

Problem 1

Problem Statement: In an online examination platform, the examination scores of 100,000 students are stored sequentially in an array on the server. Once the examination process is completed, the examination authority needs to sort the students's scores efficiently in order to prepare rank lists and perform further analysis. Write a C program to implement the Randomized Quicksort algorithm for sorting the array of students's scores. The program should consider and handle the following three input scenarios:

- i) Best-case-like scenario: when the array of scores is already sorted in ascending order.
- ii) Worst-case-like scenario for deterministic approaches: when the array is sorted in reverse (descending) order.
- iii) Average-case scenario: when the array elements are in a random, unsorted order.

Finally, count the total number of comparisons performed during the sorting process and measure the execution time required to complete the sorting operation.

Code

```
1 #include <stdbool.h>
2 #include <stdio.h>
3 #include <stdlib.h>
4 #include <time.h>
5
6 void swap(int *a, int *b) {
7     if (a == NULL || b == NULL)
8         return;
9     int temp = *a;
10    *a = *b;
11    *b = temp;
12 }
13
14 int partition(int *a, int low, int high, int *comparisons) {
15     int pivot_index = low + (rand() % (high - low + 1));
16     int i = low - 1;
17     int pivot = a[pivot_index];
18     swap(&a[pivot_index], &a[high]);
19
20     for (int j = low; j < high; j++) {
21         (*comparisons)++;
22         if (a[j] <= pivot) {
23             swap(&a[++i], &a[j]);
24         }
25     }
26     swap(&a[++i], &a[high]);
27     return i;
28 }
29
30 void quickSort(int *a, int low, int high, int *comparisons) {
31     if (low < high) {
32         int partition_index = partition(a, low, high, comparisons);
33         quickSort(a, low, partition_index - 1, comparisons);
34         quickSort(a, partition_index + 1, high, comparisons);
35     }
36 }
37
38 void printArray(int *a, int n) {
```

```

39     for (int i = 0; i < n; i++) {
40         printf("%d ", a[i]);
41     }
42
43     printf("\n");
44 }
45
46 bool isSorted(int *a, int n) {
47     for (int i = 1; i < n; i++) {
48         if (a[i - 1] > a[i])
49             return false;
50     }
51     return true;
52 }
53
54 int main() {
55     srand(time(NULL));
56     int comparisons = 0;
57     clock_t start, end;
58
59     int n = (int)1e5;
60
61     int a[n];
62
63     for (int i = 0; i < n; i++) {
64         a[i] = rand() % 101;
65     }
66
67     if (isSorted(a, n)) {
68         printf("Array is already sorted!\n");
69         return 1;
70     }
71     printf("Array has been successfully populated!\n");
72     printf("First 10 elements of array: \n");
73     printArray(a, 10);
74
75     printf("Sorting array!\n");
76     start = clock();
77     quickSort(a, 0, n - 1, &comparisons);
78     end = clock();
79     printf("Done sorting!\n");
80
81     printf("First 10 elements of array after sorting : \n");
82     printArray(a, 10);
83
84     printf("Time taken : %f\n", (double)(end - start) / CLOCKS_PER_SEC);
85     printf("Number of comparisons : %d", comparisons);
86
87     return 0;
88 }
```

Output

```
> .\RandomizedQuickSort.exe
● Array has been successfully populated!
First 10 elements of array:
17 32 87 27 95 13 11 34 65 22
Sorting array!
Done sorting!
First 10 elements of array after sorting :
0 0 0 0 0 0 0 0 0
Time taken : 0.120000
Number of comparisons : 50201103
```

Problem 2

Problem Statement: Write a C program to study the impact of duplicate keys on the performance of standard quicksort and randomized quicksort. The program should generate three integer arrays, each of size 100,000, with varying proportions of duplicate elements in order to simulate different real-world data distributions. The arrays should be constructed as follows:

- i) Array-I: Contains approximately 90% duplicate values, representing highly repetitive data.
- ii) Array-II: Contains approximately 50% duplicate values, representing moderately repetitive data.
- iii) Array-III: Contains approximately 10% duplicate values, representing data with low repetition.

After generating the three arrays, implement and apply the Standard Quicksort (a fixed pivot selection strategy) and Randomized Quicksort (a random pivot selection strategy). For each combination of array type and sorting algorithm, the program must count the total number of key comparisons performed during sorting, measure the maximum recursion depth encountered during execution, and measure the execution time required to complete the sorting process. Finally, analyze and compare the performance of Standard Quicksort and Randomized Quicksort across all three data distributions. Plot appropriate 2D graphs (such as input distribution vs. execution time, number of comparisons, and recursion depth) to visually illustrate the effect of duplicate values on the efficiency and stability of both algorithms.

Code

```
1 #include <stdbool.h>
2 #include <stdio.h>
3 #include <stdlib.h>
4 #include <string.h>
5 #include <time.h>
6 #define ll long long
7
8 typedef struct {
9     ll comparisons;
10    int max_depth;
11    double time_taken;
12 } SortStats;
13
14 void swap(int *a, int *b) {
15     if (a == NULL || b == NULL)
16         return;
17     int temp = *a;
18     *a = *b;
19     *b = temp;
20 }
21
22 void shuffleArray(int *a, int n) {
23     for (int i = n - 1; i > 0; i--) {
24         int j = rand() % (i + 1);
25         swap(&a[i], &a[j]);
26     }
27 };
28
```

```

29 int StandardPartition(int *a, int low, int high, ll *comparisons) {
30     int pivot_index = high;
31     int i = low - 1;
32     int pivot = a[pivot_index];
33     swap(&a[pivot_index], &a[high]);
34
35     for (int j = low; j < high; j++) {
36         (*comparisons)++;
37         if (a[j] <= pivot) {
38             swap(&a[++i], &a[j]);
39         }
40     }
41     swap(&a[++i], &a[high]);
42     return i;
43 }
44
45 int RandomPartition(int *a, int low, int high, ll *comparisons) {
46     int pivot_index = low + (rand() % (high - low + 1));
47     swap(&a[pivot_index], &a[high]);
48     return StandardPartition(a, low, high, comparisons);
49 }
50
51 void RandomQuickSort(int *a, int low, int high, SortStats *stats,
52                      int currentDepth) {
53     if (currentDepth > stats->max_depth) {
54         stats->max_depth = currentDepth;
55     }
56     if (low < high) {
57         int partition_index =
58             RandomPartition(a, low, high, &stats->comparisons);
59         RandomQuickSort(a, low, partition_index - 1, stats, currentDepth + 1);
60         RandomQuickSort(a, partition_index + 1, high, stats, currentDepth + 1);
61     }
62 }
63
64 void StandardQuickSort(int *a, int low, int high, SortStats *stats,
65                        int currentDepth) {
66     if (currentDepth > stats->max_depth) {
67         stats->max_depth = currentDepth;
68     }
69     if (low < high) {
70         int partition_index =
71             StandardPartition(a, low, high, &stats->comparisons);
72         StandardQuickSort(a, low, partition_index - 1, stats, currentDepth + 1);
73         StandardQuickSort(a, partition_index + 1, high, stats,
74                           currentDepth + 1);
75     }
76 }
77
78 SortStats runStandardSort(int *a, int n) {
79     SortStats s = {0, 0, 0.0};
80     clock_t start = clock();
81     StandardQuickSort(a, 0, n - 1, &s, 0);
82     clock_t end = clock();
83     s.time_taken = (double)(end - start) / CLOCKS_PER_SEC;
84     return s;
85 }
86
87 SortStats runRandomSort(int *a, int n) {
88     SortStats s = {0, 0, 0.0};

```

```

89     clock_t start = clock();
90     RandomQuickSort(a, 0, n - 1, &s, 0);
91     clock_t end = clock();
92     s.time_taken = (double)(end - start) / CLOCKS_PER_SEC;
93     return s;
94 }
95
96 void printArray(int *a, int n) {
97     for (int i = 0; i < n; i++) {
98         printf("%d ", a[i]);
99     }
100    printf("\n");
101 }
102
103 void analyze(char *name, int percent_duplicates, int n) {
104     printf("--- Analyzing %s (%d% Duplicates) ---\n", name,
105           percent_duplicates);
106     int *original_data = (int *)malloc(n * sizeof(int));
107     int duplicate_count = (n * percent_duplicates) / 100;
108     int unique_count = n - duplicate_count;
109
110     for (int i = 0; i < duplicate_count; i++)
111         original_data[i] = 1;
112     for (int i = duplicate_count; i < n; i++)
113         original_data[i] = rand();
114
115     shuffleArray(original_data, n);
116
117     int *arr_std = (int *)malloc(n * sizeof(int));
118     int *arr_rnd = (int *)malloc(n * sizeof(int));
119
120     memcpy(arr_std, original_data, n * sizeof(int));
121     memcpy(arr_rnd, original_data, n * sizeof(int));
122
123     SortStats standard = runStandardSort(arr_std, n);
124     printf("[Standard QS] Time: %.4fs | Comparisons: %llu | Max Depth: %d\n",
125           standard.time_taken, standard.comparisons, standard.max_depth);
126
127     SortStats random = runRandomSort(arr_rnd, n);
128     printf(
129         "[Randomized QS] Time: %.4fs | Comparisons : %llu | Max depth : %d\n",
130         random.time_taken, random.comparisons, random.max_depth);
131     printf("\n");
132
133     free(original_data);
134     free(arr_rnd);
135     free(arr_std);
136 }
137
138 int main() {
139     int n = (int)1e5;
140     srand(time(NULL));
141
142     printf("Running analysis on array size %d\n", n);
143
144     // 90% Duplicates
145     analyze("Array I", 90, n);
146
147     // 50% Duplicates
148     analyze("Array II", 50, n);

```

```

149
150 // 10% Duplicates
151 analyze("Array III", 10, n);
152
153 return 0;
154 }
```

Output

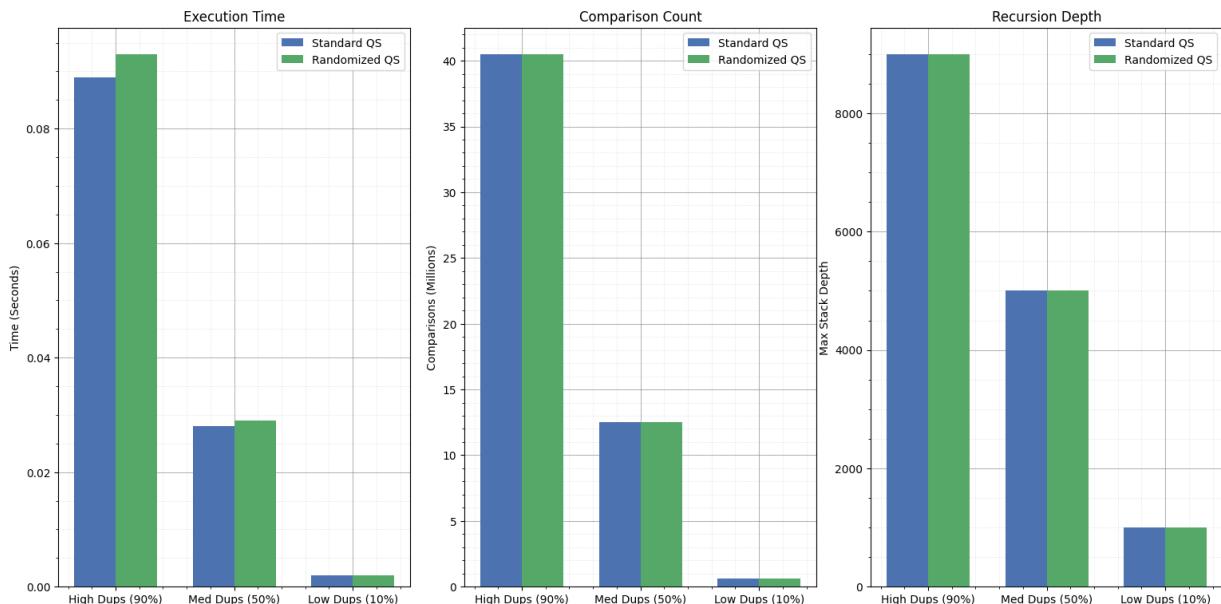


Figure 1: Performance Graphs: Input Distribution vs Time/Comparisons

```

> .\PerformanceComparisonQSort.exe
• Running analysis on array size 10000
--- Analyzing Array I (90% Duplicates) ---
[Standard QS] Time: 0.0920s | Comparisons: 40507692 | Max Depth: 8999
[Randomized QS] Time: 0.0890s | Comparisons : 40508067 | Max depth : 8999

--- Analyzing Array II (50% Duplicates) ---
[Standard QS] Time: 0.0280s | Comparisons: 12573343 | Max Depth: 4999
[Randomized QS] Time: 0.0300s | Comparisons : 12575266 | Max depth : 4999

--- Analyzing Array III (10% Duplicates) ---
[Standard QS] Time: 0.0010s | Comparisons: 642583 | Max Depth: 1002
[Randomized QS] Time: 0.0020s | Comparisons : 650936 | Max depth : 1001
```

Figure 2: Console Output Metrics

Inference

Based on the experimental data comparing Standard vs. Randomized Quicksort across varying duplicate distributions (90%, 50%, 10%):

1. Impact of Duplicates on Performance: There is a massive degradation in performance for **both** algorithms as duplicates increase.

- At **10% duplicates**, the sort took ≈ 0.002 s with ≈ 0.65 million comparisons.
- At **90% duplicates**, the sort took ≈ 0.09 s with ≈ 40.5 million comparisons.

This exponential-like growth indicates that neither standard nor randomized pivoting handles duplicates efficiently on its own. Without a specialized partitioning scheme (like 3-way partitioning), the recursion depth spikes (reaching ≈ 9000) because the partition containing equal elements remains large.

2. Ineffectiveness of Randomization for Duplicates: The graphs show almost identical bar heights for Standard and Randomized Quicksort. This is because randomization is designed to fix *sorted* input patterns, not *duplicate* values. If 90% of the data is identical, a randomly selected pivot is 90% likely to be one of those duplicates, leading to the same unbalanced partitions as the standard algorithm.

3. Conclusion: High numbers of duplicate keys are a pathological case for basic Quicksort implementations, regardless of pivot strategy. To handle Array-I (90% duplicates) effectively, a scheme like "median of 3" can be beneficial.

Problem 3

Problem Statement: Consider an integer array of size 100,000 in which approximately 80 are already in nearly sorted order, while the remaining elements are randomly positioned. Such data distributions are common in real-world applications.

Write a C program to implement both the Quicksort and Merge Sort algorithms for sorting the given array. For both sorting technique, Count the total number of key comparisons performed during execution, measure the maximum recursion depth reached during the sorting process, measure and record the execution time required to complete the sorting operation. Based on a comparative analysis of these performance metrics, justify which algorithm is more suitable for the given input conditions.

Code

```
1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4 #include <time.h>
5 #define ll long long
6
7 typedef struct {
8     ll comparisons;
9     int maxDepth;
10 } sortMetrics;
11
12 void swap(int *a, int *b) {
13     if (a == NULL || b == NULL)
14         return;
15     int temp = *a;
16     *a = *b;
17     *b = temp;
18 }
19
20 int partition(int *a, int low, int high, sortMetrics *metrics) {
21     // int pivot_index = low + rand() % (high - low + 1);
22     int pivot_index = (high + low) >> 1;
23     swap(&a[pivot_index], &a[high]);
24
25     int i = low - 1;
26     int pivot = a[high];
27
28     for (int j = low; j < high; j++) {
29         metrics->comparisons++;
30         if (a[j] <= pivot) {
31             swap(&a[++i], &a[j]);
32         }
33     }
34     swap(&a[++i], &a[high]);
35     return i;
36 }
37
38 void quickSort(int *a, int low, int high, int currentDepth,
39                 sortMetrics *metrics) {
40     if (low < high) {
41         if (currentDepth > metrics->maxDepth) {
42             metrics->maxDepth = currentDepth;
43         }
44     }
45 }
```

```

44
45     int partition_index = partition(a, low, high, metrics);
46     quickSort(a, low, partition_index - 1, currentDepth + 1, metrics);
47     quickSort(a, partition_index + 1, high, currentDepth + 1, metrics);
48 }
49 }
50
51 void merge(int *leftArray, int leftSize, int *rightArray, int rightSize,
52             int *array, sortMetrics *metrics) {
53     int i = 0, l = 0, r = 0;
54     while (l < leftSize && r < rightSize) {
55         metrics->comparisons++;
56         if (leftArray[l] < rightArray[r])
57             array[i++] = leftArray[l++];
58         else
59             array[i++] = rightArray[r++];
60     }
61     while (l < leftSize)
62         array[i++] = leftArray[l++];
63     while (r < rightSize)
64         array[i++] = rightArray[r++];
65 }
66
67 void mergeSort(int *array, int n, int currentDepth, sortMetrics *metrics) {
68     if (n <= 1)
69         return;
70
71     if (currentDepth > metrics->maxDepth) {
72         metrics->maxDepth = currentDepth;
73     }
74
75     int mid = n / 2;
76     int leftSize = mid;
77     int rightSize = n - mid;
78
79     int *leftArray = (int *)malloc(leftSize * sizeof(int));
80     int *rightArray = (int *)malloc(rightSize * sizeof(int));
81
82     if (leftArray == NULL || rightArray == NULL) {
83         printf("Memory allocation failed.\n");
84         return;
85     }
86     memcpy(leftArray, array, leftSize * sizeof(int));
87     memcpy(rightArray, &array[mid], rightSize * sizeof(int));
88
89     mergeSort(leftArray, leftSize, currentDepth + 1, metrics);
90     mergeSort(rightArray, rightSize, currentDepth + 1, metrics);
91     merge(leftArray, leftSize, rightArray, rightSize, array, metrics);
92
93     free(leftArray);
94     free(rightArray);
95 }
96
97 void generateData(int *a, int n) {
98     int sorted = n * 0.8;
99     // 80% of data is sorted
100    for (int i = 0; i < sorted; i++) {
101        a[i] = i;
102    }
103 }
```

```

104 // From that 80%, 5% of it is randomized/unsorted
105 for (int i = 0; i < sorted / 20; i++) {
106     int i1 = rand() % sorted;
107     int i2 = rand() % sorted;
108     swap(&a[i1], &a[i2]);
109 }
110
111 // rest of it is unsorted
112 for (int i = sorted; i < n; i++) {
113     a[i] = rand() % n;
114 }
115 }
116
117 int main() {
118     int n = (int)1e5;
119     srand(time(NULL));
120
121     int *arrayQuickSort = (int *)malloc(n * sizeof(int));
122     int *arrayMergeSort = (int *)malloc(n * sizeof(int));
123
124     if (!arrayMergeSort || !arrayQuickSort) {
125         printf("Memory allocation failed\n");
126         return -1;
127     }
128
129     printf("Generating array : %d elements (80% nearly sorted)\n", n);
130     generateData(arrayQuickSort, n);
131     memcpy(arrayMergeSort, arrayQuickSort, n * sizeof(int));
132     printf("Generated array!\n");
133
134     sortMetrics quickSortMetrics = {0, 0};
135     printf("\nRunning Quick Sort (randomized pivot)\n");
136
137     clock_t start = clock();
138     quickSort(arrayQuickSort, 0, n - 1, 0, &quickSortMetrics);
139     clock_t end = clock();
140
141     double quickSortTime = ((double)(end - start)) / CLOCKS_PER_SEC;
142
143     printf(" Execution Time      : %f seconds\n", quickSortTime);
144     printf(" Key Comparisons      : %lld\n", quickSortMetrics.comparisons);
145     printf(" Max Recursion Depth : %d\n", quickSortMetrics.maxDepth);
146
147     sortMetrics mergeSortMetrics = {0, 0};
148
149     printf("\nRunning Merge Sort\n");
150
151     start = clock();
152     mergeSort(arrayMergeSort, n, 0, &mergeSortMetrics);
153     end = clock();
154
155     double mergeSortTime = ((double)(end - start)) / CLOCKS_PER_SEC;
156
157     printf(" Execution Time      : %f seconds\n", mergeSortTime);
158     printf(" Key Comparisons      : %lld\n", mergeSortMetrics.comparisons);
159     printf(" Max Recursion Depth : %d\n", mergeSortMetrics.maxDepth);
160
161     free(arrayMergeSort);
162     free(arrayQuickSort);
163

```

```
164     return 0;  
165 }
```

Output

```
• Generating array : 100000 elements (80% nearly sorted)  
Generated array!  
  
Running Quick Sort (randomized pivot)  
Execution Time      : 0.006000 seconds  
Key Comparisons    : 1922705  
Max Recursion Depth : 37  
  
Running Merge Sort  
Execution Time      : 0.011000 seconds  
Key Comparisons    : 1158887  
Max Recursion Depth : 16
```

Inference

Analyzing the performance metrics for the 100,000-element, 80% nearly sorted array:

1. **Efficiency of Randomization:** The Randomized Quicksort achieved a maximum recursion depth of **37**. Given that $\log_2(100,000) \approx 17$, a depth of 37 is excellent and confirms that randomization successfully broke the "sorted" pattern. Without randomization, a standard Quicksort on this dataset would likely have crashed due to stack overflow (depth $\approx 100,000$).
 2. **The Comparisons vs. Time Paradox:** Merge Sort was more efficient in terms of algorithmic steps, performing only **1.15 million comparisons** compared to Quicksort's **1.92 million**. However, Randomized Quicksort was nearly **2x faster** in execution time (0.006s vs 0.011s).
 3. **Justification for Result:** Although Merge Sort did less "work" (fewer comparisons), it incurs significant overhead by allocating auxiliary memory and copying data back and forth. Quicksort operates **in-place**, which benefits from superior CPU cache locality.
- Conclusion:** For this specific nearly-sorted dataset, **Randomized Quicksort** is the more suitable choice if raw speed is the priority, as it mitigates the sorting risk while outperforming Merge Sort in runtime. Merge Sort remains the safer choice only if strict $O(N \log N)$ worst-case guarantees are required.