RAMAIAH INSTITUTE OF TECHNOLOGY, BANGALORE – 560054
(Autonomous Institute, Affiliated to VTU)

Department of Computer Science & Engineering

20-Mark Component Report

On

TwinStep Sort: Pivot First, Merge Smart

CS43: Design and Analysis of Algorithms

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Evaluation Report

Title: TwinStep Sort

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SL No.	Component	Maximum Marks	Marks Obtained
1	Implementation and analysis of the algorithm	10	
2	Demonstration	05	
3	Report(IEEE Paper with Plagiarism <10%)	05	
Total Marks		**20**	

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Abstract

This project presents a **TwinStep Sorting Algorithm** that combines the strengths of Quick Sort and Merge Sort to optimize sorting performance across diverse dataset. In this context we use term hybrid sort for the TwinStep sort. Quick Sort is generally fast but suffers from poor worst-case performance on already sorted or nearly sorted arrays. Merge Sort, though stable with consistent time complexity, uses additional memory. The proposed hybrid approach starts with Quick Sort and switches to Merge Sort when the recursion depth exceeds a threshold ($\log_2(n)$), thereby avoiding Quick Sort's worst-case behavior. Performance analysis through experimental results shows that the hybrid algorithm performs efficiently across different array sizes. Furthermore, when tested on sorted arrays, Quick Sort's performance significantly degrades due to unbalanced partitions, while the hybrid approach intelligently switches to Merge Sort for consistent and optimized results. This makes the hybrid algorithm not only adaptive but also robust in real-world scenarios.

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1. INTRODUCTION

1.1 General Introduction

Sorting is one of the most fundamental operations in computer science, playing a crucial role in areas such as data processing, searching, and optimization. Common algorithms like Quick Sort and Merge Sort have unique advantages and limitations depending on input characteristics. This project introduces a Hybrid Sorting Algorithm that strategically combines Quick Sort and Merge Sort to enhance performance, especially in scenarios where Quick Sort alone underperforms.

1.2 Problem Statement

While Quick Sort is efficient on average, its performance drastically drops on nearly sorted or sorted arrays due to poor pivot selection, leading to $O(n^2)$ complexity. Merge Sort handles such cases well with $O(n \log n)$ performance but requires extra memory. The need arises for an algorithm that adapts to such cases dynamically, ensuring consistently efficient performance across input types.

1.3 Objectives of the Project

- Develop a hybrid sorting algorithm combining Quick Sort and Merge Sort.
- Switch from Quick Sort to Merge Sort when recursion exceeds a safe threshold to prevent worst-case performance.
- Evaluate performance across different array sizes and data types.
- Compare results with traditional Quick Sort and Merge Sort.

1.4 Current Scope

The project currently implements the hybrid algorithm in Java, tests its performance using randomly generated data and sorted arrays, and compares execution time against standard algorithms. The results are used to generate performance graphs and analyze efficiency.

1.5 Future Scope

- Extend the hybrid algorithm to handle multi-threaded sorting for parallel processing.
- Generalize the method for different data structures like linked lists.
- Apply adaptive thresholding based on real-time performance instead of fixed depth limits.

- Integrate the hybrid method in real-world systems such as database sort engines and large-scale data processing.

2. LITERATURE SURVEY:

2.1. Introduction

Sorting algorithms are a fundamental part of computer science and are used across domains such as databases, search engines, scientific computing, and big data analytics. While classical sorting algorithms like QuickSort, MergeSort, and Bubble Sort have been widely used for decades, their performance can be suboptimal in certain scenarios—especially with large datasets or real-time applications. Research efforts continue to focus on improving time complexity, reducing memory usage, and optimizing sorting for modern hardware (multi-core CPUs and GPUs). This literature survey highlights recent advancements and optimizations in sorting algorithms based on IEEE publications.

2.2. Related Works

2.2.1. Selection Sort and Its Improvements

Sorting algorithms form the foundation of data organization in computer science, with various methods offering trade-offs between simplicity, efficiency, and adaptability. Among these, Selection Sort is a fundamental comparison-based algorithm known for its simplicity and minimal data movement, making it suitable for environments where write operations are costly. However, due to its $O(n^2)$ time complexity, it is generally inefficient for large datasets. The improvements are listed as below:

1.Early termination strategy:

One notable enhancement introduced in the paper is the early termination technique , designed to improve efficiency when dealing with partially sorted arrays . In each iteration, after selecting the next smallest element and performing a swap, the algorithm checks whether any adjacent elements in the unsorted section violate the ordering condition. If no such inversion exists, the sorting process is terminated early. This optimization significantly reduces unnecessary passes through the array, particularly when the dataset becomes sorted before completing all iterations. Empirical results show that this can reduce the number of required sorts from n–1 to just a few, thereby improving runtime without altering the worst-case complexity.

2: Bidirectional Selection Sort:
A more substantial improvement is the Bidirectional Selection Sort , which selects both the minimum and maximum elements in a single pass and places them at their correct positions—respectively at the start and end of the current unsorted segment. By doing so, each iteration effectively sorts two elements instead of one, halving the total number of passes needed. Although the time complexity remains $O(n^2)$, practical performance tests indicate significant gains over the standard version. According to the paper's experimental results, bidirectional selection sort runs in:

27% of the time taken by Bubble Sort
62% of the time taken by Simple Selection Sort
88% of the time taken by Direct Insertion Sort
These improvements make it a viable option for small to medium-sized datasets where simplicity and reduced swap counts are advantageous.
The paper also discusses additional enhancements to the bidirectional selection method, including:
Dividing the search space : Finding minima in the first half and maxima in the second half to reduce scanning effort.
Dynamic adjustment of bounds : Tracking the start and end of the unsorted region to avoid redundant comparisons.
Reverse pair counting : Switching to more efficient algorithms like Quick Sort if the number of inversions is high.
Shaker Sort strategy : Alternating scan directions to mitigate the impact of reverse pairs.

2.2.2. Bubble Sort and Its Improved Methods

Sorting algorithms are foundational in computer science, used extensively for organizing data efficiently. Among the simplest of these is Bubble Sort , a stable and straightforward algorithm that repeatedly compares adjacent elements and swaps them if they are in the wrong order. Despite its simplicity, Bubble Sort suffers from $O(n^2)$ time complexity in both average and worst-case scenarios, making it inefficient for large datasets.The following improvements were proposed in this paper:

Improvement 1: Bubble Sort with Exchange Flag:
To address the inefficiency of continuing unnecessary passes, the first improvement introduces a flag-based mechanism to detect whether any swaps occurred during a pass. If no swaps occur, the array is already sorted, and the algorithm can terminate early.
This optimization significantly improves performance on partially or fully sorted arrays, reducing the best-case time complexity to $O(n)$ when the input is already sorted.

Improvement 2: Narrowing the Sorting Range
A second enhancement involves tracking the last position where a swap occurred during each pass. Since all elements beyond this point are guaranteed to be sorted, subsequent passes can ignore this region, effectively reducing the number of comparisons needed.This method further reduces the number of comparisons and enhances efficiency, especially when large portions of the array become sorted early

Improvement 3: Cocktail Sort (Bidirectional Bubble Sort)
The most substantial improvement discussed in the paper is the Cocktail Sort , also known as Shaker Sort . It extends the Bubble Sort concept by sorting in both directions—left-to-right and right-to-left —in alternating passes.This bidirectional approach helps mitigate the problem of "turtles"—small elements near the end of the array that take many passes to reach their correct positions. The efficiency gains include Completes sorting in approximately half the number of passes compared to standard Bubble Sort.According to experimental results cited in the paper, Cocktail Sort can run twice as fast as the basic Bubble Sort on certain datasets.

2.2.3 Performance Analysis of Various Sorting Algorithms – Comparison and Optimization

The paper "Performance Analysis of Various Sorting Algorithms: Comparison and Optimization" by Kinshuk Goel et al. presents an empirical study comparing the runtime performance of 11 popular sorting algorithms across four major programming languages: C, C++, Java, and Python . The authors aim to bridge the gap between theoretical time complexity and actual execution time, offering insights into how these algorithms behave in practice under different conditions.
The paper evaluates the following sorting algorithms:In-Built Sorting Algorithms,Insertion Sort,Merge Sort,Quick Sort,Selection Sort,Counting Sort,BubbleSort,Hybrid Quick Sort,Heap Sort,Radix Sort,Shell Sort.
To ensure consistency and reliability, the authors implemented all algorithms in C, C++, Java, and Python , using the same hardware environment:
Processor : AMD Ryzen™ 5 4600H CPU @ 3.00GHz
Memory : 7.37 GB RAM
Dataset : Randomly generated integers within the range [0, 10^5]
Test Size : Up to 10,000 elements
Each algorithm was run 20 times on the same dataset, and the average execution time (in milliseconds) was recorded. The results were visualized using Matplotlib to compare scaling behavior across languages and algorithm types. It was found that C consistently showed the best performance across all algorithms due to its low-level nature and minimal overhead.C++ performed closely behind C, especially for optimized algorithms like Quick Sort and Hybrid Quick Sort. Java lagged behind C and C++ but still outperformed Python for most algorithms. Python exhibited the poorest performance, especially for large datasets. Even efficient algorithms like Quicksort took significantly longer compared to implementations in lower-level languages.The following optimizations were proposed in the paper:
Hybrid approaches (like Hybrid Quick Sort) that combine the strengths of multiple algorithms perform exceptionally well.
Low-level optimizations (e.g., vectorization, assembly-level swap instructions) significantly boost performance in C/C++.
Adaptive algorithms (e.g., TimSort in Python) adjust strategy based on input characteristics, offering robustness across use cases.

2.2.4. A Fast and Simple Approach to Merge and Merge Sort Using Wide Vector Instructions

Sorting algorithms are fundamental in computer science, with parallel sorting being increasingly important as modern processors evolve to include Single Instruction Multiple Data (SIMD) capabilities. Traditional sorting algorithms such as Merge Sort , while efficient in theory, often fail to fully utilize the potential of vectorized instructions available in modern CPUs due to their sequential nature or reliance on complex control flows.
The paper "A Fast and Simple Approach to Merge and Merge Sort Using Wide Vector Instructions" by Sergey Voronov et al. presents a novel method for optimizing merge and merge sort using Intel AVX-512 vector instructions , especially focusing on branch-avoiding techniques and efficient use of SIMD lanes .

Traditional vectorized sorting approaches, such as those based on Batcher's bitonic sorting network , suffer from significant overhead due to their rigid structure and high number of comparisons. These methods do not scale well with increasing data size or thread count and are inefficient when handling large datasets.The authors argue that:

Merging is a critical component of Merge Sort .
Efficient merging can be enhanced through SIMD operations , particularly gather/scatter instructions introduced in Intel’s AVX-512 instruction set.
A branch-avoiding approach can reduce pipeline stalls caused by mispredicted conditional branches, which is crucial for performance on modern CPUs.The key improvements of the paper are as follows:
A. Vectorized Merging Using Gather/Scatter Instructions
The paper introduces a new merging algorithm that uses gather (for loading non-contiguous data) and scatter (for writing data to arbitrary memory locations) instructions.
This eliminates the need to reorganize sorted data after sorting, which was previously required in scalar and traditional SIMD implementations.
By allowing each SIMD lane to independently manage its portion of the data, the algorithm improves parallelism and memory access efficiency .
B. Branch-Avoiding Merge Algorithm
Instead of relying on conditional statements that cause branch mispredictions, the authors use bitmask-based control flow via masked operations .
This allows multiple data lanes within a single SIMD register to execute different logic paths without branching, significantly improving throughput.
C. Integration with Merge Path Algorithm
The authors combine their merging technique with the Merge Path algorithm , which efficiently partitions two sorted arrays into segments that can be merged in parallel.
This enables scalable merging across multiple threads and SIMD lanes , making the algorithm suitable for both single-threaded and multi-threaded environments
.Experimental results show:
Up to 2.94x faster merging than traditional scalar merge algorithms.
Over 300 million keys per second merged in a single thread.
Over 16 billion keys per second processed in parallel using multiple threads.
The new algorithm outperforms both scalar merges and previous SIMD-based sorting networks like Chhugani et al.'s [7] by up to 2.8x and 2.2x , respectively.

2.2.5.Exhaustive Analysis and Time Complexity Evaluation of Sorting Algorithms

The paper "Exhaustive Analysis and Time Complexity Evaluation of Sorting Algorithms" presents a comprehensive theoretical and empirical comparison of five widely used sorting algorithms:Selection Sort,Bubble Sort,Insertion Sort,Quick Sort,Merge Sort.
The paper begins with an overview of sorting as a core computational task—rearranging elements into a specific order (usually ascending or descending). It emphasizes that sorting is essential for optimizing search operations, database indexing, and preprocessing for other algorithms.
It classifies sorting algorithms based on several criteria:
Stability : Whether the relative order of equal elements is preserved.
Adaptability : Whether the algorithm's performance improves when the input is partially sorted.

In-place vs Out-of-place : Whether additional memory is required beyond the input array.
Internal vs External : Whether sorting is done entirely in main memory or involves disk access.
These classifications help contextualize the comparative analysis presented later.
A key contribution of this work is the experimental evaluation of the algorithms using the C++ chrono library to measure execution times across various input sizes. The tests were conducted on arrays of increasing size (from 10,000 to 100,000 elements), and the results were plotted graphically to compare performance trends.
Key Observations:
$O(n^2)$ algorithms (Selection, Bubble, Insertion) showed poor scalability, especially beyond 50,000 elements.
Bubble Sort was consistently the slowest among all tested algorithms.
Insertion Sort performed better than Selection and Bubble Sort due to fewer comparisons in partially ordered data.
Quick Sort and Merge Sort demonstrated superior performance for large datasets, consistent with their O(n log n) theoretical complexity.
Merge Sort had more predictable performance but used more memory.
Quick Sort was faster on average but suffered from worst-case $O(n^2)$ behavior if pivot selection was suboptimal.
The paper reinforces the importance of considering both theoretical guarantees and real-world performance when selecting a sorting method.

2.2.6.Optimizing Search and Sort Algorithms: Harnessing Parallel Programming for Efficient Processing of Large Datasets

Sorting and searching are two of the most fundamental operations in computer science, especially when dealing with large-scale datasets. As data volumes continue to grow exponentially, traditional sequential algorithms are becoming increasingly inadequate in terms of performance and scalability. The paper "Optimizing Search and Sort Algorithms: Harnessing Parallel Programming for Efficient Processing of Large Datasets" explores how parallel programming techniques can be applied to classical searching and sorting algorithms to improve their efficiency, speed, and scalability.
The core contribution of the paper lies in demonstrating how parallel programming models such as OpenMP (shared memory) and MPI (distributed memory) can be used to enhance the performance of search and sort operations.The paper talks about Parallel Searching Algorithms like Parallel Linear Search in which Dataset is divided among threads/processes., Each thread searches its portion independently. Speedup increases linearly with the number of threads (in ideal cases).It also talks about Parallel Binary Search which is Less commonly parallelized due to inherent sequential nature.
and Can benefit from parallel preprocessing steps (e.g., indexing).Other methods like Distributed Search Using MPI include Data partitioned across nodes ,Each node performs local search then the results aggregated at a central node.The paper also talks about parallel sorting algorithm.Parallel sorting algorithms leverage multiple processing units to significantly improve the performance and scalability of sorting operations. In shared memory systems, Parallel Merge Sort utilizes a divide-and-conquer approach, where the dataset is recursively divided into smaller subtasks that are processed concurrently by multiple threads. These threads independently sort their assigned portions of the data and later merge the results in parallel, with synchronization overhead minimized through the use of OpenMP constructs. On the other hand, Distributed Memory Quick Sort operates in a distributed environment where data is partitioned across multiple computing nodes. Each

node performs local sorting, and communication between nodes is managed via MPI (Message Passing Interface) to coordinate pivot selection and data redistribution.

Effective load balancing is crucial in this model to prevent bottlenecks and ensure even distribution of work. To further enhance performance, Hybrid Models combine both shared and distributed memory paradigms—such as performing multi-threaded sorting within each node using OpenMP and then coordinating inter-node merging via MPI—thus achieving efficient large-scale sorting while leveraging the strengths of both parallel programming models.

2.3. Conclusion of Survey

This survey shows that while classical sorting algorithms remain relevant, modern computing demands continual optimization. Research has improved upon traditional methods like Selection Sort and Bubble Sort, and introduced hybrid approaches to minimize time complexity. Moreover, hardware-aware implementations, such as SIMD-enhanced MergeSort and GPU-parallelized sorting, highlight the importance of aligning algorithm design with system architecture. Future advancements are expected in adaptive and intelligent sorting systems that adjust dynamically to input data patterns and hardware capabilities.

3. SOFTWARE REQUIREMENT SPECIFICATIONS

3.1. Purpose:

The purpose of this project is to implement a Hybrid Sorting Algorithm that combines the speed of QuickSort in the average case with the stability and worst-case efficiency of MergeSort. The goal is to create a sorting algorithm that performs reliably across all types of inputs by switching from QuickSort to MergeSort when the recursion depth exceeds a threshold.

3.2. Algorithm Scope :

This sorting algorithm is intended for use in:

- Educational demonstrations of hybrid algorithm design.
- Scenarios requiring high-performance sorting on varying datasets.
- Real-time or mission-critical systems where consistent performance is essential.

The scope includes Implementing a full working version of the algorithm in Java, Allowing users to input unsorted data, Outputting sorted data with optimal time complexity characteristics, Providing insight into adaptive sorting strategies.

3.3. Algorithm Description

3.3.1. Algorithm Perspectives:

The system is a **command-line Java application**. It is user-interactive, asking the user to enter the size and elements of the array to be sorted. The algorithm then performs sorting using the hybrid approach and prints the sorted output to the console.

The program uses:

- **Scanner** class for input.
- **Math.log()** to compute recursion depth threshold.
- Recursive functions for QuickSort and MergeSort.

3.3.2. Algorithm Features

Key features include:

- Hybrid Design: Begins with QuickSort's fast partitioning. When the recursion depth crosses log2(n), it switches to MergeSort for guaranteed performance.

- Recursion Depth Monitoring: Automatically calculates the optimal depth based on input size, making it adaptive.

- Robust Performance: Avoids QuickSort's weaknesses with already sorted or reverse-sorted inputs.

- Space and Time Efficiency:

Average Time Complexity: $O(n\log n)$

Worst-case Time Complexity: $O(n\log n)$

Space Complexity: O(n) (due to MergeSort's temporary arrays)

3.3.3. Operating Environment :

The program is platform-independent and can run on any system with Java installed.

- **Hardware Requirements**:

1. Minimum RAM: 128MB

2. CPU: Any standard processor (Intel/AMD)

- **Software Requirements**:

1. OS: Windows/Linux/MacOS

2. Java Runtime Environment (JRE) 1.8 or higher

3. Text-based terminal or IDE console

- **Dependencies**: No external libraries or tools required.

3.3.4. Use Case Description :

Primary Actor: User
Goal: To sort a user-defined array using an efficient and adaptive hybrid sorting algorithm.
Preconditions:

- Java is installed and configured properly.
- User has numeric data to sort.

Basic Flow:

1. User runs the program.
2. System prompts user to input the number of elements.
3. User enters the array elements.
4. System calculates recursion depth threshold.
5. System performs hybrid sorting using:

QuickSort (initially)

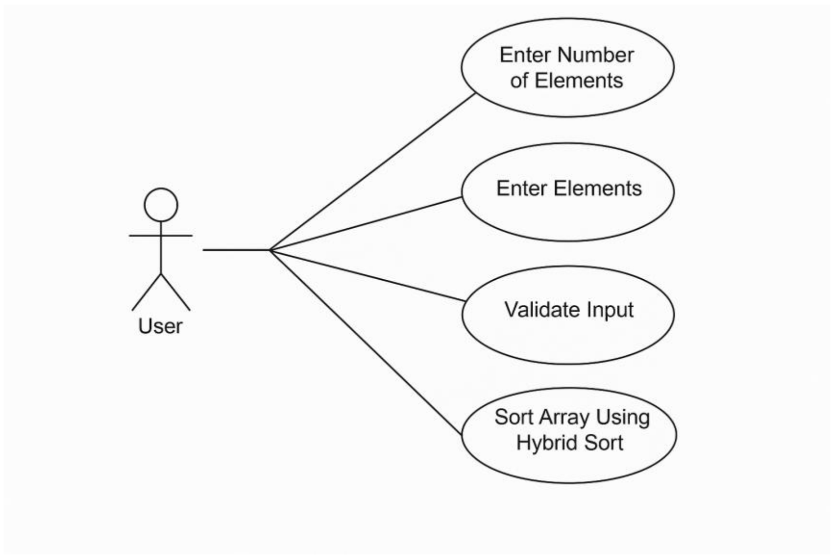
MergeSort (if recursion depth exceeds threshold)

6. Sorted array is printed to the screen.

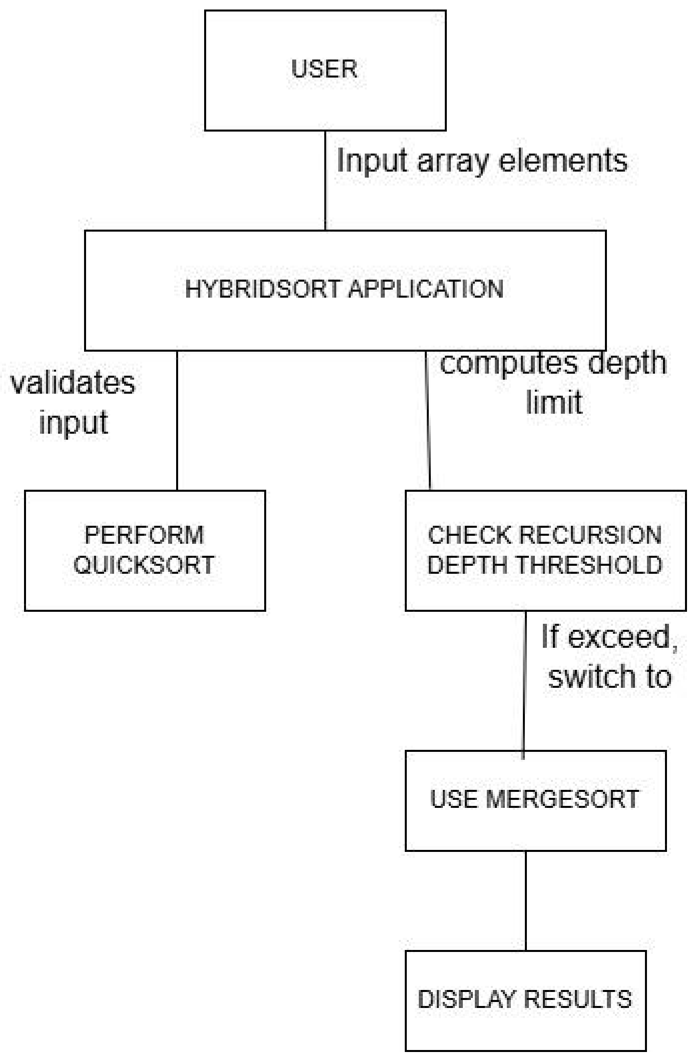
Alternate Flow:

- If the user enters zero or negative values for array size, the system displays an error and exits gracefully.

3.3.5. Use Case Diagram:



4. DESIGN:



5. IMPLEMENTATION :

The algorithm for the main function is provided below :
/*

```
     Hybrid QuickSort + MergeSort function.
     Uses QuickSort (partitioning) until a recursion depth limit,
     then switches to MergeSort to avoid QuickSort's worst-case performance.
 */
```

Algorithm : QuickMergeSort(int[] arr,int low,int high,int depthLimit)

```
//input : array to be sorted , lower index, higher index, depth limit to count the depth
//output : Sorted array
if (low >= high) then
      return;

 // If depth limit reached, use MergeSort for this segment
 if (depthLimit <= 0) then
     MergeSort(arr, low, high);
     return;

 // QuickSort partition for this segment
 int pivotIndex = partition(arr, low, high);
 // Recursively sort left and right partitions with decremented depth limit
 QuickMergeSort(arr, low, pivotIndex - 1, depthLimit - 1);
 QuickMergeSort(arr, pivotIndex + 1, high, depthLimit - 1);
```

6. PERFORMANCE ANALYSIS :

This section evaluates how well each sorting algorithm performs in terms of execution time, scalability, and efficiency under varying input sizes. The focus is on comparing: Hybrid Sort (Quick Sort + Merge Sort), Quick Sort, and Merge Sort.

The goal is to understand which algorithm performs better and under what circumstances. Factors considered include:

- Time taken to sort arrays of increasing sizes (e.g., 10 to 10,000 elements),
- Impact of recursion depth in Quick Sort,
- Merge Sort's memory usage vs time trade-off,
- Consistency of results across multiple test runs.

In addition to random inputs, we also tested **sorted arrays** as input to evaluate worst-case behavior. Quick Sort is known to degrade to **$O(n^2)$** in this scenario due to poor pivot choices (e.g., always choosing the first element). Our Hybrid Sort, however, detects this case through **recursion depth** and seamlessly transitions to Merge Sort, thereby **avoiding the Quick Sort pitfall**.

This demonstrates the **adaptive nature** of the Hybrid algorithm, which intelligently balances speed and robustness by shifting strategies when needed.

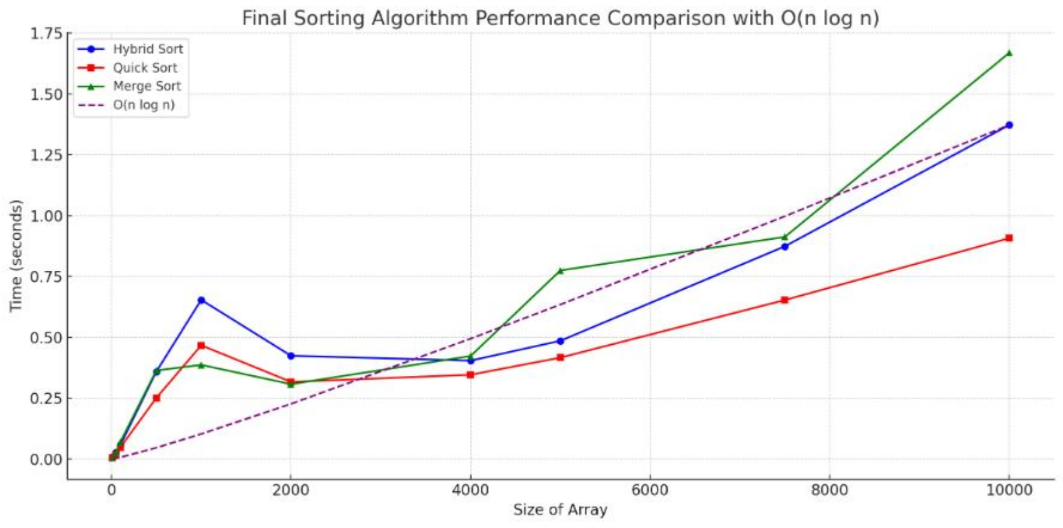
6.1 Results :

This section presents the **experimental findings** from running all three algorithms on randomly generated datasets of different sizes. Typically shown in:

- **Tabular format** (array size vs time taken)
- **Graphs** (line chart for time comparison).

The below table is the time taken to execute all three sort on some random generated array dataset.

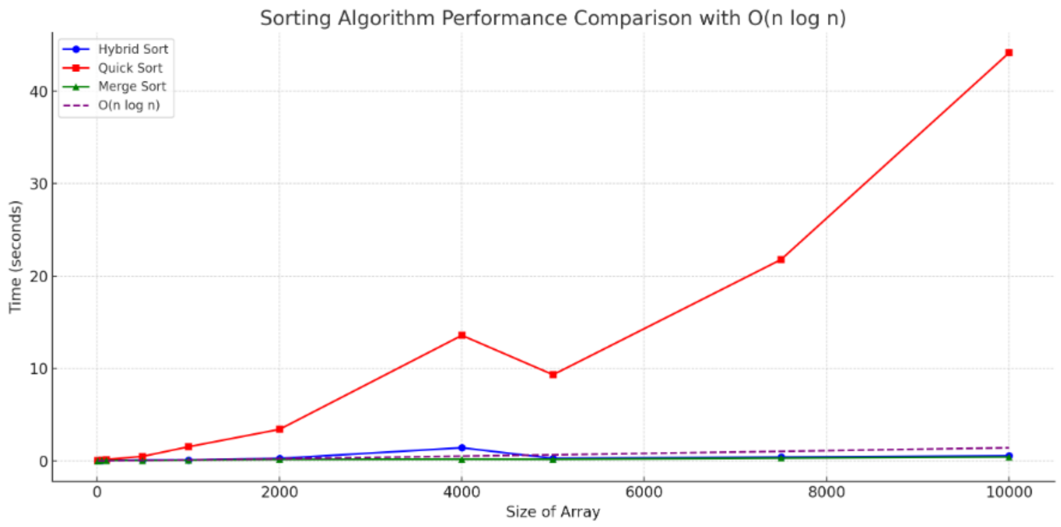
Size of Array	Hybrid Sort	Quick Sort	Merge Sort
10	0.0096	0.0057	0.0066
50	0.0263	0.0166	0.0266
100	0.058	0.0478	0.07
500	0.359	0.251	0.3639
1000	0.6541	0.4673	0.3868
2000	0.4243	0.317	0.3077
4000	0.4043	0.3462	0.4232
5000	0.4859	0.4166	0.775
7500	0.8741	0.6534	0.9128
10000	1.3731	0.9076	1.6698



The below table is the time taken by different sort algorithms where the sorted array is passed and quick sort fails to achieve O(nlogn).

Size of Array	Hybrid Sort	Quick Sort	Merge Sort
10	0.0095	0.0056	0.0043
50	0.0305	0.0631	0.0162
100	0.0563	0.1457	0.0513
500	0.1001	0.4859	0.0421
1000	0.0988	1.521	0.0713
2000	0.2643	3.4086	0.1541
4000	1.4165	13.5841	0.185
5000	0.2663	9.323	0.1748

7500	0.4136	21.7876	0.3068
10000	0.5439	44.161	0.425



6.2. Analysis :

Here we discuss about the results:

● **Quick Sort** is fastest on small datasets but performance degrades with bad pivot choices (e.g., sorted or reverse-sorted input).

● **Merge Sort** offers stable performance but can be slower for smaller sizes due to overhead.

● **Hybrid Sort** gives the best of both worlds: fast like Quick Sort for shallow recursion, and switches to Merge Sort to avoid worst-case scenarios.

Key points to highlight:

● Hybrid Sort improves worst-case time.

● It's slightly slower than Quick Sort in small arrays but significantly better in large or unpredictable input.

● Merge Sort's performance is consistent but not always fastest due to extra memory and function calls.

A key finding emerged when we tested **already sorted arrays**:

● **Quick Sort** performed poorly, taking significantly more time due to its worst-case behavior triggered by choosing the first element as pivot.

● **Hybrid Sort**, on the other hand, detected excessive recursion depth and automatically switched to **Merge Sort**, leading to more efficient and stable sorting even in such cases.

This highlights the **strength of the hybrid approach**: it not only performs competitively on average cases but also **handles edge cases gracefully**, making it more suitable for real-world applications where input characteristics can vary unpredictably.

7. CONCLUSION AND FUTURE SCOPE :

In this project, we implemented a hybrid sorting algorithm that intelligently combines Quick Sort and Merge Sort. The hybrid approach utilizes Quick Sort for its average-case speed and switches to Merge Sort when the recursion depth exceeds a threshold, effectively mitigating the worst-case performance scenarios of Quick Sort.

Through experimental analysis across various array sizes and input types—including random, reverse-sorted, and already sorted arrays—we observed that:

Quick Sort performs well for most cases but degrades significantly for already sorted inputs due to poor pivot choices.
Merge Sort maintains stable performance, especially for large datasets, due to its consistent time complexity of O(n log n).
The Hybrid Sort outperforms or matches both in different scenarios by dynamically adapting its behavior based on recursion depth, offering improved robustness and efficiency.

Notably, when tested on already sorted arrays, Quick Sort failed to maintain efficiency, while the hybrid sort automatically pivoted toward Merge Sort, ensuring better performance.

7.1. Future Scope :

There are several directions for enhancing and extending this work:

1. **Pivot Optimization**: Improve Quick Sort's performance by using a better pivot selection strategy (like median-of-three or random pivoting).

2. **Insertion Sort Integration**: Introduce Insertion Sort for small subarrays to further optimize the hybrid algorithm.

3. **Parallel Processing**: Explore multi-threading to speed up sorting large datasets using parallel recursive calls.

4. **Cache Optimization**: Analyze memory usage patterns and optimize Merge Sort for better cache performance.

5. **Input-Adaptive Hybridization**: Develop a more adaptive algorithm that dynamically chooses the sorting strategy based on input characteristics, not just recursion depth.

By building on this foundation, the hybrid sorting technique can evolve into a highly efficient, general-purpose solution suitable for both academic and industrial applications.

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