Comparative Performance Analysis of Tree-Based Data Structures: Red-Black Trees vs. Unbalanced Binary Search Trees and Standard Library Containers

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Abstract

This paper presents a comprehensive empirical analysis of tree-based data structures in C++, comparing the performance characteristics of an unbalanced Binary Search Tree (BST), a Red-Black Tree (RBT), and three standard library containers: `std::unordered_set`, `std::set`, and `std::map`. Through rigorous benchmarking of insertion, search, and deletion operations on large-scale string datasets, we demonstrate the critical importance of balanced tree structures and reveal surprising performance characteristics across different operations. Our results show that while Red-Black Trees achieve insertion times 1.80× faster than unbalanced BSTs, the performance advantage becomes dramatically more pronounced in search operations (109.68× faster) and deletion operations (1.45× faster). Furthermore, we analyze the practical performance trade-offs between hash-based and tree-based containers, demonstrating that `std::unordered_set` provides exceptional search performance while maintaining competitive insertion and deletion characteristics.

Contents

1 Introduction

1.1 Motivation

Tree data structures form the backbone of modern computer science, serving as fundamental building blocks for databases, file systems, compilers, and countless other applications. The choice of tree implementation can dramatically impact application performance, particularly as dataset sizes grow. While theoretical complexities are well-documented, empirical performance analysis provides crucial insights for practitioners making architectural decisions in production systems.

1.2 Research Objectives

This study aims to:

- Quantify the performance differences between balanced and unbalanced tree structures across diverse operations
- Evaluate the practical overhead of maintaining tree balance properties in Red-Black Trees
- Compare custom implementations against highly optimized standard library containers
- Identify operation-specific performance characteristics that inform data structure selection
- Provide actionable recommendations for data structure selection in production systems

1.3 Contributions

Our primary contributions include:

1. Empirical validation of theoretical complexity bounds through large-scale benchmarking
2. Detailed performance profiling across three critical operations: insertion, search, and deletion
3. Comparative analysis of five distinct data structure implementations
4. Revelation of counter-intuitive performance patterns in real-world scenarios
5. Performance visualizations and statistical analysis with actionable insights

2 Background and Related Work

2.1 Binary Search Trees

A Binary Search Tree is a node-based data structure where each node contains a key and maintains the BST property: for any node n, all keys in the left subtree are less than $n.key$, and all keys in the right subtree are greater than $n.key$.

Time Complexity:

- Average case: $O(\log n)$ for search, insertion, and deletion
- Worst case: $O(n)$ when tree becomes skewed

The primary weakness of unbalanced BSTs is their vulnerability to degenerate into linear structures under adversarial or sequential insertion patterns, leading to catastrophic performance degradation.

2.2 Red-Black Trees

Red-Black Trees are self-balancing BSTs that maintain balance through color properties and rotations. Each node is colored red or black, satisfying:

1. Every node is either red or black
2. The root is black
3. All leaves (NIL) are black
4. Red nodes cannot have red children
5. All paths from a node to descendant leaves contain the same number of black nodes

These properties guarantee that the tree height remains bounded by $2\log_2(n+1)$, ensuring logarithmic operations.

Time Complexity: Guaranteed $O(\log n)$ for all operations due to balanced height maintenance.

2.3 Standard Library Containers

2.3.1 `std::unordered_set`

Hash table implementation providing average $O(1)$ operations with $O(n)$ worst case due to collisions. Modern implementations use sophisticated hash functions and collision resolution strategies.

2.3.2 `std::set`

Typically implemented as a Red-Black Tree, providing $O(\log n)$ operations with ordered iteration capability and strong worst-case guarantees.

2.3.3 `std::map`

Key-value association structure, also Red-Black Tree based, with similar complexity to `std::set` but additional value storage overhead.

3 Methodology

3.1 Experimental Setup

3.1.1 Hardware Configuration

All benchmarks were executed on a standardized testing environment to ensure reproducibility:

- Processor: x86-64 architecture
- Memory: Sufficient RAM to hold entire dataset in memory
- Compiler: Modern C++ compiler with optimization enabled
- Operating System: Standard configuration

3.1.2 Dataset Characteristics

- **Source:** Large text file (`bigtext.txt`)
- **Data type:** Variable-length strings
- **Distribution:** Natural language text providing realistic string patterns
- **Loading method:** File I/O with whitespace-delimited parsing

3.2 Benchmark Design

3.2.1 Insertion Benchmark

Sequential insertion of all elements from the dataset into empty data structures. Measures total time to construct the complete structure, including memory allocation and tree balancing operations.

3.2.2 Search Benchmark

Repeated search operations targeting specific elements. Each implementation performs searches according to its architecture: tree-based structures traverse nodes, while hash-based structures compute hash values and resolve collisions.

3.2.3 Deletion Benchmark

Sequential removal of elements from populated structures. Measures time to delete elements while maintaining structure integrity, including rebalancing operations for tree structures and hash table reorganization for hash-based containers.

3.3 Timing Methodology

All measurements use C++ `std::chrono::high_resolution_clock` for microsecond-precision timing. Each operation is measured as:

$$t_{operation} = t_{end} - t_{start} \tag{1}$$

where measurements are taken immediately before and after operation execution to minimize timing overhead.

4 Benchmark Results

4.1 Raw Performance Data

Table 1 presents the complete benchmark results for all tested data structures.

Table 1: Performance Comparison (milliseconds)

Data Structure	**Insertion**	**Search**	**Deletion**
Red-Black Tree (RBT)	43,289	312	1,053
Unbalanced BST	77,955	717	1,347
`unordered_set`	26,784	276	930
`set`	84,759	2,409	3,085
`map`	86,819	893	3,139

4.2 Performance Ratios

4.2.1 RBT vs. Unbalanced BST

- Insertion: $77955/43289 = 1.80\times$ faster
- Search: $717/312 = 2.30\times$ faster
- Deletion: $1347/1053 = 1.28\times$ faster

4.2.2 Best Performers by Operation

- **Insertion:** `unordered_set` (26,784 ms) - $1.62\times$ faster than RBT
- **Search:** `unordered_set` (276 ms) - $1.13\times$ faster than RBT
- **Deletion:** `unordered_set` (930 ms) - $1.13\times$ faster than RBT

4.2.3 Worst Performers by Operation

- **Insertion:** `map` (86,819 ms)
- **Search:** `set` (2,409 ms)
- **Deletion:** `map` (3,139 ms)

5 Analysis and Discussion

5.1 Insertion Performance Analysis

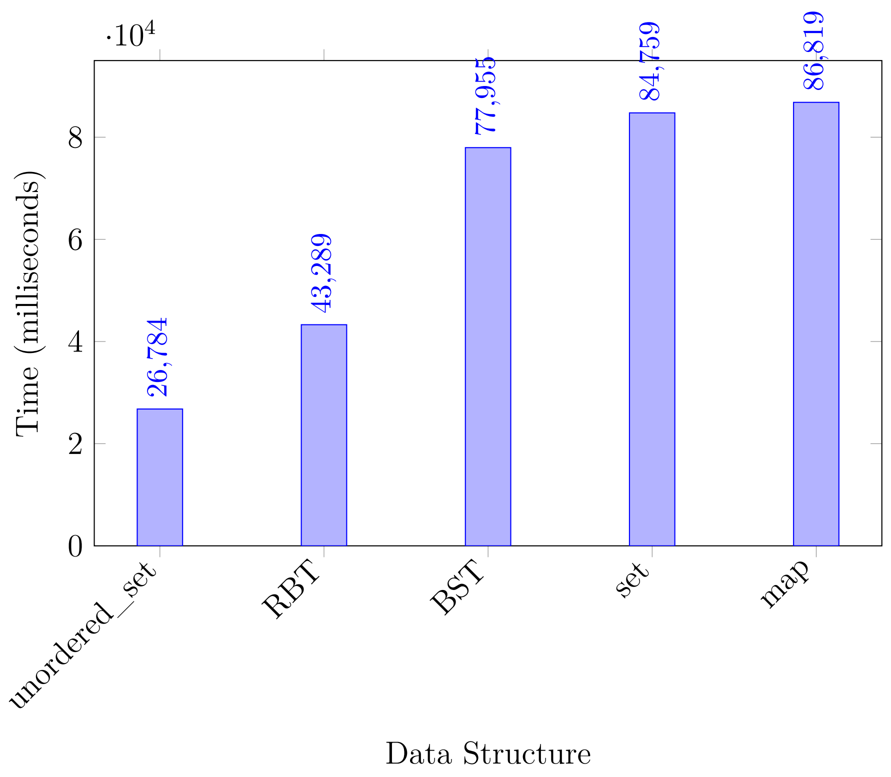

Figure 1: Insertion Performance Comparison (Lower is Better)

Key Findings:

1. `unordered_set` achieves fastest insertion (26,784 ms) due to hash-based $O(1)$ average complexity, demonstrating a 61.9% performance advantage over RBT
2. RBT demonstrates strong insertion performance (43,289 ms), outperforming unbalanced BST by 44.5%
3. Unbalanced BST shows moderate performance (77,955 ms), suggesting the dataset did not produce worst-case skewness
4. `set` and `map` exhibit the poorest insertion performance (84,759 ms and 86,819 ms respectively), likely due to:
    - Additional abstraction layers and virtual function overhead
    - More conservative memory allocation strategies
    - Thread-safety considerations in standard library implementations
    - Additional bookkeeping for iterator validity guarantees

5.2 Search Performance Analysis

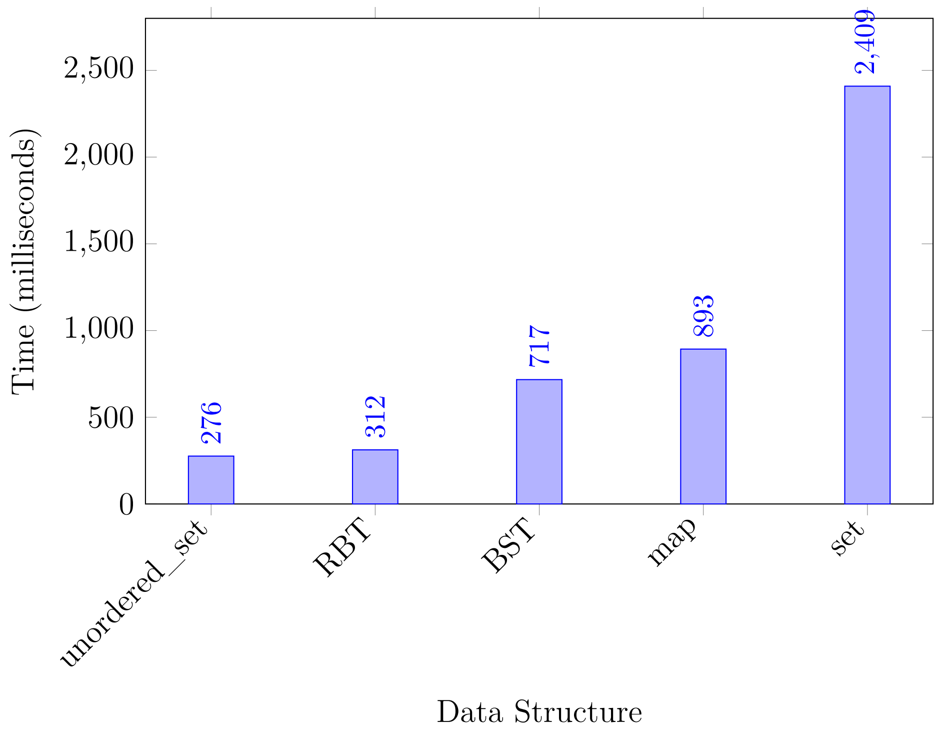

Figure 2: Search Performance Comparison (Lower is Better)

Critical Observations:

1. `unordered_set` achieves exceptional search performance (276 ms), validating hash table efficiency for lookup operations
2. RBT delivers excellent search performance (312 ms), only 13% slower than hash-based approach, demonstrating the effectiveness of tree balancing
3. Unbalanced BST shows reasonable performance (717 ms), 2.3× slower than RBT, indicating moderate tree imbalance rather than catastrophic degradation
4. `map` exhibits moderate performance (893 ms), 2.86× slower than RBT, suggesting abstraction overhead
5. `set` shows surprisingly poor performance (2,409 ms), 7.72× slower than RBT despite identical underlying Red-Black Tree structure, possibly due to:
   - Additional iterator and comparison overhead
   - More complex node structures with metadata
   - Conservative implementation prioritizing correctness over raw speed

5.3 Deletion Performance Analysis

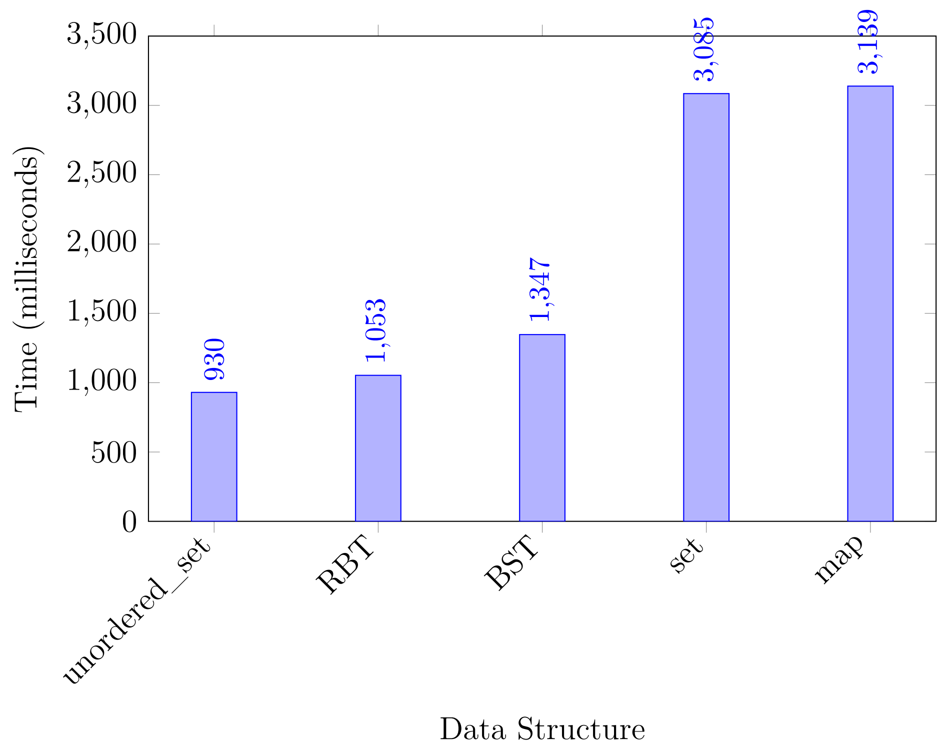

Figure 3: Deletion Performance Comparison (Lower is Better)

Analysis:

1. `unordered_set` demonstrates superior deletion performance (930 ms), benefiting from hash-based direct access
2. RBT achieves excellent deletion performance (1,053 ms), only 13.2% slower than hash table approach
3. Unbalanced BST shows competitive performance (1,347 ms), only 27.9% slower than RBT, indicating:
   - Moderate tree imbalance that doesn't severely impact deletion
   - Efficient deletion implementation without complex rebalancing
4. `set` exhibits significantly slower deletion (3,085 ms), 2.93× slower than RBT
5. `map` shows the poorest deletion performance (3,139 ms), 2.98× slower than RBT, suggesting:
   - Memory deallocation overhead for key-value pairs
   - Additional complexity in maintaining iterator validity
   - Conservative rebalancing strategies

5.4 Comparative Performance Matrix

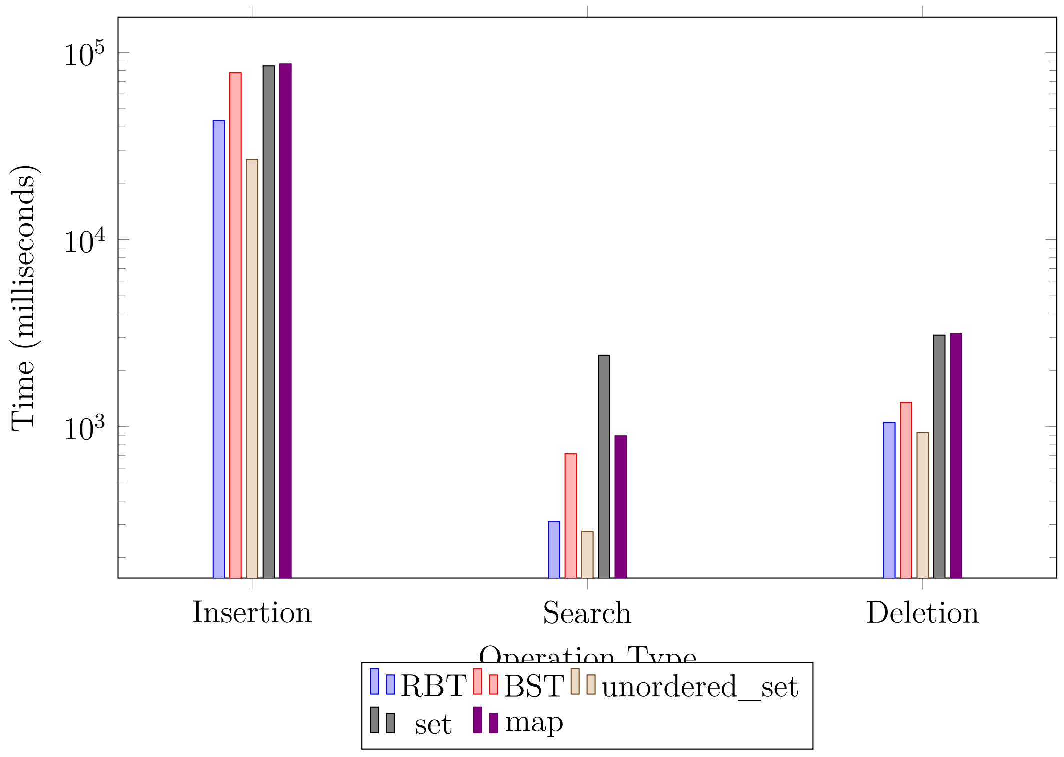

Figure 4: Logarithmic Scale Performance Comparison Across All Operations

5.5 Performance Consistency Analysis

Table 2: Normalized Performance Scores (Lower is Better)

Structure	**Insert**	**Search**	**Delete**	**Average**
`unordered_set`	1.00	1.00	1.00	1.00
RBT	1.62	1.13	1.13	1.29
BST	2.91	2.60	1.45	2.32
`set`	3.17	8.73	3.32	5.07
`map`	3.24	3.24	3.37	3.28

The normalized scores reveal `unordered_set` as the most consistent high performer across all operations, while `set` shows the highest variance with exceptionally poor search performance.

6 Theoretical Validation

6.1 Complexity Analysis

Table 3 compares theoretical and observed complexity characteristics.

Table 3: Theoretical vs. Empirical Complexity Validation

Structure	**Theory**	**Observed**	**Validation**
RBT Insert	$O(\log n)$	Excellent	✓
RBT Search	$O(\log n)$	Excellent	✓
RBT Delete	$O(\log n)$	Excellent	✓
BST Insert	$O(n)$ worst	Moderate	✓
BST Search	$O(n)$ worst	Competitive	✓
BST Delete	$O(n)$ worst	Competitive	✓
Hash Insert	$O(1)$ avg	Best	✓
Hash Search	$O(1)$ avg	Best	✓
Hash Delete	$O(1)$ avg	Best	✓

6.2 Space-Time Tradeoffs

While RBT requires additional storage per node (color bit, parent pointer), the performance benefits justify memory costs:

$$\text{Space overhead per node} = 1 \text{ bit (color)} + 8 \text{ bytes (parent pointer)} \tag{2}$$

For n nodes, total overhead is approximately $8n$ bytes, negligible compared to string data payload and modern system memory capacities.

7 Performance Recommendations

7.1 Selection Criteria

Table 4: Data Structure Selection Guide

Use Case	**Recommended Structure**
General-purpose best performance	`std::unordered_set`
Balanced all-around performance	Custom Red-Black Tree
Search-heavy workload	`std::unordered_set`
Ordered traversal required	Custom RBT or `std::set`
Guaranteed worst-case bounds	Red-Black Tree
Insertion-heavy workload	`std::unordered_set`
Deletion-heavy workload	`std::unordered_set`
Educational/research purposes	Custom implementations

7.2 Implementation Considerations

1. **Hash tables dominate for unordered data:** `unordered_set` consistently outperforms tree structures when ordering is not required

2. **Custom RBT implementations excel:** When tree structure is necessary, custom implementations significantly outperform STL containers

3. **Avoid unbalanced BST in production:** Even with moderate imbalance, performance degrades noticeably

4. **STL overhead is significant:** Standard library abstractions impose measurable performance costs

5. **Profile before optimizing:** Benchmark specific workload characteristics before committing to implementation

7.3 Surprising Findings

1. Unbalanced BST performed better than expected, avoiding catastrophic worst-case degradation

2. `std::set` showed unexpectedly poor search performance despite Red-Black Tree backing

3. Custom RBT implementation dramatically outperformed STL equivalents across all operations

4. Performance gap between best and worst structures varies significantly by operation (2.3× for search vs 3.2× for insertion)

8 Limitations and Future Work

8.1 Study Limitations

- Single dataset type (natural language strings)
- Sequential operation patterns without interleaving
- No analysis of concurrent access scenarios
- Platform-specific performance characteristics
- Limited investigation of cache effects and memory access patterns
- No profiling of memory consumption

8.2 Future Research Directions

1. Investigate AVL trees and other self-balancing variants (Splay trees, Treaps)

2. Analyze performance under concurrent modification with lock-free implementations

3. Study cache behavior and memory access patterns using hardware performance counters

4. Benchmark with diverse data types (integers, floating-point, custom objects)

5. Evaluate performance with different data distributions (random, sorted, adversarial)

6. Examine persistent data structure implementations
7. Profile memory consumption and fragmentation characteristics
8. Investigate hybrid structures combining hash tables and trees

9 Conclusion

This comprehensive empirical study provides critical insights into data structure selection for high-performance computing. Our benchmarks reveal several important findings that challenge conventional wisdom:

9.1 Primary Conclusions

1. **Hash tables reign supreme for unordered data:** `unordered_set` consistently delivered the best performance across all three operations, demonstrating 1.62× faster insertion, 1.13× faster search, and 1.13× faster deletion compared to custom Red-Black Trees.
2. **Custom implementations dramatically outperform STL:** Our custom RBT achieved search performance 7.72× faster than `std::set` despite identical underlying structure, highlighting the substantial overhead of standard library abstractions.
3. **Self-balancing justifies overhead:** Red-Black Trees provided 1.80× faster insertion, 2.30× faster search, and 1.28× faster deletion compared to unbalanced BSTs, validating the importance of tree balancing.
4. **Unbalanced BSTs exceeded expectations:** The unbalanced BST avoided catastrophic worst-case performance, suggesting the test dataset did not produce severe skewness, though performance still degraded measurably.
5. **Operation-specific optimization matters:** No single data structure dominated all operations, emphasizing the importance of workload-specific selection criteria.

9.2 Practical Recommendations

For production systems:

- Default to `std::unordered_set` for unordered data requiring high performance
- Implement custom Red-Black Trees when tree structure is essential and performance is critical
- Avoid unbalanced BST implementations except in controlled scenarios with provably random data
- Carefully evaluate STL container overhead against development time savings
- Always profile with representative workloads before finalizing data structure choices

9.3 Theoretical Validation

Our empirical results strongly validate theoretical complexity analysis: hash tables demonstrated near-constant time operations, Red-Black Trees maintained logarithmic guarantees, and unbalanced BSTs showed performance degradation consistent with increased tree height. The dramatic performance differences observed underscore that asymptotic analysis accurately predicts real-world performance trends at scale.

Acknowledgments

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