# Red-Black Tree | Set 3 (Delete)

Difficulty Level : Hard • Last Updated : 23 Dec, 2021

We have discussed the following topics on the Red-Black tree in previous posts. We strongly recommend referring following post as a prerequisite of this post.

Red-Black Tree Introduction

Red Black Tree Insert

**Insertion Vs Deletion:**

Like Insertion, recoloring and rotations are used to maintain the Red-Black properties. In the insert operation, we check the color of the uncle to decide the appropriate case. In the delete operation, ***we check the color of the sibling*** to decide the appropriate case.

The main property that violates after insertion is two consecutive reds. In delete, the main violated property is, change of black height in subtrees as deletion of a black node may cause reduced black height in one root to leaf path.

Deletion is a fairly complex process. To understand deletion, the notion of double black is used. When a black node is deleted and replaced by a black child, the child is marked as ***double black***. The main task now becomes to convert this double black to single black.

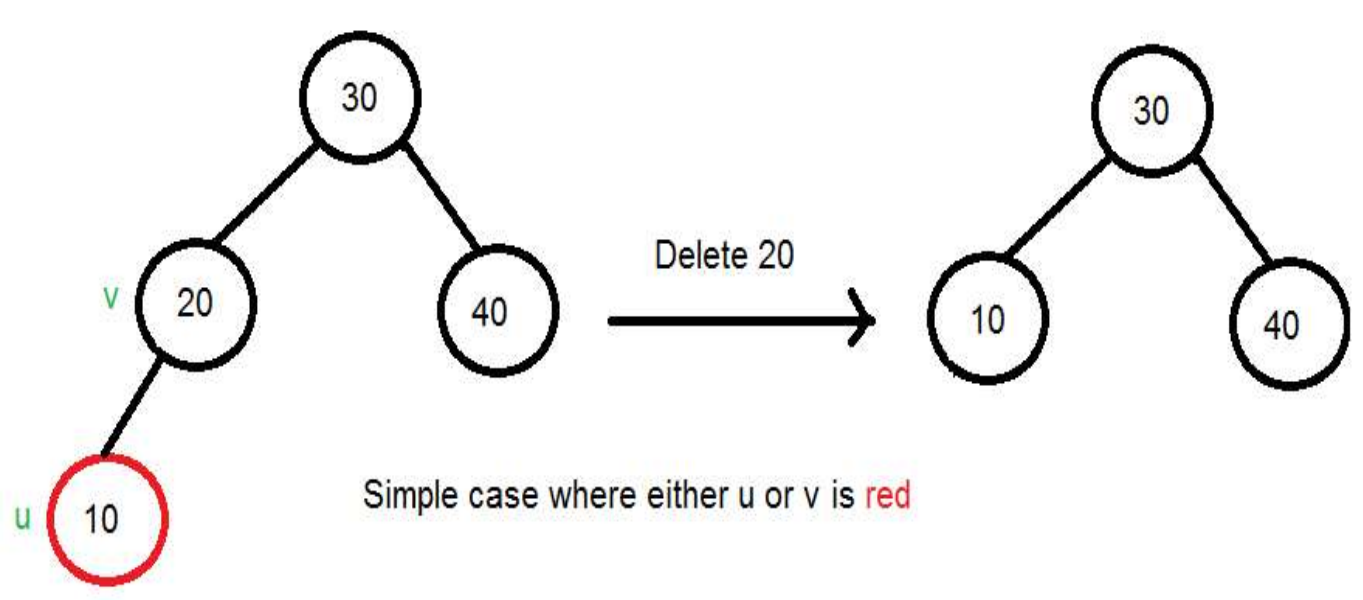
**Deletion Steps**

Following are detailed steps for deletion.

**1)** Perform standard BST delete. When we perform standard delete operation in BST, we always end up deleting a node which is an either leaf or has only one child (For an

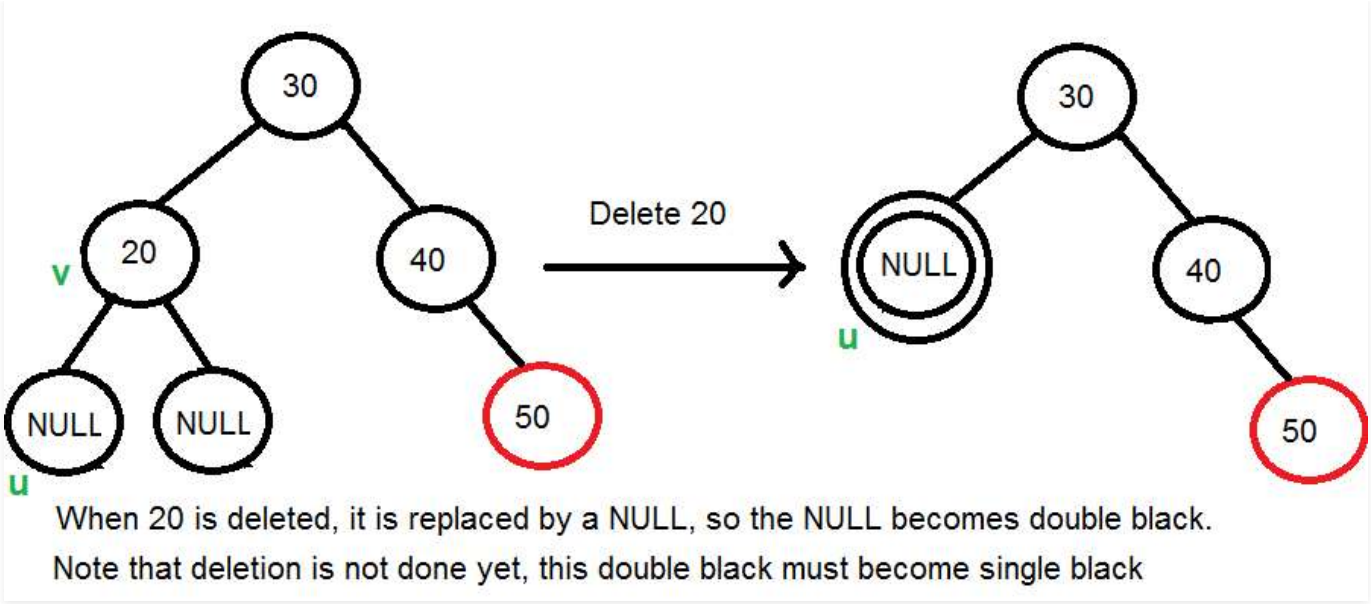
child that replaces v (Note that u is NULL when v is a leaf and color of NULL is considered as Black).

**2) Simple Case: If either u or v is red,** we mark the replaced child as black (No change in black height). Note that both u and v cannot be red as v is parent of u and two consecutive reds are not allowed in red-black tree.




**3) If Both u and v are Black**.

**3.1)** Color u as double black. Now our task reduces to convert this double black to single black. Note that If v is leaf, then u is NULL and color of NULL is considered black. So the deletion of a black leaf also causes a double black.



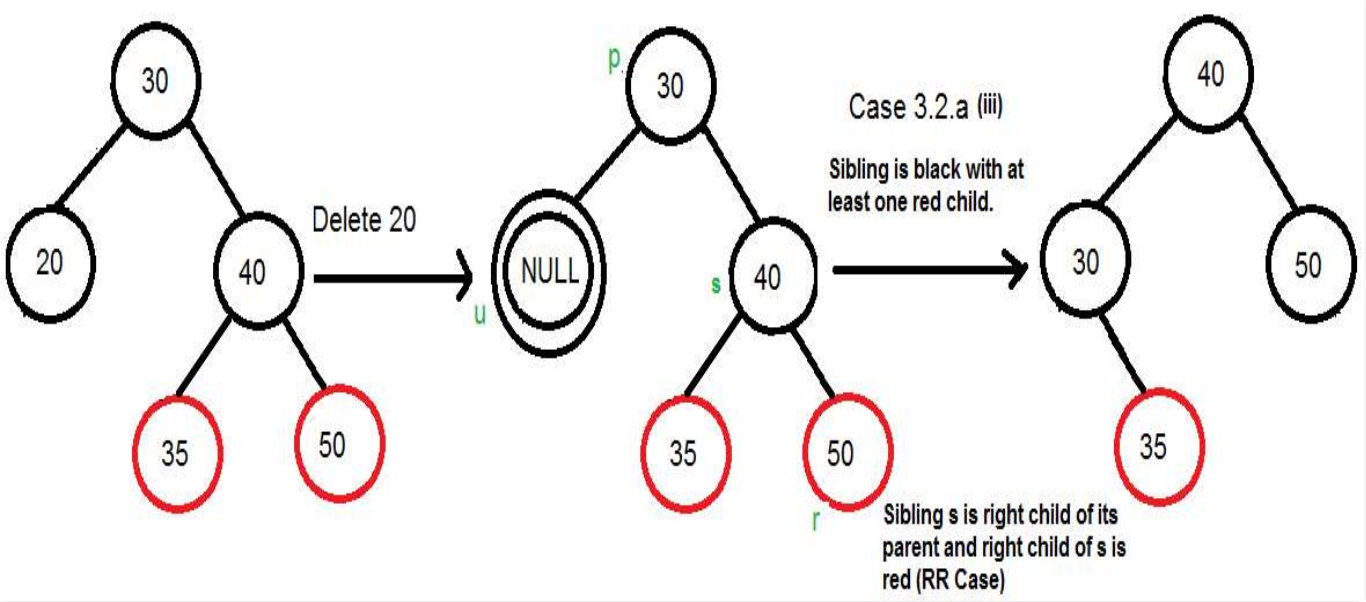

**3.2)** Do following while the current node u is double black, and it is not the root. Let sibling of node be **s**.

....**(a): If sibling s is black and at least one of sibling's children is red**, perform rotation(s). Let the red child of s be **r**. This case can be divided in four subcases depending upon positions of s and r.

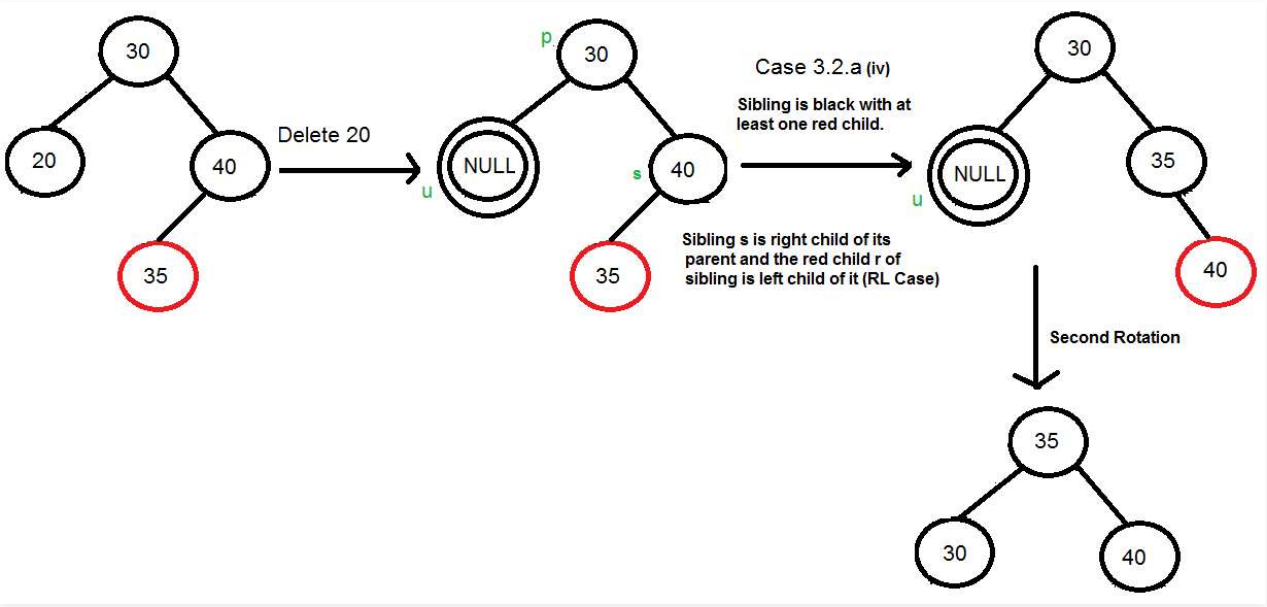
.....**(i)** Left Left Case (s is left child of its parent and r is left child of s or both children of s are red). This is mirror of right right case shown in below diagram.

.....**(ii)** Left Right Case (s is left child of its parent and r is right child). This is mirror of right left case shown in below diagram.

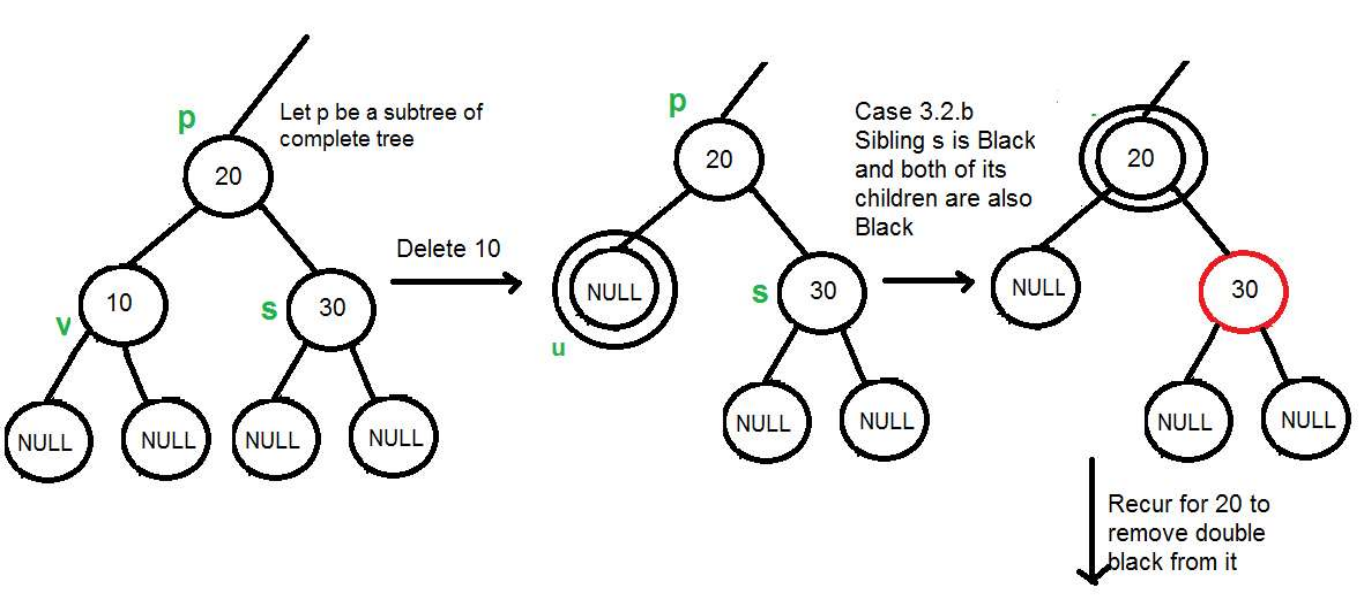
.....**(iii)** Right Right Case (s is right child of its parent and r is right child of s or both children of s are red)




.....**(iv)** Right Left Case (s is right child of its parent and r is left child of s)




.....**(b): If sibling is black and its both children are black**, perform recoloring, and recur for the parent if parent is black.

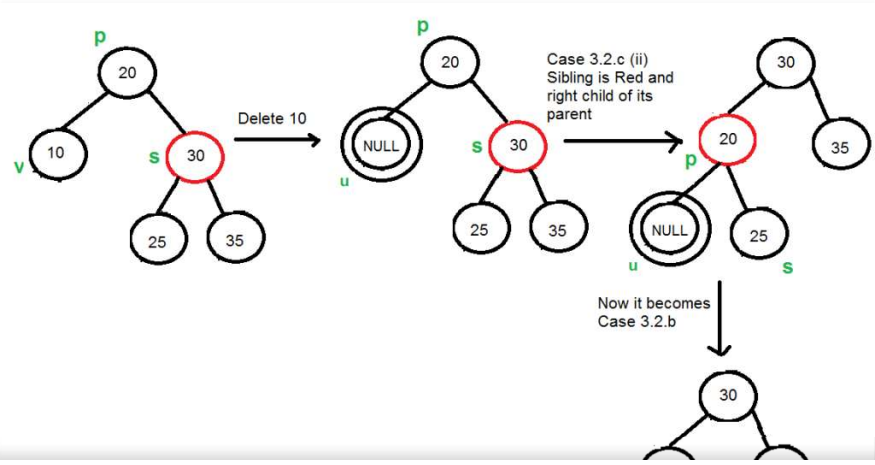



In this case, if parent was red, then we didn't need to recur for parent, we can simply make it black (red + double black = single black)

.....**(c): If sibling is red**, perform a rotation to move old sibling up, recolor the old sibling and parent. The new sibling is always black (See the below diagram). This mainly converts the tree to black sibling case (by rotation) and leads to case (a) or (b). This case can be divided in two subcases.

.....**(i)** Left Case (s is left child of its parent). This is mirror of right right case shown in below diagram. We right rotate the parent p.

.....**(ii)** Right Case (s is right child of its parent). We left rotate the parent p.



**3.3)** If u is root, make it single black and return (Black height of complete tree reduces by 1).

below is the C++ implementation of above approach:

---

```
#include <iostream>
#include <queue>
using namespace std;

enum COLOR { RED, BLACK };

class Node {
public:
  int val;
  COLOR color;
  Node *left, *right, *parent;

  Node(int val) : val(val) {
    parent = left = right = NULL;

    // Node is created during insertion
    // Node is red at insertion
    color = RED;
  }

  // returns pointer to uncle
  Node *uncle() {
    // If no parent or grandparent, then no uncle
    if (parent == NULL or parent->parent == NULL)
      return NULL;

    if (parent->isOnLeft())
      // uncle on right
      return parent->parent->right;
    else
      // uncle on left
      return parent->parent->left;
  }
```

```
    if (parent == NULL)
      return NULL;

    if (isOnLeft())
      return parent->right;

    return parent->left;
  }

  // moves node down and moves given node in its place
  void moveDown(Node *nParent) {
    if (parent != NULL) {
      if (isOnLeft()) {
        parent->left = nParent;
      } else {
        parent->right = nParent;
      }
    }
    nParent->parent = parent;
    parent = nParent;
  }

  bool hasRedChild() {
    return (left != NULL and left->color == RED) or
           (right != NULL and right->color == RED);
  }
};

class RBTree {
  Node *root;

  // left rotates the given node
  void leftRotate(Node *x) {
    // new parent will be node's right child
    Node *nParent = x->right;

    // update root if current node is root
    if (x == root)
      root = nParent;

    x->moveDown(nParent);

    // connect x with new parent's left element
    x->right = nParent->left;
```

```
  nParent->left = x;
}

void rightRotate(Node *x) {
  // new parent will be node's left child
  Node *nParent = x->left;

  // update root if current node is root
  if (x == root)
    root = nParent;

  x->moveDown(nParent);

  // connect x with new parent's right element
  x->left = nParent->right;
  // connect new parent's right element with node
  // if it is not null
  if (nParent->right != NULL)
    nParent->right->parent = x;

  // connect new parent with x
  nParent->right = x;
}

void swapColors(Node *x1, Node *x2) {
  COLOR temp;
  temp = x1->color;
  x1->color = x2->color;
  x2->color = temp;
}

void swapValues(Node *u, Node *v) {
  int temp;
  temp = u->val;
  u->val = v->val;
  v->val = temp;
}

// fix red red at given node
void fixRedRed(Node *x) {
  // if x is root color it black and return
  if (x == root) {
    x->color = BLACK;
    return;
```

```
    if (parent->color != BLACK) {
      if (uncle != NULL && uncle->color == RED) {
        // uncle red, perform recoloring and recurse
        parent->color = BLACK;
        uncle->color = BLACK;
        grandparent->color = RED;
        fixRedRed(grandparent);
      } else {
        // Else perform LR, LL, RL, RR
        if (parent->isOnLeft()) {
          if (x->isOnLeft()) {
            // for left right
            swapColors(parent, grandparent);
          } else {
            leftRotate(parent);
            swapColors(x, grandparent);
          }
          // for left left and left right
          rightRotate(grandparent);
        } else {
          if (x->isOnLeft()) {
            // for right left
            rightRotate(parent);
            swapColors(x, grandparent);
          } else {
            swapColors(parent, grandparent);
          }

          // for right right and right left
          leftRotate(grandparent);
        }
      }
    }
  }

  // find node that do not have a left child
  // in the subtree of the given node
  Node *successor(Node *x) {
    Node *temp = x;

    while (temp->left != NULL)
      temp = temp->left;

    return temp;
```

```
    return successor(x->right);

  // when leaf
  if (x->left == NULL and x->right == NULL)
    return NULL;

  // when single child
  if (x->left != NULL)
    return x->left;
  else
    return x->right;
}

// deletes the given node
void deleteNode(Node *v) {
  Node *u = BSTreplace(v);

  // True when u and v are both black
  bool uvBlack = ((u == NULL or u->color == BLACK) and (v->color == BLACK));
  Node *parent = v->parent;

  if (u == NULL) {
    // u is NULL therefore v is leaf
    if (v == root) {
      // v is root, making root null
      root = NULL;
    } else {
      if (uvBlack) {
        // u and v both black
        // v is leaf, fix double black at v
        fixDoubleBlack(v);
      } else {
        // u or v is red
        if (v->sibling() != NULL)
          // sibling is not null, make it red"
          v->sibling()->color = RED;
      }

      // delete v from the tree
      if (v->isOnLeft()) {
        parent->left = NULL;
      } else {
        parent->right = NULL;
      }
```

```
    // v has 1 child
    if (v == root) {
      // v is root, assign the value of u to v, and delete u
      v->val = u->val;
      v->left = v->right = NULL;
      delete u;
    } else {
      // Detach v from tree and move u up
      if (v->isOnLeft()) {
        parent->left = u;
      } else {
        parent->right = u;
      }
      delete v;
      u->parent = parent;
      if (uvBlack) {
        // u and v both black, fix double black at u
        fixDoubleBlack(u);
      } else {
        // u or v red, color u black
        u->color = BLACK;
      }
    }
    return;
  }

  // v has 2 children, swap values with successor and recurse
  swapValues(u, v);
  deleteNode(u);
}

void fixDoubleBlack(Node *x) {
  if (x == root)
    // Reached root
    return;

  Node *sibling = x->sibling(), *parent = x->parent;
  if (sibling == NULL) {
    // No sibiling, double black pushed up
    fixDoubleBlack(parent);
  } else {
    if (sibling->color == RED) {
      // Sibling red
      parent->color = RED;
```

```
            leftRotate(parent);
          }
          fixDoubleBlack(x);
        } else {
          // Sibling black
          if (sibling->hasRedChild()) {
            // at least 1 red children
            if (sibling->left != NULL and sibling->left->color == RED) {
              if (sibling->isOnLeft()) {
                // left left
                sibling->left->color = sibling->color;
                sibling->color = parent->color;
                rightRotate(parent);
              } else {
                // right left
                sibling->left->color = parent->color;
                rightRotate(sibling);
                leftRotate(parent);
              }
            } else {
              if (sibling->isOnLeft()) {
                // left right
                sibling->right->color = parent->color;
                leftRotate(sibling);
                rightRotate(parent);
              } else {
                // right right
                sibling->right->color = sibling->color;
                sibling->color = parent->color;
                leftRotate(parent);
              }
            }
            parent->color = BLACK;
          } else {
            // 2 black children
            sibling->color = RED;
            if (parent->color == BLACK)
              fixDoubleBlack(parent);
            else
              parent->color = BLACK;
          }
        }
      }
    }
```

```
    // queue for level order
    queue<Node *> q;
    Node *curr;

    // push x
    q.push(x);

    while (!q.empty()) {
      // while q is not empty
      // dequeue
      curr = q.front();
      q.pop();

      // print node value
      cout << curr->val << " ";

      // push children to queue
      if (curr->left != NULL)
        q.push(curr->left);
      if (curr->right != NULL)
        q.push(curr->right);
    }
  }

  // prints inorder recursively
  void inorder(Node *x) {
    if (x == NULL)
      return;
    inorder(x->left);
    cout << x->val << " ";
    inorder(x->right);
  }

public:
  // constructor
  // initialize root
  RBTree() { root = NULL; }

  Node *getRoot() { return root; }

  // searches for given value
  // if found returns the node (used for delete)
  // else returns the last node while traversing (used in insert)
```

```
      else
        temp = temp->left;
    } else if (n == temp->val) {
      break;
    } else {
      if (temp->right == NULL)
        break;
      else
        temp = temp->right;
    }
  }

  return temp;
}

// inserts the given value to tree
void insert(int n) {
  Node *newNode = new Node(n);
  if (root == NULL) {
    // when root is null
    // simply insert value at root
    newNode->color = BLACK;
    root = newNode;
  } else {
    Node *temp = search(n);

    if (temp->val == n) {
      // return if value already exists
      return;
    }

    // if value is not found, search returns the node
    // where the value is to be inserted

    // connect new node to correct node
    newNode->parent = temp;

    if (n < temp->val)
      temp->left = newNode;
    else
      temp->right = newNode;

    // fix red red voilaton if exists
    fixRedRed(newNode);
```

```
      // Tree is empty
      return;

    Node *v = search(n), *u;

    if (v->val != n) {
      cout << "No node found to delete with value:" << n << endl;
      return;
    }

    deleteNode(v);
  }

  // prints inorder of the tree
  void printInOrder() {
    cout << "Inorder: " << endl;
    if (root == NULL)
      cout << "Tree is empty" << endl;
    else
      inorder(root);
    cout << endl;
  }

  // prints level order of the tree
  void printLevelOrder() {
    cout << "Level order: " << endl;
    if (root == NULL)
      cout << "Tree is empty" << endl;
    else
      levelOrder(root);
    cout << endl;
  }
};

int main() {
  RBTree tree;

  tree.insert(7);
  tree.insert(3);
  tree.insert(18);
  tree.insert(10);
  tree.insert(22);
  tree.insert(8);
  tree.insert(11);
```

```
  tree.printLevelOrder();

  cout<<endl<<"Deleting 18, 11, 3, 10, 22"<<endl;

  tree.deleteByVal(18);
  tree.deleteByVal(11);
  tree.deleteByVal(3);
  tree.deleteByVal(10);
  tree.deleteByVal(22);

  tree.printInOrder();
  tree.printLevelOrder();
  return 0;
}
```

Output:

```
Inorder:
2 3 6 7 8 10 11 13 18 22 26
Level order:
10 7 18 3 8 11 22 2 6 13 26

Deleting 18, 11, 3, 10, 22
Inorder:
2 6 7 8 13 26
Level order:
13 7 26 6 8 2
```

**References:**

https://www.cs.purdue.edu/homes/ayg/CS251/slides/chap13c.pdf

Introduction to Algorithms 3rd Edition by Clifford Stein, Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest

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