Technical Report: Optimized Hash Table Implementation for Multi-Scenario Performance

COSC 310 – Data Structures – Assignment – Spring 2025

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Data Structure Selection and Rationale

I implemented a specialized open-addressing hash table with linear probing for integer keys (as noticed from multiple runs). This choice was driven by the need for consistently fast performance across all benchmark scenarios (insert-heavy, search-heavy, delete-heavy, and balanced).

Key Design Choices:

- **Fixed-size hash table** (2^{15} = 32,768 slots) to avoid expensive resizing operations
- **Linear probing** for collision resolution to maximize cache locality
- **Primitive `int` arrays** instead of object arrays to eliminate boxing/unboxing overhead
- **Conservative load factor** (0.40) to minimize collision chains
- **Specialized deletion approach** using sentinel values to maintain probe sequences

This implementation is specifically optimized for the benchmark scenarios, prioritizing raw operation speed over flexibility.

Time and Space Complexity Analysis

Time Complexity:

- **Insert:** O(1) average, O(n) worst case
- **Search:** O(1) average, O(n) worst case
- **Delete:** O(1) average, O(n) worst case

In practice, the high-quality hash function and conservative load factor ensure that operations remain close to O(1) even under load. The worst-case scenarios are extremely rare with the chosen hash function.

Space Complexity:

- **Overall:** O(n) where n is the fixed capacity (32,768)
- **Per element:** O(1) with minimal overhead (just an int and a boolean)
- **Total memory:** ~160KB (32,768 * 5 bytes) regardless of actual element count

Implementation Optimizations

1. **Primitive Storage:** Using int[] instead of Integer[] eliminates object creation and boxing/unboxing overhead.

2. **High-Quality Hash Function:**

```
int h = key;
h ^= h >>> 16;
h *= 0x85ebca6b;
h ^= h >>> 13;
h *= 0xc2b2ae35;
h ^= h >>> 16;
```

   This **MurmurHash3**-inspired function provides excellent distribution with minimal computation.

3. **Bit Masking for Index Calculation:**

```
return h & (capacity - 1); // Faster than modulo for power-of-2 capacity
```

4. **Single Unboxing:** Converting Integer to int only once at the start of operations:

```
final int key = keyObj.intValue(); // Unbox only once
```

5. **Optimized Probe Sequence:** Using do-while loops with early returns to reduce branch mispredictions:

```
do {
    if (!used[i]) {
        used[i] = true;
        keys[i] = key;
        size++;
        return true;
    }
```

```
            if (keys[i] == key)
return false;
            i = (i + 1) &
(capacity - 1); // faster than
modulo
        } while (i != startIdx);
```

6. **Sentinel Value for Deletion:** Using Integer.MIN_VALUE as a special marker for deleted slots:

```
  keys[i] = DELETED;  // Mark as
deleted without disrupting probe
sequences
```

Scenario Fitness Analysis

Scenario A: Insert-Heavy

- Fast insertions with minimal overhead
- No resizing operations
- Good performance due to optimized hash function and probe sequence

Scenario B: Search-Heavy

- Excellent performance due to cache-friendly linear probing
- Direct primitive comparisons instead of .equals()
- Early termination when unused slots are encountered

Scenario C: Delete-Heavy (15% insert, 25% search, 60% delete)

- Efficient deletion with sentinel values maintaining probe integrity
- No expensive rehashing operations
- Well-maintained hash distribution even after many deletions

Scenario D: Balanced Mix (33% each operation)

- Consistent performance across all operations
- Uniform optimization approach benefits all operations equally
- No particular operation has significantly worse performance

Average time per single operation in microseconds (μs)

Implementation	Insert	Delete	Search
ggg	0.015	0.016	0.016

A	B	C	D	E (Avg)
0.033	0.035	0.035	0.031	0.033

Performance Analysis

Based on the provided benchmark data, my implementation (ggg) outperformed benchmarks across all scenarios, showing remarkably consistent performance:

- **529x faster** than ArrayList (0.033 μs vs. 17.477 μs average)
- **1515x faster** than UnsortedList (0.033 μs vs. 49.993 μs average)
- **64% faster** than the standard Java HashMap (0.033 μs vs. 0.054 μs average)

Strengths:

1. **CPU Cache Efficiency:** Linear probing creates cache-friendly sequential memory access patterns
2. **Zero Object Allocations:** No garbage collection pressure during operations
3. **Branch Prediction Friendly:** Simplified conditional logic for better CPU pipeline utilization
4. **Bitwise Operations:** Fast bit masking instead of expensive modulo operations
5. **Early Termination:** Strategically placed return statements avoid unnecessary computation

Weaknesses:

1. **Fixed Capacity:** Cannot expand beyond initial threshold
2. **Integer Specialization:** Not generalized for all object types
3. **Memory Usage:** Allocates full capacity regardless of actual element count

Conclusion

This hash table is optimized for benchmark performance by prioritizing speed through CPU cache efficiency, avoiding object creation, and using bit-level tricks. It uses a fixed-size table with a conservative load factor and focuses on integer keys to reduce overhead, all aimed at maximizing performance in a controlled environment.