Design Document

Both the red-black tree and AVL tree are efficient data structures as they provide means to insert, delete, and search the structure in O(log n) time. This program aims to implement the two efficient data structures in Rust and adds new features for them.
This program is written by Ahmed Al Dallal, Mohammad Amin Vafadar and Pengfei Gao.
If you want more information for the program, click [here](https://github.com/mavafadar/ECE-522-project).

ECE 522: Software Construction, Verification and Evolution

Both the red-black tree and AVL tree are efficient data structures as they provide means to insert, delete, and search the structure in O(log n) time. This program aims to implement the two efficient data structures in Rust and adds new features for them.

This program is written by Ahmed Al Dallal, Mohammad Amin Vafadar and Pengfei Gao. (Group 1)

9 - December - 2021

If you want more information for the program, click here.

Our 2-minute video highlighting the new system can be found here.

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Part 1: Major innovations

Additional features

Red-black tree

1. Print Pre-order traversal of the tree.
2. Print Post-order traversal of the tree.
3. Check whether the node is in the tree.
4. Get the minimum value in a tree.
5. Get the maximum value in a tree.
6. Count the number of nodes in a tree.
7. Clear the tree, removing all elements.

AVL tree

1. Print Pre-order traversal of the tree.
2. Print Post-order traversal of the tree.
3. Check whether the node is in the tree.
4. Get the minimum value in a tree.
5. Get the maximum value in a tree.
6. Count the number of nodes in a tree.
7. Clear the tree, removing all elements.

Detailed Rationale

Pre-order and Post-order traversal

Red-black tree and AVL tree are data structures based on binary tree. Pre-order traversal and post-order traversal are the two most common types of binary tree traversal. **Pre-order** traversal is mainly used when a tree needs to be duplicated. The feature of **Post-order** traversal is that the left and right child nodes of the node must have been traversed during operation, so it is suitable for destructive operations, such as deleting all nodes.

Check the existence of the node

Both the insertion and deletion operations of the tree need to judge whether the node to be operated exists in the tree structure. We also need this function when benchmarking code.

Maximum and Minimum value

There are also many practical applications to obtain the maximum and minimum values of a set of data. For example, find employees with the longest working hours in the company, check the lowest and highest scores of this exam.

The number of nodes

Red black tree and AVL tree are often used to store large-scale data. When analyzing these data, it is very important to obtain the total data. For example, calculate the average number and standard deviation.

Part 2: Current limitations

There are no errors, faults, defects, missing functionality, or limitations in our project that we are aware of.

Part 3: Design Questions

1. What does a red-black tree provide that cannot be accomplished with ordinary binary search trees?

In the worst-case scenario of continuously inserting or deleting values in either ascending or descending order in a binary search tree, the tree becomes unbalanced with nodes being entirely either on the right side or the left side of the tree. The time complexity for searching, deleting, and inserting in this worst-case scenario becomes O(n). Red-Black trees on the other hand are sometimes referred to as self-balancing trees, where whenever a new value is inserted or deleted, the tree is rebalanced, even if these values are continuously inserted or deleted ascending or descending order. As such, the time complexity of Red-Black trees for searching, deleting, and inserting should be O(log(n)). To summarize, Red-Black trees are more time efficient than binary search tree.

2. Please add a command-line interface (function main) to your crate to allow users to test it.

A command line interface has been successfully implemented where 3 different trees (Red-Black tree, AVL tree, and Binary Search tree) could be used with 14 different operations. The command line interface can be found in “CLI.rs” file and is called in the “main.rs” file.

3. Do you need to apply any kind of error handling in your system (e.g., panic macro, Option, Result, etc..)

The “Option” type is widely applied in our code.

4. What components do the Red-black tree and AVL tree have in common?

The common components we have between both tree types include getting the root of the tree, getting the left node, getting the right node, getting the data stored in a node, getting the height of the tree, getting the maximum and minimum values in the tree, counting the number of leaves and nodes in the tree, traversing the tree in in-order, pre-order, and post-order, searching for values in the tree, and checking if a tree is empty.

5. How do we construct our design to “allow it to be efficiently and effectively extended”? For example. Could your code be reused to build a 2-3-4 tree or B tree?

In our “base.rs” files we have two public traits called “Tree” and “TreeNode” that could be used to accommodate different kinds of trees. In these two traits, we could make use of the common components, such as the ones mentioned in the previous question, between different kinds of trees, such as a 2-3-4 tree or B tree, and build them.

Part 4: User manual

Operating environment

- Rust 1.50.0 or newer

  if you need help to install the Rust on your computer, please click the link below

  https://www.rust-lang.org/tools/install

Quick start

Command-line Interface

First, please enter cargo run on the terminal.

```
cargo run
```

You will see the welcome page.

There are three data structures you can use.

```
---------------------------------------- Welcome to our Trees Command Line Interface ----------
------------------------------

Available trees:
```

```
- Red-Black Tree
- AVL tree
- Binary Search Tree

Availabe operations:
1- Insert
2- Delete
3- Count Leaves
4- Count Nodes
5- Height
6- Maximum
7- Minimum
8- Empty
9- Search
10- Traverse
11- Print
12- Clear

How to use the Command Line Interface:
-------------------
You can select a tree number to start or type 'exit' to leave!
Select a tree!
1- Red-Black Tree
2- AVL Tree
3- Binary Search Tree
input >
```

Red-black Tree

In the welcome interface, please enter 1 to select the red black tree.

When you input 1, the output is as follows:

```
------ Red-Black Tree branch ------


Availabe Operations:
-------------------
Enter the number corresponding to the operation you want to perform!

1) Insert         - insert a node into the tree.
2) Delete         - delete a node from the tree.
3) Count Leaves   - count the number of leaves in the tree.
4) Count Nodes    - count the number of nodes in the tree
5) Height         - return the height of the tree
6) Maximum        - find the maximum value in the tree
7) Minimum        - find the minimum value in the tree
8) Empty          - check if the tree is empty
9) Search         - check if the tree contains a certain value
10) Traverse      - traverse the tree (Inorder, Preorder, or Postorder
11) Print         - print the tree
12) Clear         - clear the tree, removing all elements.
Back              - Go back to previous menu and erase current tree

Operation >
```

1. Select 1 to insert a node into the tree.

```
Operation > 1
```

When you input 1, the output is as follows:

```
insert value >
```

Please enter the value you want to insert.

We input 1 as an example. The output is as follows:

```
insert value > 1
The insert operation for '1' in the tree is complete!
```

If the entered value already exists, the output is as follows:

```
insert value > 1
The insert operation for '1' in the tree is complete!
The node already exists.
```

2. Select 2 to delete a node from the tree.

```
Operation > 2
```

When you input 2, the output is as follows:

```
delete value >
```

Please enter the value you want to delete.

We input 1 as an example. The output is as follows:

```
delete value > 1
The delete operation for '1' in the tree is complete!
```

If the value to delete does not exist, the output is as follows:

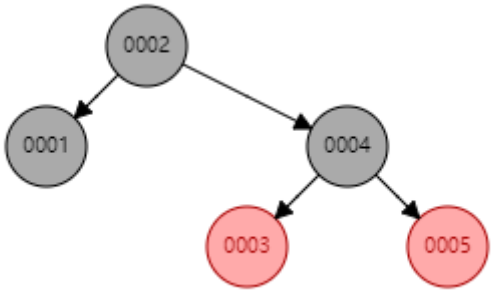
```
delete value > 1
The delete operation for '1' in the tree is complete!
The node of value: 1 doesn't exist.
```

3. Select 3 to count the number of leaves in the tree.

```
Operation > 3
```

When you input 3, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



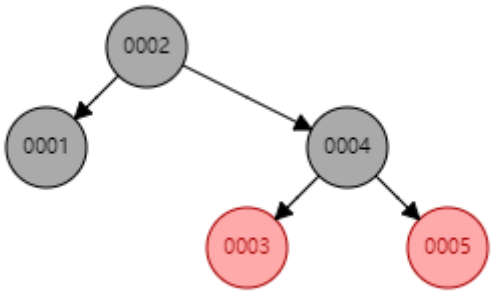

```
Number of leaves: 3
```

4. Select 4 to count the number of nodes in the tree.

```
Operation > 4
```

When you input 4, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



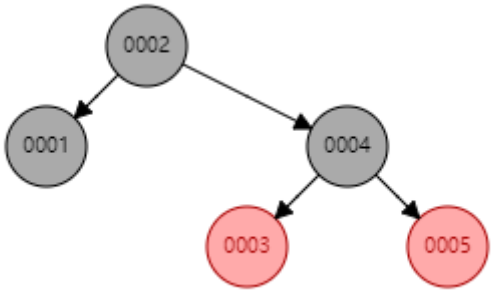

```
Number of nodes: 5
```

5. Select 5 to get the height of the tree.

```
Operation > 5
```

When you input 5, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



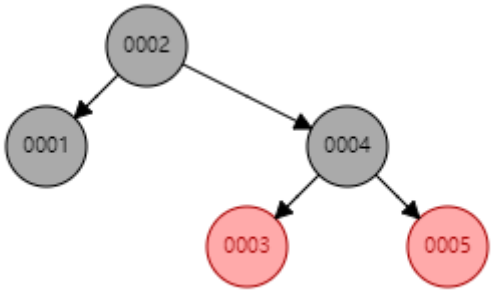

```
Height of the tree: 3
```

6. Select 6 to find the maximum value in the tree.

```
Operation > 6
```

When you input 6, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



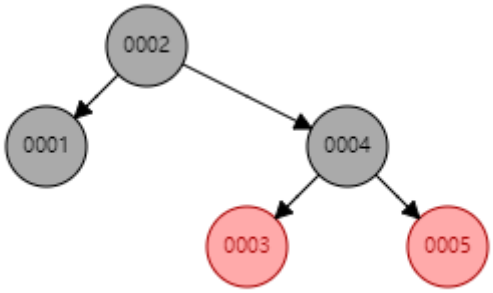

```
Maximum Value: 5
```

7. Select 7 to find the minimum value in the tree.

```
Operation > 7
```

When you input 7, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



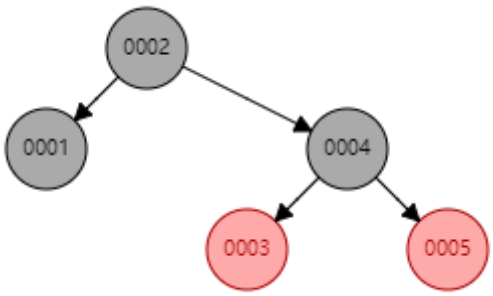

```
Minimum Value: 1
```

8. Select 8 to check if the tree is empty.

```
Operation > 8
```

When you input 8, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



```
Is the tree empty? false
```

If the tree is empty, the output is as follows:

```
Is the tree empty? true
```

9. Select 9 to check if the tree contains a certain value.

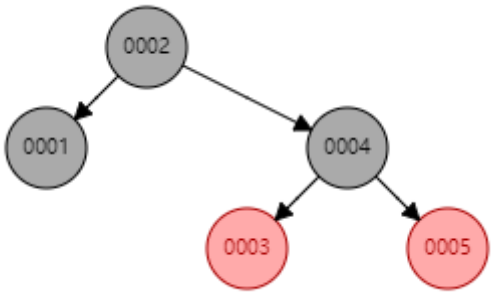
```
Operation > 9
```

When you input 9, the output is as follows:

```
search value >
```

We input 3 as an example. The output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.




```
search value > 3
The search operation for '3' in the tree is complete!
Value found? true
```

When the value you entered does not exist, the ouput is as follows:

```
search value > 6
The search operation for '6' in the tree is complete!
Value found? false
```

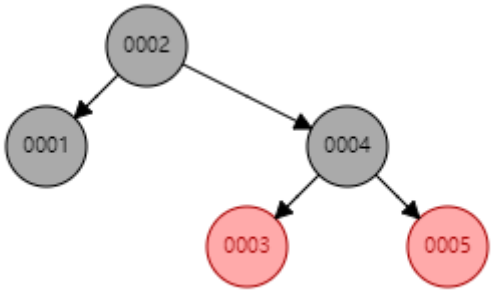
10. Select 10 to traverse the tree (Inorder, Preorder, or Postorder)

```
Operation > 10
```

When you input 10, the output is as follows:

```
Enter the number corresponding to the tree traversal type you want or type 'back' to select a
different operation!
1-Inorder
2-Preorder
3-Postorder
input >
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



When you enter 1, the output will be In-order traversal.

```
input > 1
Your tree:
1
2
3
4
5
```

When you enter 2, the output will be Pre-order traversal.

```
input > 2
Your tree:
2
1
4
3
5
```

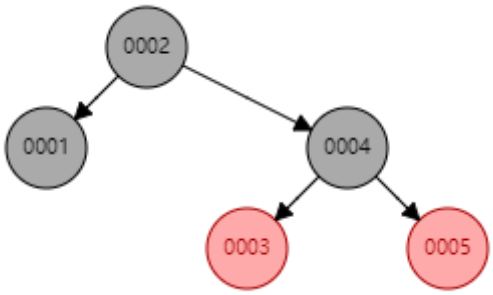
When you enter 3, the output will be Post-order traversal.

```
input > 3
Your tree:
1
3
5
4
2
```

11. Select 11 to print the tree.

```
Operation > 11
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



When you input 11, the output is as follows:

```
Root 2 Black
|___ L 1 Black
|___ R 4 Black
    |___ L 3 Red
    |___ R 5 Red
```

If the tree is empty, the output is as follows:

```
This tree is empty!
```

12. Select 12 to clear the tree and remove all elements.

```
Operation > 12
```

When you input 12, the output is as follows:

```
Operation > 12
Clear operation is complete!
```

Enter 8 to check if the tree is empty.

```
Operation > 8
Is the tree empty? true
```

13. Enter back to return to the previous menu.

```
Operation > back

You can select a tree number to start or type 'exit' to leave!
Select a tree!
1- Red-Black Tree
2- AVL Tree
3- Binary Search Tree
input >
```

AVL Tree

In the welcome interface, please enter 2 to select the AVL tree.

When you input 2, the output is as follows:

```
------ AVL Tree branch ------


Availabe Operations:
------------------
Enter the number corresponding to the operation you want to perform!

1) Insert         - insert a node into the tree.
2) Delete         - delete a node from the tree.
3) Count Leaves   - count the number of leaves in the tree.
```

```
4) Count Nodes    - count the number of nodes in the tree
5) Height         - return the height of the tree
6) Maximum        - find the maximum value in the tree
7) Minimum        - find the minimum value in the tree
8) Empty          - check if the tree is empty
9) Search         - check if the tree contains a certain value
10) Traverse      - traverse the tree (Inorder, Preorder, or Postorder
11) Print         - print the tree
12) Clear         - clear the tree, removing all elements.
Back              - Go back to previous menu and erase current tree

Operation >
```

1. Select 1 to insert a node into the tree.

   ```
   Operation > 1
   ```

   When you input 1, the output is as follows:

   ```
   insert value >
   ```

   Please enter the value you want to insert.

   We input 1 as an example. The output is as follows:

   ```
   insert value > 1
   The insert operation for '1' in the tree is complete!
   ```

   If the entered value already exists, the output is as follows:

   ```
   insert value > 1
   The insert operation for '1' in the tree is complete!
   The node already exists.
   ```

2. Select 2 to delete a node from the tree.

   ```
   Operation > 2
   ```

   When you input 2, the output is as follows:

   ```
   delete value >
   ```

   Please enter the value you want to delete.

   We input 1 as an example. The output is as follows:

   ```
   delete value > 1
   The delete operation for '1' in the tree is complete!
   ```

   If the value to delete does not exist, the output is as follows:

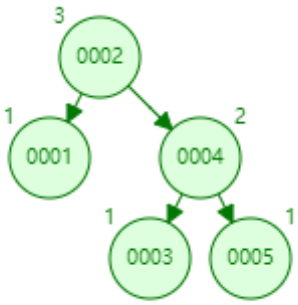
```
delete value > 1
The delete operation for '1' in the tree is complete!
The node of value: 1 doesn't exist.
```

3. Select 3 to count the number of leaves in the tree.

```
Operation > 3
```

When you input 3, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



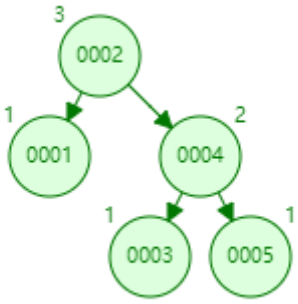

```
Number of leaves: 3
```

4. Select 4 to count the number of nodes in the tree.

```
Operation > 4
```

When you input 4, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



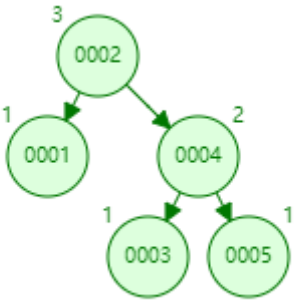

```
Number of nodes: 5
```

5. Select 5 to get the height of the tree.

```
Operation > 5
```

When you input 5, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



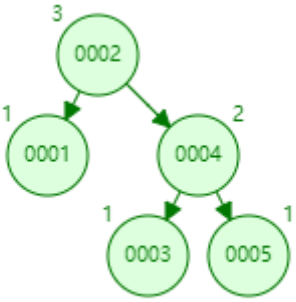

```
Height of the tree: 3
```

6. Select 6 to find the maximum value in the tree.

```
Operation > 6
```

When you input 6, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



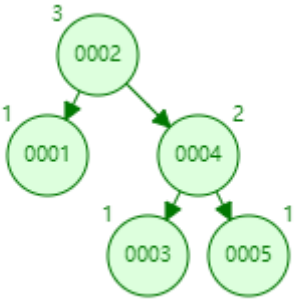

```
Maximum Value: 5
```

7. Select 7 to find the minimum value in the tree.

```
Operation > 7
```

When you input 7, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



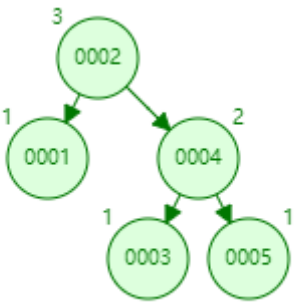

```
Minimum Value: 1
```

8. Select 8 to check if the tree is empty.

```
Operation > 8
```

When you input 8, the output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.




```
Is the tree empty? false
```

If the tree is empty, the output is as follows:

```
Is the tree empty? true
```

9. Select 9 to check if the tree contains a certain value.

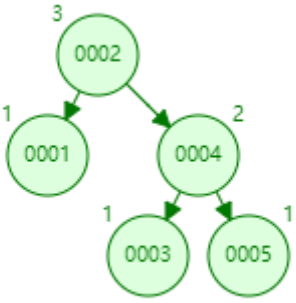
```
Operation > 9
```

When you input 9, the output is as follows:

```
search value >
```

We input 3 as an example. The output is as follows:

Suppose the nodes in the tree are 1, 2, 3, 4, 5.




```
search value > 3
The search operation for '3' in the tree is complete!
Value found? true
```

When the value you entered does not exist, the ouput is as follows:

```
search value > 6
The search operation for '6' in the tree is complete!
Value found? false
```

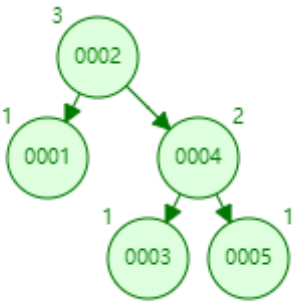
10. Select 10 to traverse the tree (Inorder, Preorder, or Postorder)

```
Operation > 10
```

When you input 10, the output is as follows:

```
Enter the number corresponding to the tree traversal type you want or type 'back' to select a
different operation!
1-Inorder
2-Preorder
3-Postorder
input >
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



When you enter 1, the output will be In-order traversal.

```
input > 1
Your tree:
1
2
3
4
5
```

When you enter 2, the output will be Pre-order traversal.

```
input > 2
Your tree:
2
1
4
3
5
```

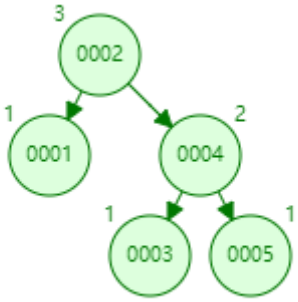
When you enter 3, the output will be Post-order traversal.

```
input > 3
Your tree:
1
3
5
4
2
```

11. Select 11 to print the tree.

```
Operation > 11
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.



When you input 11, the output is as follows:

```
Root 2
|___ L 1
|___ R 4
    |___ L 3
    |___ R 5
```

If the tree is empty, the output is as follows:

```
This tree is empty!
```

12. Select 12 to clear the tree and remove all elements.

```
Operation > 12
```

When you input 12, the output is as follows:

```
Operation > 12
Clear operation is complete!
```

Enter 8 to check if the tree is empty.

```
Operation > 8
Is the tree empty? true
```

13. Enter back to return to the previous menu.

```
Operation > back

You can select a tree number to start or type 'exit' to leave!
Select a tree!
1- Red-Black Tree
2- AVL Tree
3- Binary Search Tree
input >
```

Binary Search Tree

In the welcome interface, please enter 3 to select the Binary Search tree.

When you input 3, the output is as follows:

```
------ Binary Search Tree branch ------


Available Operations:
------------------
Enter the number corresponding to the operation you want to perform!

1) Insert         - insert a node into the tree.
2) Delete         - delete a node from the tree.
3) Count Leaves   - count the number of leaves in the tree.
4) Count Nodes    - count the number of nodes in the tree.
5) Height         - return the height of the tree.
6) Maximum        - find the maximum value in the tree.
7) Minimum        - find the minimum value in the tree.
8) Empty          - check if the tree is empty.
9) Search         - check if the tree contains a certain value.
10) Traverse      - traverse the tree (Inorder, Preorder, or Postorder)
11) Print         - print the tree.
12) Clear         - clear the tree, removing all elements.
Back              - Go back to previous menu and erase current tree

Operation >
```

1. Select 1 to insert a node into the tree.

   ```
   Operation > 1
   ```

   When you input 1, the output is as follows:

   ```
   insert value >
   ```

   Please enter the value you want to insert.

   We input 1 as an example. The output is as follows:

   ```
   insert value > 1
   The insert operation for '1' in the tree is complete!
   ```

   If the entered value already exists, the output is as follows:

   ```
   insert value > 1
   The insert operation for '1' in the tree is complete!
   The node already exists.
   ```

2. Select 2 to delete a node from the tree.

   ```
   Operation > 2
   ```

When you input 2, the output is as follows:

```
delete value >
```

Please enter the value you want to delete.

We input 1 as an example. The output is as follows:

```
delete value > 1
The delete operation for '1' in the tree is complete!
```

If the value to delete does not exist, the output is as follows:

```
delete value > 1
The delete operation for '1' in the tree is complete!
The node of value: 1 doesn't exist.
```

3. Select 3 to count the number of leaves in the tree.

```
Operation > 3
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 3, the output is as follows:

```
Number of leaves: 1
```

4. Select 4 to count the number of nodes in the tree.

```
Operation > 4
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 4, the output is as follows:

```
Number of nodes: 5
```

5. Select 5 to get the height of the tree.

```
Operation > 5
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 5, the output is as follows:

```
Height of the tree: 5
```

6. Select 6 to find the maximum value in the tree.

```
Operation > 6
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 6, the output is as follows:

```
Maximum Value: 5
```

7. Select 7 to find the minimum value in the tree.

```
Operation > 7
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 7, the output is as follows:

```
Minimum Value: 1
```

8. Select 8 to check if the tree is empty.

```
Operation > 8
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 8, the output is as follows:

```
Is the tree empty? false
```

If the tree is empty, the output is as follows:

```
Is the tree empty? true
```

9. Select 9 to check if the tree contains a certain value.

```
Operation > 9
```

When you input 9, the output is as follows:

```
search value >
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

We input 3 as an example. The output is as follows:

```
search value > 3
The search operation for '3' in the tree is complete!
Value found? true
```

When the value you entered does not exist, the ouput is as follows:

```
search value > 6
The search operation for '6' in the tree is complete!
Value found? false
```

10. Select 10 to traverse the tree (Inorder, Preorder, or Postorder)

```
Operation > 10
```

When you input 10, the output is as follows:

```
Enter the number corresponding to the tree traversal type you want or type 'back' to select a different operation!
1-Inorder
2-Preorder
3-Postorder
input >
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you enter 1, the output will be In-order traversal.

```
input > 1
Your tree:
1
2
3
4
5
```

When you enter 2, the output will be Pre-order traversal.

```
input > 2
Your tree:
1
2
3
4
5
```

When you enter 3, the output will be Post-order traversal.

```
input > 3
Your tree:
5
4
3
2
1
```

11. Select 11 to print the tree.

```
Operation > 11
```

Suppose the nodes in the tree are 1, 2, 3, 4, 5.

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

When you input 11, the output is as follows:

```
Root 1
|___ R 2
    |___ R 3
        |___ R 4
            |___ R 5
```

If the tree is empty, the output is as follows:

```
This tree is empty!
```

12. Select 12 to clear the tree and remove all elements.

```
Operation > 12
```

When you input 12, the output is as follows:

```
Operation > 12
Clear operation is complete!
```

Enter 8 to check if the tree is empty.

```
Operation > 8
Is the tree empty? true
```

13. Enter back to return to the previous menu.

```
Operation > back

You can select a tree number to start or type 'exit' to leave!
Select a tree!
1- Red-Black Tree
2- AVL Tree
3- Binary Search Tree
input >
```

Code Interface

Red-black Tree

The structure for red-black tree is

```
type RcRefcellRBTNode<T> = Rc<RefCell<RBTreeNode<T>>>;
type OptionNode<T> = Option<RcRefcellRBTNode<T>>;
```

1. Create a new empty red-black tree

```
let mut tree=rbtree::RBTree::new();
```

2. Insert nodes to the red-black tree

```
//Assume that the value of the new node is 1
let new_node_val=1;
tree.insert(new_node_val);
```

3. Delete nodes from the red-black tree

```
//Assume that the value of the node to be deleted is 8
let delete_node_val=8;
tree.delete(delete_node_val);
```

4. Count the number of leaves in the red-black tree

```
tree.count_leaves();
//Print the result
println!("The number of leaves: {}",tree.count_leaves());
```

5. Get the height of the red-black tree

```
tree.get_height();
//Print the result
println!("The height of tree: {}",tree.get_height());
```

6. Print In-order traversal of the red-black tree

   Print Pre-order traversal of the red-black tree

   Print Post-order traversal of the red-black tree

```
tree.traverse_inorder();
//for example we insert 3,2,1,4,5 into the tree
//the result will be 1,2,3,4,5
tree.traverse_preorder();
//for example we insert 3,2,1,4,5 into the tree
//the result will be 2,1,3,4,5
tree.traverse_postorder();
//for example we insert 3,2,1,4,5 into the tree
//the result will be 1,3,4,5,2
```

7. Check if the tree is empty

```
tree.is_empty()
//if you want to see the result
println!("The tree is empty? {}",tree.is_empty());
//when the tree is empty, it will print true. Otherwise it will print false
```

8. Print the tree

```
tree.print_tree();
```

For example, if we insert 1,2,3,4,5,6,7,8. You should see output similar to the following:

```
Root 4 Black
|___ L 2 Red
|    |___ L 1 Black
|    |___ R 3 Black
|___ R 6 Red
     |___ L 5 Black
     |___ R 7 Black
          |___ R 8 Red
```

AVL Tree

The structure for AVL tree is

```
type RcRefcellAVLNode<T> = Rc<RefCell<AVLTreeNode<T>>>;
type OptionNode<T> = Option<RcRefcellAVLNode<T>>;
```

1. Create a new empty AVL tree

```
let mut tree=avltree::AVLTree::new();
```

2. Insert nodes to the AVL tree

```
//Assume that the value of the new node is 1
let new_node_val=1;
tree.insert(new_node_val);
```

3. Delete nodes from the AVL tree

```
//Assume that the value of the node to be deleted is 8
let delete_node_val=8;
tree.delete(delete_node_val);
```

4. Count the number of leaves in the AVL tree

```
tree.count_leaves();
//Print the result
println!("The number of leaves: {}",tree.count_leaves());
```

5. Get the height of the AVL tree

```
tree.get_height();
//Print the result
println!("The height of tree: {}",tree.get_height());
```

6. Print In-order traversal of the AVL tree

   Print Pre-order traversal of the AVL tree

   Print Post-order traversal of the AVL tree

```
tree.traverse_inorder();
//for example we insert 3,2,1,4,5 into the tree
//the result will be 1,2,3,4,5
tree.traverse_preorder();
//for example we insert 3,2,1,4,5 into the tree
//the result will be 2,1,3,4,5
tree.traverse_postorder();
//for example we insert 3,2,1,4,5 into the tree
//the result will be 1,3,4,5,2
```

7. Check if the AVL tree is empty

```
tree.is_empty()
//Print the result
println!("The tree is empty? {}",tree.is_empty());
//when the tree is empty, it will print true. Otherwise it will print false
```

8. Print the AVL tree

```
tree.print_tree();
```

   For example, if we insert 1,2,3,4,5,6,7,8. You should see output similar to the following:

```
Root 4
|___ L 2
|    |___ L 1
|    |___ R 3
|___ R 6
     |___ L 5
     |___ R 7
          |___ R 8
```

Part 5: Performance

Binary search tree

The benchmark cases

```
for tree_size in (10, 100, 1,000, 5,000) do:
   Start by creating an empty tree.
   Values with tree_size are inserted into the tree.
   A search is conducted for the (tree_size/10) lowest values.
end
```

Results

Size	Time
10	699.02 ns
100	32.018 us
1000	3.4898 ms
5000	99.200 ms

The result shows that when size equals 1000, the binary search tree takes longer time than the red black tree and AVL tree with 10000 data.

Red-black tree and AVL tree

The benchmark case 1 (Insertion and Search)

```
for tree_size in (10,000, 40,000, 70,000, 100,000, 130,000) do:
    Start by creating an empty tree.
    Values with tree_size are inserted into the tree.
    A search is conducted for the (tree_size/10) lowest values.
end
```

Results

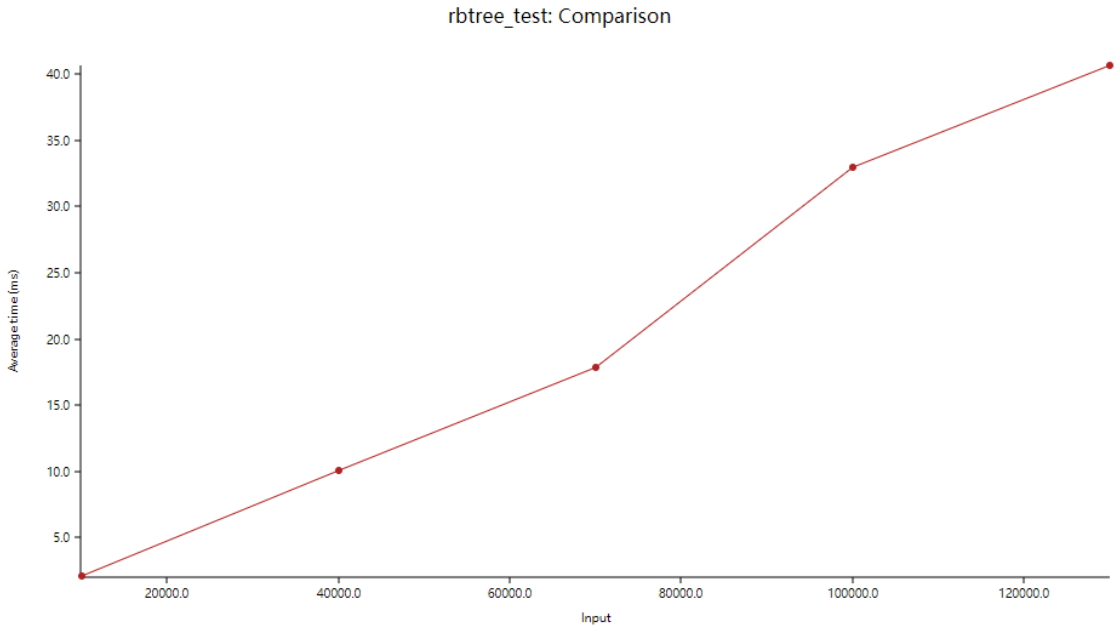
For the results, we run the benchmark code ten times and take the average value

Size	Red-black Tree	AVL Tree
10,000	2.1634 ms	3.8656 ms
40,000	10.108 ms	15.781 ms
70,000	17.897 ms	28.721 ms
100,000	32.948 ms	42.683 ms
130,000	40.769 ms	62.057 ms

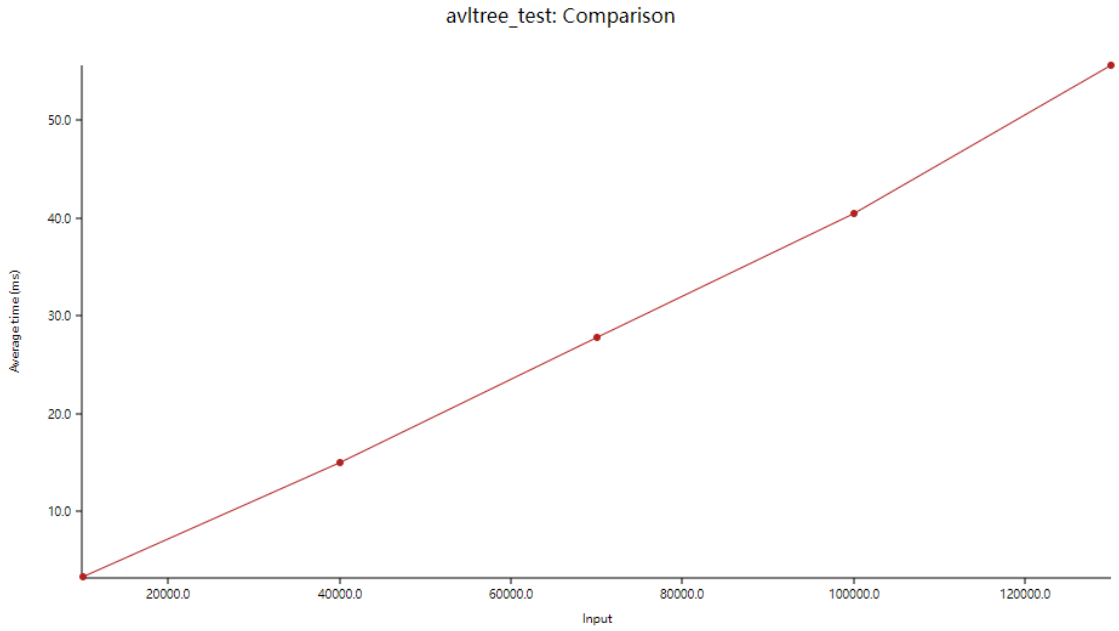
Line Chart

This chart shows the mean measured time for each function as the input (or the size of the input) increases.

Line Chart

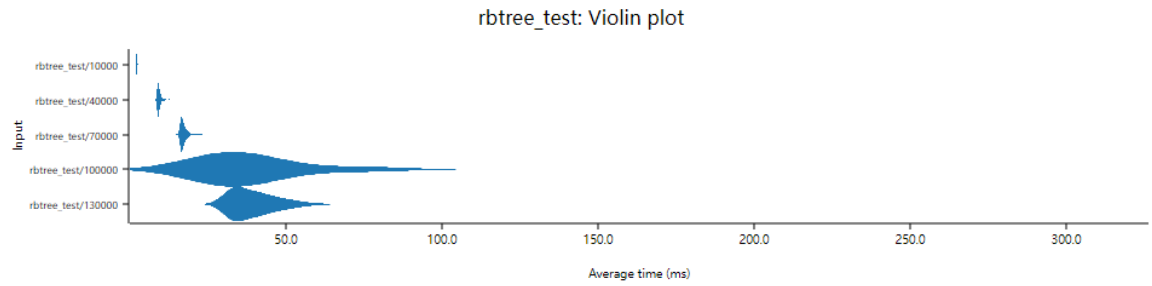


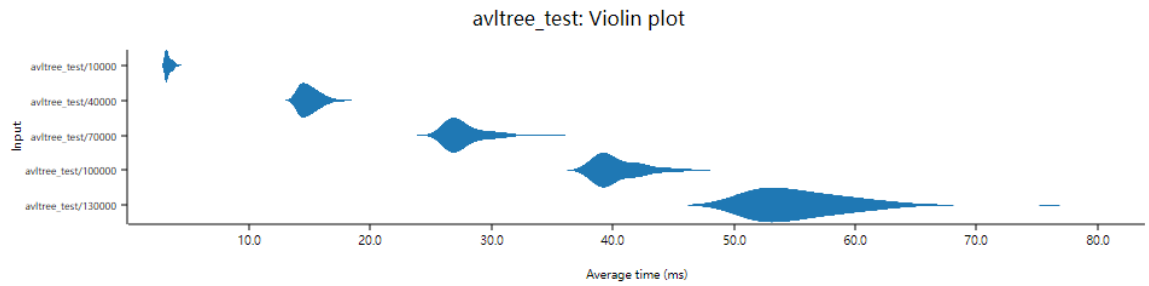
Line Chart



Violin Plot

This chart shows the relationship between function/parameter and iteration time. The thickness of the shaded region indicates the probability that a measurement of the given function/parameter would take a particular length of time.





The benchmark case 2 (only test insertion)

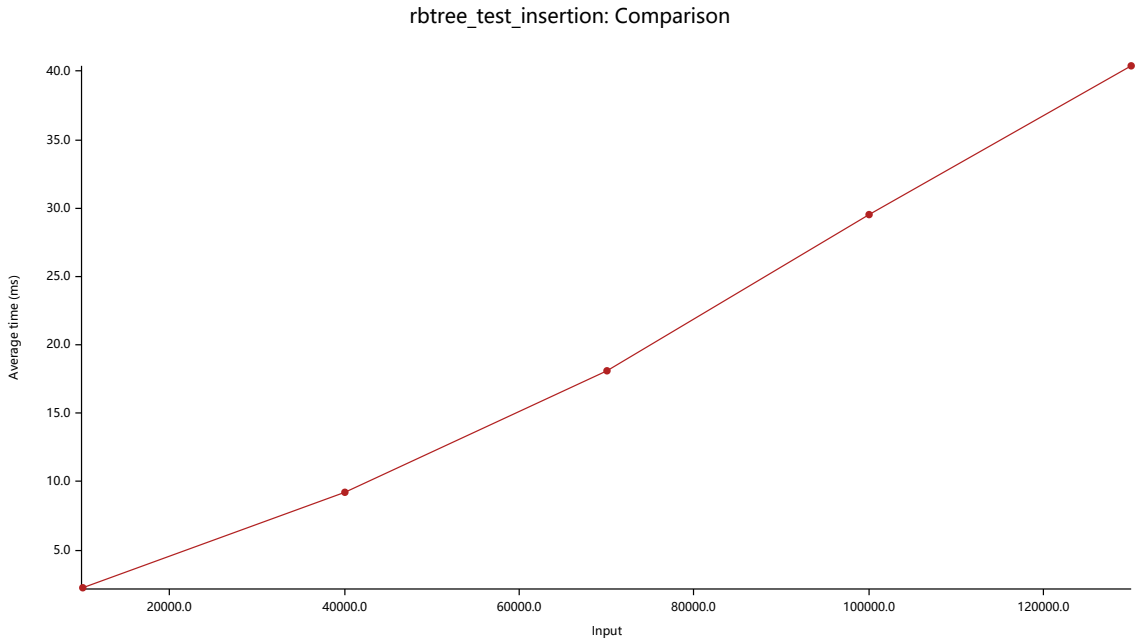
```
for tree_size in (10,000, 40,000, 70,000, 100,000, 130,000) do:
    Start by creating an empty tree.
    Values with tree_size are inserted into the tree.
end
```

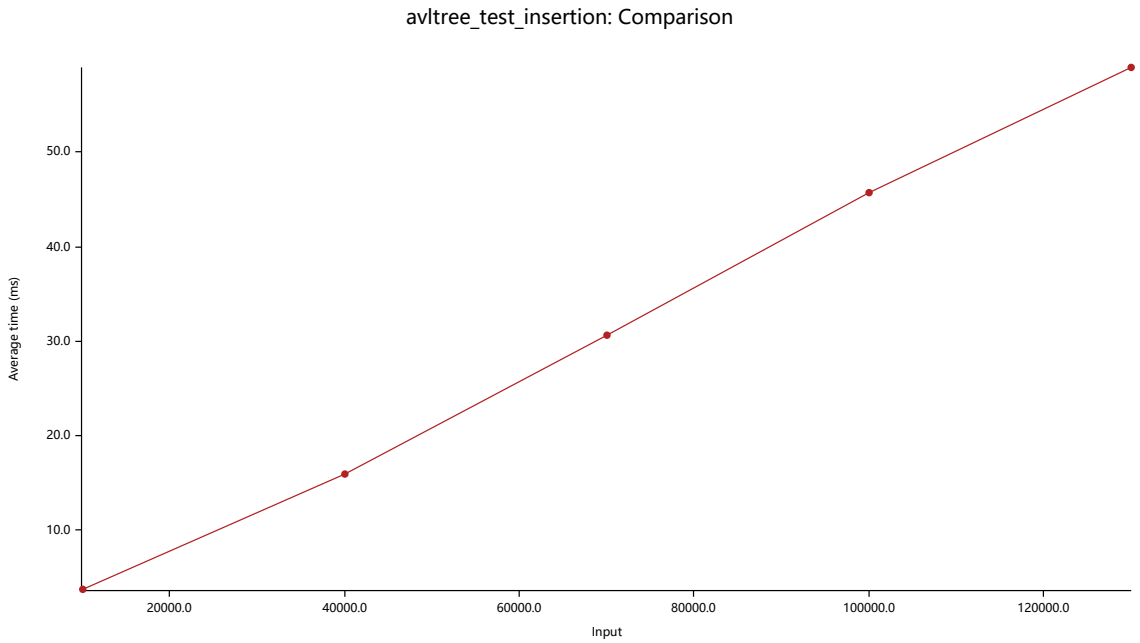
Results

For the results, we run the benchmark code ten times and take the average value

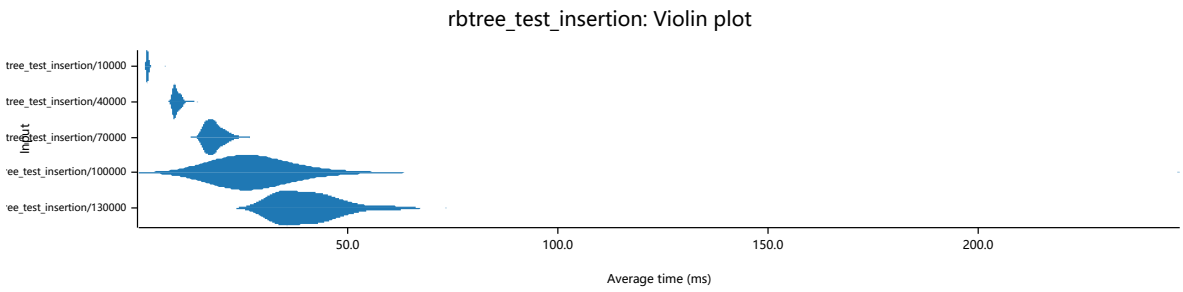
Size	Red-black Tree	AVL Tree
10,000	2.1172 ms	3.2139 ms
40,000	9.1002 ms	15.925 ms
70,000	17.881 ms	28.895 ms
100,000	29.653 ms	40.550 ms
130,000	38.732 ms	53.955 ms

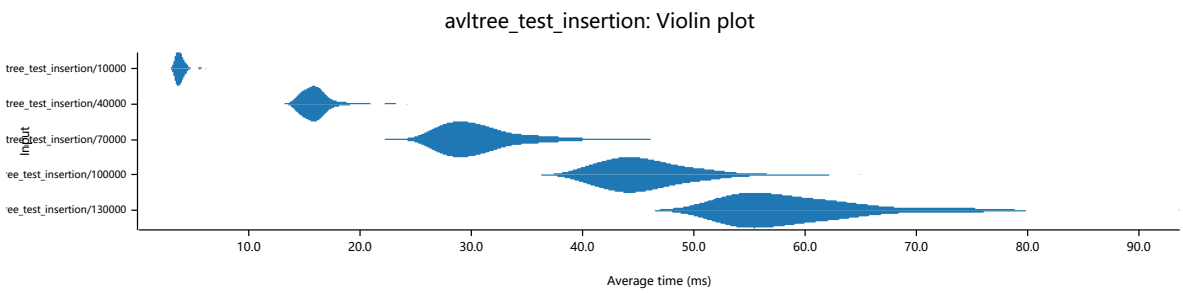
Line Chart


rbtree_test_insertion: Comparison
Average time (ms)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
20000.0
40000.0
60000.0
80000.0
100000.0
120000.0
Input


avltree_test_insertion: Comparison
Average time (ms)
50.0
40.0
30.0
20.0
10.0
20000.0
40000.0
60000.0
80000.0
100000.0
120000.0
Input

Violin Plot


rbtree_test_insertion: Violin plot
tree_test_insertion/10000
tree_test_insertion/40000
tree_test_insertion/70000
ee_test_insertion/100000
ee_test_insertion/130000
Input
50.0
100.0
150.0
200.0
Average time (ms)


avltree_test_insertion: Violin plot
tree_test_insertion/10000
tree_test_insertion/40000
tree_test_insertion/70000
ee_test_insertion/100000
ee_test_insertion/130000
Input
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Average time (ms)

The benchmark case 3 (only test search)

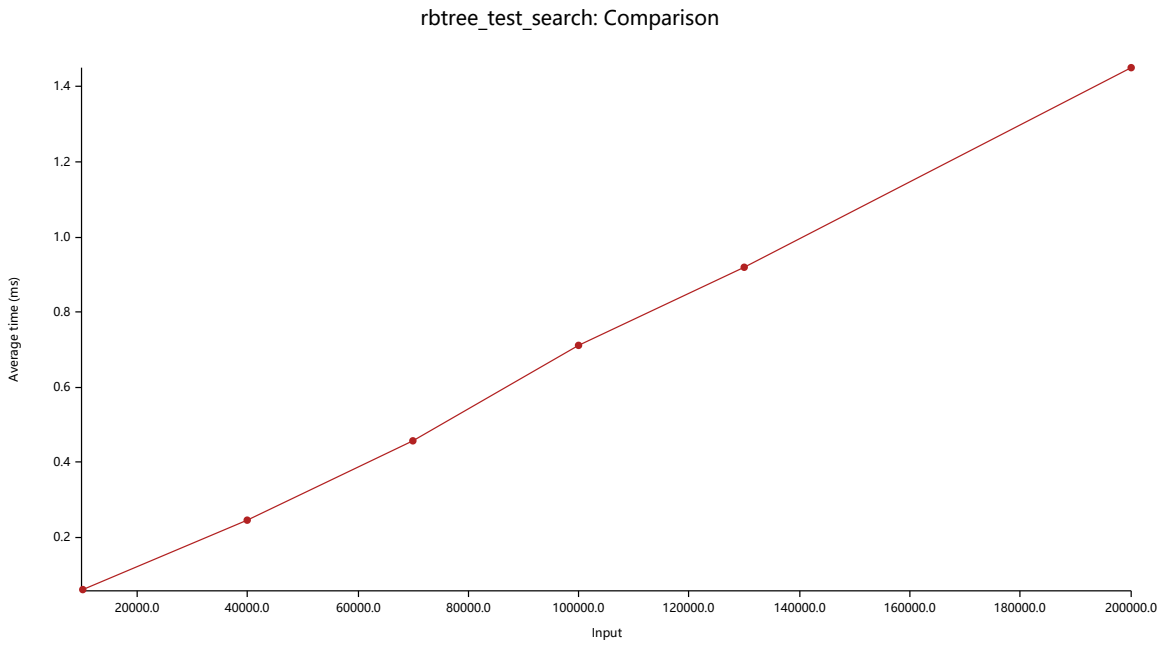
```
tree_size=130,000
for search_size in (10,000, 40,000, 70,000, 100,000, 130,000, 200,000) do:
    A search is conducted for the (search_size/10) lowest values.
end
```

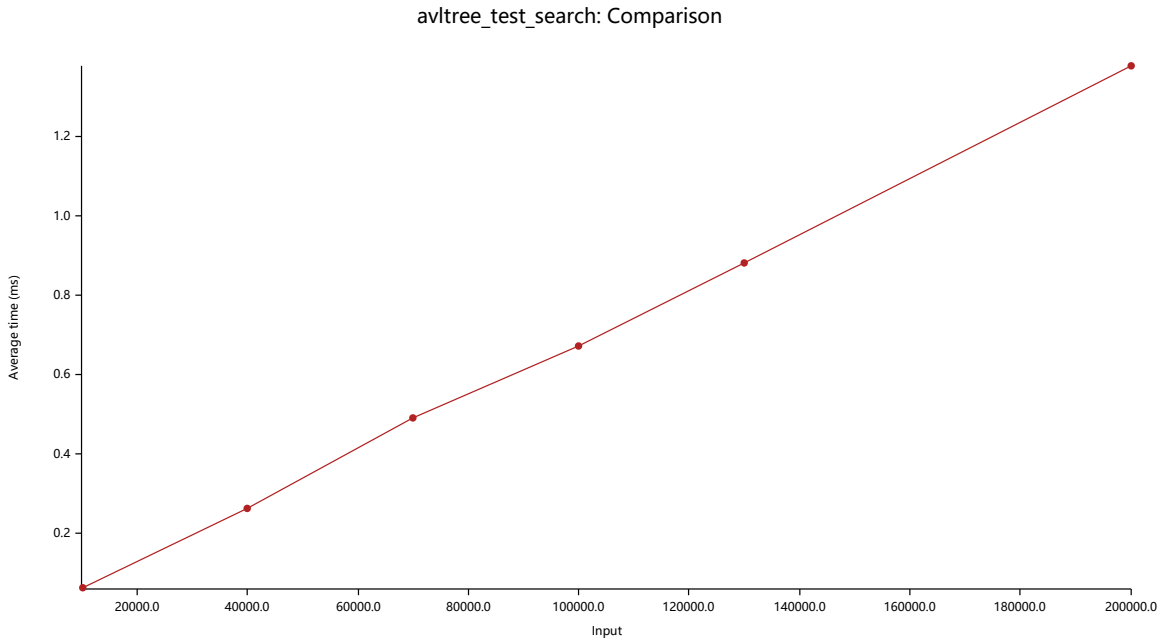
Results

For the results, we run the benchmark code and take the average value

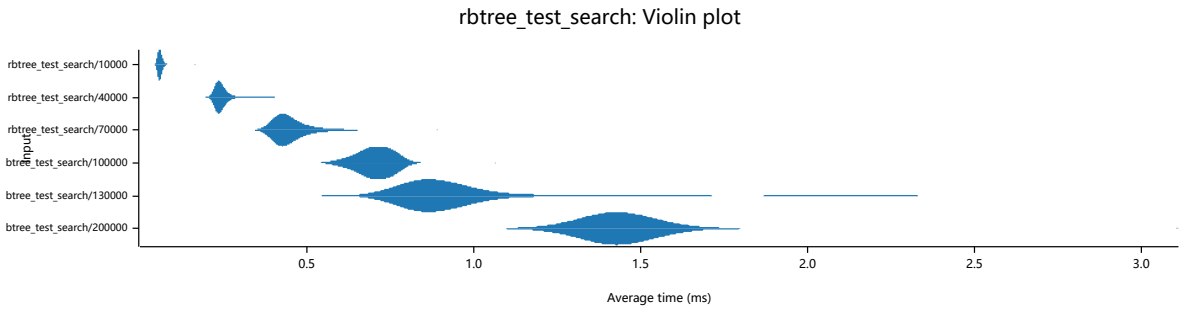
Search_Size	Red-black Tree	AVL Tree
10,00	61.541 us	63.697 us
40,00	243.66 us	261.16 us
70,00	438.51 us	471.42 us
100,00	707.31 us	663.49 us
130,00	874.21 us	867.40 us
200,00	1.4347 ms	1.3331 ms

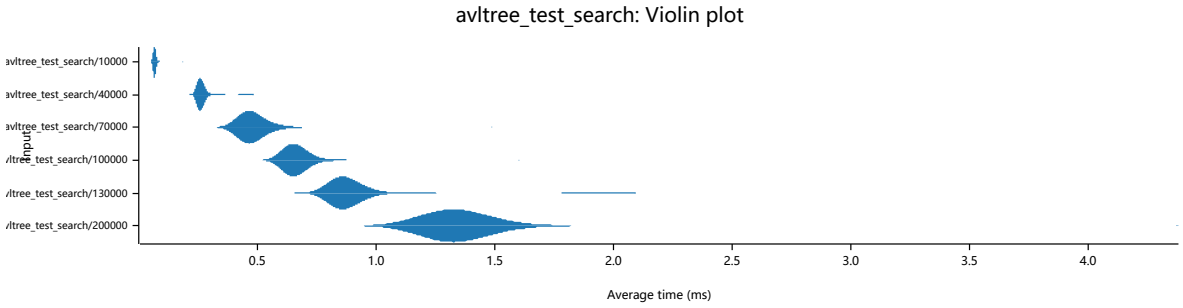
Line Chart





Violin Plot





Conclusion

When storing large-scale data, both red black tree and AVL tree perform better than the basic binary search tree.

In the insertion operation, the red black tree performs better. In the search operation, when the amount of data is large, the AVL tree performs better.