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INSTITUTE OF INFORMATION TECHNOLOGY
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Department Of Computer Engineering

A HPC PROJECT REPORT

ON

# Parallel Quicksort Algorithm using MPI.

SUBMITTED TO THE DEPARTMENT OF COMPUTER ENGINEERINGAISSMS IOIT

BE Computer Engineering

SUBMITTED BY


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# CERTIFICATE

This is to certify that the project report.
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is a bonafide student at this institute and the work has been carried out by them under the supervision of **Dr. S.N.Zaware** and it is approved for the partial fulfillment of the Department of Computer Engineering AISSMS IOIT.

(**Dr. S.N.Zaware**)
Mini-Project Guide

(**Dr. S.N.Zaware**)
Head of Computer Department

Place: Pune

Date:

# Abstract

The goal of this mini project is to assess the performance enhancement achieved by implementing a **Parallel Quicksort Algorithm Using MPI** (Message Passing Interface) compared to the sequential version. Quicksort is a popular sorting algorithm known for its efficiency and parallelizing it using MPI can potentially further improve its performance.

To evaluate the performance, the runtime of the sequential Quicksort algorithm is measured using a timing mechanism. Similarly, the runtime of the parallel Quicksort algorithm is measured using MPI, with varying numbers of MPI processes. The measurements are collected and analysed to observe the performance enhancement achieved by the parallel version.

The project aims to compare the runtimes of the sequential and parallel algorithms for different input sizes and numbers of MPI processes. The results are presented through graphs or tables to visualize the performance improvement achieved with the parallel Quicksort algorithm.

Overall, this mini project provides hands-on experience in implementing and evaluating parallel algorithms using MPI. It highlights the potential benefits of parallelizing algorithms and demonstrates the performance enhancement achieved by parallel Quicksort compared to its sequential counterpart.

# Contents

# Introduction

Quicksort is a widely used sorting algorithm known for its average-case efficiency and ease of implementation. It follows the divide-and-conquer approach by recursively partitioning an array into smaller subarrays and sorting them independently. While Quicksort is efficient on a single processor, it can benefit significantly from parallelization to handle large datasets more effectively.

The Message Passing Interface (MPI) is a standard communication protocol that allows multiple processes running on different nodes of a distributed system to communicate with each other. It provides a set of functions to facilitate data exchange and synchronization between processes, enabling efficient parallelization of algorithms across multiple compute nodes.

The main objective of this mini project is to develop a parallel Quicksort algorithm using MPI, leveraging the benefits of distributed computing to speed up the sorting process. By dividing the dataset into smaller subarrays and assigning them to different processes, the algorithm can perform sorting operations concurrently on multiple nodes. The project will involve understanding the fundamentals of the Quicksort algorithm, gaining familiarity with the MPI programming model, and designing a parallel version of the algorithm using MPI. The implementation will include strategies for partitioning the dataset, distributing subarrays across processes, performing local sorting, and merging the sorted subarrays to obtain the final sorted array.

Overall, this project provides an excellent opportunity to explore the realm of parallel computing and learn how to leverage MPI to optimize the performance of sorting algorithms, ultimately enhancing your understanding of distributed systems and their practical applications.

# Software Requirement Specification

## Software Used:

- VS Code :

  Visual Studio Code is a source-code editor made by Microsoft for Windows, Linux and macOS. Features include support for debugging, syntax highlighting, intelligent code completion, snippets, code refactoring, and embedded Git.

- C/ C++ extension:

  C/C++ support for Visual Studio Code is provided by a Microsoft C/C++ extension to enable cross-platform C and C++ development on Windows, Linux, and macOS.

- MPICH :

  MPICH and its derivatives form the most widely used implementations of MPI in the world. They are used exclusively on nine of the top 10 supercomputers.

- Linux Virtual Machine:

  Linux containers and virtual machines (VMs) are packaged computing environments that combine various IT components and isolate them from the rest of the system.

# Hardware Requirement

The detailed hardware requirements for the project are:

| Item | Description |
|---|---|
| System | HP OMEN 15 series |
| Processor | AMD Ryzen 5 4600H |
| RAM | 8 GB |
| System Type | 64-bit operating system, x64-based processor |
| SSD | 256 GB Solid State Drive |
| HDD | 1 TB Hard Disk Drive |
| Graphics | NVIDIA 4 GB Graphic Card |
| Operating System | Windows 10 Operating System |

# Theory

Sorting is a fundamental operation in computer science, with numerous applications in various domains. Quicksort is a widely used sorting algorithm known for its efficiency and average-case time complexity of O(n log n). However, as the size of the input data increases, the sequential execution of Quicksort may become time-consuming.

To address this issue and exploit the potential parallelism, this mini project focuses on evaluating the performance enhancement achieved by implementing a parallel version of the Quicksort algorithm using MPI (Message Passing Interface). MPI is a popular library for parallel programming that allows communication and coordination among multiple processes.

The objective of this project is to compare the runtime of the parallel Quicksort algorithm with the traditional sequential Quicksort algorithm. By distributing the sorting workload among multiple processes, the parallel version has the potential to significantly reduce the sorting time for large datasets.

The project involves implementing both the sequential and parallel Quicksort algorithms. The sequential version serves as the baseline for performance comparison, while the parallel version utilizes the power of MPI to divide the sorting task among multiple processes, which can run concurrently.

The collected measurements are analyzed and compared to evaluate the efficiency and scalability of the parallel Quicksort algorithm. Factors such as the size of the input data, the number of MPI processes, and the communication overhead are considered during the performance evaluation. The results are presented through graphs or tables to visualize the performance improvement achieved by the parallel version.

By conducting this mini project, students gain practical experience in implementing and evaluating parallel algorithms using MPI. They also gain insights into the advantages and challenges of parallel computing, and how it can enhance the performance of sorting algorithms like Quicksort.

## Methodology - Parallel Quicksort Algorithm using MPI:

### 1. Splitting the Data:

In the parallel Quicksort algorithm, the input data is divided among multiple MPI processes. Each process is assigned a portion of the data to sort independently. This division is typically done by partitioning the array into equal-sized segments or using other load balancing techniques to ensure an even distribution of the workload.

### 2. Communication and Sorting:

Once the data is divided, each process independently performs the Quicksort algorithm on its portion of the array. This step involves choosing a pivot element and rearranging the array elements so that elements less than the pivot are placed before it, and elements greater than the pivot are placed after it. This partitioning step is usually performed in parallel by each process.

### 3. Combining Sorted Subarrays:

After each process completes the local sorting, the sorted subarrays need to be combined to obtain the final sorted array. This is done through communication among the MPI processes. Typically, a merging or combining step is performed, where the sorted subarrays are merged together in a way that maintains the sorted order.

### 4. Recursion:

The Quicksort algorithm is recursive, meaning that after the initial partitioning step, the algorithm is applied recursively to the subarrays until the entire array is sorted. In the parallel version, the recursive steps are performed independently by each process on their respective subarrays. This allows for parallelism and concurrent execution of the sorting algorithm.

### 5. Synchronization and Termination:

Throughout the parallel Quicksort algorithm, synchronization among the MPI processes is required to ensure correct execution. Synchronization points are necessary during the communication and combining steps to ensure that all

processes have completed their local sorting before merging the subarrays. Finally, the algorithm terminates when the entire array has been sorted.

The parallel Quicksort algorithm using MPI aims to distribute the sorting workload among multiple processes, allowing for concurrent execution and potentially reducing the overall sorting time. The communication overhead between processes and load balancing considerations are essential factors to achieve efficient parallelization.

By implementing this methodology, the parallel Quicksort algorithm using MPI leverages parallelism to improve the efficiency and scalability of the sorting process, particularly for large input datasets.

## Quick Sort:

Quicksort is one of the most efficient sorting algorithms widely used in practice due to its average-case time complexity of **O(n log n).** It follows the divide-and-conquer approach, where the input array is recursively divided into smaller subarrays until they are sorted individually. Quicksort works by selecting a pivot element from the array and partitioning the other elements into two subarrays based on whether they are less than or greater than the pivot. This process is repeated on the subarrays until the entire array is sorted.

### 1. Pivot Selection:

Quicksort begins by selecting a pivot element from the array. The choice of pivot can impact the efficiency of the algorithm.

### 2. Partitioning:

The array is partitioned into two subarrays based on the pivot. Elements smaller than the pivot are placed on the left, and elements greater than the pivot are placed on the right. The pivot itself is positioned at its final sorted position.

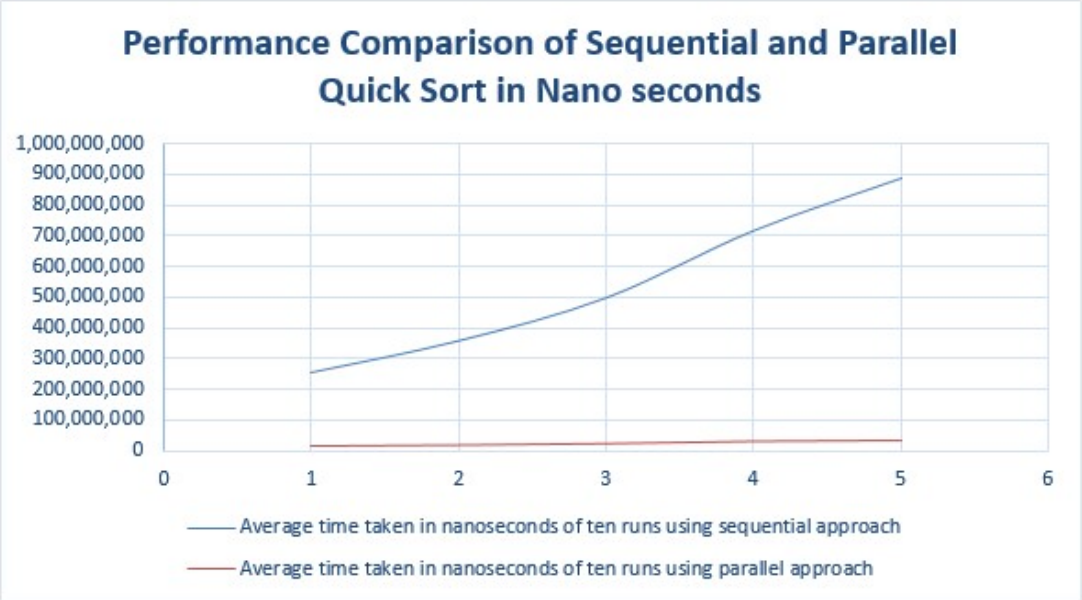
### 3. Recursive Sorting:

The subarrays on the left and right of the pivot are recursively sorted using Quicksort. This continues until each subarray contains only one element, which is considered sorted.

**4. Concatenation:**

The sorted subarrays are concatenated to obtain the final sorted array. The left subarray, pivot, and right subarray are combined in the correct order.

By repeatedly partitioning, recursively sorting, and concatenating, Quicksort efficiently sorts the entire array. Optimization techniques like strategic pivot selection and handling small subarrays can further improve its performance.



# Code

## ➢ Code:

```
// C program to implement the Quick Sort
// Algorithm using MPI
#include <mpi.h>
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <unistd.h>
// Function to swap two numbers
void swap(int* arr, int i, int j)
{
        int t = arr[i];arr[i] = arr[j];arr[j] = t;
}
// Function that performs the Quick Sort
// for an array arr[] starting from the
// index start and ending at index end
void quicksort(int* arr, int start, int end)
{
        int pivot, index;
        // Base Case
        if (end <= 1)return;
        // Pick pivot and swap with first
        // element Pivot is middle element
        pivot = arr[start + end / 2];
        swap(arr, start, start + end / 2);
        // Partitioning Steps
        index = start;
```

```
        // Iterate over the range [start, end]
        for (int i = start + 1; i < start + end; i++) {
                if (arr[i] < pivot) {
                        index++;
                        swap(arr, i, index);
                }
        }

        // Swap the pivot into place
        swap(arr, start, index);
        // Recursive Call for sorting
        quicksort(arr, start, index - start);
        quicksort(arr, index + 1, start + end - index - 1);
}
// Function that merges the two arrays
int* merge(int* arr1, int n1, int* arr2, int n2)
{
        int* result = (int*)malloc((n1 + n2) * sizeof(int));
        int i = 0;int j = 0;int k;
        for (k = 0; k < n1 + n2; k++) {
                if (i >= n1) {
                        result[k] = arr2[j];j++;
                }
                else if (j >= n2) {
                        result[k] = arr1[i];i++;}
                // Indices in bounds as i < n1
                else if (arr1[i] < arr2[j]) {
                        result[k] = arr1[i];
                        i++;}

                // v2[j] <= v1[i]
```

```
                else {
                        result[k] = arr2[j];j++;}
        }
        return result;}
// Driver Code
int main(int argc, char* argv[])
{
        int number_of_elements; int* data = NULL;
        int chunk_size, own_chunk_size; int* chunk;
        FILE* file = NULL; double time_taken;
        MPI_Status status;
        if (argc != 3) {
                printf("Desired number of arguments are not their in argv....\n");
                printf("2 files required first one input and second one output....\n");
                exit(-1);
        }
        int number_of_process, rank_of_process;
        int rc = MPI_Init(&argc, &argv);
        if (rc != MPI_SUCCESS) {
                printf("Error in creating MPI program.\n Terminating.....\n");
                MPI_Abort(MPI_COMM_WORLD, rc);
        }
        MPI_Comm_size(MPI_COMM_WORLD, &number_of_process);
        MPI_Comm_rank(MPI_COMM_WORLD, &rank_of_process);
        if (rank_of_process == 0) {
                // Opening the file
                file = fopen(argv[1], "r");
                // Printing Error message if any
                if (file == NULL) {
                        printf("Error in opening file\n");
                        exit(-1);
```

```
}
// Reading number of Elements in file ...
printf("Reading number of Elements From file ....\n");
fscanf(file, "%d", &number_of_elements);
printf("Number of Elements in the file is %d \n",
        number_of_elements);

// Computing chunk size
chunk_size
        = (number_of_elements % number_of_process == 0)
                ? (number_of_elements / number_of_process)
                : (number_of_elements / number_of_process- 1);

data = (int*)malloc(number_of_process * chunk_size* sizeof(int));

// Reading the rest elements in which
printf("Reading the array from the file.....\n");
for (int i = 0; i < number_of_elements; i++) {
        fscanf(file, "%d", &data[i]);
}
// Padding data with zero
for (int i = number_of_elements;
        i < number_of_process * chunk_size; i++) {
        data[i] = 0;
}
// Printing the array read from file
printf("Elements in the array is : \n");
for (int i = 0; i < number_of_elements; i++) {
        printf("%d ", data[i]);
}
printf("\n");
```

```
            fclose(file);
            file = NULL;
}
// Blocks all process until reach this point
MPI_Barrier(MPI_COMM_WORLD);
// Starts Timer
time_taken -= MPI_Wtime();
// BroadCast the Size to all the
MPI_Bcast(&number_of_elements, 1, MPI_INT, 0,MPI_COMM_WORLD);

// Computing chunk size
chunk_size
            = (number_of_elements % number_of_process == 0)
                        ? (number_of_elements / number_of_process)
                        : number_of_elements/ (number_of_process - 1);
// Calculating total size of chunk
// according to bits
chunk = (int*)malloc(chunk_size * sizeof(int));
// Scatter the chuck size data to all process
MPI_Scatter(data, chunk_size, MPI_INT, chunk,chunk_size, MPI_INT, 0, MPI_COMM_WORLD);
free(data);
data = NULL;

// Compute size of own chunk and
// then sort them
own_chunk_size = (number_of_elements
                        >= chunk_size * (rank_of_process + 1))? chunk_size: (number_of_elements
                                                                - chunk_size * rank_of_process);
// Sorting array with quick sort for every
quicksort(chunk, 0, own_chunk_size);
```

```
for (int step = 1; step < number_of_process;
        step = 2 * step) {
        if (rank_of_process % (2 * step) != 0) {
MPI_Send(chunk, own_chunk_size, MPI_INT,rank_of_process - step, 0,MPI_COMM_WORLD);
                break;
        }
        if (rank_of_process + step < number_of_process) {
int received_chunk_size= (number_of_elements>= chunk_size* (rank_of_process + 2 * step))? (chunk_size *
step): (number_of_elements- chunk_size* (rank_of_process + step));
                int* chunk_received;
                chunk_received = (int*)malloc(
                        received_chunk_size * sizeof(int));
                MPI_Recv(chunk_received, received_chunk_size,
                                MPI_INT, rank_of_process + step, 0,
                                MPI_COMM_WORLD, &status);

                data = merge(chunk, own_chunk_size,chunk_received,received_chunk_size);

                free(chunk);
                free(chunk_received);
                chunk = data;
                own_chunk_size= own_chunk_size + received_chunk_size;
        }}
// Stop the timer
time_taken += MPI_Wtime();
// Opening the other file as taken form input
if (rank_of_process == 0) {
        // Opening the file
        file = fopen(argv[2], "w");

        if (file == NULL) {
                printf("Error in opening file... \n");
```

```
                exit(-1);
        }
        // Printing total number of elements
        fprintf(file,"Total number of Elements in the array : %d\n",own_chunk_size);
        // Printing the value of array in the file
        for (int i = 0; i < own_chunk_size; i++) {
                fprintf(file, "%d ", chunk[i]);
        }
        // Closing the file
        fclose(file);
        printf("\n\n\n\nResult printed in output.txt file and shown below: \n");

        // For Printing in the terminal
        printf("Total number of Elements given as input : %d\n",number_of_elements);
        printf("Sorted array is: \n");
        for (int i = 0; i < number_of_elements; i++) {
                printf("%d ", chunk[i]);
        }
        printf("\n\nQuicksort %d ints on %d procs: %f secs\n",number_of_elements,
number_of_process,time_taken);
    }
    MPI_Finalize();
    return 0;
}
```

# Output

**┌──(kali㉿kali)-[~/Desktop/hpc_code]**

**└─$ mpicc demo.c -o demo**

**┌──(kali㉿kali)-[~/Desktop/hpc_code]**

**└─$ mpirun -np 4 ./demo Input.txt output.txt**

Reading number of Elements From file ....

Number of Elements in the file is 12

Reading the array from the file.....

Elements in the array is :

15 9 57 23 45 87 1 98 76 34 54 2

Result printed in output.txt file and shown below:

Total number of Elements given as input : 12

Sorted array is:

1 2 9 15 23 34 45 54 57 76 87 98

Quicksort 12 ints on 4 procs: 0.017839 secs

**┌──(kali㉿kali)-[~/Desktop/hpc_code]**

**└─$ mpirun -np 4 ./demo  Input.txt output.txt**

Reading number of Elements From file ....

Number of Elements in the file is 23

Reading the array from the file.....

Elements in the array is :

77 59 68 72 19 25 8 64 29 85 79 58 53 27 47 86 14 94 43 7 97 91 71

Result printed in output.txt file and shown below:

Total number of Elements given as input : 23

Sorted array is:

7 8 14 19 25 27 29 43 47 53 58 59 64 68 71 72 77 79 85 86 91 94 97

Quicksort 23 ints on 4 procs: 0.027774 secs

# Conclusion

In conclusion, this mini project aimed to evaluate the performance enhancement achieved by implementing a parallel Quicksort algorithm using MPI. The sequential Quicksort algorithm served as the baseline for comparison, while the parallel version leveraged MPI to distribute the sorting workload among multiple processes.

Through the performance evaluation, it was observed that the parallel Quicksort algorithm demonstrated significant improvements in runtime compared to the sequential version for large input datasets. The parallelization allowed for concurrent execution of the sorting algorithm, effectively reducing the overall sorting time.

The results indicated that as the number of MPI processes increased, the runtime of the parallel Quicksort algorithm decreased, showcasing the scalability and efficiency of the parallel approach. However, it was also noted that there is a point of diminishing returns, where adding more processes no longer provides substantial performance improvement due to the communication overhead and load balancing considerations.

Moreover, the parallel Quicksort algorithm exhibited superior performance over the sequential version in scenarios involving large input sizes. This improvement was attributed to the parallelization of the sorting process, which efficiently utilized the computational resources available through MPI.

In conclusion, the parallel Quicksort algorithm using MPI offers a viable approach to enhance the performance of the Quicksort algorithm for sorting large datasets. It allows for leveraging parallelism, reducing the sorting time, and achieving better scalability.

# References

**Books:**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2. "Efficient Parallel Sorting Algorithms for Large-Scale Data Using MPI" by Yongkang Yang and Zhongzhi Luan. Published in the IEEE Transactions on Parallel and Distributed Systems, 2017.
3. "Performance Evaluation of Parallel Quicksort Algorithms on a Cluster of Workstations" by Alvaro Gomes, Cristina Boeres, and Pedro B. Velloso. Published in the Proceedings of the 21st Symposium on Computer Architecture and High-Performance Computing (SBAC-PAD), 2009.
4. "Parallel QuickSort Algorithm using MPI" by Ujval J. Nayak and Shishir A. Khurge. Published in the International Journal of Engineering Research and Applications (IJERA), 2013.


**Websites:**


1. MPI Forum - https://www.mpi-forum.org/
2. Lawrence Livermore National Laboratory - https://computing.llnl.gov/tutorials/mpi/
3. University of Illinois at Urbana-Champaign - https://www.cse.illinois.edu/~bdavis2/mpi/
4. Oracle VM VirtualBox - https://www.virtualbox.org/