The Faculty of Information and Communication Technology

Mahidol University

Group Assignment: OpenMP Quick Sort

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ITCS443 Parallel and Distributed Systems

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Explanation of the program

The OpenMPQuickSort.c program implements a hybrid sorting approach that combines Quicksort for large arrays and Insertion Sort for smaller subarrays. It is designed to efficiently sort an array of random integer numbers, ranging from 0 to 99999, with adjustable dataset sizes defined by '*#define ARRAY_SIZE 2000000*'. Moreover, to change the number of threads, locate the line '*#pragma omp parallel sections num_threads(8)*', where replace the 8 with your desired number of threads.

Data Generation: The program initializes by generating an array of random integers based on the specified size.

```
// Generate a random number between 0 and RANGE
for (int i = 0; i < ARRAY_SIZE; i++) {
arr[i] = rand() % (RANGE + 1);
}
printf("Random numbers: ");
int countnum = 0;
for (int i = 0; i < ARRAY_SIZE; i++) {
printf("%d ", arr[i]);
countnum ++;
}
printf("\nTotal numbers: %d\n", countnum);
```

Parallelization Strategy: The program employs a parallelization strategy based on a user-defined threshold. When the array size is below the threshold (currently set to 1000), the program switches to using Insertion Sort.

```
// [Parallel Section] --> Begin parallel sorting
#pragma omp parallel
{
#pragma omp single nowait
quickSort(arr, 0, ARRAY_SIZE - 1);
}
```

Quicksort with Parallelization: When the array size is sufficiently large, the program switches to Quicksort, parallelized using OpenMP. Quicksort selects a pivot element from the array and

divides the other elements into two subarrays. These subarrays are sorted recursively, depending on whether they are less than or greater than the selected pivot.

```
// [Quicksort (left)] reference:
https://github.com/koszio/QuickSort-with-OpenMP/blob/master/quickSortOpenMP.c
void quickSort(int arr[], int low, int high) {
if (low < high) {
int pi = partition(arr, low, high, low); // Use arr[low] as the pivot
if (high - low > 1000) { // Parallelize only if the size of the array is large
enough
// The number of compute nodes (MPI) or the number of threads (OpenMP) is varied
from 1, 4, 8, 12 and 16.
#pragma omp parallel sections num_threads(8) // Specify the number of threads here
{
#pragma omp section
quickSort(arr, low, pi - 1); // Recurse on the left partition
#pragma omp section
quickSort(arr, pi + 1, high); // Recurse on the right partition
}
} else { // [Threshold Check] --> Check if threshold reached
insertionSort(arr, low, high); // [Insertion Sort] --> Apply insertion sort
}
}
}
```

Insertion Sort: For smaller subarrays, the Insertion Sort algorithm is used. This algorithm efficiently generates a sorted portion of the array by inserting elements from the unsorted section into their correct positions within the sorted part.

```
// [Insertion Sort]
void insertionSort(int arr[], int low, int high) {
for (int i = low + 1; i <= high; i++) {
int key = arr[i];
int j = i - 1;

while (j >= low && arr[j] > key) {
arr[j + 1] = arr[j];
j = j - 1;
}
arr[j + 1] = key;
```

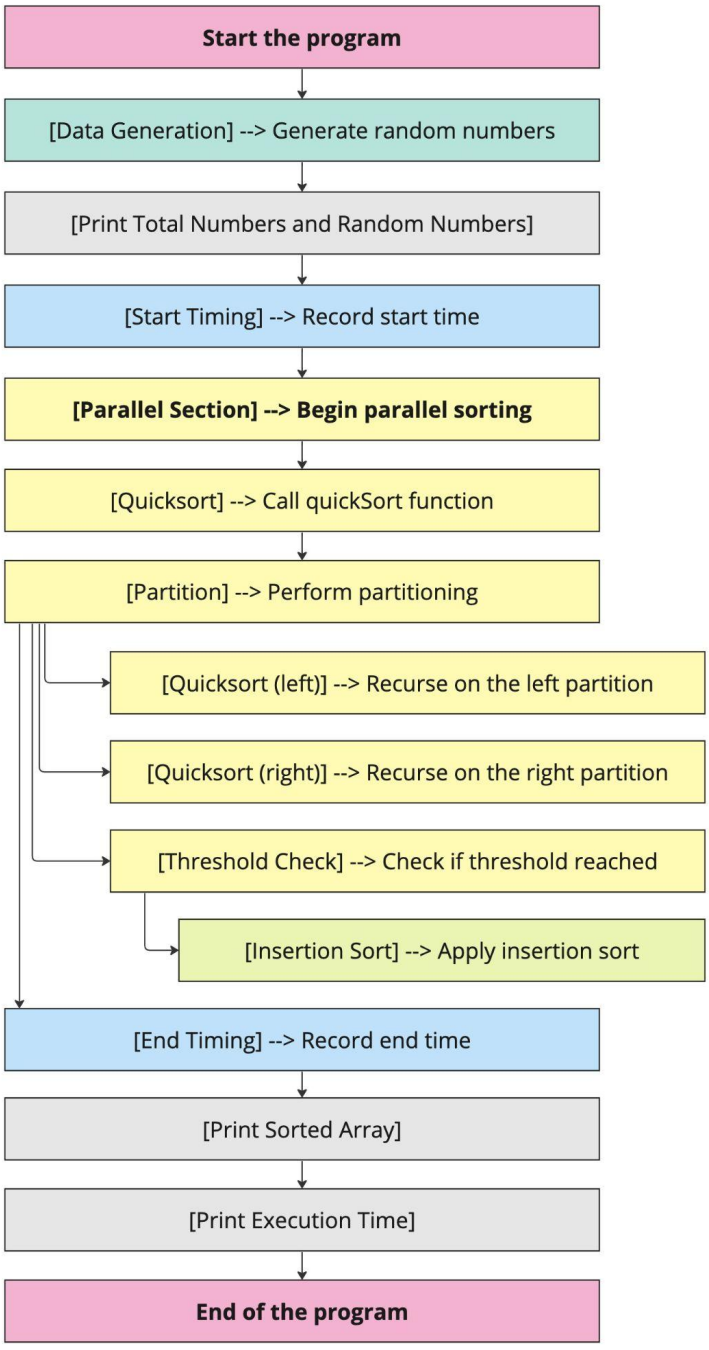
```
}
}
```

Execution Time Measurement: The program uses the omp_get_wtime function to measure the execution time. It records the start time before sorting and the end time after successful sorting to calculate the time taken. This execution time is then printed along with the sorted array.

```
// [Start Timing] --> Record start time
double start_time, run_time;
start_time = omp_get_wtime();
```

```
// [End Timing] --> Record end time
run_time = omp_get_wtime() - start_time;
// [Print Sorted Array]
printf("Sorted array: ");
printArray(arr, ARRAY_SIZE);
// [Print Execution Time]
printf("Execution time was %lf seconds\n ", run_time);
```

Explanation of the program as a diagram



The outline of the code and data structures used

Testing results

<table>
<tr><th>Integer numbers</th><th>Execution time</th></tr>
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716 24728 24731 24742 24743 24745 24748 24756 24757 24758 24763 24765 24766 24768 24777 24779 24788 24796 24803 24
25298 25303 25307 25311 25314 25315 25320 25321 25322 25322 25322 25329 25330 25331 25337 25340 25344 25344 25360
6 25889 25892 25893 25898 25898 25901 25902 25910 25910 25911 25920 25920 25921 25921 25923 25931 25931 25934 2593
481 26482 26487 26489 26494 26500 26502 26513 26520 26523 26527 26529 26530 26530 26532 26536 26537 26538 26540 26
27019 27028 27036 27040 27046 27047 27048 27060 27061 27064 27069 27072 27078 27079 27080 27083 27087 27087 27091
7 27659 27662 27668 27668 27669 27674 27675 27682 27684 27685 27687 27689 27697 27697 27700 27702 27703 27703 2776
115 28118 28130 28134 28135 28138 28155 28157 28169 28170 28171 28172 28178 28182 28186 28187 28199 28200 28201 28
28689 28689 28691 28701 28702 28703 28707 28709 28714 28715 28721 28723 28727 28728 28729 28730 28730 28734 28744
1 29192 29196 29199 29200 29202 29205 29213 29215 29216 29219 29223 29225 29226 29232 29237 29239 29240 29250 2925
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0 32578 32578 32579 32580 32584 32585 32589 32599 32600 32604 32606 32611 32616 32620 32623 32623 32625 32640 3264
Execution time was 0.007000 seconds</td></tr>
<tr><td>num_threads(4): Execution time was 0.008000 seconds</td></tr>
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7 25200 25202 25204 25204 25204 25204 25207 25210 25214 25218 25222 25224 25227 25235 25242 25243 25243 25246 25
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3 26970 26973 26974 26990 26990 26992 26996 26997 27001 27011 27012 27019 27021 27026 27040 27042 27044 27045 27
595 27606 27609 27617 27619 27619 27619 27625 27627 27634 27641 27642 27646 27646 27649 27649 27650 27652 27655
28139 28144 28145 28147 28152 28155 28159 28162 28165 28166 28167 28168 28170 28171 28174 28183 28185 28192 2819
3 28736 28737 28754 28758 28762 28767 28771 28773 28776 28778 28779 28781 28785 28786 28787 28793 28797 28797 28
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29830 29831 29834 29835 29840 29844 29844 29848 29850 29853 29854 29855 29855 29870 29870 29881 29883 29888 2989
8 30389 30389 30391 30393 30398 30402 30405 30410 30411 30414 30415 30417 30417 30422 30423 30433 30438 30440 30
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8 31990 31990 31993 31998 31999 32005 32008 32012 32017 32019 32024 32026 32028 32038 32041 32045 32055 32063 32
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Execution time was 0.008000 seconds</td></tr>
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23651 23657 23658 23660 23666 23670 23671 23674 23677 23686 23696 23696 23698 23702 23704 23715 23715 23723 23724
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889 24893 24902 24903 24917 24923 24928 24929 24931 24933 24934 24941 24944 24944 24947 24948 24948 24951 24959 2
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2 26105 26107 26107 26109 26114 26115 26118 26119 26128 26128 26130 26130 26134 26134 26135 26135 26137 26142 261
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7 27680 27682 27684 27689 27701 27702 27706 27708 27715 27717 27721 27722 27727 27727 27728 27729 27732 27732 277
240 28242 28242 28255 28257 28264 28265 28279 28281 28284 28287 28289 28291 28292 28294 28298 28303 28305 28307 2
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3 29367 29367 29369 29382 29384 29386 29394 29396 29396 29397 29399 29409 29411 29412 29414 29421 29426 29429 294
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Execution time was 0.009000 seconds</td></tr>
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	num_threads(4): Execution time was 0.067000 seconds
	Screen capture

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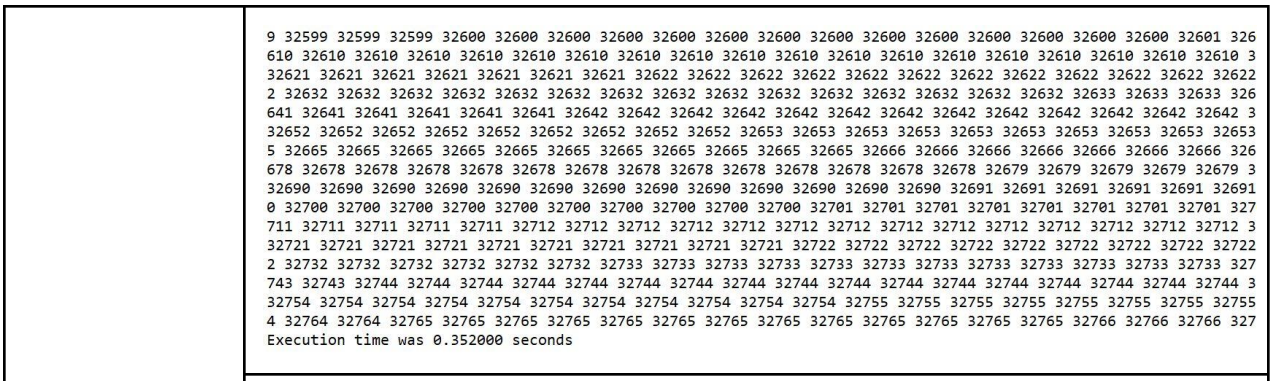
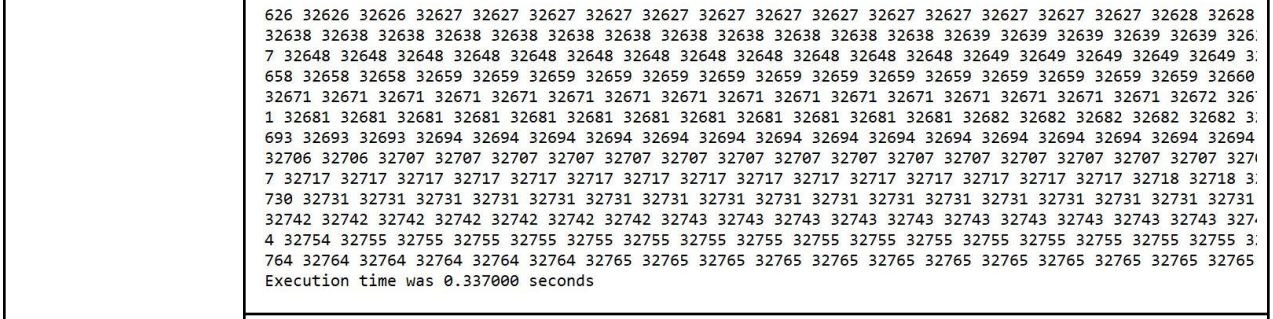
	Screen capture



Execution time was 0.352000 seconds

num_threads(4): Execution time was 0.337000 seconds

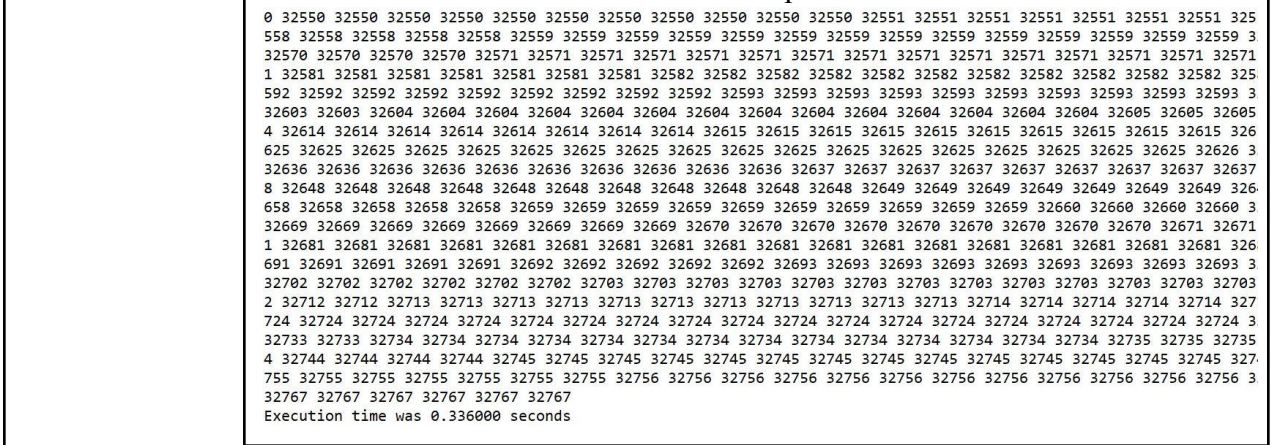
Screen capture



Execution time was 0.337000 seconds

num_threads(8): Execution time was 0.336000 seconds

Screen capture



Execution time was 0.336000 seconds

num_threads(12): Execution time was 0.347000 seconds

Screen capture

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2 million	num_threads(1): Execution time was 1.333000seconds
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	num_threads(4): Execution time was 1.322000 seconds
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	num_threads(8): Execution time was 1.381000 seconds
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	num_threads(12): Execution time was 1.355000 seconds
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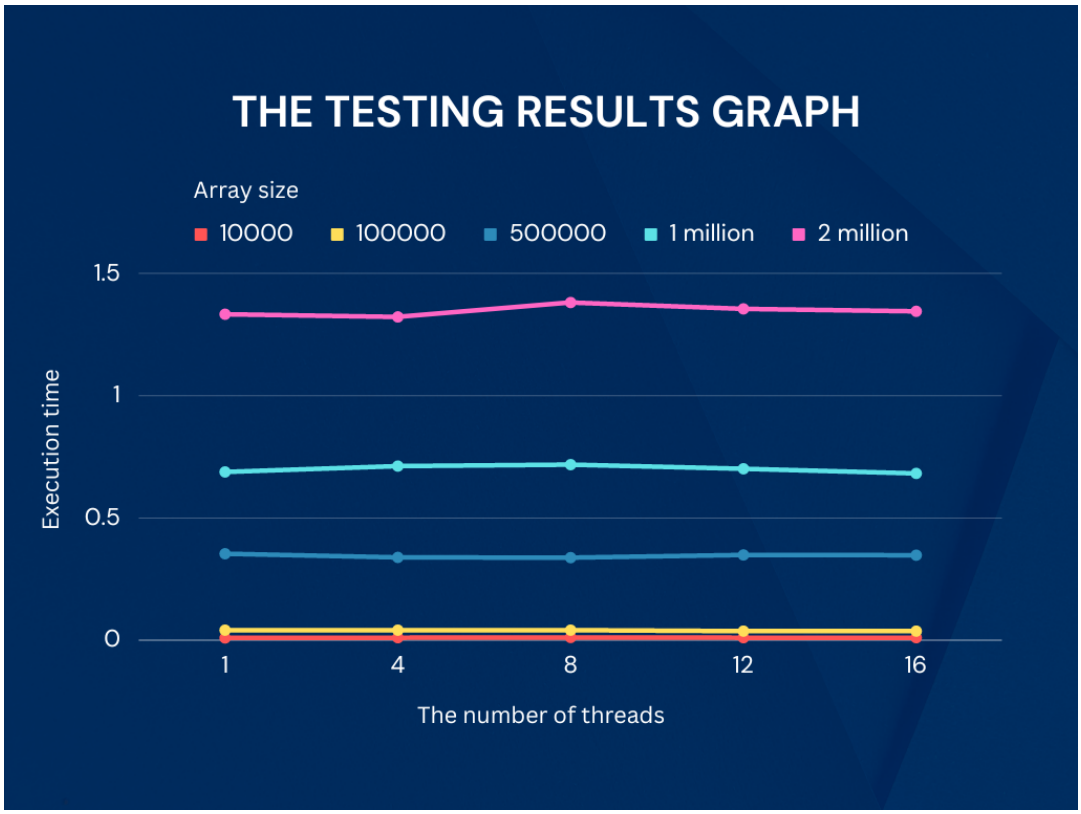
Plot the testing results as a speedup graph



According to the result from this program, as the size of the array increase, the execution time of the sorting process generally also increases. Therefore, larger arrays require more time to sort. The relationship between execution time and the number of threads is as follows: a large number of threads can potentially reduce execution time. It is necessary to compare and find the optimal number of threads and the result of parallelization on different array sizes for balancing between array size, the number of threads, and execution time to achieve the best performance.