

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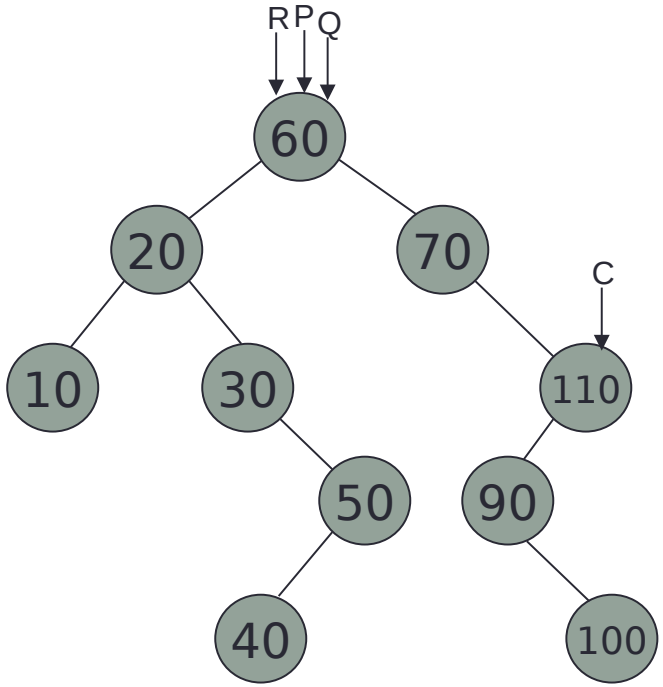

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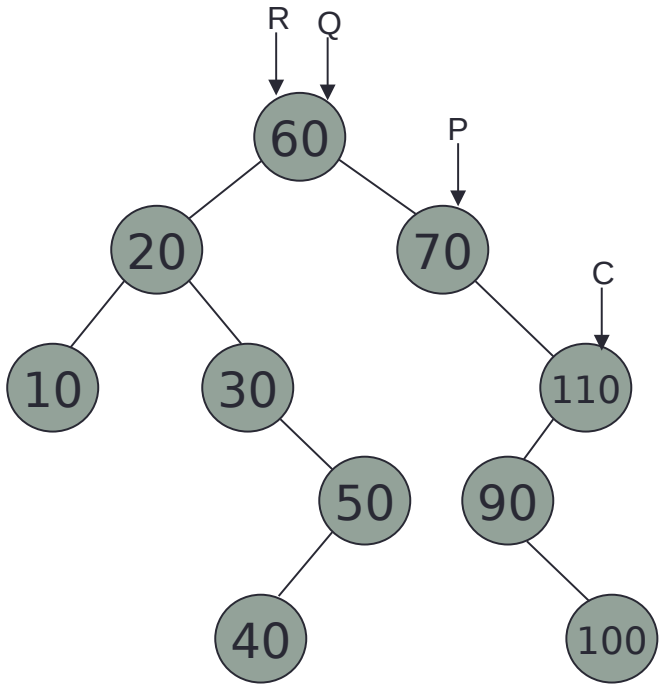

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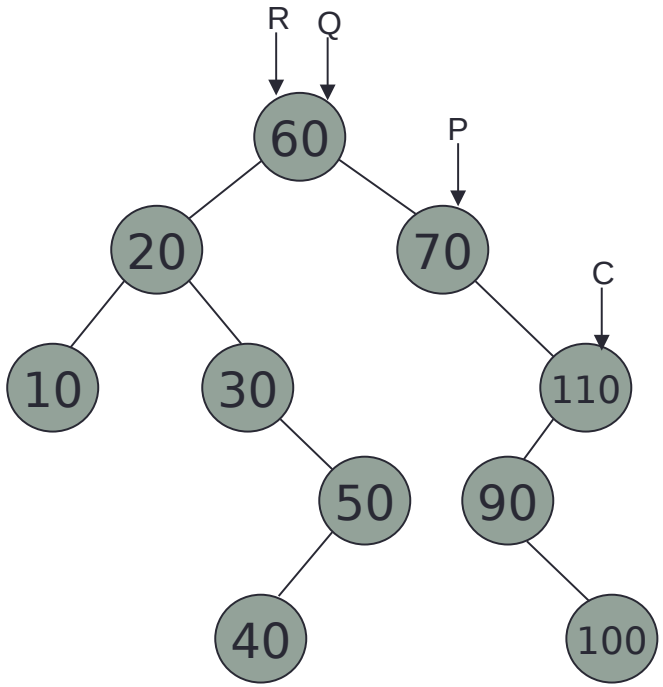

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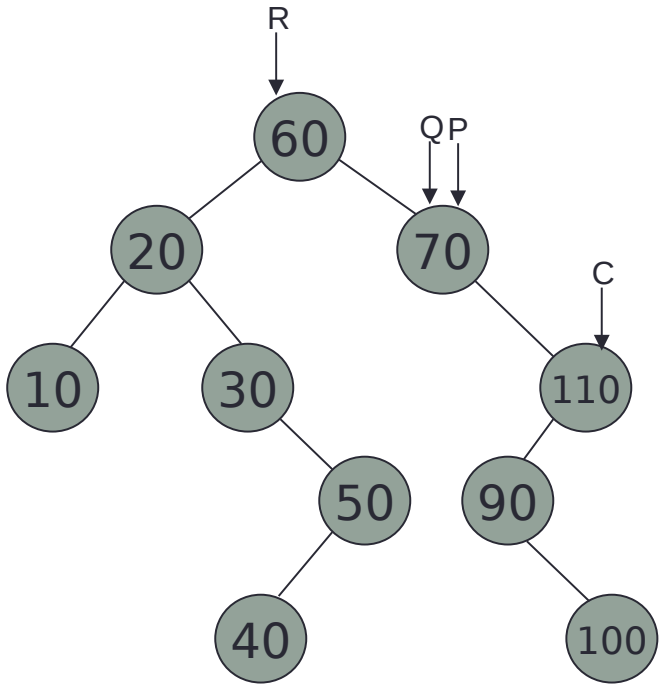

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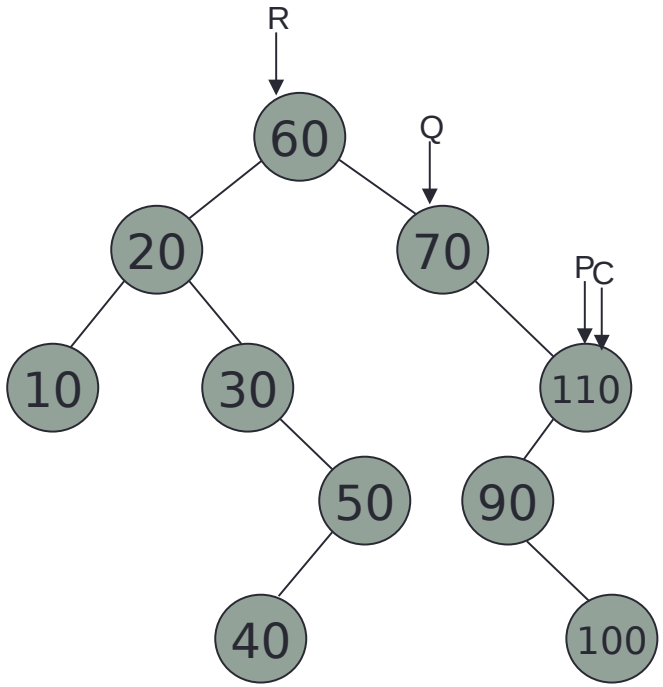

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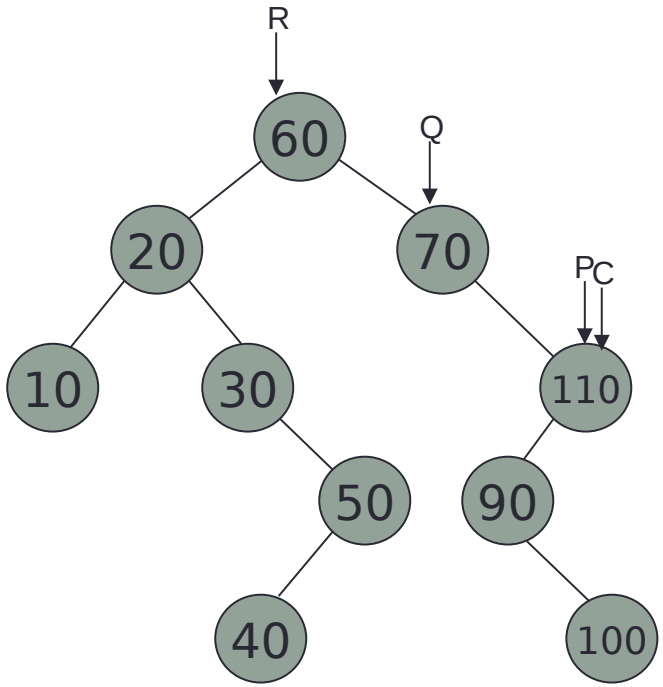

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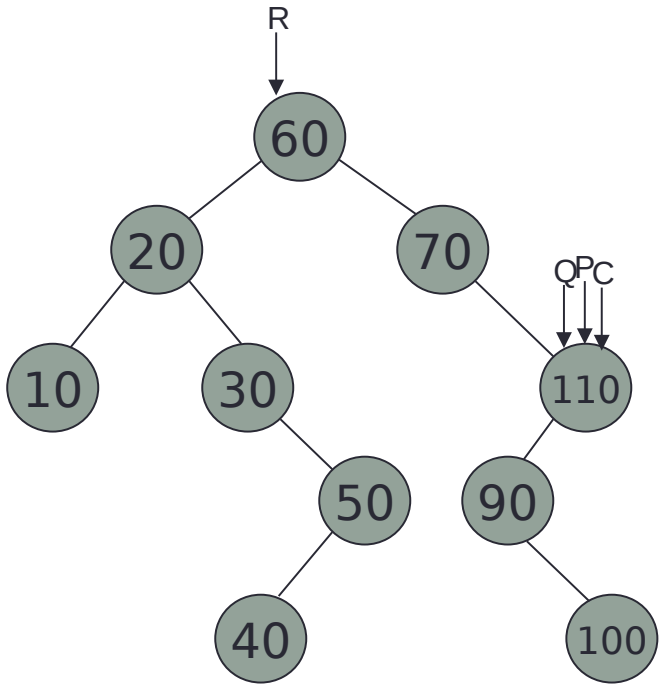

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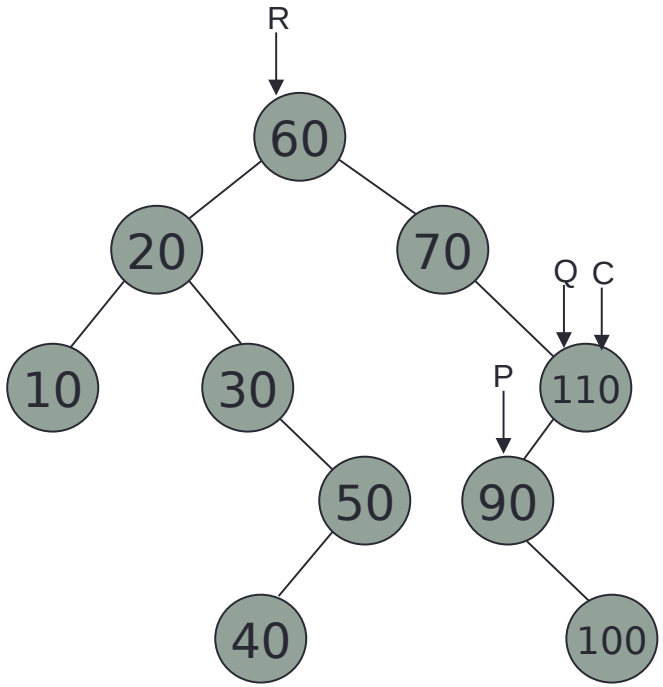

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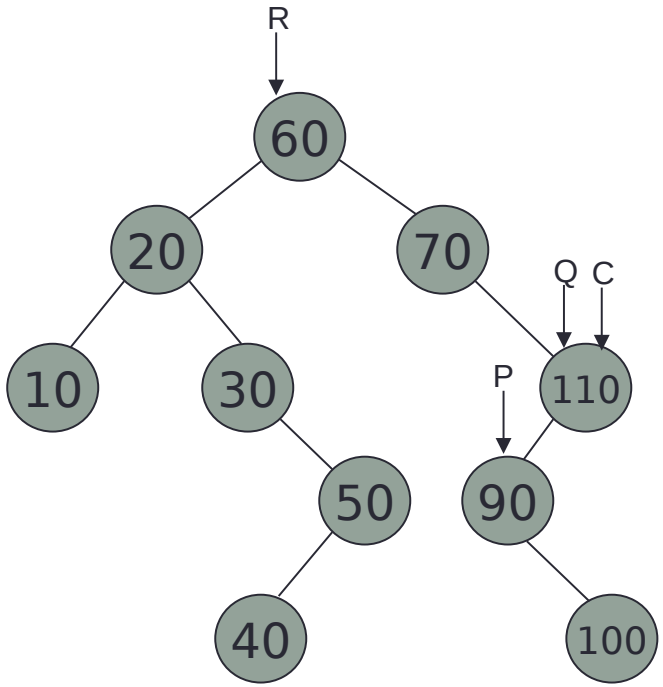

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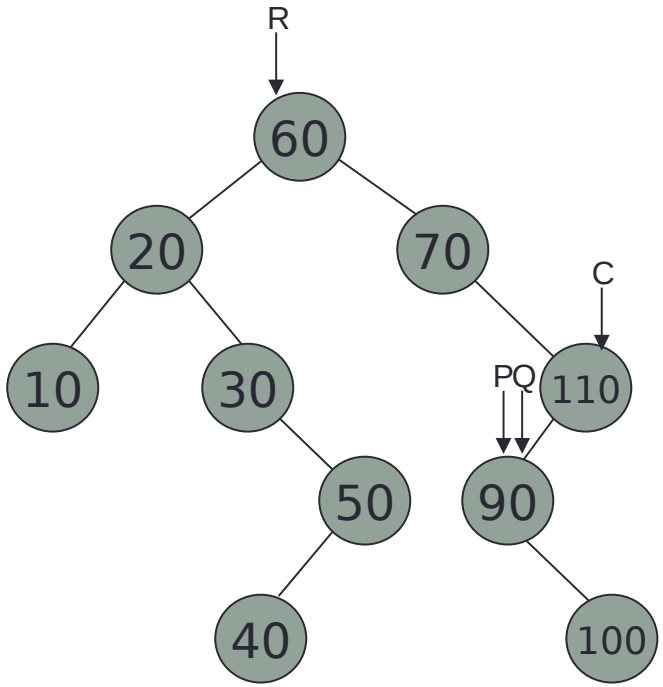

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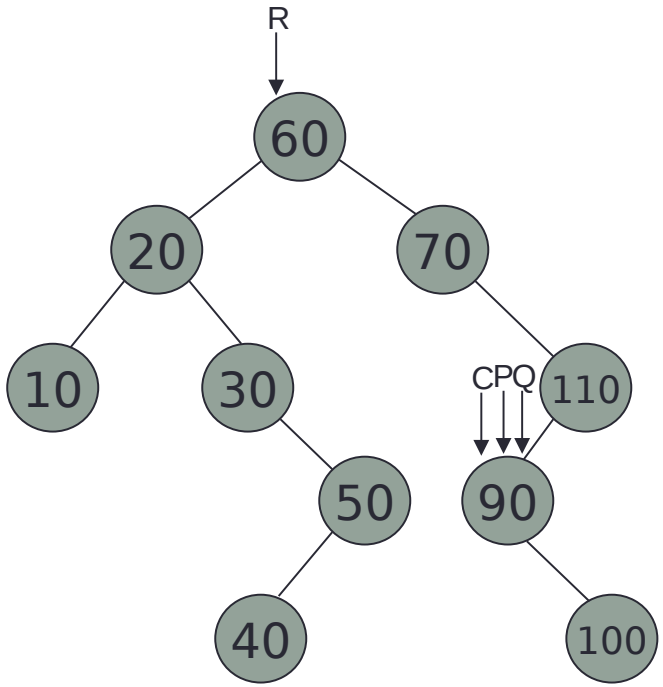

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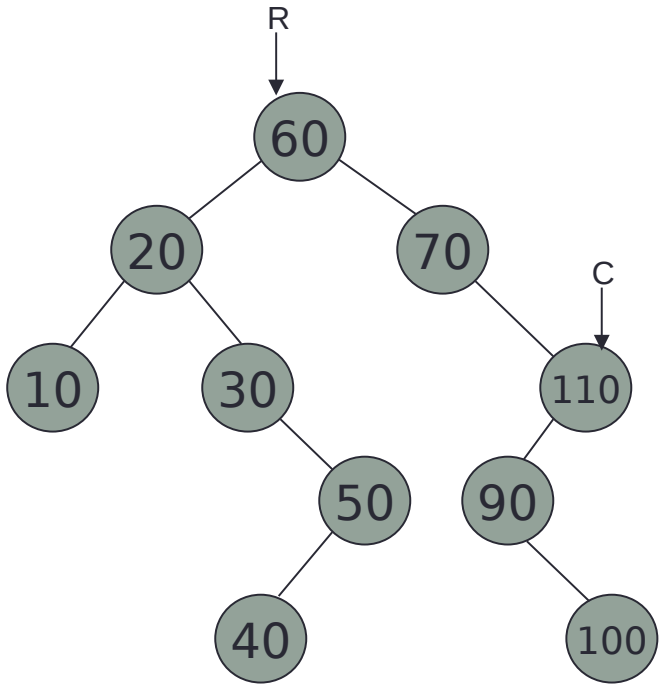
Example #4

tkey = 25



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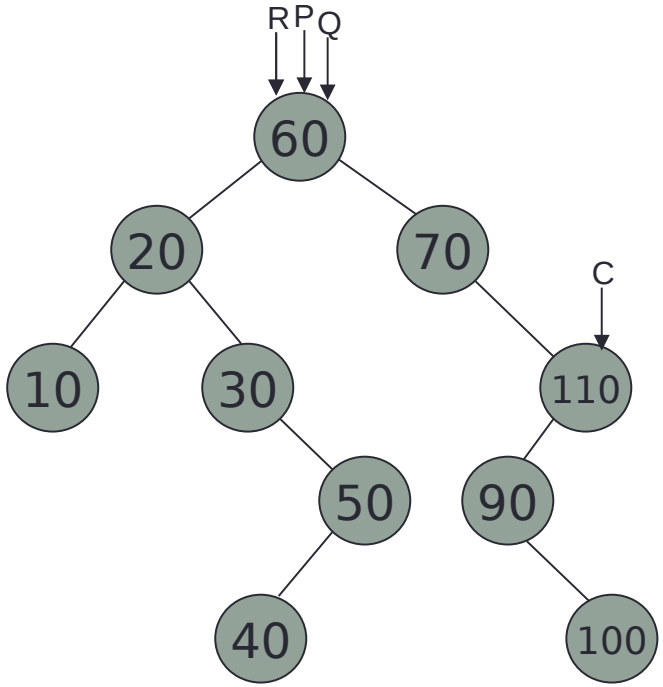

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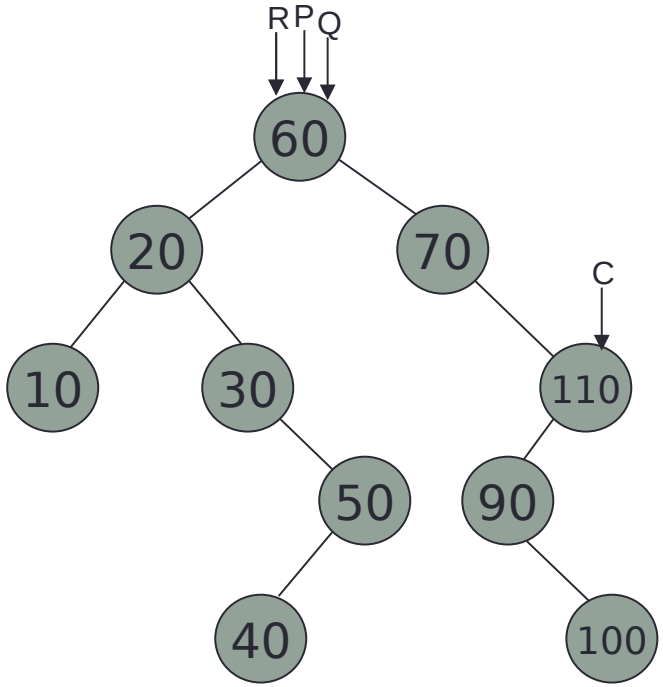

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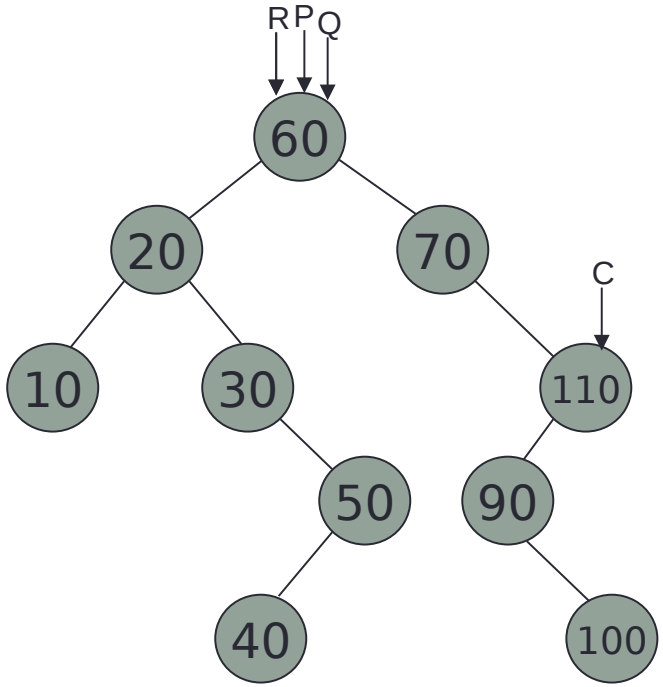

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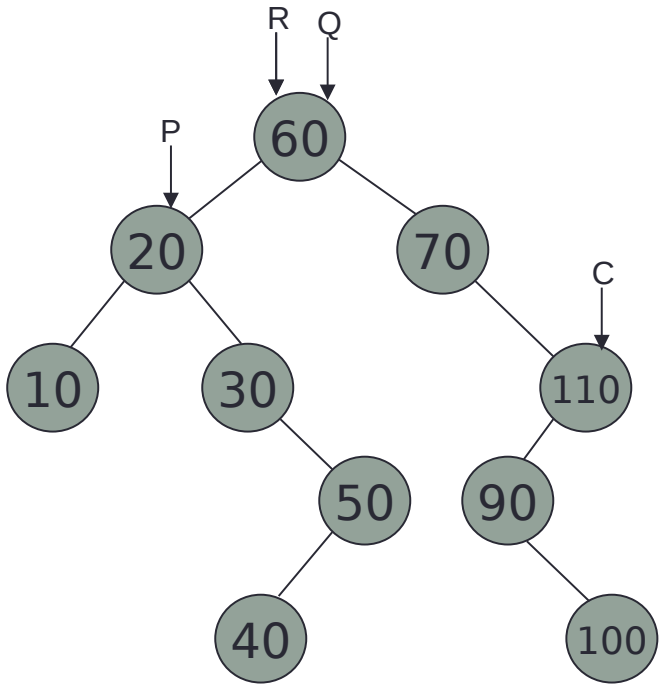

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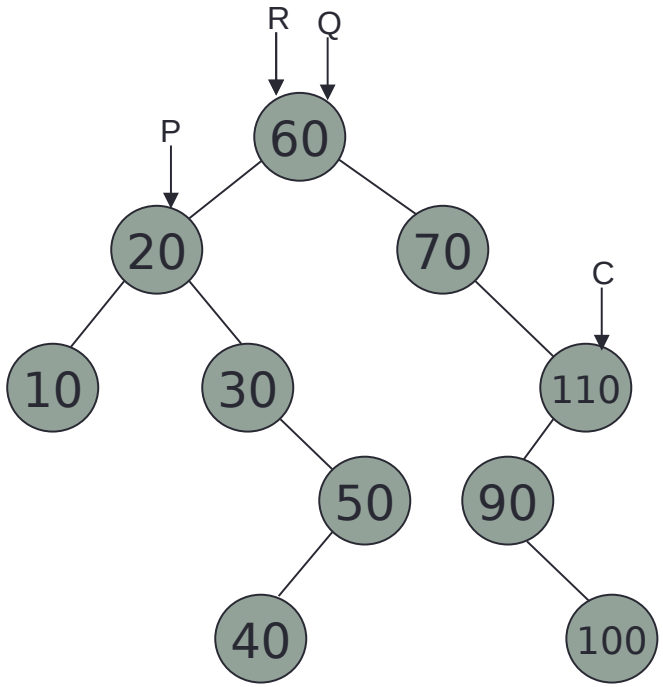

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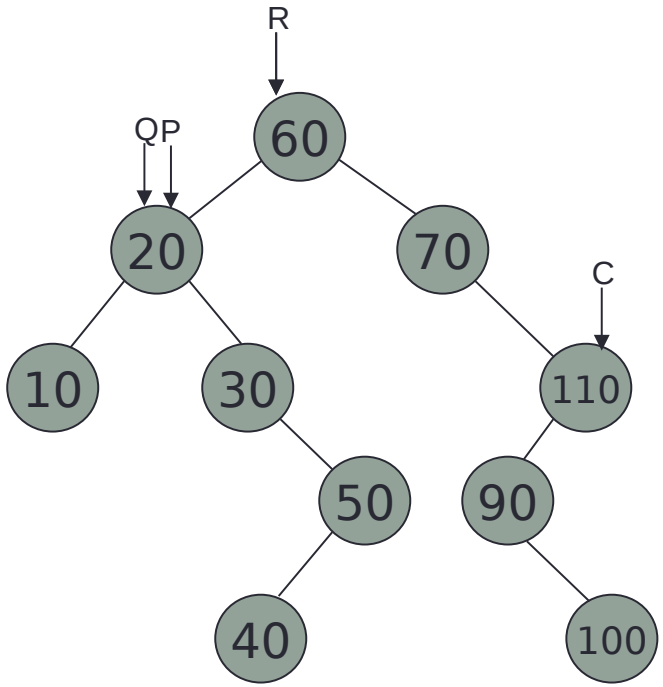

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Example #4

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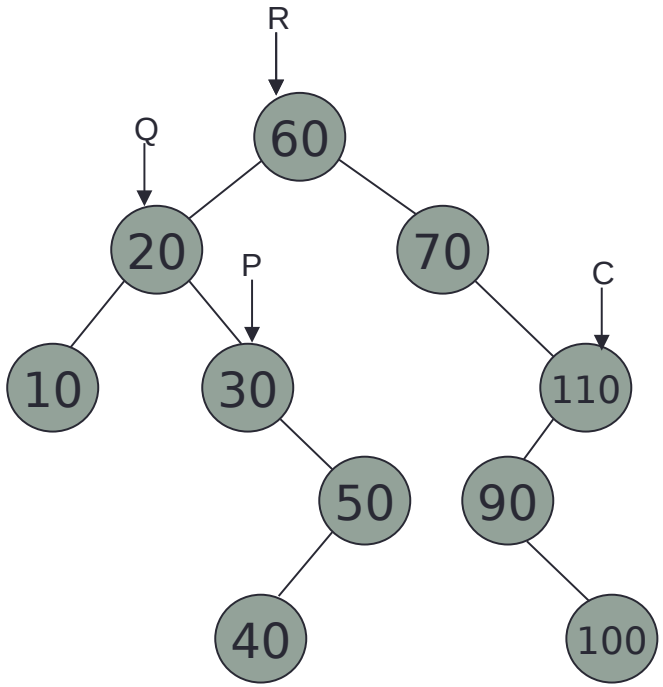

ADT Binary Search Tree: Implementation

```
public boolean findkey(int tkey) {
BSTNode<T> p = root,q = root;

if(empty())
return false;

while(p != null) {
q = p;
if(p.key == tkey) {
current = p;
return true;
}
else if(tkey < p.key)
p = p.left;
else
p = p.right;
}

current = q;
return false;
}
```

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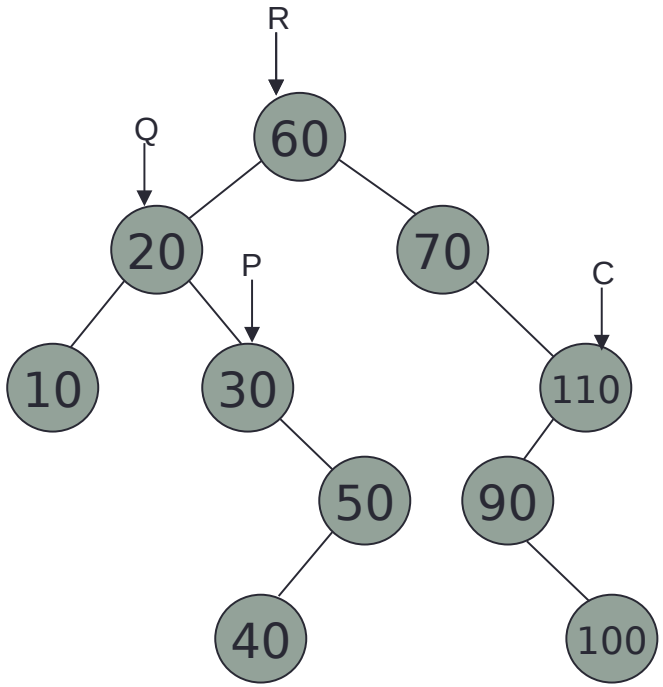

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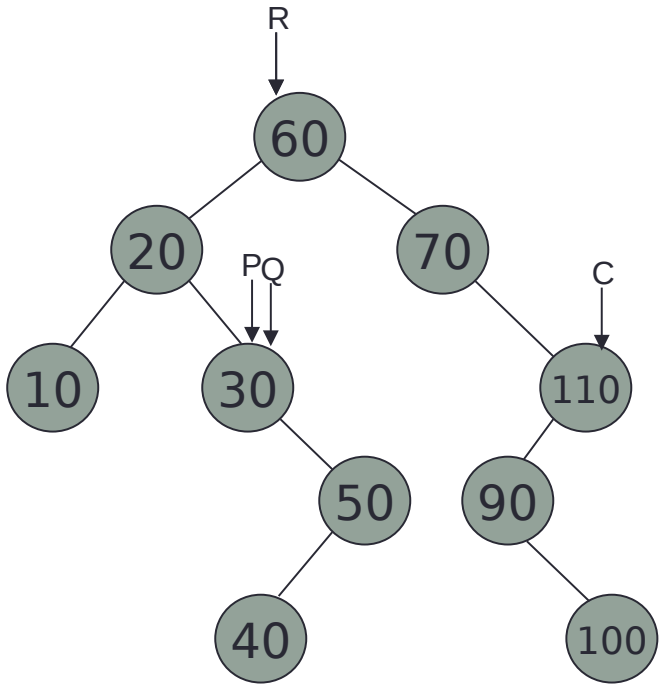

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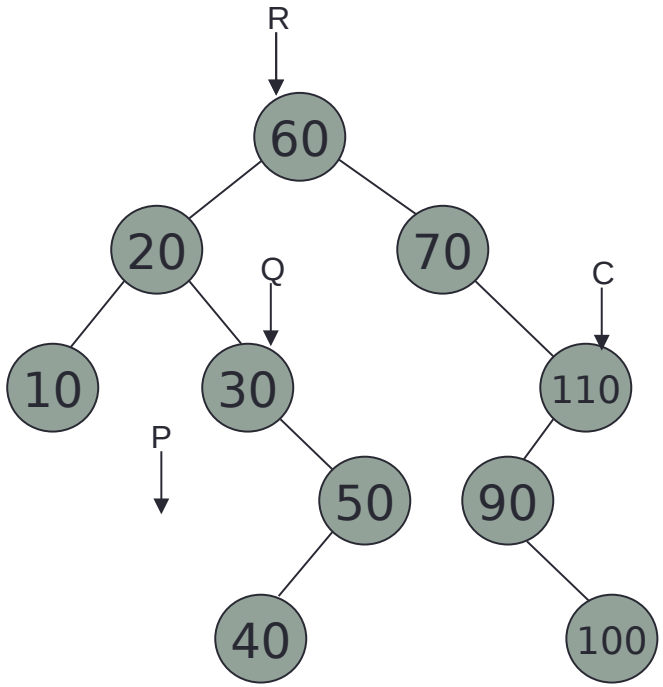

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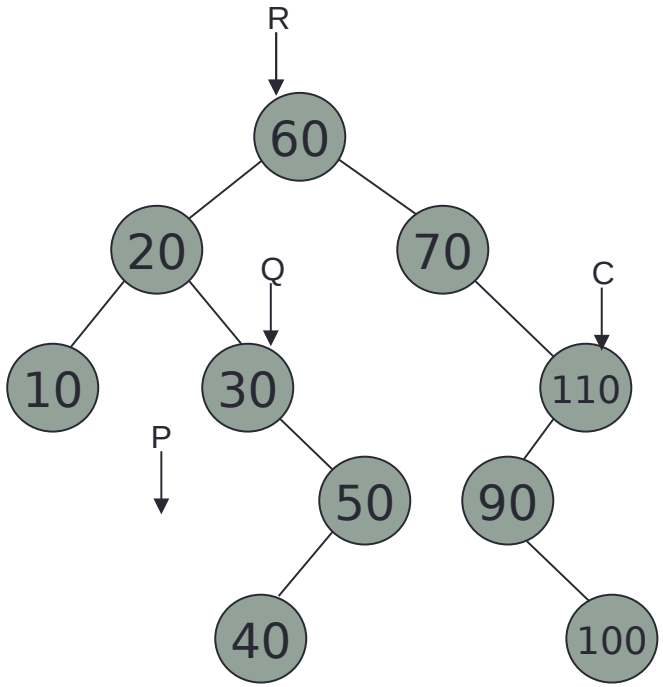

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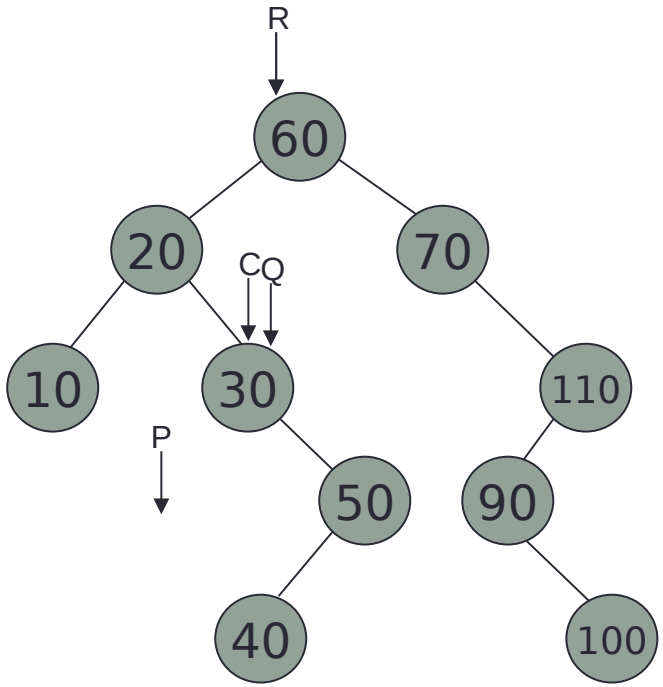

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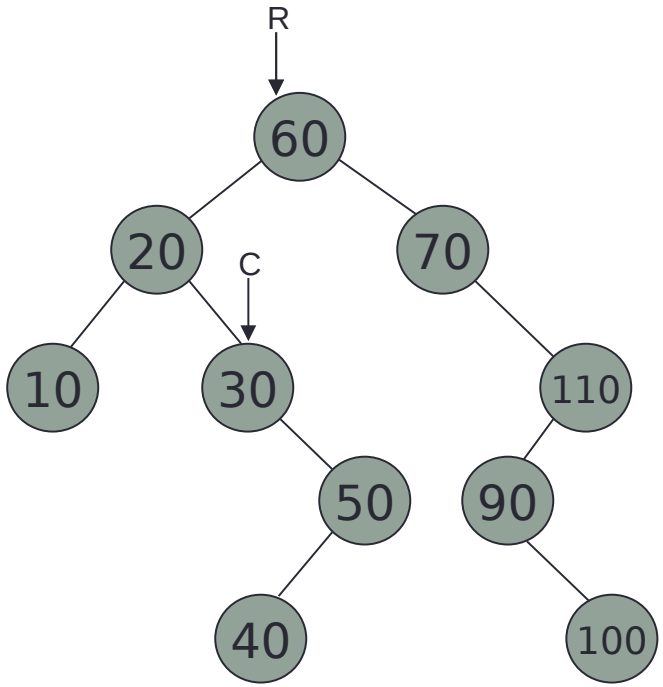

ADT Binary Search Tree: Implementation

```
public boolean insert(int k, T val) {
BSTNode<T> p, q = current;

if(findkey(k)) {
current = q;  // findkey() modified current
return false; // key already in the BST
}

p = new BSTNode<T>(k, val);
if (empty()) {
root = current = p;
return true;
}
else {
// current is pointing to parent of the new key
if (k < current.key)
current.left = p;
else
current.right = p;
current = p;
return true;
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```

ADT Binary Search Tree: Implementation

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}
```

Example #1

k = 60

ADT Binary Search Tree: Implementation

```
public boolean insert(int k, T val) {
BSTNode<T> p, q = current;

if(findkey(k)) {
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current.left = p;
else
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current = p;
return true;
}
}
```
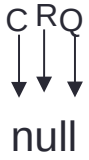

Example #1

k = 60



ADT Binary Search Tree: Implementation

```
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BSTNode<T> p, q = current;

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current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```
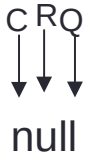

Example #1

k = 60



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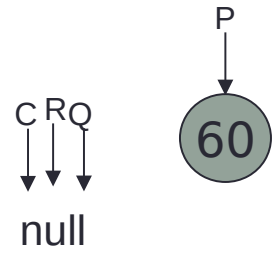

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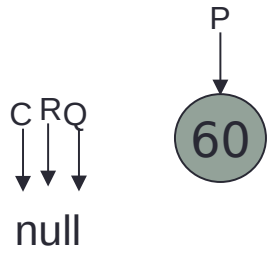

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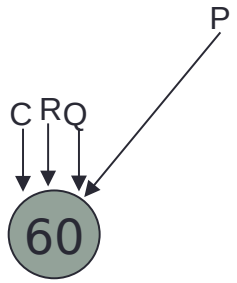

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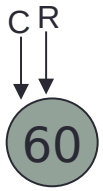

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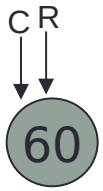
Example #2

k = 20



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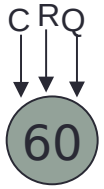

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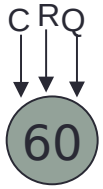

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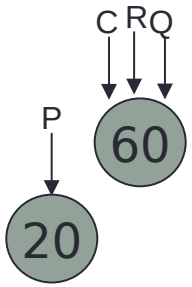

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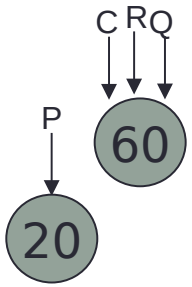

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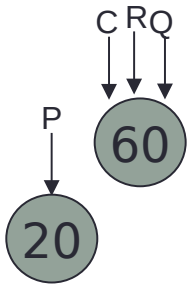

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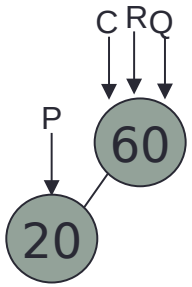

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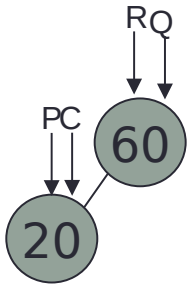
Example #2

k = 20



ADT Binary Search Tree: Implementation

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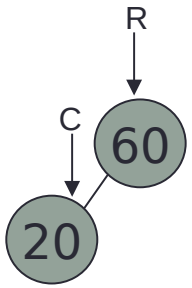
Example #2

k = 20



ADT Binary Search Tree: Implementation

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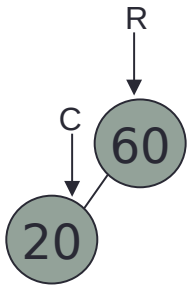
}
}
```

Example #3

k = 70



ADT Binary Search Tree: Implementation

```
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BSTNode<T> p, q = current;

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// current is pointing to parent of the new key
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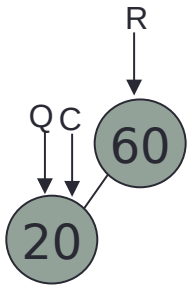
current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```

Example #3

k = 70



ADT Binary Search Tree: Implementation

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return true;
}
}
```
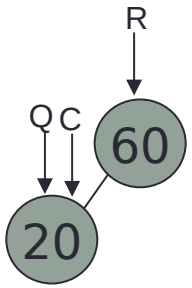

Example #3

k = 70



ADT Binary Search Tree: Implementation

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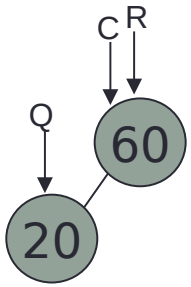
Example #3

k = 70



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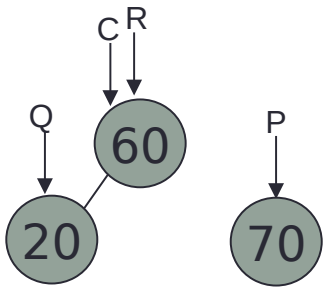

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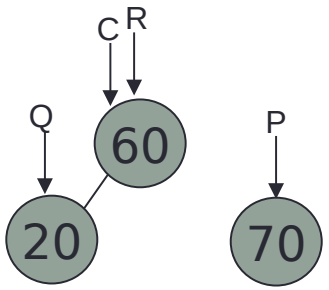

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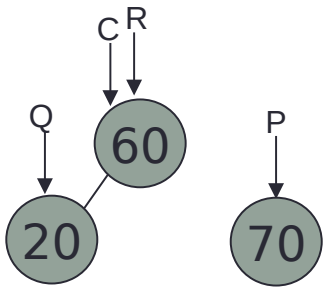

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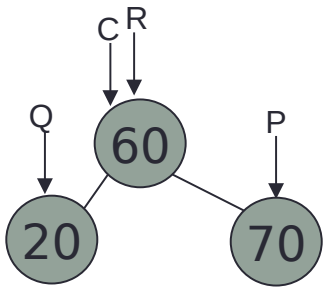

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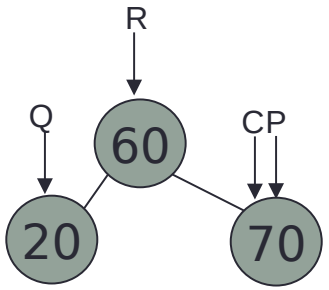

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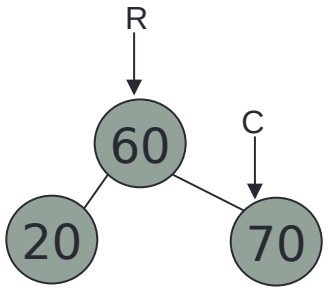

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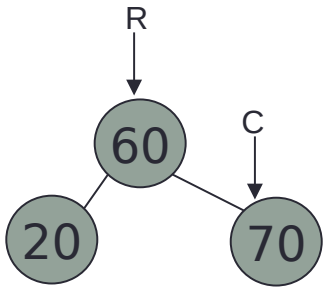
k = 30



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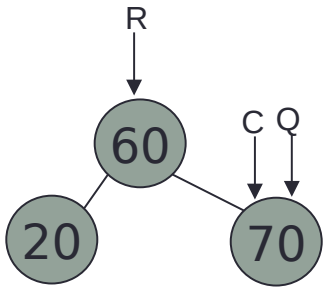

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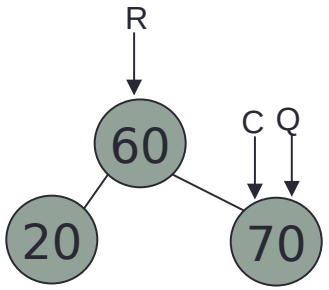

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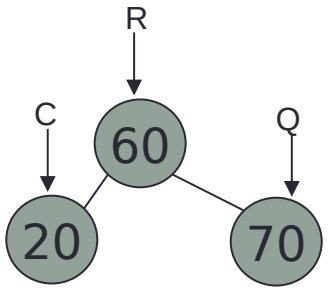

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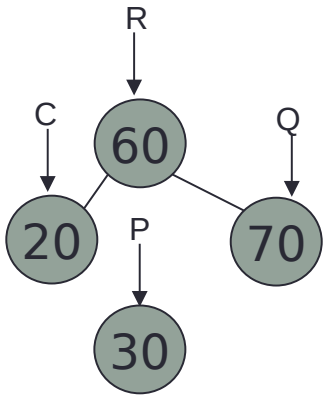

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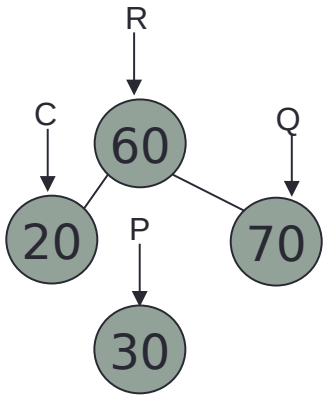

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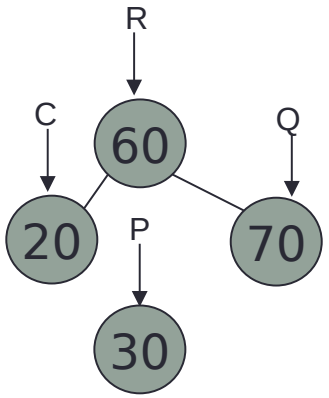

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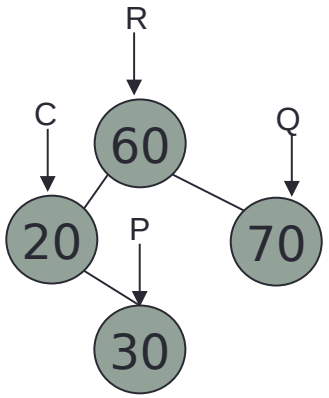

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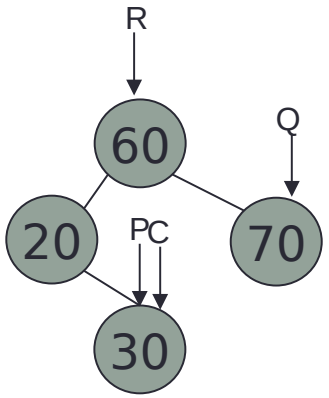

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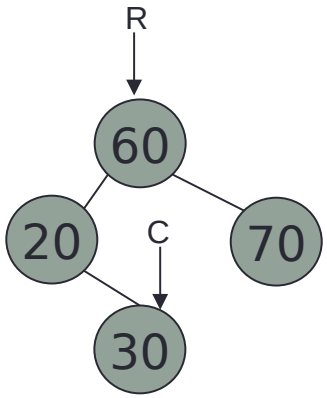

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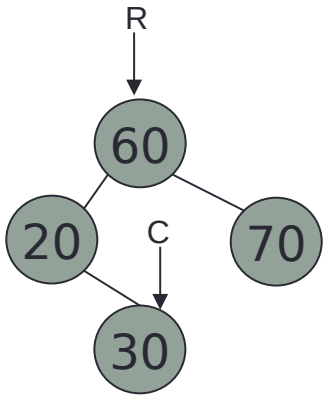

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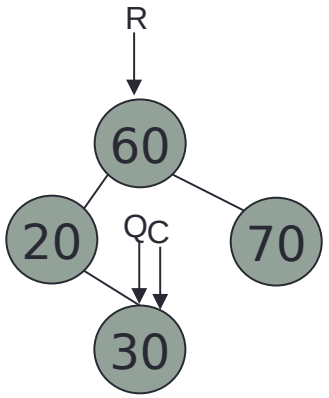

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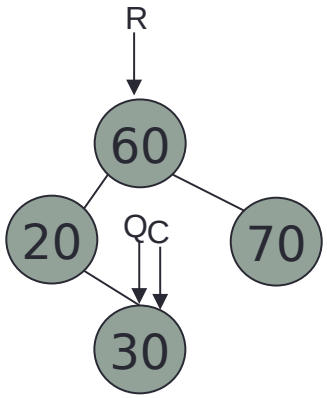

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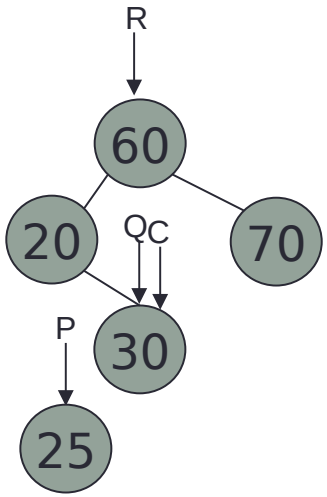

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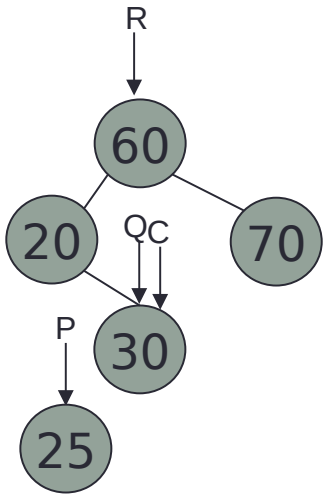

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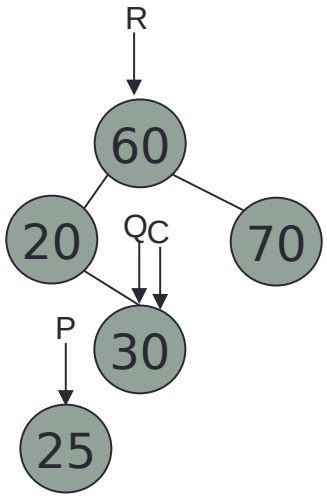

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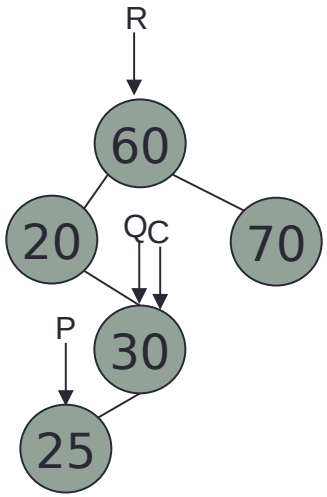

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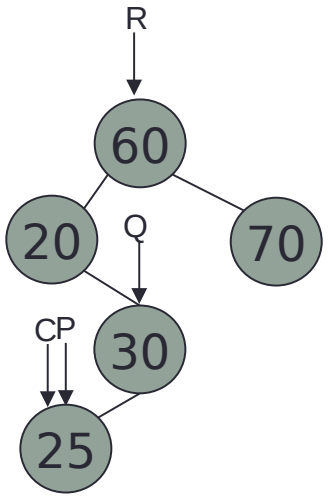

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current = q;  // findkey() modified current
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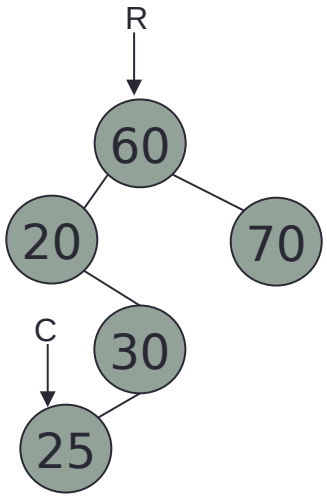
}

p = new BSTNode<T>(k, val);
if (empty()) {
root = current = p;
return true;
}
else {
// current is pointing to parent of the new key
if (k < current.key)
current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```

Example #4

k = 25



ADT Binary Search Tree: Implementation

```
public boolean insert(int k, T val) {
BSTNode<T> p, q = current;

if(findkey(k)) {
current = q;  // findkey() modified current
return false; // key already in the BST
}

p = new BSTNode<T>(k, val);
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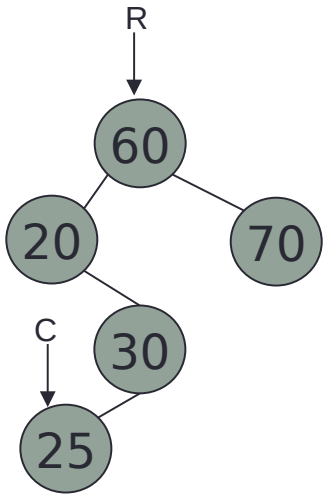
root = current = p;
return true;
}
else {
// current is pointing to parent of the new key
if (k < current.key)
current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```

Example #5

k = 90



ADT Binary Search Tree: Implementation

```
public boolean insert(int k, T val) {
BSTNode<T> p, q = current;

if(findkey(k)) {
current = q;  // findkey() modified current
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p = new BSTNode<T>(k, val);
if (empty()) {
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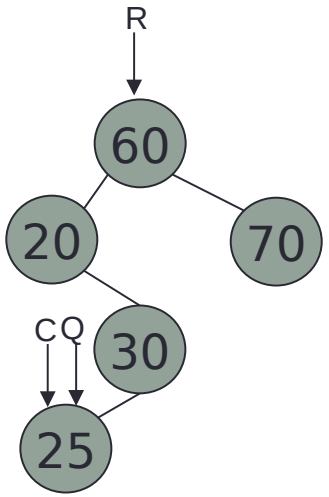
return true;
}
else {
// current is pointing to parent of the new key
if (k < current.key)
current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```

Example #5

k = 90



ADT Binary Search Tree: Implementation

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BSTNode<T> p, q = current;

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current = q;  // findkey() modified current
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}

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}
else {
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current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```
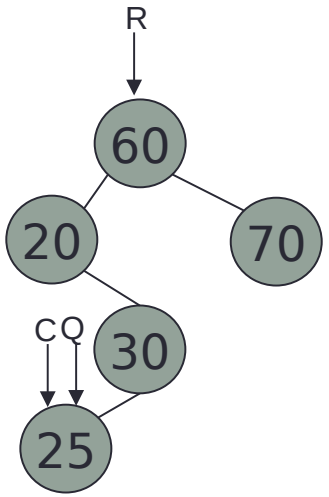

Example #5

k = 90



ADT Binary Search Tree: Implementation

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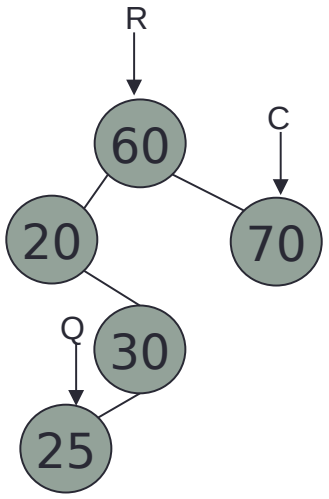
Example #5

k = 90



ADT Binary Search Tree: Implementation

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current.right = p;
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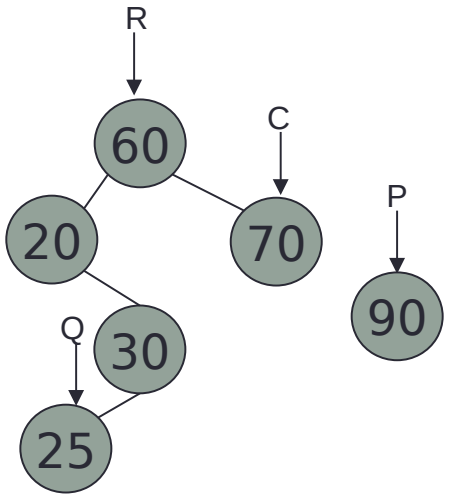
}
```

Example #5

k = 90



ADT Binary Search Tree: Implementation

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return true;
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}
```
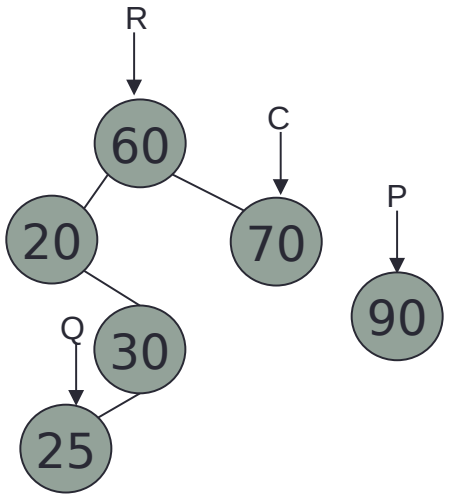

Example #5

k = 90



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current.left = p;
else
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current = p;
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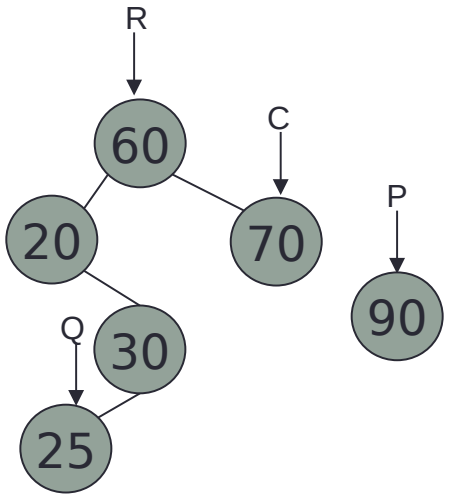
Example #5

k = 90



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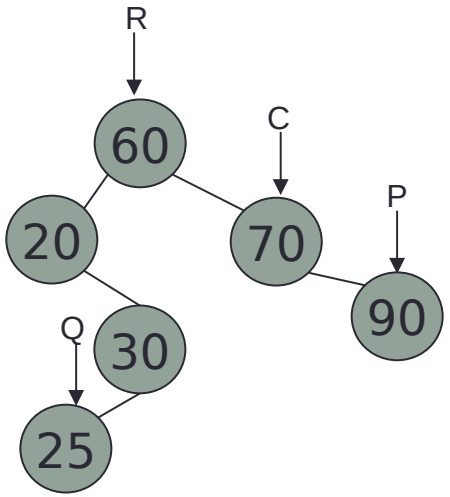
Example #5

k = 90



ADT Binary Search Tree: Implementation

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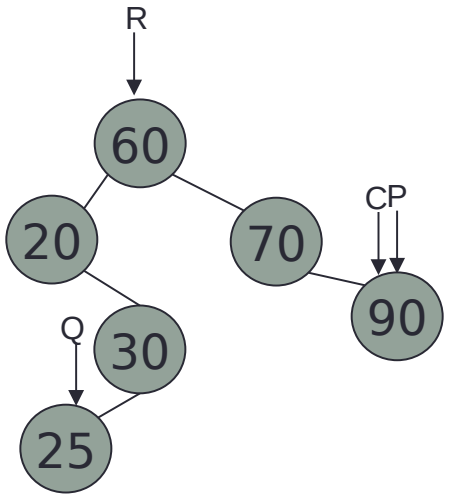
Example #5

k = 90



ADT Binary Search Tree: Implementation

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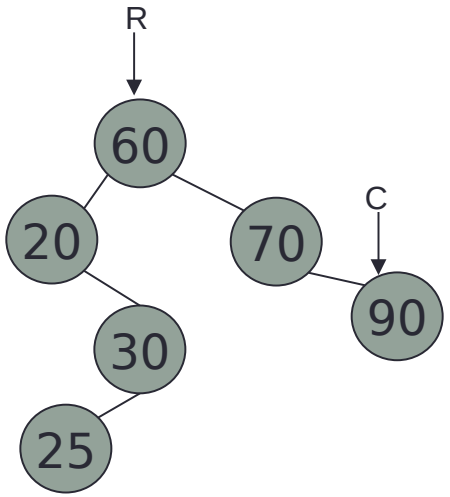
Example #5

k = 90



ADT Binary Search Tree: Implementation

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else
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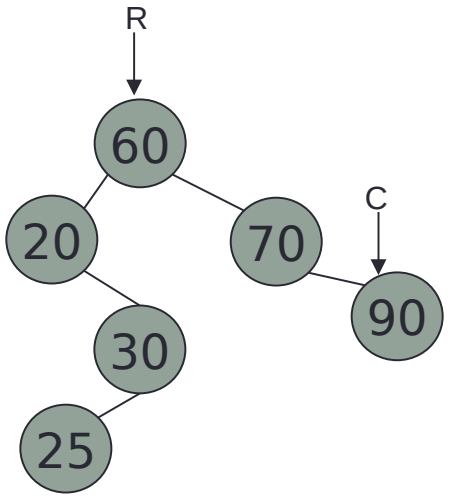
current = p;
return true;
}
}
```

Example #6

k = 10



ADT Binary Search Tree: Implementation

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return true;
}
}
```
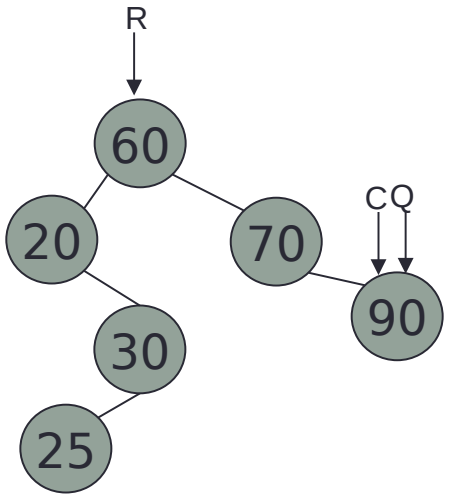

Example #6

k = 10



ADT Binary Search Tree: Implementation

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public boolean insert(int k, T val) {
BSTNode<T> p, q = current;

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return false; // key already in the BST
}

p = new BSTNode<T>(k, val);
if (empty()) {
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// current is pointing to parent of the new key
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else
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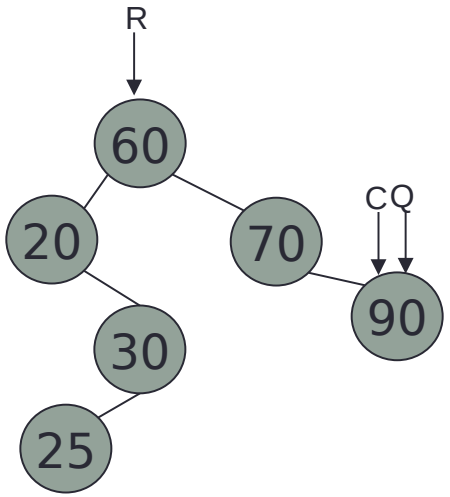
current = p;
return true;
}
}
```

Example #6

k = 10



ADT Binary Search Tree: Implementation

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public boolean insert(int k, T val) {
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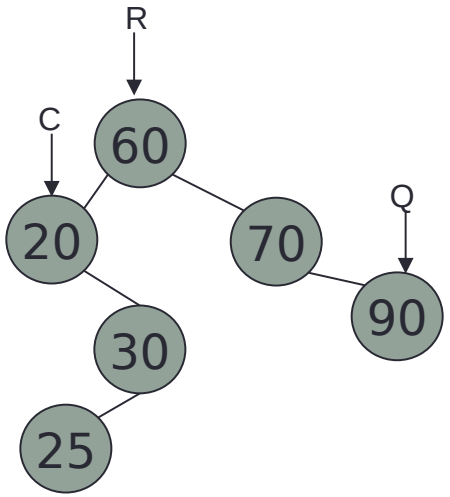

ADT Binary Search Tree: Implementation

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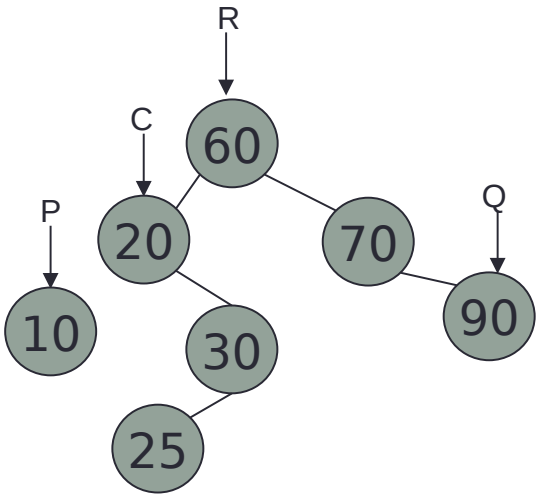

ADT Binary Search Tree: Implementation

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Example #6

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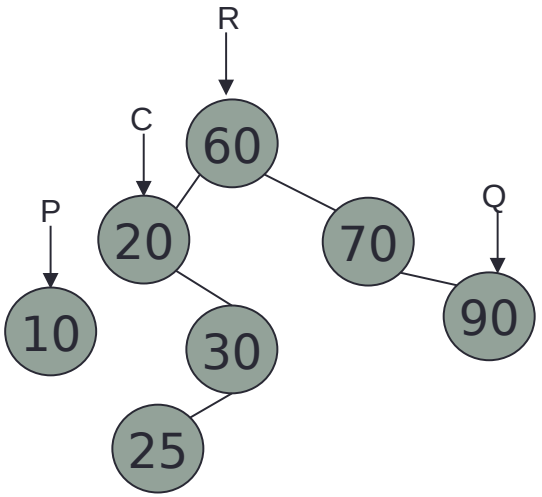

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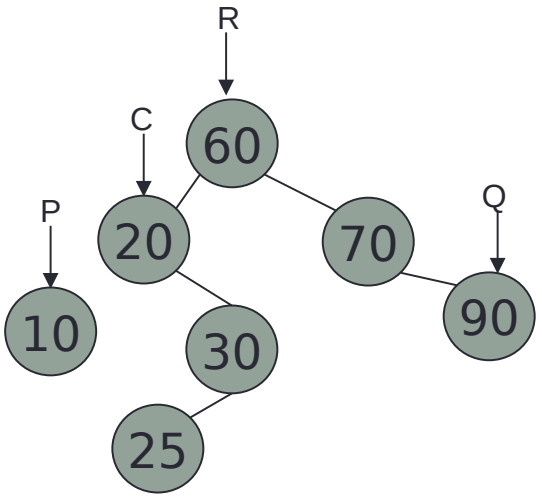

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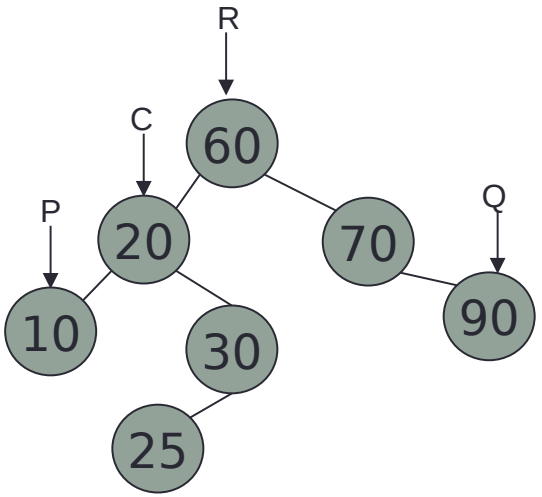
Example #6

k = 10



ADT Binary Search Tree: Implementation

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Example #6

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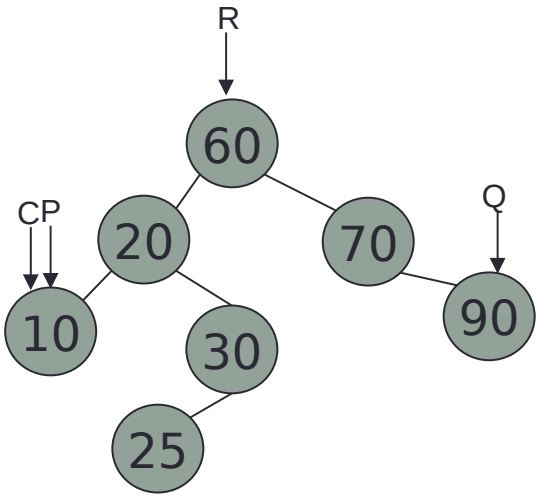

ADT Binary Search Tree: Implementation

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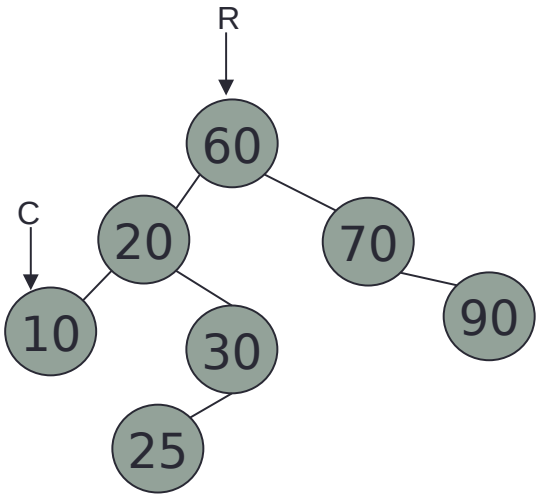
Example #6

k = 10



ADT Binary Search Tree: Implementation

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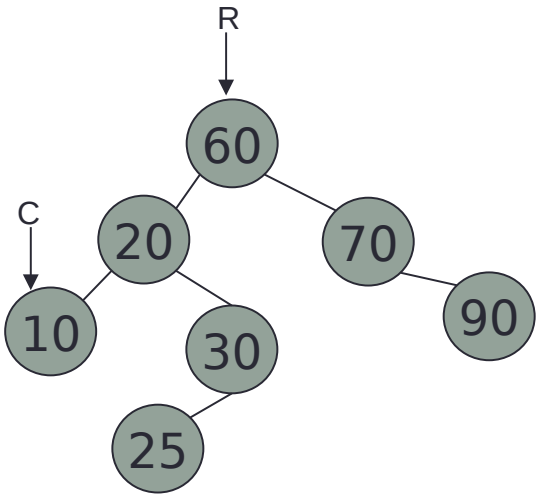
Example #7

k = 30



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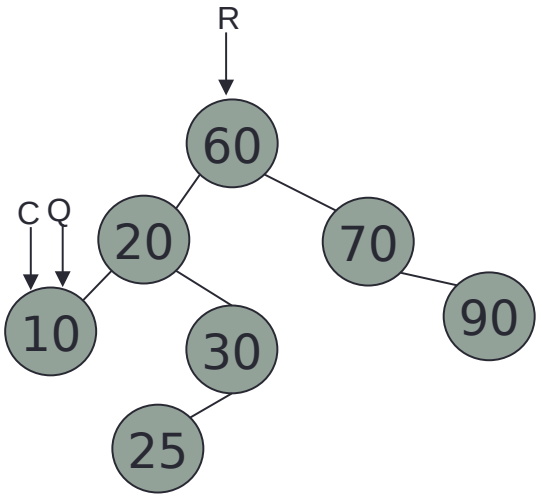
Example #7

k = 30



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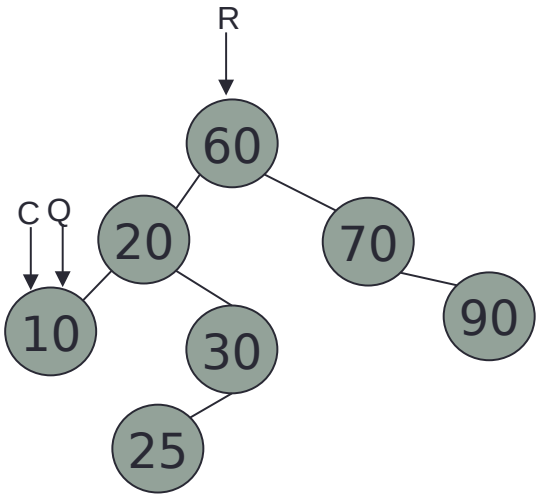

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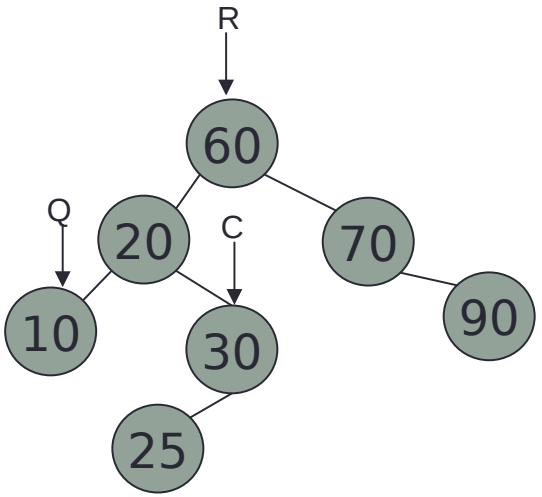

ADT Binary Search Tree: Implementation

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BSTNode<T> p, q = current;

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return false; // key already in the BST
}

p = new BSTNode<T>(k, val);
if (empty()) {
root = current = p;
return true;
}
else {
// current is pointing to parent of the new key
if (k < current.key)
current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```
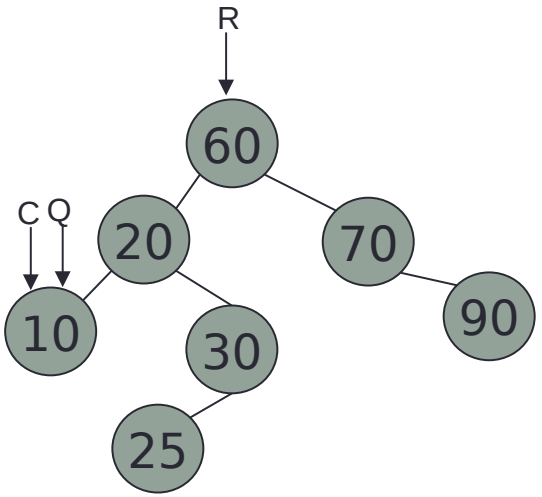

Example #7

k = 30

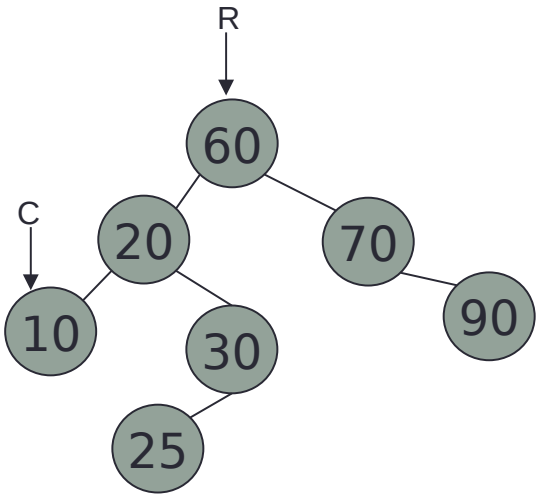


ADT Binary Search Tree: Implementation

```
public boolean insert(int k, T val) {
BSTNode<T> p, q = current;

if(findkey(k)) {
current = q;  // findkey() modified current
return false; // key already in the BST
}

p = new BSTNode<T>(k, val);
if (empty()) {
root = current = p;
return true;
}
else {
// current is pointing to parent of the new key
if (k < current.key)
current.left = p;
else
current.right = p;
current = p;
return true;
}
}
```

Example #7

k = 30



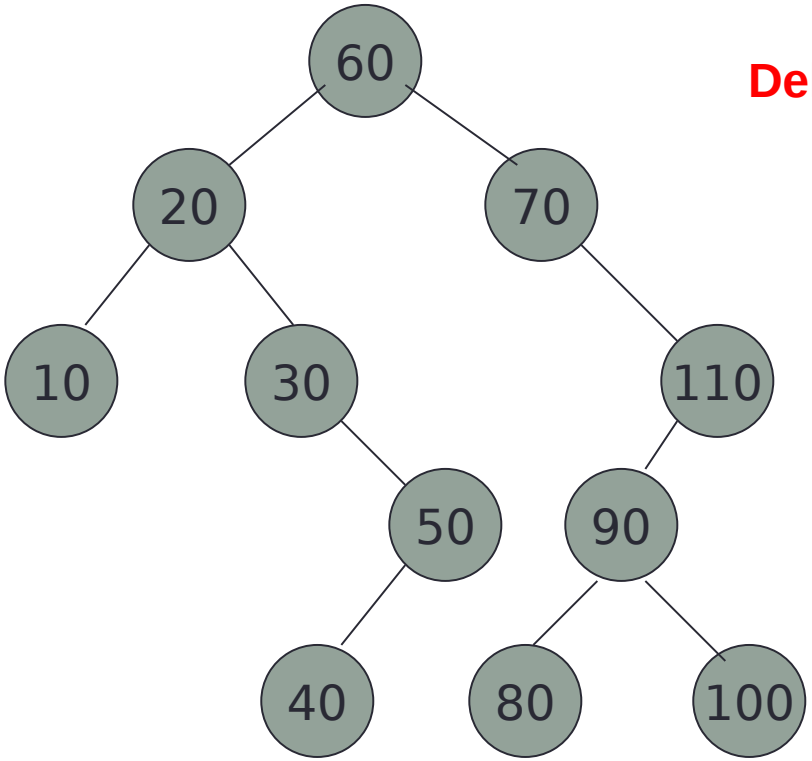
BST Node Deletion

- There are three cases:
  - Case 1: Node to be deleted has no children.
  - Case 2: Node to be deleted has one child.
  - Case 3: Node to be deleted has two children.
- In all these case it is always a leaf node that gets deleted.

BST Deletion: Case 1

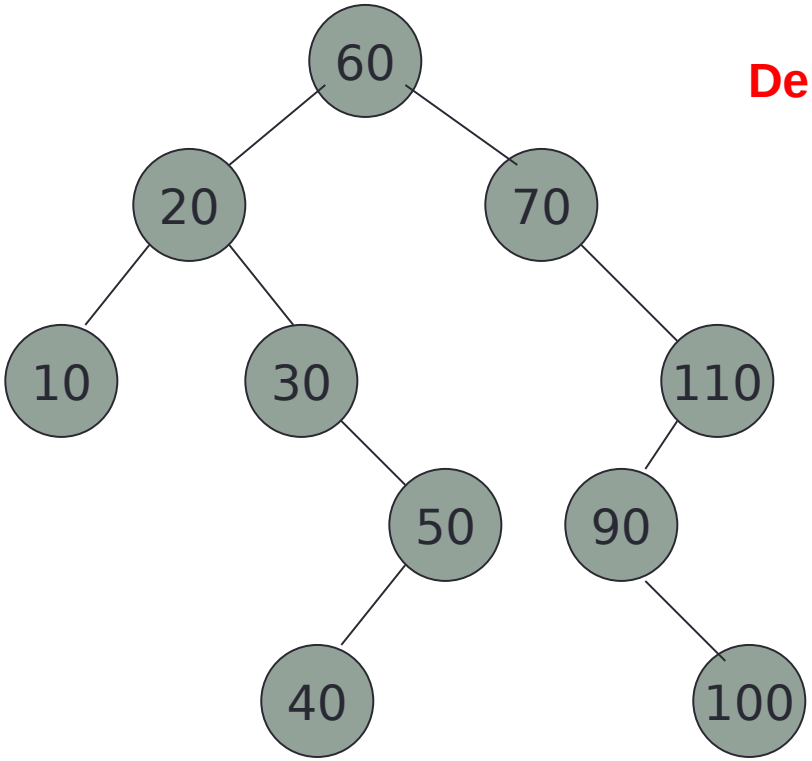
- Node to be deleted has no children.
- Simplest case. Unlink the node from its parent.
- The parent will be linked with null in the place of the deleted node.

BST Deletion: Case 1



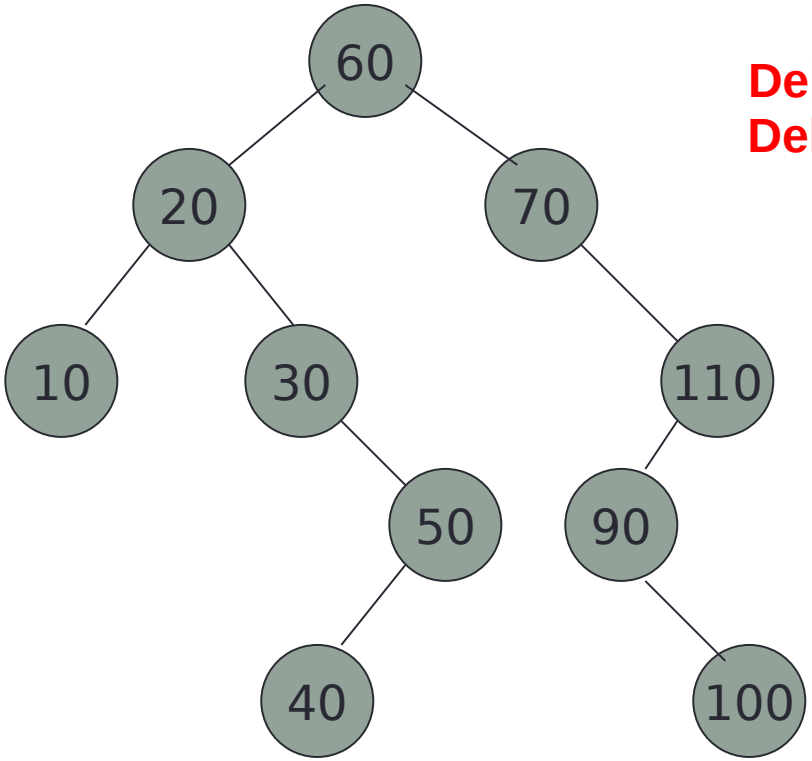
Delete 80

BST Deletion: Case 1



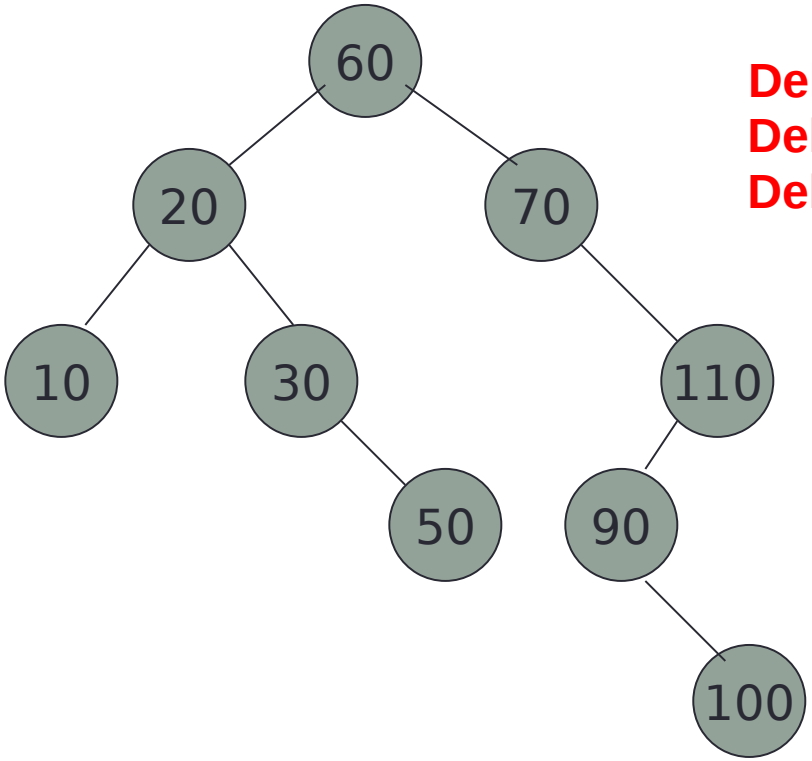
Delete 80

BST Deletion: Case 1



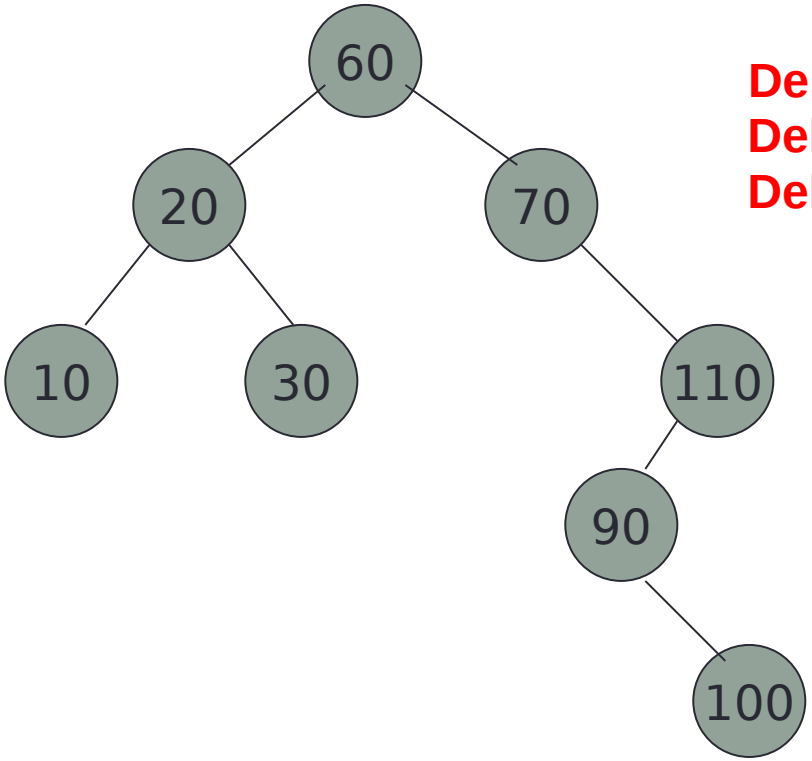
Delete 80
Delete 40

BST Deletion: Case 1



Delete 80
Delete 40
Delete 50

BST Deletion: Case 1

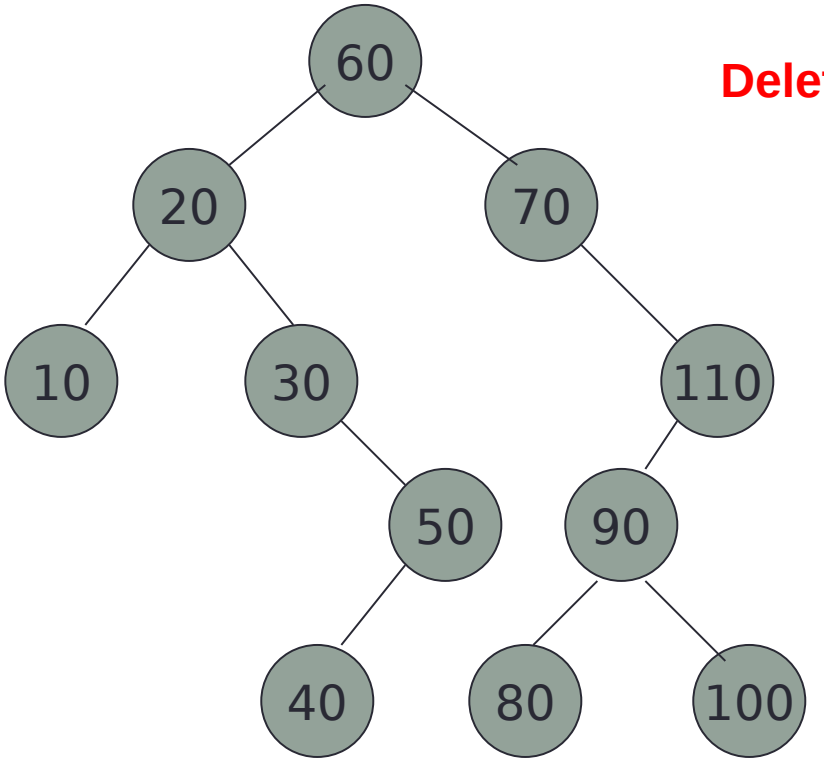


Delete 80
Delete 40
Delete 50

BST Deletion: Case 2

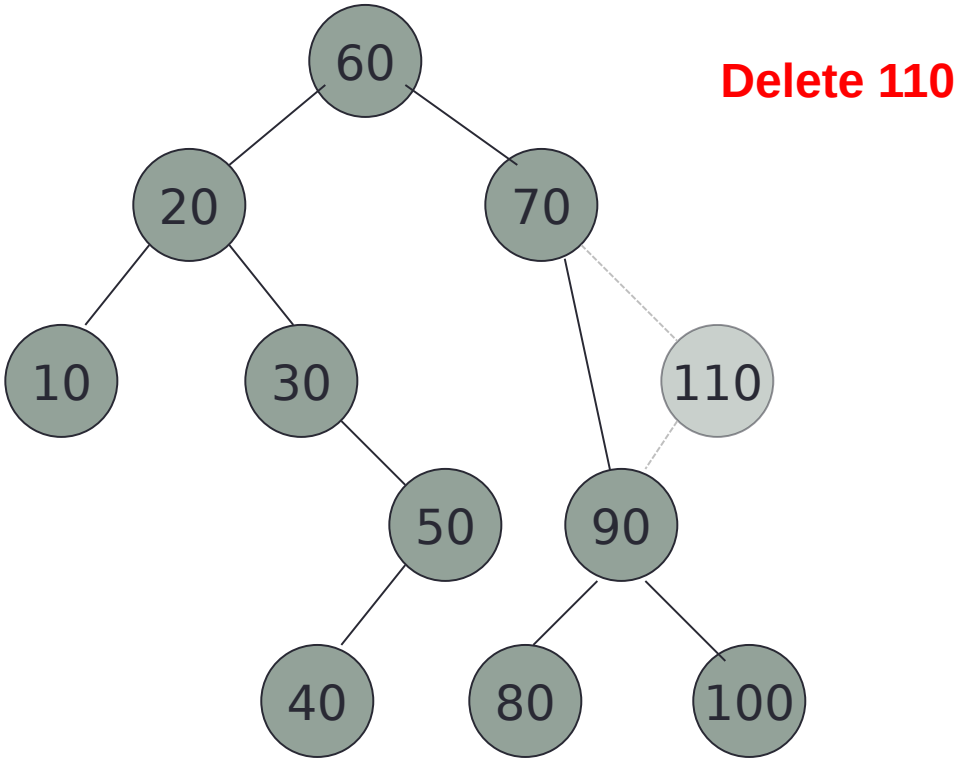
- Node to be deleted has one child.
- Remove the node, and place its child (along with its subtree) in its place.
- The parent will be linked with the child of the deleted node.

BST Deletion: Case 2

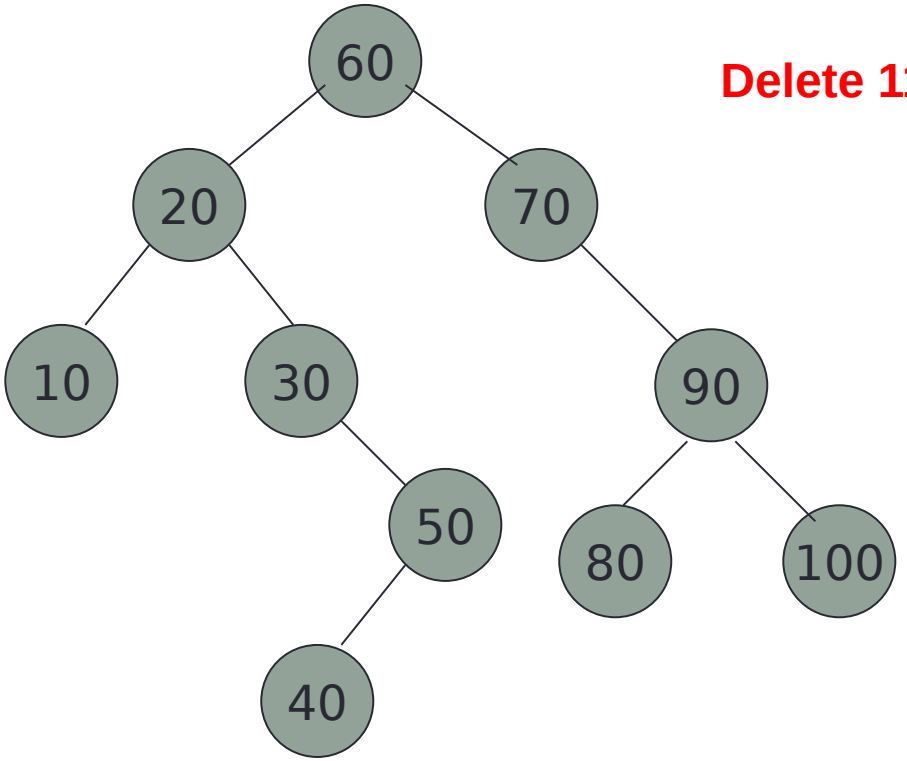


Delete 110

BST Deletion: Case 2

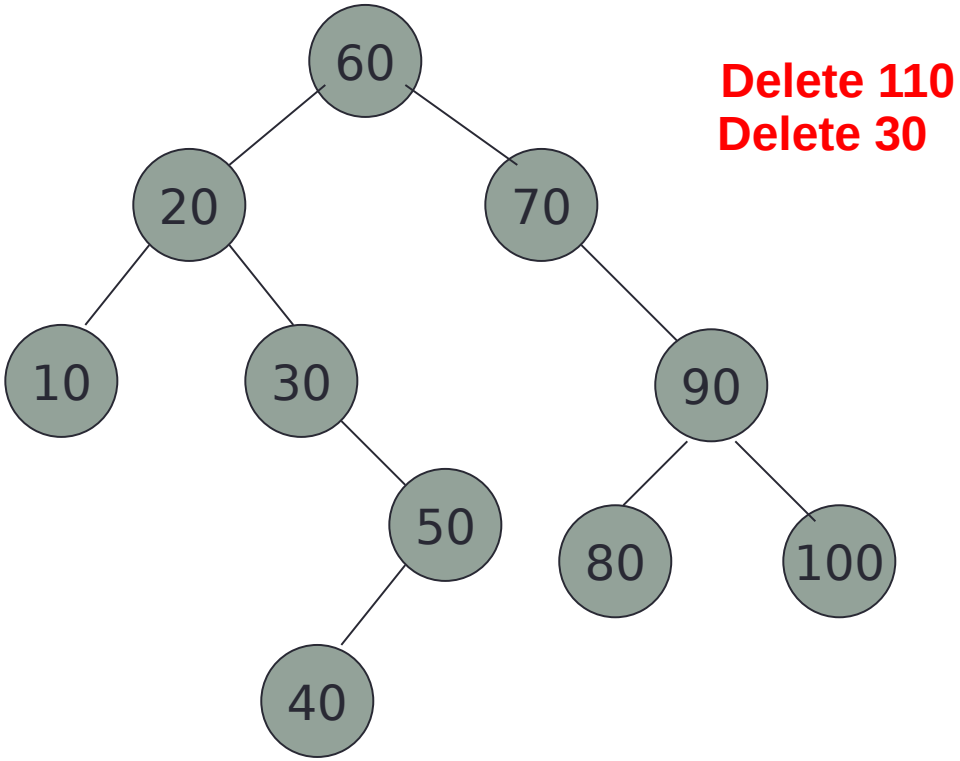


BST Deletion: Case 2

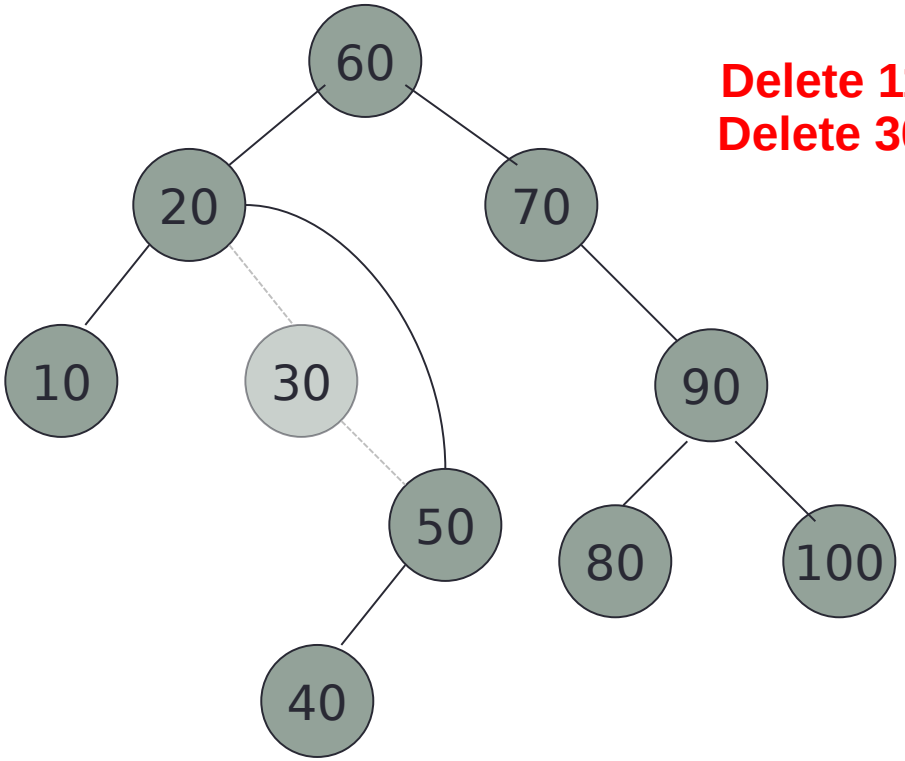


Delete 110

BST Deletion: Case 2

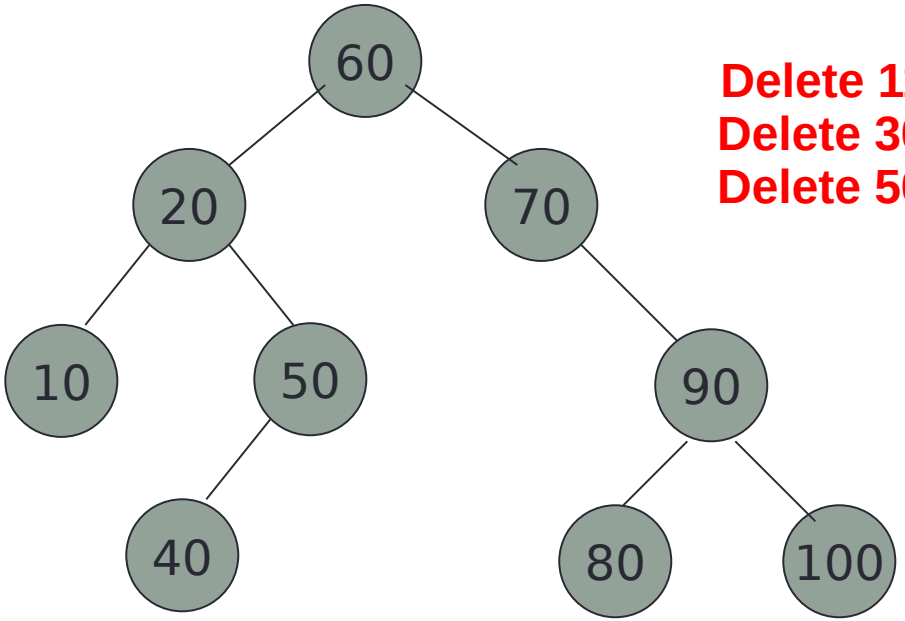


BST Deletion: Case 2



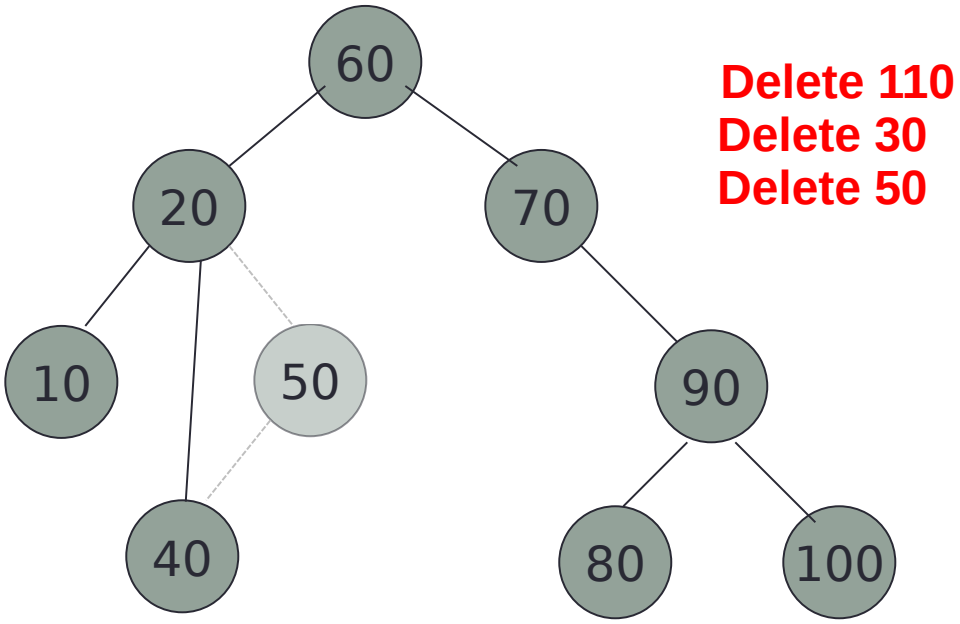
Delete 110
Delete 30

BST Deletion: Case 2



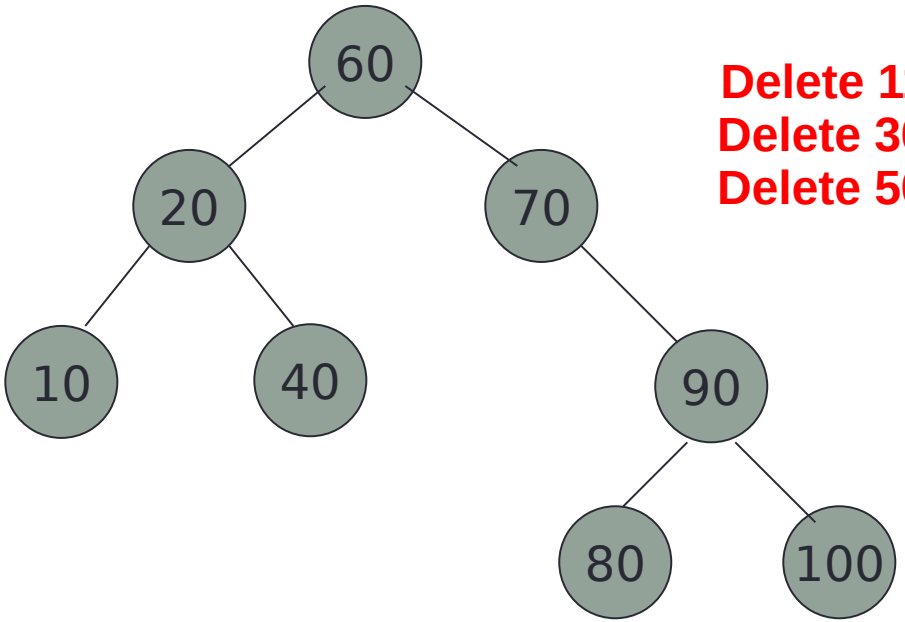
Delete 110
Delete 30
Delete 50

BST Deletion: Case 2



Delete 110
Delete 30
Delete 50

BST Deletion: Case 2

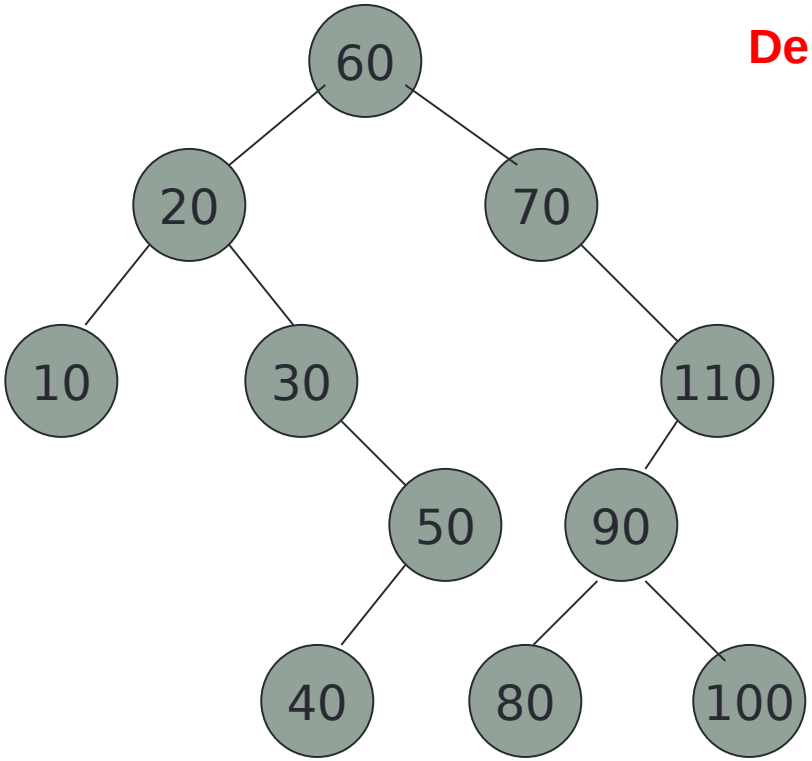


Delete 110
Delete 30
Delete 50

BST Deletion: Case 3

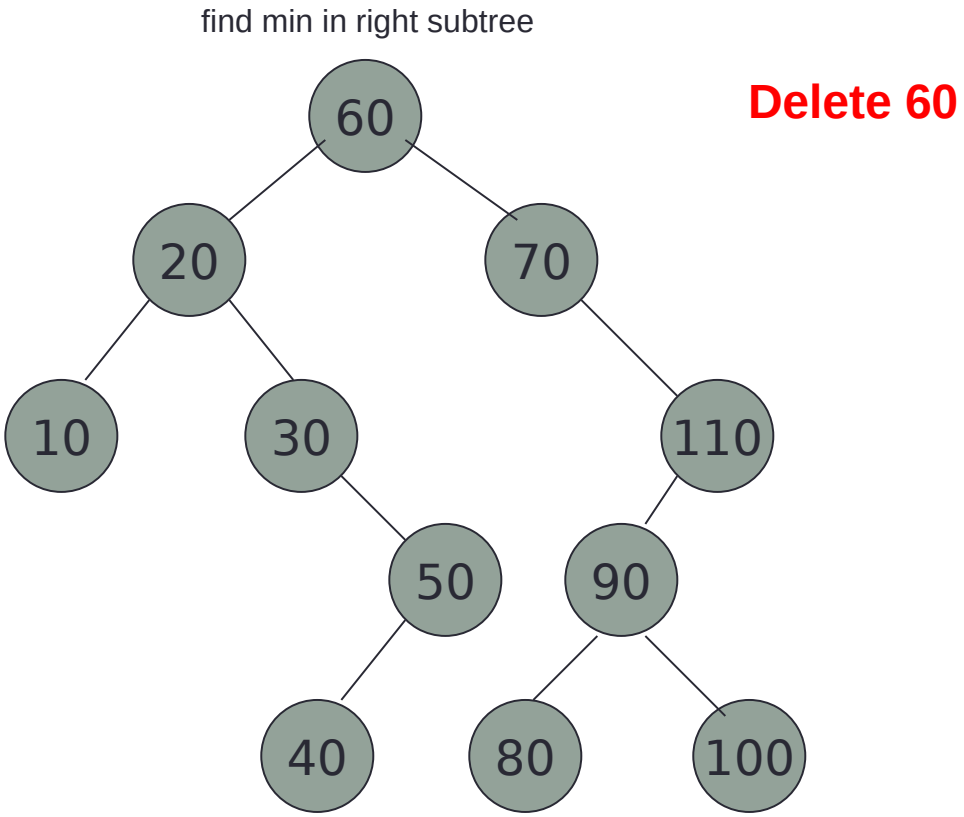
- Node to be deleted has two children.
- Complex case:
  - Find the node with the minimum key in the right subtree (left-most node in the right subtree).
  - Copy its key/data over the node to be deleted.
  - Delete the duplicate node (using either Case 1 or 2)
- The node will be overwritten by the minimum node in the right subtree. Then that duplicate node will be deleted.

BST Deletion: Case 3

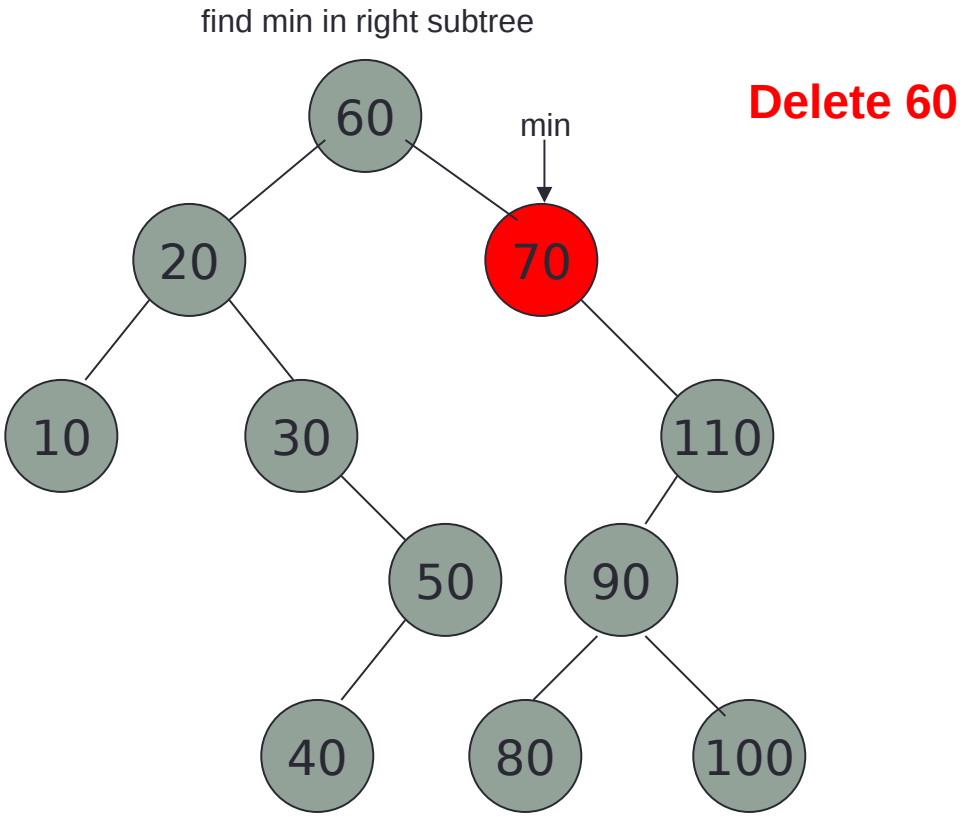


Delete 60

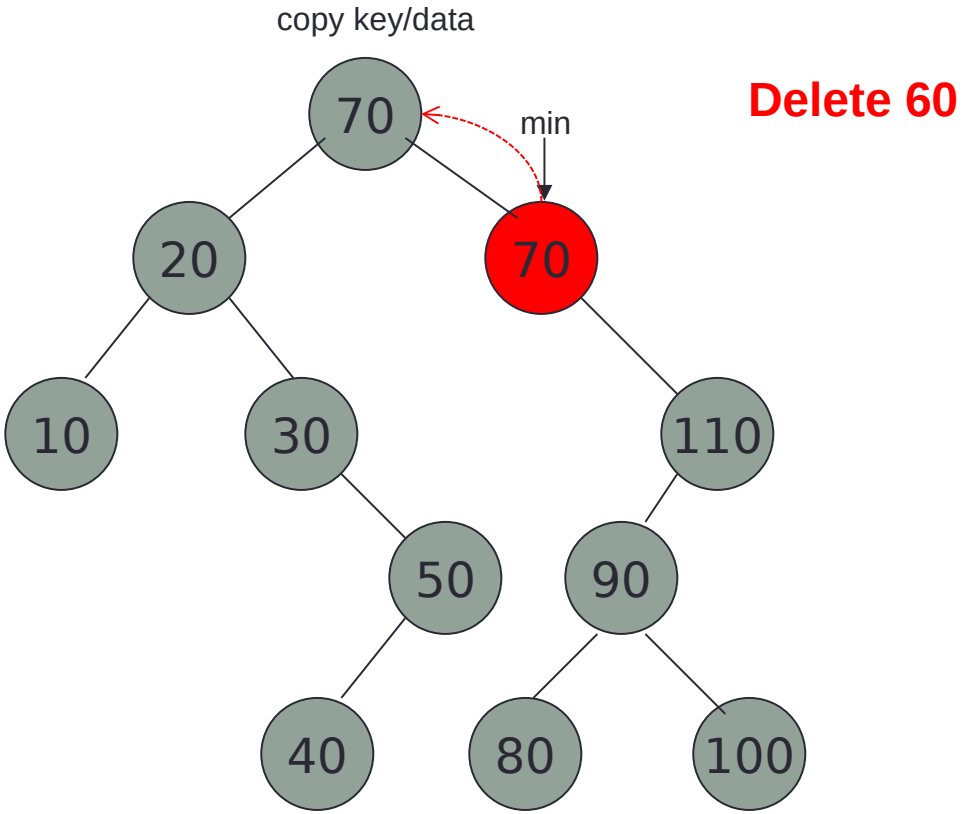
BST Deletion: Case 3



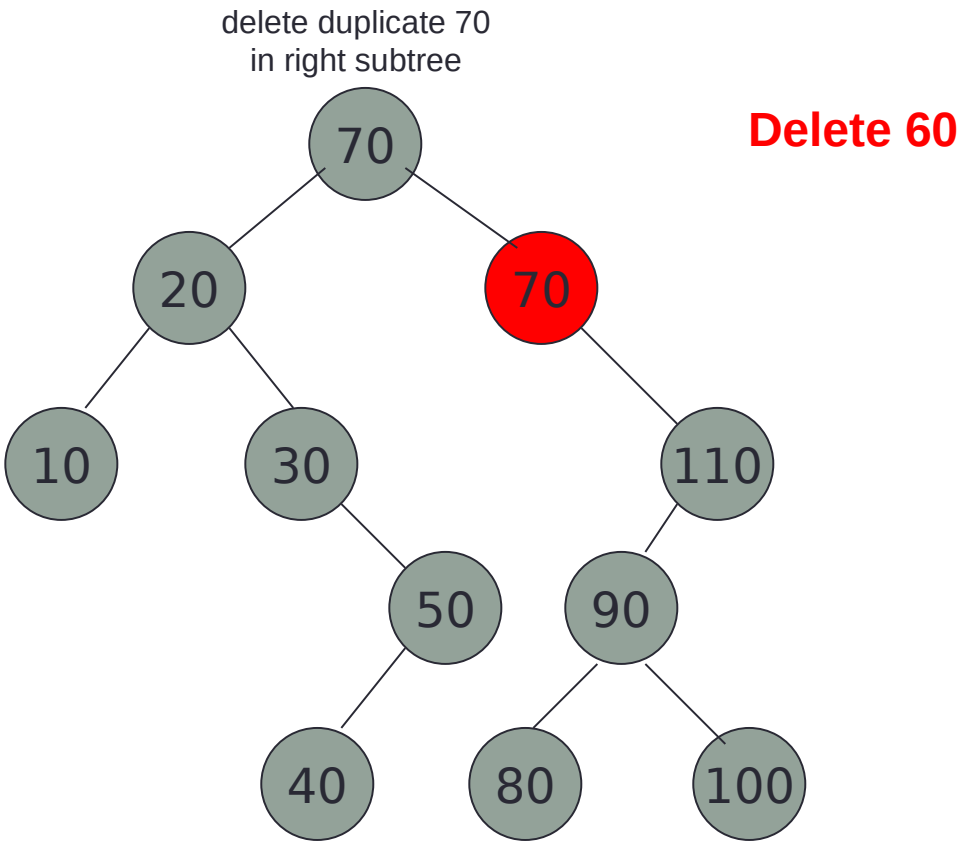
BST Deletion: Case 3



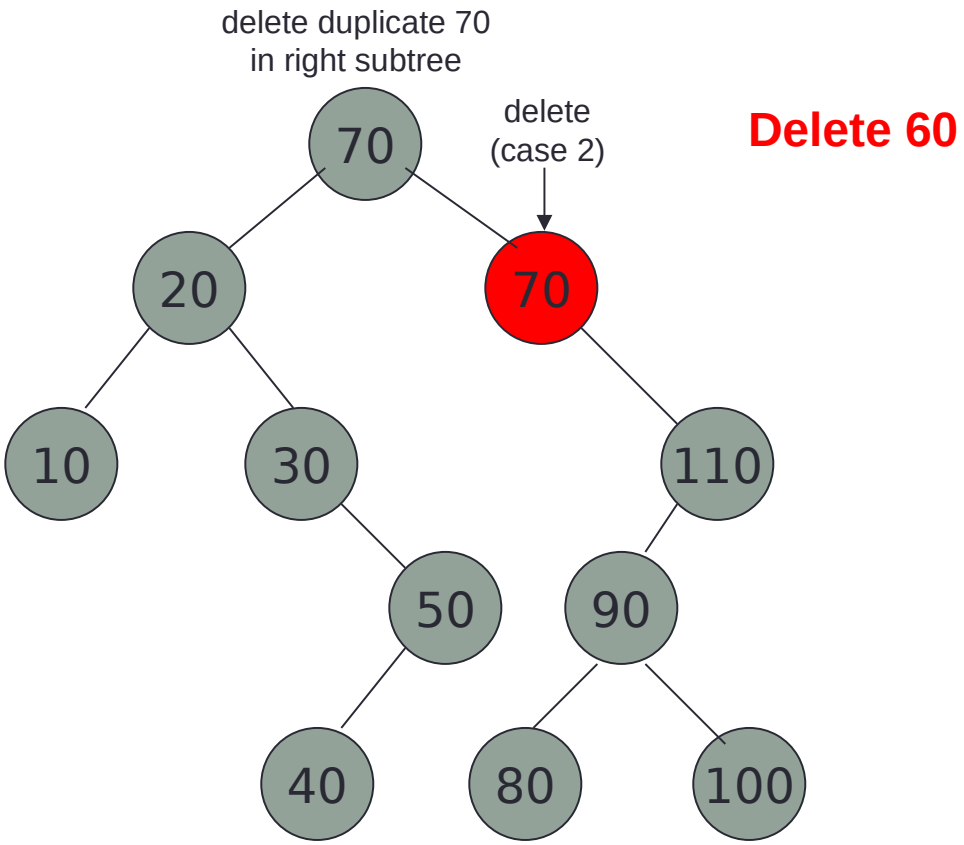
BST Deletion: Case 3



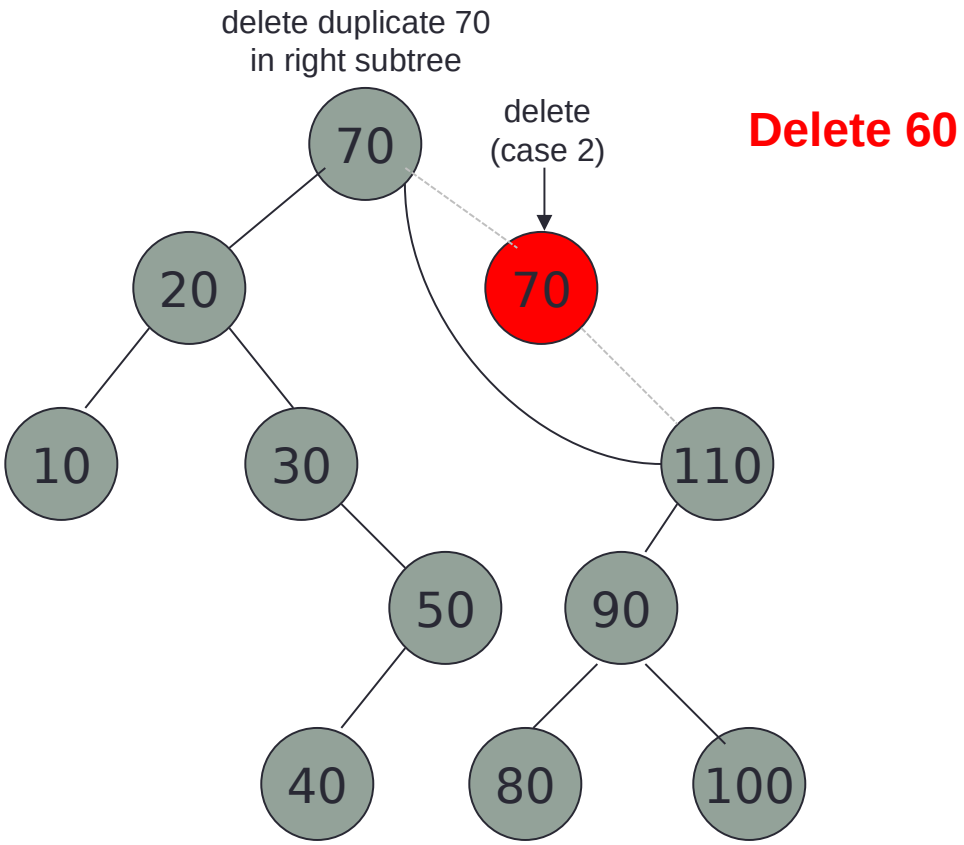
BST Deletion: Case 3



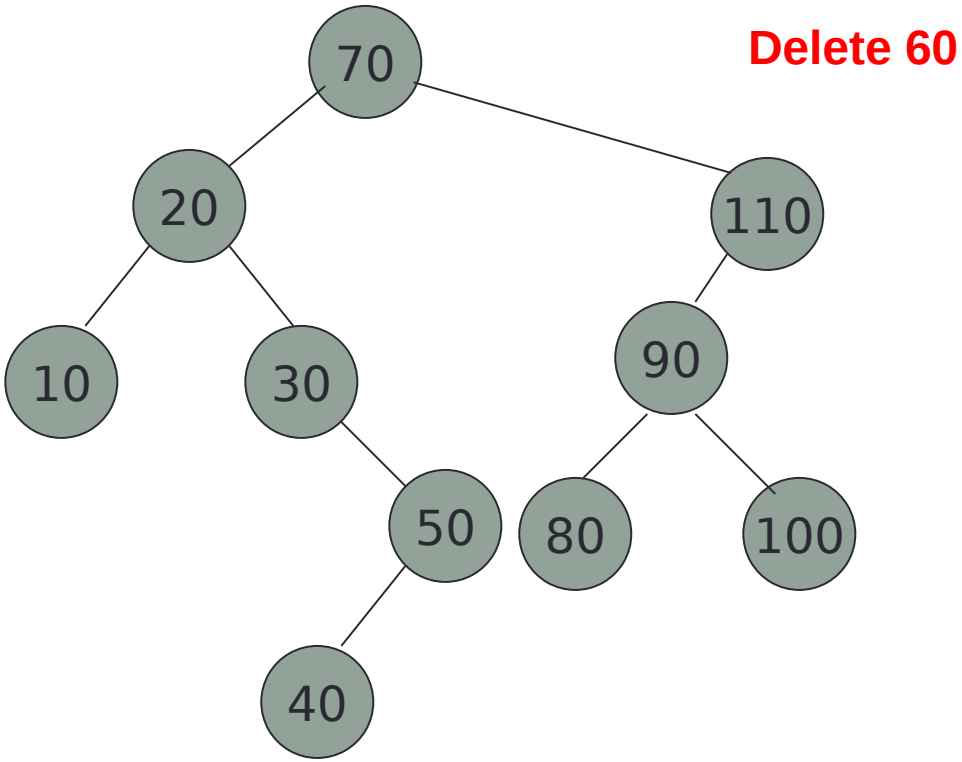
BST Deletion: Case 3



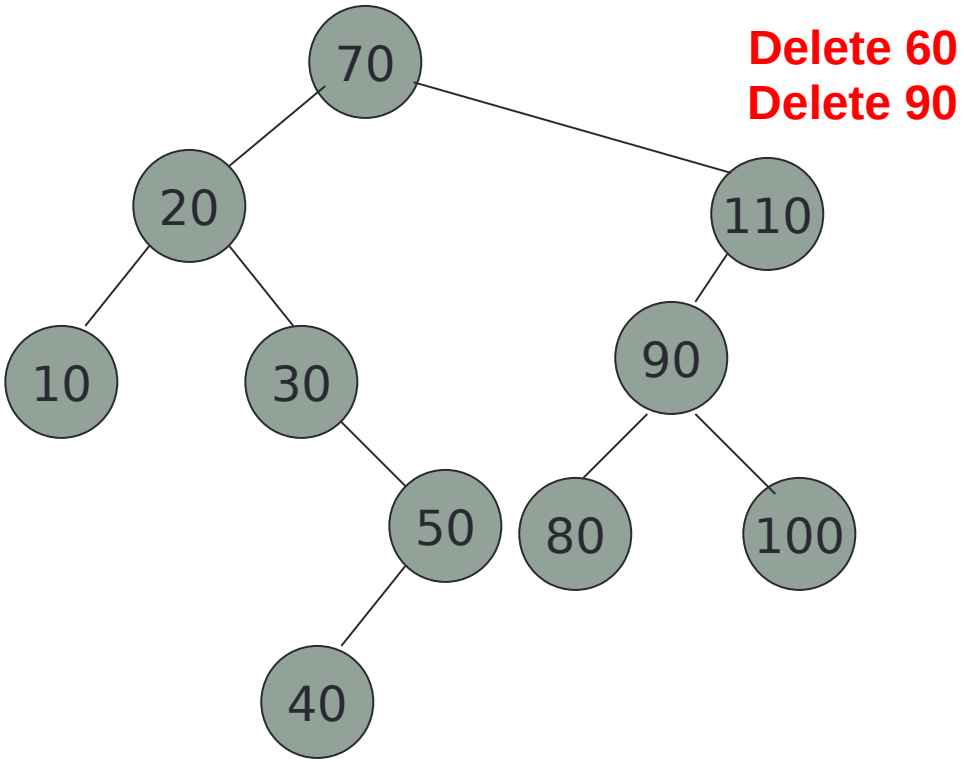
BST Deletion: Case 3



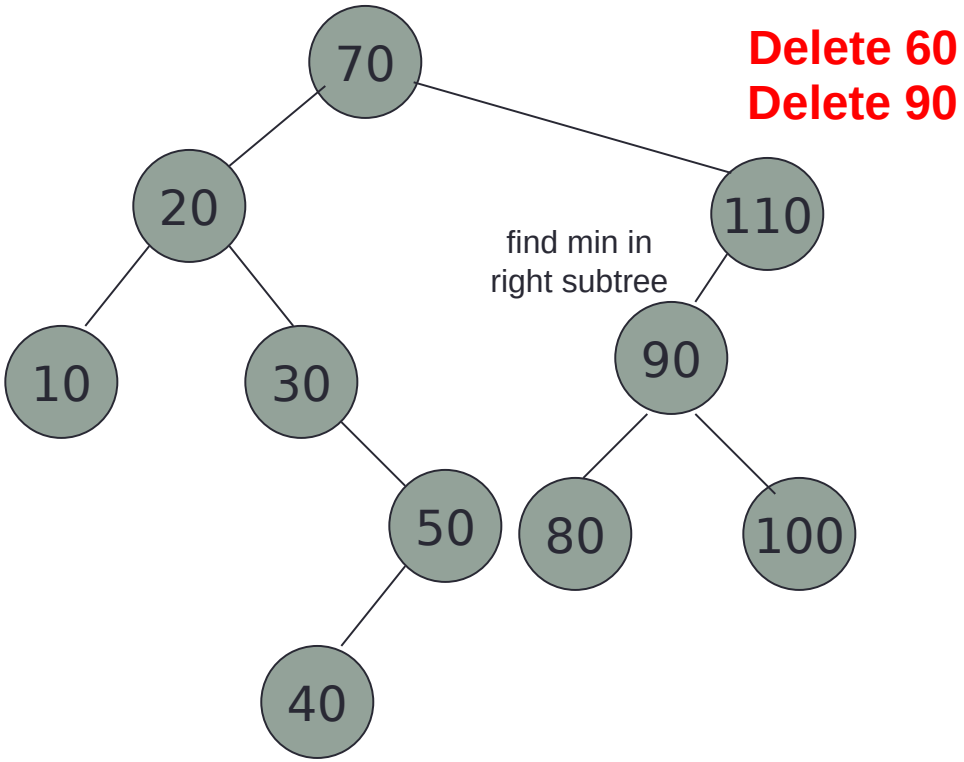
BST Deletion: Case 3



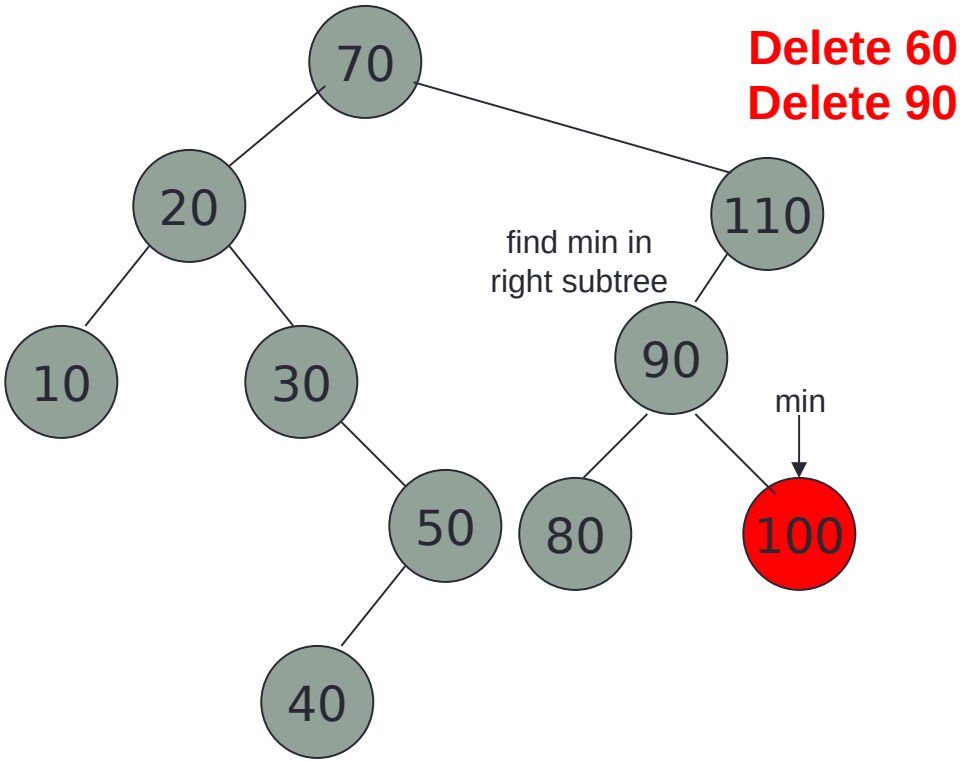
BST Deletion: Case 3



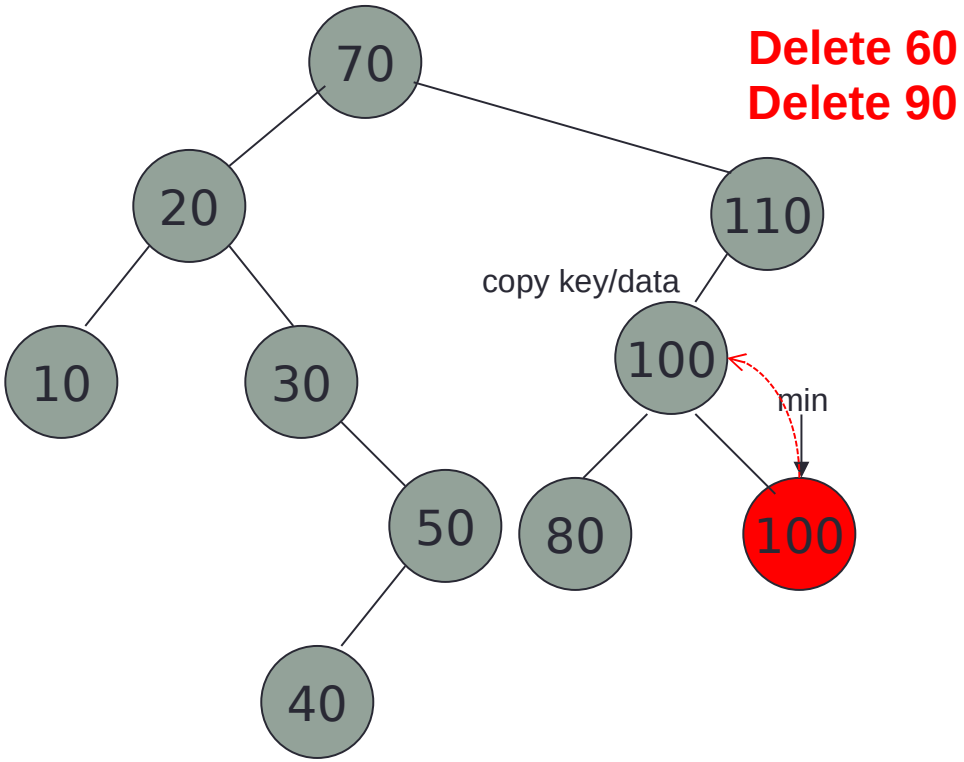
BST Deletion: Case 3



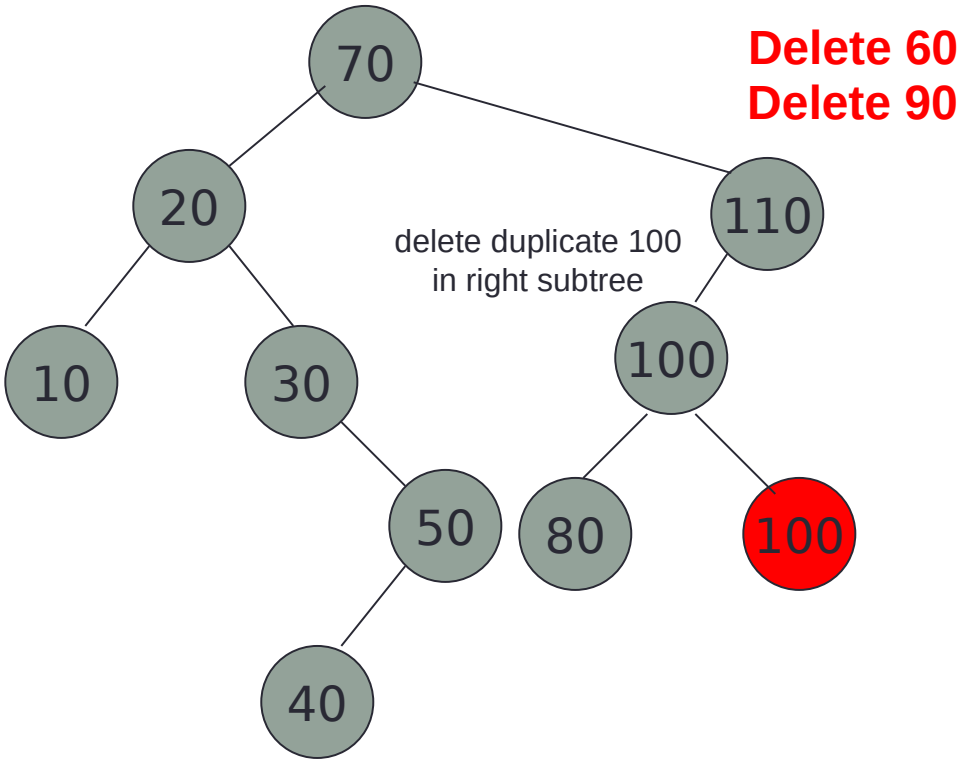
BST Deletion: Case 3



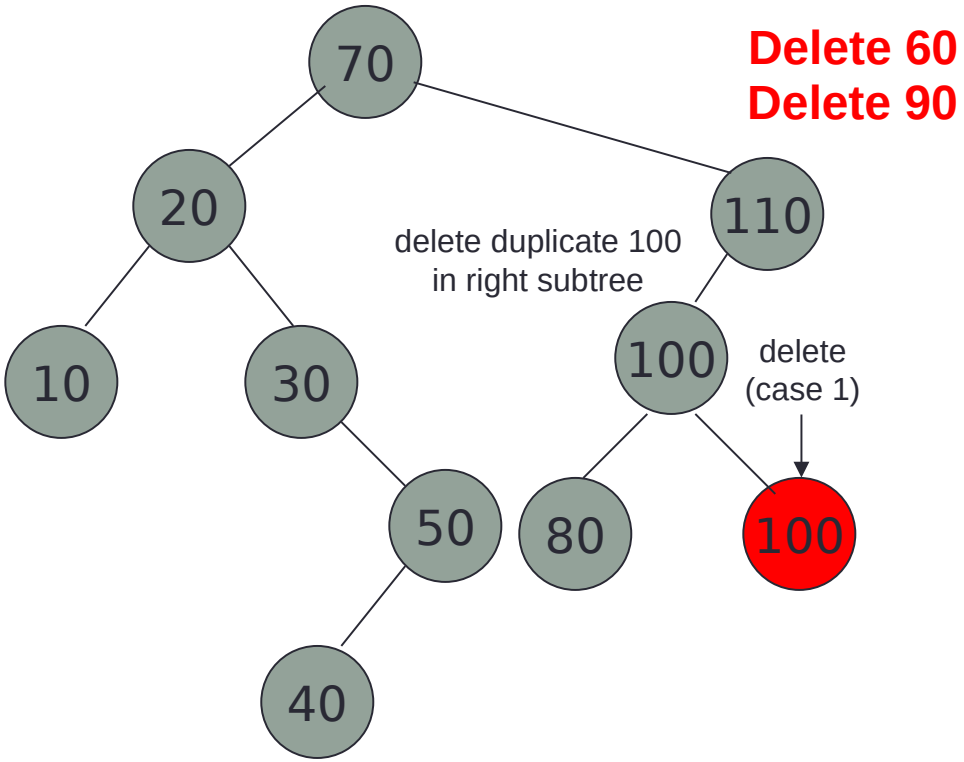
BST Deletion: Case 3



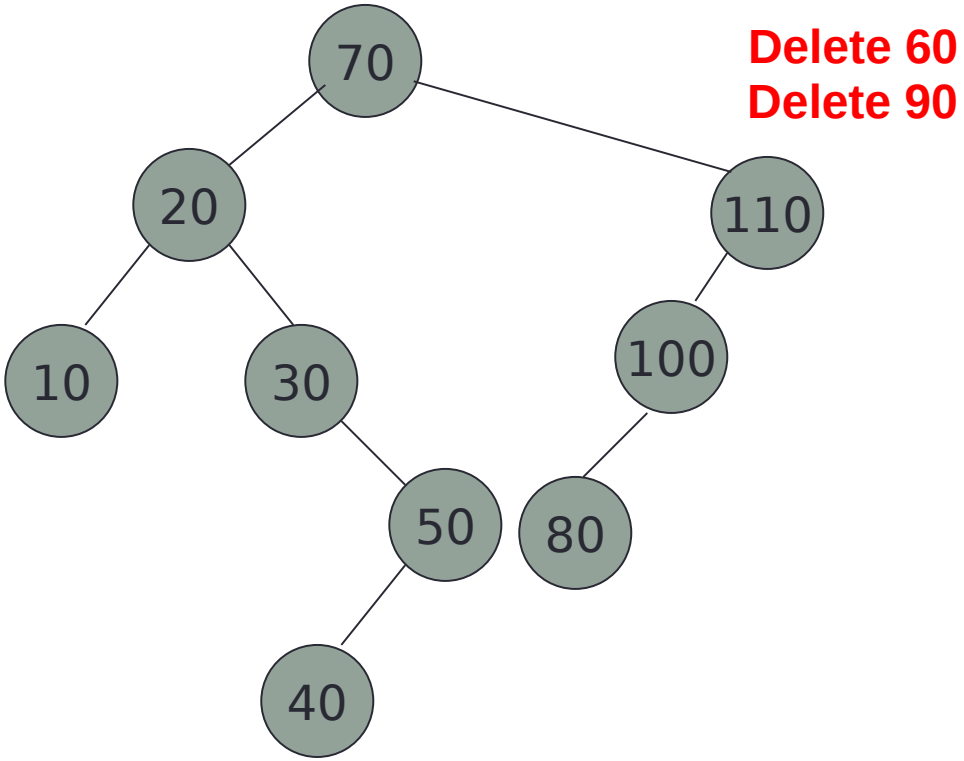
BST Deletion: Case 3



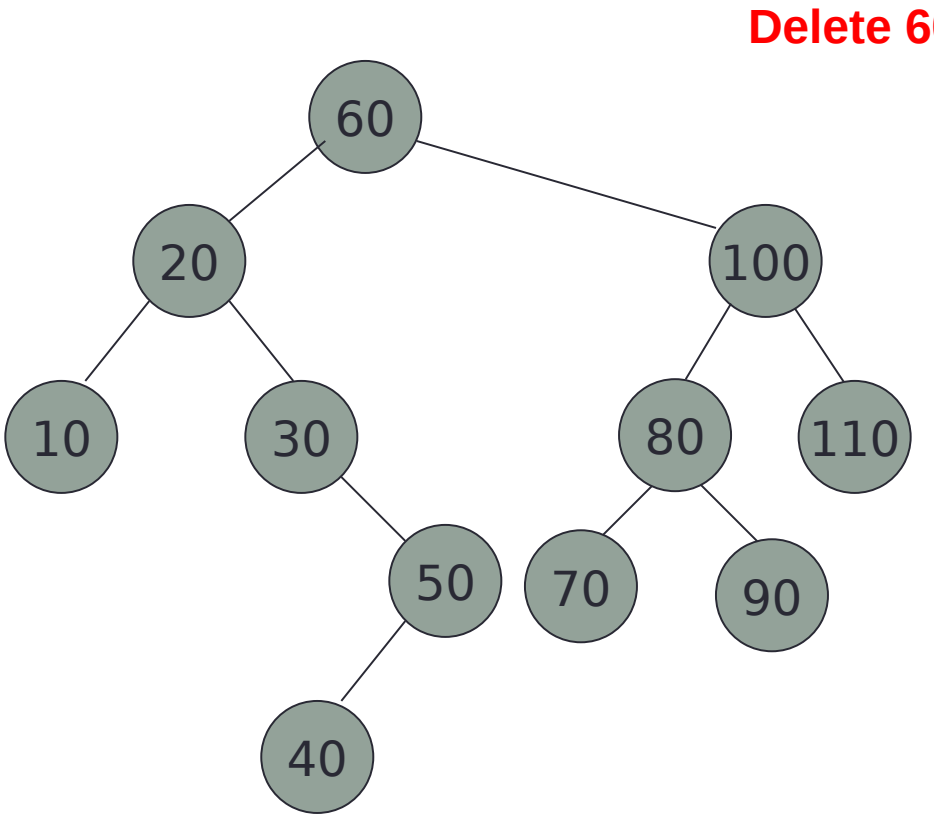
BST Deletion: Case 3



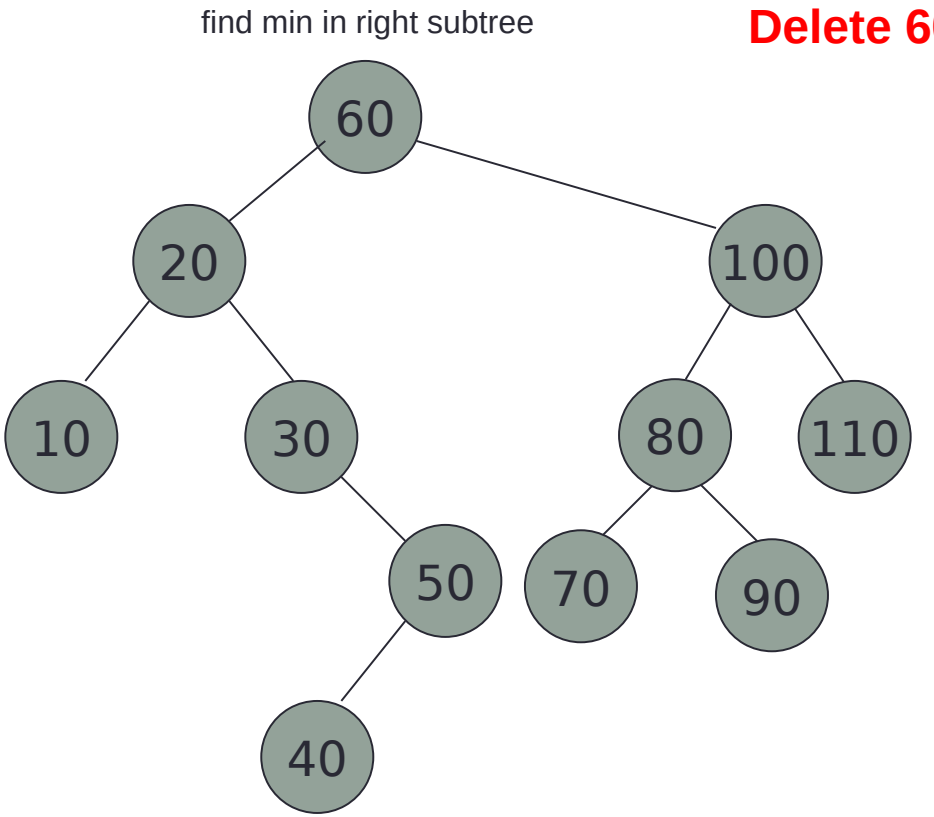
BST Deletion: Case 3



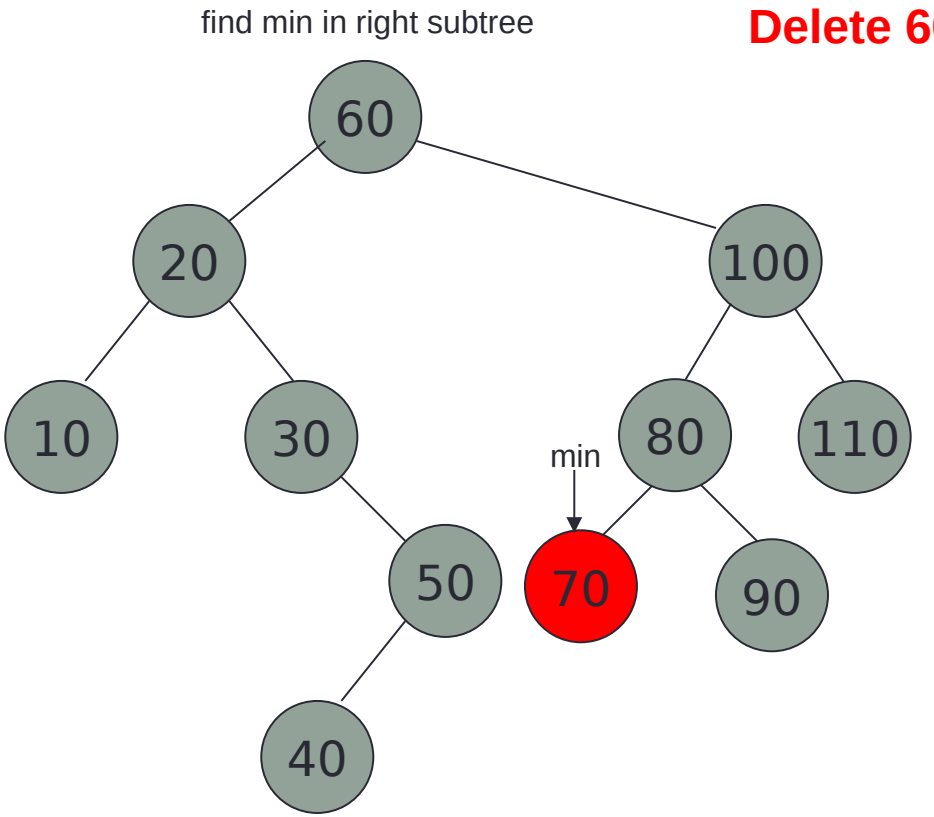
BST Deletion: Case 3



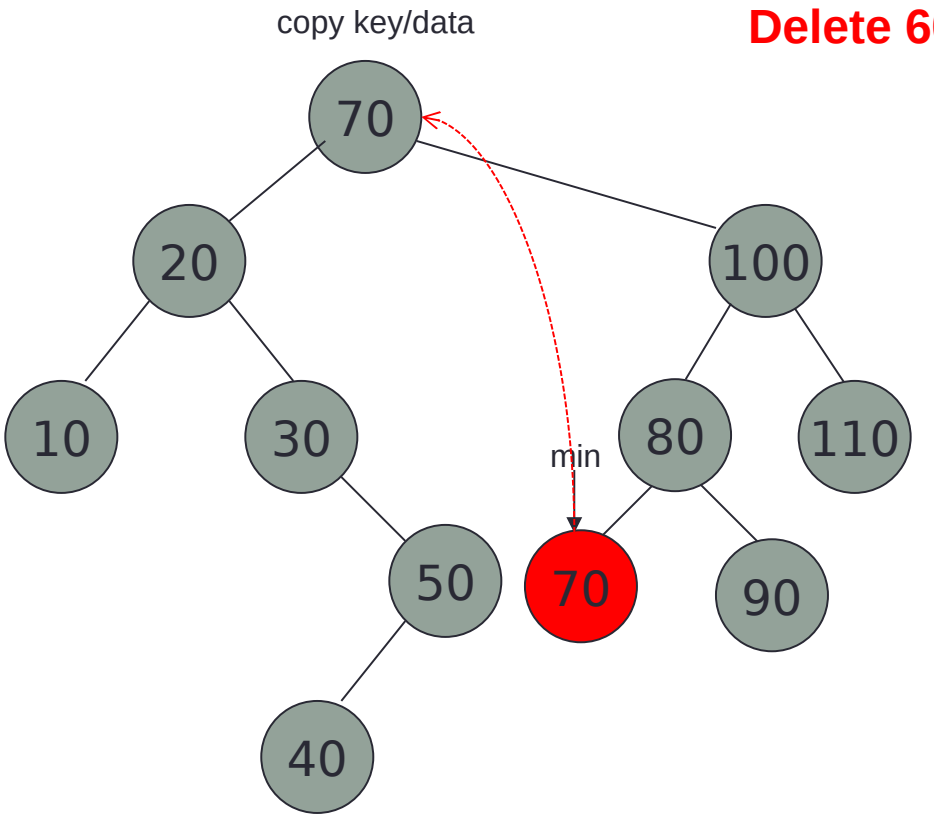
BST Deletion: Case 3



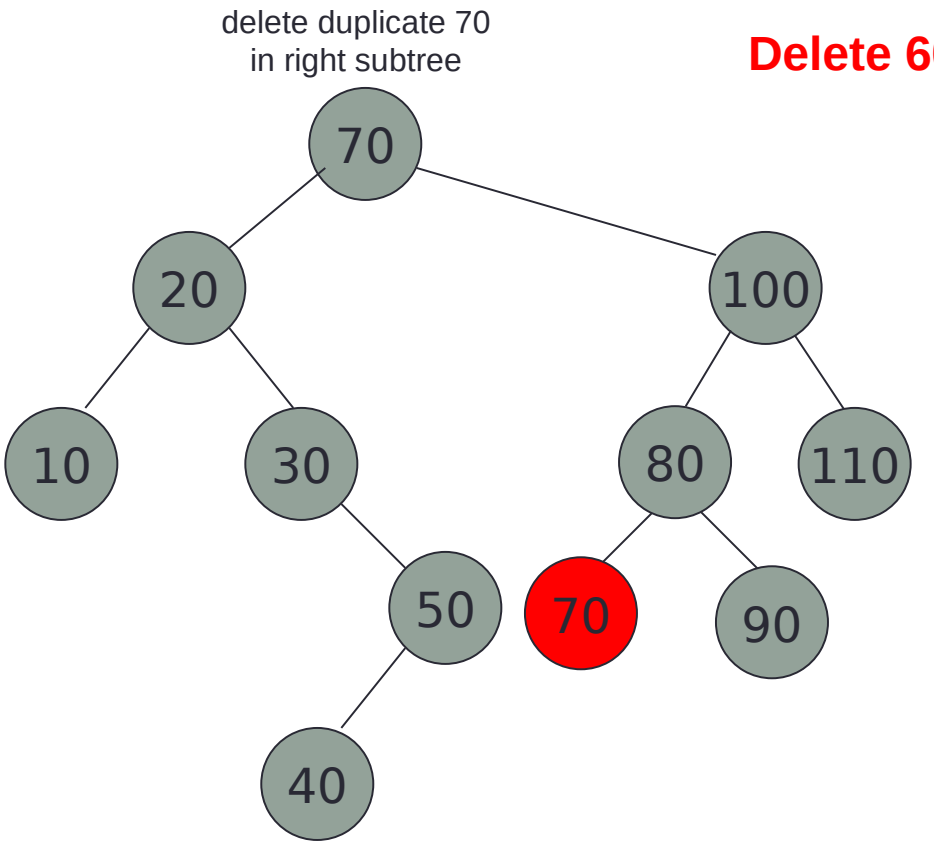
BST Deletion: Case 3



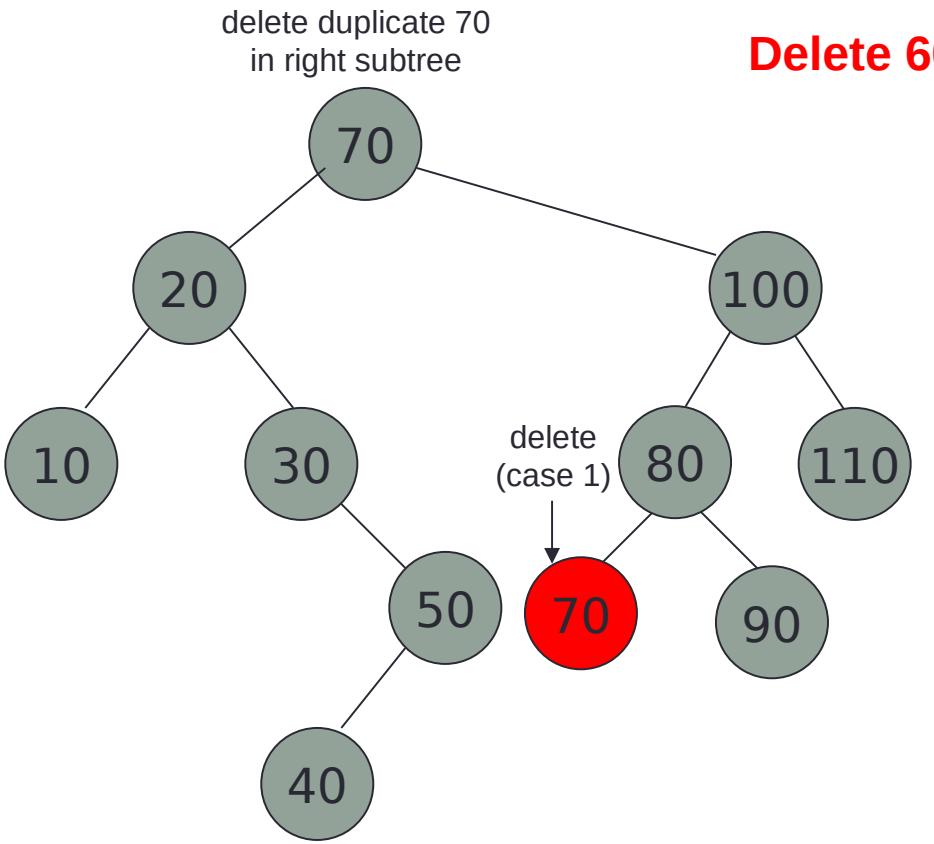
BST Deletion: Case 3



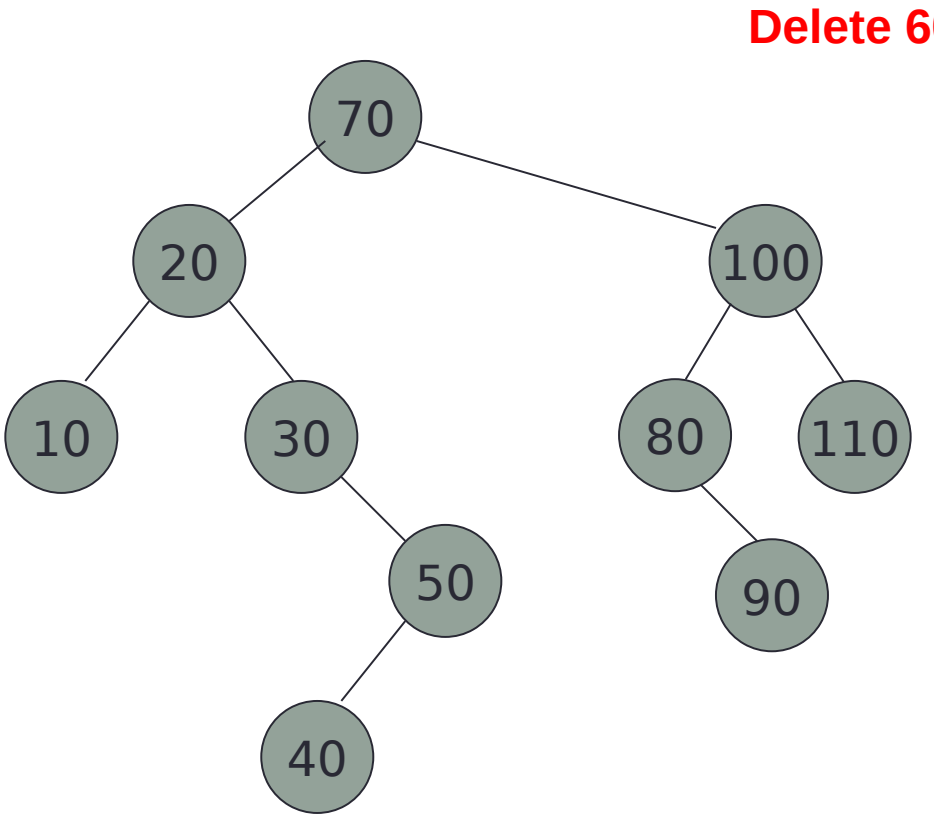
BST Deletion: Case 3



BST Deletion: Case 3



BST Deletion: Case 3



ADT Binary Search Tree: Implementation

```
public boolean remove_key (int tkey){
    Boolean removed = new Boolean(false);
    BSTNode<T> p;
    p = remove_aux(tkey, root, removed);
    current = root = p;
    return removed;
}
```

ADT Binary Search Tree: Implementation

```
public boolean remove_key (int tkey){
BooleanWrapper removed = new
BooleanWrapper(false);
    BSTNode<T> p;
    p = remove_aux(tkey, root, removed);
    current = root = p;
    return removed.get();
}
```

Traverse the tree to find the key and handle remove cases (all 3 cases). If found, it will *remove* and set removed to (true). Otherwise, *removed* will not change (false). The method will return the modified tree.

ADT Binary Search Tree: Implementation

```
private BSTNode<T> remove_aux(int key, BSTNode<T> p,
BooleanWrapper flag) {
BSTNode<T> q, child = null;
if(p == null)
return null;
if(key < p.key)
p.left = remove_aux(key, p.left, flag); //go left
else if(key > p.key)
p.right = remove_aux(key, p.right, flag); //go right
else {
flag.set( true);
if (p.left != null && p.right != null){ //two children
q = find_min(p.right);
p.key = q.key;
p.data = q.data;
p.right = remove_aux(q.key, p.right, flag);
}
```

ADT Binary Search Tree: Implementation

```
            else {
                if (p.right == null) //one child
                    child = p.left;
                else if (p.left == null) //one child
                    child = p.right;
                return child;
            }
        }
        return p;
}
```

ADT Binary Search Tree: Implementation

```
private BSTNode<T> find_min(BSTNode<T> p){
    if(p == null)
        return null;

    while(p.left != null){
        p = p.left;
    }

    return p;
}
```

Find left-most node (minimum key node) in any tree p

ADT Binary Search Tree: Implementation

```
  public boolean update(int key, T data){
        remove_key(current.key);
        return insert(key, data);
  }

}
```

To update the current key/value:
1). Remove the current node.
2). Insert a new node with the new key/data.
Note: The new node will be set the current after insert.

ADT Binary Search Tree: Implementation

```
//Method removeKey: iterative
public boolean removeKey(int k) {

        // Search for k
        int k1 = k;
        BSTNode<T> p = root;
        BSTNode<T> q = null; // Parent of p
        while (p != null) {

           if (k1 < p.key) {
              q =p;
              p = p.left;
           } else if (k1 > p.key) {
              q = p;
              p = p.right;
           }
```

ADT Binary Search Tree: Implementation

```
else { // Found the key

            // Check the three cases
            if ((p.left != null) && (p.right != null)) {
        // Case 3: two children
               // Search for the min in the right subtree
               BSTNode<T> min = p.right;
               q = p;
               while (min.left != null) {
                  q = min;
                  min = min.left;
               }
               p.key = min.key;
               p.data = min.data;
               k1 = min.key;
               p = min;
               // Now fall back to either case 1 or 2
            }
```

ADT Binary Search Tree: Implementation

```
            // The subtree rooted at p will change here
             if (p.left != null) { // One child
                p = p.left;
             } else { // One or no children
                p = p.right;
             }

             if (q == null) { // No parent for p, root must change
                root = p;
             } else {
                if (k1 < q.key) {
                   q.left = p;
                } else {
                   q.right = p;
                }
             }
             current = root;
             return true;

          }
       }

       return false; // Not found
    }
}
```

Ex

Insert the following keys into an empty BST and show the BST after each insertion: 10, 12, 8, 17, 11, 14, 9, 4, 3,20, 5.

```
BST<String> bst;
   bst = new BST<String>();
bst.insert(10, ”L");
bst.insert(12, ”N ");
bst.insert(8, ”E");
bst.insert(17, ”:");
bst.insert(11, ”E");
bst.insert(14, ”T");
bst.insert(9, ”L");
bst.insert(4, ”X");
bst.insert(3, ”E");
bst.insert(20, ”)");
bst.insert(5, ”C");
```

Print the BST nodes using in_order travers

find(9)
find(6)

Try to delete node with key 10