```java
/*
 * HSR − Uebungen ’Algorithmen & Datenstrukturen 2’
 * Version: Mon Oct  8 16:47:09 CEST 2018
 */

package uebung04.as.aufgabe01;

import java.util.Collection;

import uebung02.ml.aufgabe01.BinarySearchTree.Entry;


public class AVLTree <K extends Comparable<? super K>, V> {

  private AVLTreeImpl<K, V> avlTreeImpl = new AVLTreeImpl<K, V>();

  // Start the GVS−Server first: Double−Click ’GVS_Server_v1.4.jar’
  //private AVLTreeImpl<K, V> avlTreeImpl = new AVLTreeImplGVS<K, V>();

  public V put(K key, V value) {
    return avlTreeImpl.put(key, value);
  }

  public V get(K key) {
    return avlTreeImpl.get(key);
  }

  public V remove(K key) {
    return avlTreeImpl.remove(key);
  }

  public int getHeight() {
    return avlTreeImpl.getHeight();
  }

  public int size() {
    return avlTreeImpl.size();
  }

  public boolean isEmpty() {
    return avlTreeImpl.isEmpty();
  }

  public void clear() {
    avlTreeImpl.clear();
  }

  public Collection<Entry<K, V>> inorder() {
    return avlTreeImpl.inorder();
  }

  public void printInorder() {
    avlTreeImpl.printInorder();
  }

  public void print() {
    avlTreeImpl.print();
  }
```

```java

  protected AVLTreeImpl<K, V> getImpl() {
    return avlTreeImpl;
  }

  public static void main(String[] args) {

    AVLTree<Integer, String> avlTree = new AVLTree<Integer, String>();

    System.out.println("Inserting 5:");
    avlTree.put(5, "Str_5");
    avlTree.print();
    System.out.println("================================");
    System.out.println("Inserting 7:");
    avlTree.put(7, "Str_7");
    avlTree.print();
    System.out.println("================================");
    System.out.println("Inserting 9: Single−Rotation");
    avlTree.put(9, "Str_9");
    avlTree.print();
    System.out.println("================================");
    System.out.println("Inserting 3:");
    avlTree.put(3, "Str_3");
    avlTree.print();
    System.out.println("================================");
    System.out.println("Inserting 1: Single−Rotation");
    avlTree.put(1, "Str_1");
    avlTree.print();
    System.out.println("================================");
    System.out.println("Inserting 4: Double−Rotation");
    avlTree.put(4, "Str_4");
    avlTree.print();
    System.out.println("================================");

    if (avlTree.getImpl() instanceof AVLTreeImplGVS) {
      ((AVLTreeImplGVS<Integer, String>)avlTree.getImpl()).gvsTree.disconnect();
    }

  }

}

```

```

/* Session−Log:

Inserting 5:
 5 − Str_5  : h=0 ROOT
================================
Inserting 7:
 5 − Str_5  : h=1 ROOT
 7 − Str_7  : h=0 \ parent(key)=5
================================
Inserting 9: Single−Rotation
 5 − Str_5  : h=0 / parent(key)=7
 7 − Str_7  : h=1 ROOT
 9 − Str_9  : h=0 \ parent(key)=7
================================
Inserting 3:
 3 − Str_3  : h=0 / parent(key)=5
 5 − Str_5  : h=1 / parent(key)=7
 7 − Str_7  : h=2 ROOT
 9 − Str_9  : h=0 \ parent(key)=7
================================
Inserting 1: Single−Rotation
 1 − Str_1  : h=0 / parent(key)=3
 3 − Str_3  : h=1 / parent(key)=7
 5 − Str_5  : h=0 \ parent(key)=3
 7 − Str_7  : h=2 ROOT
 9 − Str_9  : h=0 \ parent(key)=7
================================
Inserting 4: Double−Rotation
 1 − Str_1  : h=0 / parent(key)=3
 3 − Str_3  : h=1 / parent(key)=5
 4 − Str_4  : h=0 \ parent(key)=3
 5 − Str_5  : h=2 ROOT
 7 − Str_7  : h=1 \ parent(key)=5
 9 − Str_9  : h=0 \ parent(key)=7
================================

*/
```

```
/*
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 */

package uebung04.as.aufgabe01;

import java.util.Collection;
import java.util.LinkedList;
import java.util.List;

import uebung02.ml.aufgabe01.BinarySearchTree;

class AVLTreeImpl<K extends Comparable<? super K>, V> extends
    BinarySearchTree<K, V> {

  /**
   * After a BST−operation, actionNode shall point to where the balance has to
   * be checked. −> rebalance() will then be called with actionNode.
   */
  protected AVLNode actionNode;


  protected class AVLNode extends BinarySearchTree<K, V>.Node {

    private int height;
    private Node parent;

    AVLNode(Entry<K, V> entry) {
      super(entry);
    }

    protected AVLNode setParent(AVLNode parent) {
      AVLNode old = avlNode(this.parent);
      this.parent = parent;
      return old;
    }

    protected AVLNode getParent() {
      return avlNode(parent);
    }

    protected int setHeight(int height) {
      int old = this.height;
      this.height = height;
      return old;
    }

    protected int getHeight() {
      return height;
    }

    @Override
    public AVLNode getLeftChild() {
      return avlNode(super.getLeftChild());
    }

    @Override
    public AVLNode getRightChild() {
      return avlNode(super.getRightChild());
    }
```

```java

    @Override
    public String toString() {
      String result = String.format("%2d - %-6s : h=%d",
                              getEntry().getKey(), getEntry().getValue(), height);
      if (parent == null) {
        result += " ROOT";
      } else {
        boolean left = (parent.getLeftChild() == this) ? true : false;
        result += (left ? " / " : " \\ ") + "parent(key)="
            + parent.getEntry().getKey();
      }
      return result;
    }

  } // End of class AVLNode


  protected AVLNode getRoot() {
    return avlNode(root);
  }

  public V put(K key, V value) {
    Entry<K, V> entry = find(key);
    if (entry != null) {
      // key already exists in the Tree
      return entry.setValue(value);
    } else {
      // key does not exist in the Tree yet
      super.insert(key, value);
      rebalance(actionNode);
      actionNode = null;
      return null;
    }
  }

  public V get(K key) {
    Entry<K, V> entry = super.find(key);
    if (entry != null) {
      return entry.getValue();
    } else {
      return null;
    }
  }

  @Override
  protected Node insert(Node node, Entry<K, V> entry) {
    if (node != null) {
      actionNode = avlNode(node);
    }
    // calling now the BST-insert() which will do the work:
    AVLNode result = avlNode(super.insert(node, entry));
    if (node == null) {
      // In this case: result of super.insert() is the new node!
      result.setParent(actionNode);
    }
    return result;
  }

  /**
   * The height of the tree.
   *
   * @return The actual height. -1 for an empty tree.
   */
  @Override
  public int getHeight() {
    return height(avlNode(root));
  }
```

```java

  /**
   * Returns the height of this node.
   *
   * @param node
   * @return The height or -1 if null.
   */
  protected int height(AVLNode node) {
    return (node != null) ? node.getHeight() : -1;
  }

  /**
   * Restructures the tree with rotations.
   *
   * @param xPos
   *          The X-node.
   * @return The new root-node of this subtree.
   */
  protected AVLNode restructure(AVLNode xPos) {
    // TODO Implement here...
    return null;
  }

  protected AVLNode tallerChild(AVLNode node) {
    // TODO Implement here...
    return null;
  }

  protected AVLNode rotateWithLeftChild(AVLNode k2) {
    // TODO Implement here...
    return null;
  }

  protected AVLNode doubleRotateWithLeftChild(AVLNode k3) {
    // TODO Implement here...
    return null;
  }

  protected AVLNode rotateWithRightChild(AVLNode k1) {
    // TODO Implement here...
    return null;
  }

  protected AVLNode doubleRotateWithRightChild(AVLNode k3) {
    // TODO Implement here...
    return null;
  }

  protected boolean isBalanced(AVLNode node) {
    // TODO Implement here...
    return false;
  }

  /**
   * Assures the balance of the tree from 'node' up to the root.
   *
   * @param node
   *          The node from where to start.
   */
  protected void rebalance(AVLNode node) {
    // TODO Implement here...
  }

  /**
   * Assures the correct height for node.
   *
   * @param node
   *          The node to assure its height.
   */
  protected void setHeight(AVLNode node) {
    if (node == null) {
      return;
    }
    int heightLeftChild = height(node.getLeftChild());
    int heightRightChild = height(node.getRightChild());
    node.setHeight(1 + Math.max(heightLeftChild, heightRightChild));
  }

  /**
   * Factory-Method. Creates a new node.
   *
   * @param entry
   *          The entry to be inserted in the new node.
   * @return The new created node.
   */
  @Override
  protected Node newNode(Entry<K, V> entry) {
    return new AVLNode(entry);
  }

  public V remove(K key) {
    // TODO Implement here...
    return null;
  }

  /**
   * Generates an inorder-node-list.
   *
   * @param nodeList
   *          The node-list to fill in inorder.
   * @param node
   *          The node to start from.
   */
  protected void inorder(Collection<AVLNode> nodeList, AVLNode node) {
    if (node == null)
      return;
    inorder(nodeList, node.getLeftChild());
    nodeList.add(node);
    inorder(nodeList, node.getRightChild());
  }

  @SuppressWarnings("unchecked")
  protected AVLNode avlNode(Node node) {
    return (AVLNode)node;
  }

  public void print() {
    List<AVLNode> nodeList = new LinkedList<>();
    inorder(nodeList, avlNode(root));
    for (AVLNode node: nodeList) {
      System.out.println(node + "  ");
    }
  }

}


```

```java
/*
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 */

package uebung04.as.aufgabe01;

import gvs.tree.GVSBinaryTreeNode;
import gvs.tree.GVSTreeWithRoot;
import gvs.typ.node.GVSNodeTyp;

class AVLTreeImplGVS<K extends Comparable<? super K>, V> extends
    AVLTreeImpl<K, V> {

  protected GVSTreeWithRoot gvsTree;

  private final int DELAY = 200;

  protected class AVLNodeGVS extends AVLTreeImpl<K, V>.AVLNode implements GVSBinaryTre
eNode {

    protected AVLNodeGVS(Entry<K, V> entry) {
      super(entry);
    }

    public GVSBinaryTreeNode getGVSLeftChild() {
      return (GVSBinaryTreeNode) getLeftChild();
    }

    public GVSBinaryTreeNode getGVSRightChild() {
      return (GVSBinaryTreeNode) getRightChild();
    }

    public String getNodeLabel() {
      Entry<K, V> e = getEntry();
      return e.getKey() + " "+ e.getValue();
      //return e.getKey().toString();
    }

    public GVSNodeTyp getNodeTyp() {
      return null;
    }

  } // class BinaryTreeTestGVS.NodeGVS


  AVLTreeImplGVS() {
    this("AVLTreeGVS");
  }

  AVLTreeImplGVS(String title) {
    gvsTree = new GVSTreeWithRoot(title);
  }

  @Override
  protected Node newNode(Entry<K, V> entry) {
    return new AVLNodeGVS(entry);
  }

  @Override
  public V put(K key, V value) {
    V result = super.put(key, value);
    gvsTree.setRoot((GVSBinaryTreeNode) root);
    gvsTree.display();
    try {Thread.sleep(DELAY);} catch (InterruptedException e) {}
    return result;
  }

  @Override
  protected AVLNode rotateWithRightChild(AVLNode k1) {
    gvsTree.setRoot((GVSBinaryTreeNode) root);
    gvsTree.display();
    try {Thread.sleep(DELAY);} catch (InterruptedException e) {}
    AVLNode newRoot = super.rotateWithRightChild(k1);
    return newRoot;
  }

  @Override
  protected AVLNode rotateWithLeftChild(AVLNode k2) {
    gvsTree.setRoot((GVSBinaryTreeNode) root);
    gvsTree.display();
    try {Thread.sleep(DELAY);} catch (InterruptedException e) {}
    AVLNode newRoot = super.rotateWithLeftChild(k2);
    return newRoot;
  }

  @Override
  public V remove(K key) {
    V result = super.remove(key);
    gvsTree.setRoot((GVSBinaryTreeNode) root);
    gvsTree.display();
    try {Thread.sleep(DELAY);} catch (InterruptedException e) {}
    return result;
  }

}
```

```
/*
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 */

package uebung04.as.aufgabe01;

import static org.junit.Assert.*;

import java.util.Collection;
import java.util.Hashtable;
import java.util.LinkedList;
import java.util.Map;
import java.util.Random;

import org.junit.After;
import org.junit.Before;
import org.junit.FixMethodOrder;
import org.junit.Test;
import org.junit.runners.MethodSorters;

import uebung02.ml.aufgabe01.BinarySearchTree.Entry;


@FixMethodOrder(MethodSorters.NAME_ASCENDING)
public class AVLTreeJUnitTest {

  AVLTreeImpl<Integer, String> avlTree;

  @Before
  public void setUp() {
    //System.setProperty("NoGVS", "true");
    avlTree = new AVLTree<Integer, String>().getImpl();
  }

  @After
  public void tearDown() {
    if (avlTree instanceof AVLTreeImplGVS) {
      ((AVLTreeImplGVS<Integer, String>)avlTree).gvsTree.disconnect();
    }
  }

  @Test
  public void test01Put() {
    int[] keys = { 2, 1, 3 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 ROOT",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
  }

  @Test
  public void test02Get() {
    int[] keys = { 2, 1, 5, 4, 3 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=2 ROOT",
        " 3 − Str_3  : h=0 / parent(key)=4",
        " 4 − Str_4  : h=1 \\ parent(key)=2",
        " 5 − Str_5  : h=0 \\ parent(key)=4",
    };
    runTest(keys, expected);
    assertEquals("Str_2", avlTree.get(2));
    assertEquals("Str_5", avlTree.get(5));
    assertNull(avlTree.get(0));
    assertNull(avlTree.get(6));
  }
```

```java

  @Test
  public void test03SingleRotationLeftInRoot() {
    int[] keys = { 1, 2, 3 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 ROOT",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
  }

  @Test
  public void test04SingleRotationLeftBelowRoot() {
    int[] keys = { 5, 6, 1, 2, 3 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 / parent(key)=5",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
        " 5 - Str_5  : h=2 ROOT",
        " 6 - Str_6  : h=0 \\ parent(key)=5",
    };
    runTest(keys, expected);
  }

  @Test
  public void test05SingleRotationRightInRoot() {
    int[] keys = { 3, 2, 1 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 ROOT",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
  }

  @Test
  public void test06SingleRotationRightBelowRoot() {
    int[] keys = { 2, 1, 5, 4, 3 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=2 ROOT",
        " 3 - Str_3  : h=0 / parent(key)=4",
        " 4 - Str_4  : h=1 \\ parent(key)=2",
        " 5 - Str_5  : h=0 \\ parent(key)=4",
    };
    runTest(keys, expected);
  }

  @Test
  public void test07DoubleRotationLeftInRoot() {
    int[] keys = { 1, 3, 2 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 ROOT",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
  }
```

```java

  @Test
  public void test08DoubleRotationLeftBelowRoot() {
    int[] keys = { 2, 1, 3, 5, 4 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=2 ROOT",
        " 3 - Str_3  : h=0 / parent(key)=4",
        " 4 - Str_4  : h=1 \\ parent(key)=2",
        " 5 - Str_5  : h=0 \\ parent(key)=4",
    };
    runTest(keys, expected);
  }

  @Test
  public void test09DoubleRotationRightinRoot() {
    int[] keys = { 3, 1, 2 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 ROOT",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
  }

  @Test
  public void test10DoubleRotationRightBelowRoot() {
    int[] keys = { 4, 3, 5, 1, 2 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 / parent(key)=4",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
        " 4 - Str_4  : h=2 ROOT",
        " 5 - Str_5  : h=0 \\ parent(key)=4",
    };
    runTest(keys, expected);
  }

  @Test
  public void test11MultipleSameKeys() {
    int[] keys = { 3, 1, 2 };
    String[] expected = {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_2  : h=1 ROOT",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
    avlTree.put(2, "Str_22");
    avlTree.put(2, "Str_23");
    expected = new String[] {
        " 1 - Str_1  : h=0 / parent(key)=2",
        " 2 - Str_23 : h=1 ROOT",
        " 3 - Str_3  : h=0 \\ parent(key)=2",
    };
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }

  @Test
  public void test12RemovingCase1() {
    // L?schen Fall 1 gem. BST−Folie 12:
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 6, 2, 9, 1, 4, 8 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 / parent(key)=6",
        " 4 − Str_4  : h=0 \\ parent(key)=2",
        " 6 − Str_6  : h=2 ROOT",
        " 8 − Str_8  : h=0 / parent(key)=9",
        " 9 − Str_9  : h=1 \\ parent(key)=6",
    };
    runTest(keys, expected);
    assertEquals("Str_4", avlTree.remove(4));
    expected = new String[] {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 / parent(key)=6",
        " 6 − Str_6  : h=2 ROOT",
        " 8 − Str_8  : h=0 / parent(key)=9",
        " 9 − Str_9  : h=1 \\ parent(key)=6",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }

  @Test
  public void test13RemovingCase2() {
    // L?schen Fall 2 gem. BST−Folie 13:
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 6, 2, 9, 1, 4, 8, 5 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=2 / parent(key)=6",
        " 4 − Str_4  : h=1 \\ parent(key)=2",
        " 5 − Str_5  : h=0 \\ parent(key)=4",
        " 6 − Str_6  : h=3 ROOT",
        " 8 − Str_8  : h=0 / parent(key)=9",
        " 9 − Str_9  : h=1 \\ parent(key)=6",
    };
    runTest(keys, expected);
    assertEquals("Str_4", avlTree.remove(4));
    expected = new String[] {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 / parent(key)=6",
        " 5 − Str_5  : h=0 \\ parent(key)=2",
        " 6 − Str_6  : h=2 ROOT",
        " 8 − Str_8  : h=0 / parent(key)=9",
        " 9 − Str_9  : h=1 \\ parent(key)=6",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }
```

```java

  @Test
  public void test14RemovingCase3() {
    // L?schen Fall 3 gem. BST−Folie 14:
    // Hinweis: Baum entsprechend ’aufgef?llt’ (wegen AVL!)
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 1, −10, 4, −15, −5, 2, 9, −18, −12, −7, −3, 3, 7, 10, 6 };
    String[] expected = {
        "−18 − Str_−18 : h=0 / parent(key)=−15",
        "−15 − Str_−15 : h=1 / parent(key)=−10",
        "−12 − Str_−12 : h=0 \\ parent(key)=−15",
        "−10 − Str_−10 : h=2 / parent(key)=1",
        "−7 − Str_−7 : h=0 / parent(key)=−5",
        "−5 − Str_−5 : h=1 \\ parent(key)=−10",
        "−3 − Str_−3 : h=0 \\ parent(key)=−5",
        " 1 − Str_1  : h=4 ROOT",
        " 2 − Str_2  : h=1 / parent(key)=4",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
        " 4 − Str_4  : h=3 \\ parent(key)=1",
        " 6 − Str_6  : h=0 / parent(key)=7",
        " 7 − Str_7  : h=1 / parent(key)=9",
        " 9 − Str_9  : h=2 \\ parent(key)=4",
        "10 − Str_10 : h=0 \\ parent(key)=9",
    };
    runTest(keys, expected);
    assertEquals("Str_4", avlTree.remove(4));
    expected = new String[] {
        "−18 − Str_−18 : h=0 / parent(key)=−15",
        "−15 − Str_−15 : h=1 / parent(key)=−10",
        "−12 − Str_−12 : h=0 \\ parent(key)=−15",
        "−10 − Str_−10 : h=2 / parent(key)=1",
        "−7 − Str_−7 : h=0 / parent(key)=−5",
        "−5 − Str_−5 : h=1 \\ parent(key)=−10",
        "−3 − Str_−3 : h=0 \\ parent(key)=−5",
        " 1 − Str_1  : h=3 ROOT",
        " 2 − Str_2  : h=1 / parent(key)=6",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
        " 6 − Str_6  : h=2 \\ parent(key)=1",
        " 7 − Str_7  : h=0 / parent(key)=9",
        " 9 − Str_9  : h=1 \\ parent(key)=6",
        "10 − Str_10 : h=0 \\ parent(key)=9",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }

  @Test
  public void test15RemovingAtRoot1() {
    int[] keys = { 1, 2, 3 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 ROOT",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
    assertEquals("Str_1", avlTree.remove(1));
    assertEquals(2, avlTree.size());
    assertEquals("Str_3", avlTree.remove(3));
    assertEquals(1, avlTree.size());
    assertEquals("Str_2", avlTree.remove(2));
    assertEquals(0, avlTree.size());
  }

  @Test
  public void test16RemovingAtRoot2() {
    int[] keys = { 1, 2, 3 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 ROOT",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
    assertEquals("Str_1", avlTree.remove(1));
    assertEquals(2, avlTree.size());
    assertEquals("Str_2", avlTree.remove(2));
    assertEquals(1, avlTree.size());
    assertEquals("Str_3", avlTree.remove(3));
    assertEquals(0, avlTree.size());
  }

  @Test
  public void test17RemovingAtRoot3() {
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 1, 2, 3 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 ROOT",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
    assertEquals("Str_2", avlTree.remove(2));
    expected = new String[] {
        " 1 − Str_1  : h=0 / parent(key)=3",
        " 3 − Str_3  : h=1 ROOT",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
    assertEquals(2, avlTree.size());
    assertEquals("Str_3", avlTree.remove(3));
    assertEquals(1, avlTree.size());
    assertEquals("Str_1", avlTree.remove(1));
    assertEquals(0, avlTree.size());
  }

  @Test
  public void test18RemovingAtRoot4() {
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 3, 2, 6, 4 };
    String[] expected = {
        " 2 − Str_2  : h=0 / parent(key)=3",
        " 3 − Str_3  : h=2 ROOT",
        " 4 − Str_4  : h=0 / parent(key)=6",
        " 6 − Str_6  : h=1 \\ parent(key)=3",
    };
    runTest(keys, expected);
    assertEquals("Str_3", avlTree.remove(3));
    expected = new String[] {
        " 2 − Str_2  : h=0 / parent(key)=4",
        " 4 − Str_4  : h=1 ROOT",
        " 6 − Str_6  : h=0 \\ parent(key)=4",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }
```

```java

  @Test
  public void test19RemovingAtRoot5() {
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 3, 2, 6, 1, 4, 7, 5 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 / parent(key)=3",
        " 3 − Str_3  : h=3 ROOT",
        " 4 − Str_4  : h=1 / parent(key)=6",
        " 5 − Str_5  : h=0 \\ parent(key)=4",
        " 6 − Str_6  : h=2 \\ parent(key)=3",
        " 7 − Str_7  : h=0 \\ parent(key)=6",
    };
    runTest(keys, expected);
    assertEquals("Str_3", avlTree.remove(3));
    expected = new String[] {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 / parent(key)=4",
        " 4 − Str_4  : h=2 ROOT",
        " 5 − Str_5  : h=0 / parent(key)=6",
        " 6 − Str_6  : h=1 \\ parent(key)=4",
        " 7 − Str_7  : h=0 \\ parent(key)=6",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }

  @Test
  public void test20RemovingAtRoot6() {
    int[] keys = { 1 };
    String[] expected = {
        " 1 − Str_1  : h=0 ROOT",
    };
    runTest(keys, expected);
    assertEquals(null, avlTree.remove(8888));
    assertEquals(1, avlTree.size());
    runTest(keys, expected);
    assertEquals("Str_1", avlTree.remove(1));
    assertEquals(0, avlTree.size());
  }

  @Test
  public void test21RemovingEntryNotInTree() {
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    int[] keys = { 1, 2, 3 };
    String[] expected = {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 ROOT",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
    };
    runTest(keys, expected);
    assertNull(avlTree.remove(4));
    expected = new String[] {
        " 1 − Str_1  : h=0 / parent(key)=2",
        " 2 − Str_2  : h=1 ROOT",
        " 3 − Str_3  : h=0 \\ parent(key)=2",
    };
    avlTree.inorder(nodes, avlTree.getRoot());
    verify(nodes, expected);
  }

  @Test
  public void test22StressTest() {
    final int SIZE = 10000;
    Random randomGenerator = new Random(1);
    // a Map to compare:
    Map<Integer, String> map = new Hashtable<Integer, String>();
    // key−Counters: count for every key how many time it was generated
    Map<Integer, Integer> keyCounters = new Hashtable<Integer, Integer>();
    // fill the Tree
    for (int i = 0; i < SIZE; i++) {
      int key = (int) (randomGenerator.nextFloat() * SIZE / 3);
      Integer numberOfKeys = keyCounters.get(key);
      if (numberOfKeys == null) {
        numberOfKeys = 1;
      } else {
        numberOfKeys++;
      }
      keyCounters.put(key, numberOfKeys);
      avlTree.put(key, "_" + i);
      map.put(key, "_" + i);
      assertEquals(keyCounters.size(), avlTree.size());
      assertEquals(map.size(), avlTree.size());
    }
    verifyInorder();
    // remove all Keys
    Integer[] keyArr = new Integer[1];
    keyArr = map.keySet().toArray(keyArr);
    for (int key : keyArr) {
      assertEquals(map.remove(key), avlTree.remove(key));
      assertEquals(map.size(), avlTree.size());
      verifyInorder();
    }
    assertEquals(0, avlTree.size());
  }

  private void verifyInorder() {
    Collection<Entry<Integer, String>> inorderList = avlTree.inorder();
    int last = Integer.MIN_VALUE;
    for (Entry<Integer, String> entry: inorderList) {
      Integer key = entry.getKey();
      assertTrue(key.compareTo(last) >= 0);
      last = key;
    }
  }

  private void runTest(int[] keys, String[] expected) {
    for (int key : keys) {
      avlTree.put(key, "Str_" + key);
    }
    Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes = new LinkedList<>();
    avlTree.inorder(nodes, avlTree.getRoot());
    assertEquals(expected.length, nodes.size());
    verify(nodes, expected);
  }

  private void verify(Collection<AVLTreeImpl<Integer, String>.AVLNode> nodes, String[]
 expected) {
    int i = 0;
    for (AVLTreeImpl<Integer, String>.AVLNode node: nodes) {
      String nodeStr = node.toString();
      String expectedStr = expected[i];
      assertEquals(expectedStr, nodeStr);
      i++;
    }
  }

}

```