

## **Program Structures & Algorithms**

### **Fall 2021**

### **Assignment No. 5**

#### **Task**

- Implement a parallel sorting algorithm such that each partition of the array is sorted in parallel. You will consider two different schemes for deciding whether to sort in parallel.
- (Part 1) A cutoff (defaults to, say, 1000) which you will update according to the first argument in the command line when running. It's your job to experiment and come up with a good value for this cutoff. If there are fewer elements to sort than the cutoff, then you should use the system sort instead.
- (Part 2) Recursion depth or the number of available threads. Using this determination, you might decide on an ideal number ( $t$ ) of separate threads (stick to powers of 2) and arrange for that number of partitions to be parallelized (by preventing recursion after the depth of  $\lg t$  is reached).
- (Part 3) Implement a main program to run the following benchmarks: measure the running times of this sort, using four different initial array ordering situations: random, ordered, partially-ordered and reverse-ordered.
- Show the results of your experiments and draws a conclusion (or more) about the efficacy of this method of parallelizing sort.
- Experiments should involve sorting arrays of sufficient size for the parallel sort to make a difference. You should run with many different array sizes (they must be sufficiently large to make parallel sorting worthwhile, obviously) and different cut-off schemes.

#### **Relationship Conclusion:**

After running experiments with different cutoff values and the number of threads for different array sizes, We can conclude that four threads are the optimal choice as the algorithm's performance does not increase significantly beyond four.

The lowest performance is achieved when the cutoff value is 25% of the array size.

For recursion depth ( $d$ ) and number of threads available ( $t$ ):

$$t = 2^d$$

Maximum depth possible:

$$\lg \left( \frac{\text{array size}}{\text{cutoff}} \right)$$

Any depth more significant than the max depth is not feasible as the partitioned arrays hit the cutoff and turned into a system sort.

### Evidence to support the conclusion:

Array Size = 50000

Thread = 2

| Cutoff | Runtime |
|--------|---------|
| 5000   | 71.2    |
| 10000  | 51.6    |
| 15000  | 28.8    |
| 20000  | 21.6    |
| 25000  | 20.6    |
| 30000  | 19.5    |
| 35000  | 24      |
| 40000  | 20.1    |
| 45000  | 20.5    |
| 50000  | 20      |

Thread=4

| Cutoff | Runtime |
|--------|---------|
| 5000   | 22.2    |
| 10000  | 17.4    |
| 15000  | 16.9    |
| 20000  | 16.1    |
| 25000  | 17.1    |
| 30000  | 18.8    |
| 35000  | 18.1    |
| 40000  | 18.1    |
| 45000  | 18.6    |
| 50000  | 17.2    |

Thread=8

| Cutoff | Runtime |
|--------|---------|
| 5000   | 22.7    |
| 10000  | 17      |
| 15000  | 16.5    |
| 20000  | 16.1    |
| 25000  | 16.7    |
| 30000  | 19.5    |
| 35000  | 18.5    |
| 40000  | 15.7    |

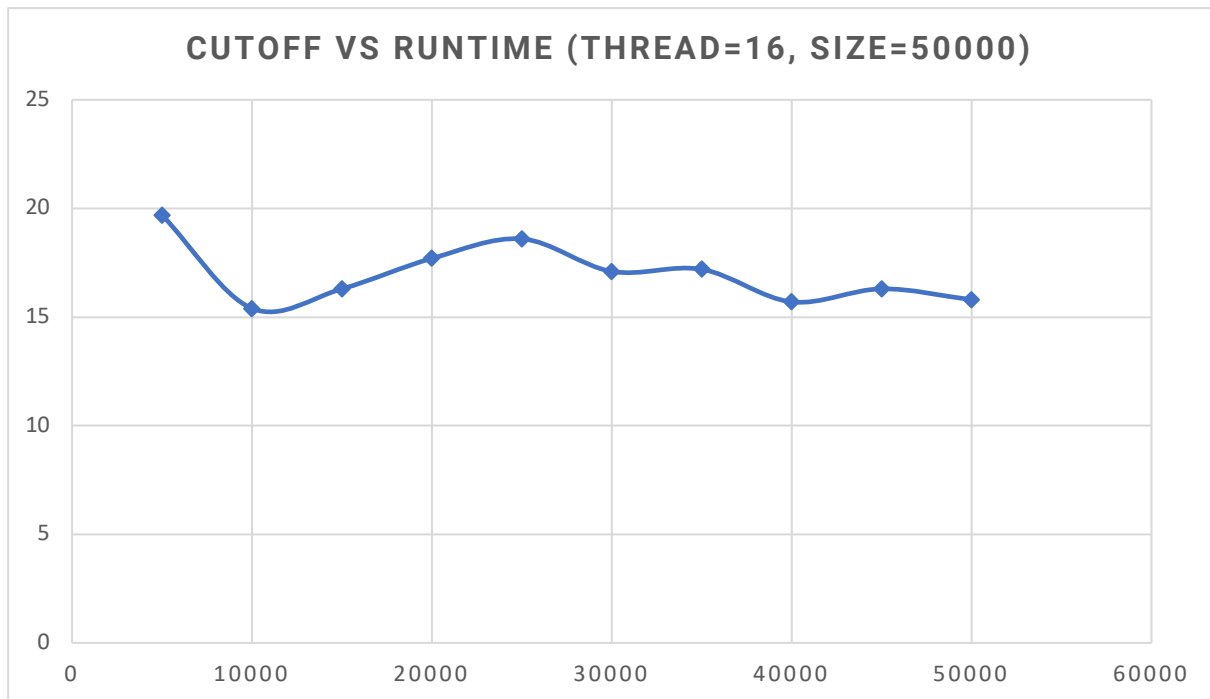
|       |      |
|-------|------|
| 45000 | 16.3 |
| 50000 | 15.5 |

Thread=16

| Cutoff | Runtime |
|--------|---------|
| 5000   | 19.7    |
| 10000  | 15.4    |
| 15000  | 16.3    |
| 20000  | 17.7    |
| 25000  | 18.6    |
| 30000  | 17.1    |
| 35000  | 17.2    |
| 40000  | 15.7    |
| 45000  | 16.3    |
| 50000  | 15.8    |

Thread=32

| Cutoff | Runtime |
|--------|---------|
| 5000   | 20.2    |
| 10000  | 15.5    |
| 15000  | 19.7    |
| 20000  | 21.2    |
| 25000  | 25.4    |
| 30000  | 23.6    |
| 35000  | 16.8    |
| 40000  | 18.1    |
| 45000  | 17      |
| 50000  | 19.6    |



Array Size = 100000

Thread=2

| Cutoff | Runtime |
|--------|---------|
| 5000   | 85.4    |
| 10000  | 68.6    |
| 15000  | 41.3    |
| 20000  | 40.6    |
| 25000  | 38.5    |
| 30000  | 45.8    |
| 35000  | 48.1    |
| 40000  | 41.4    |
| 45000  | 37.3    |
| 50000  | 36.3    |

Thread=4

| Cutoff | Runtime |
|--------|---------|
| 5000   | 60      |
| 10000  | 46      |
| 15000  | 61.5    |
| 20000  | 50.3    |
| 25000  | 47.4    |
| 30000  | 47      |
| 35000  | 44.9    |
| 40000  | 49.8    |
| 45000  | 50.7    |

|       |      |
|-------|------|
| 50000 | 48.8 |
|-------|------|

Thread=8

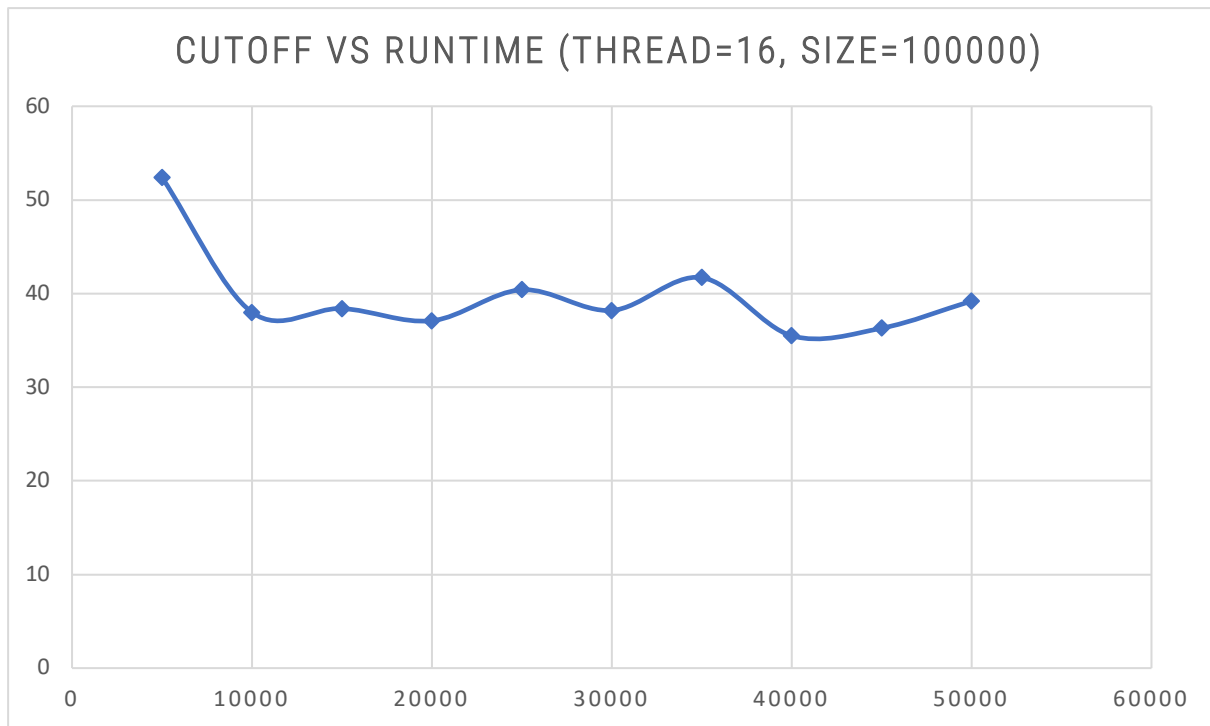
| Cutoff | Runtime |
|--------|---------|
| 5000   | 58.6    |
| 10000  | 43.4    |
| 15000  | 47.9    |
| 20000  | 50.3    |
| 25000  | 65.6    |
| 30000  | 60.2    |
| 35000  | 50.4    |
| 40000  | 57.4    |
| 45000  | 38.9    |
| 50000  | 43.6    |

Thread=16

| Cutoff | Runtime |
|--------|---------|
| 5000   | 52.4    |
| 10000  | 38      |
| 15000  | 38.4    |
| 20000  | 37.1    |
| 25000  | 40.4    |
| 30000  | 38.2    |
| 35000  | 41.7    |
| 40000  | 35.5    |
| 45000  | 36.3    |
| 50000  | 39.2    |

Thread=32

| Cutoff | Runtime |
|--------|---------|
| 5000   | 41.7    |
| 10000  | 38.8    |
| 15000  | 38.9    |
| 20000  | 44.4    |
| 25000  | 43.2    |
| 30000  | 41.7    |
| 35000  | 40.3    |
| 40000  | 36.8    |
| 45000  | 40      |
| 50000  | 35.7    |



Array Size = 200000

Thread=2

| Cutoff | Runtime |
|--------|---------|
| 5000   | 170.8   |
| 10000  | 155.1   |
| 15000  | 92.8    |
| 20000  | 88.5    |
| 25000  | 92.9    |
| 30000  | 96.2    |
| 35000  | 93.1    |
| 40000  | 94.2    |
| 45000  | 91.1    |
| 50000  | 96.5    |

Thread=4

| Cutoff | Runtime |
|--------|---------|
| 5000   | 106.5   |
| 10000  | 85.1    |
| 15000  | 93.6    |
| 20000  | 93.6    |
| 25000  | 100.4   |
| 30000  | 97      |
| 35000  | 106.7   |
| 40000  | 100.7   |
| 45000  | 101.2   |

|       |      |
|-------|------|
| 50000 | 93.7 |
|-------|------|

Thread=8

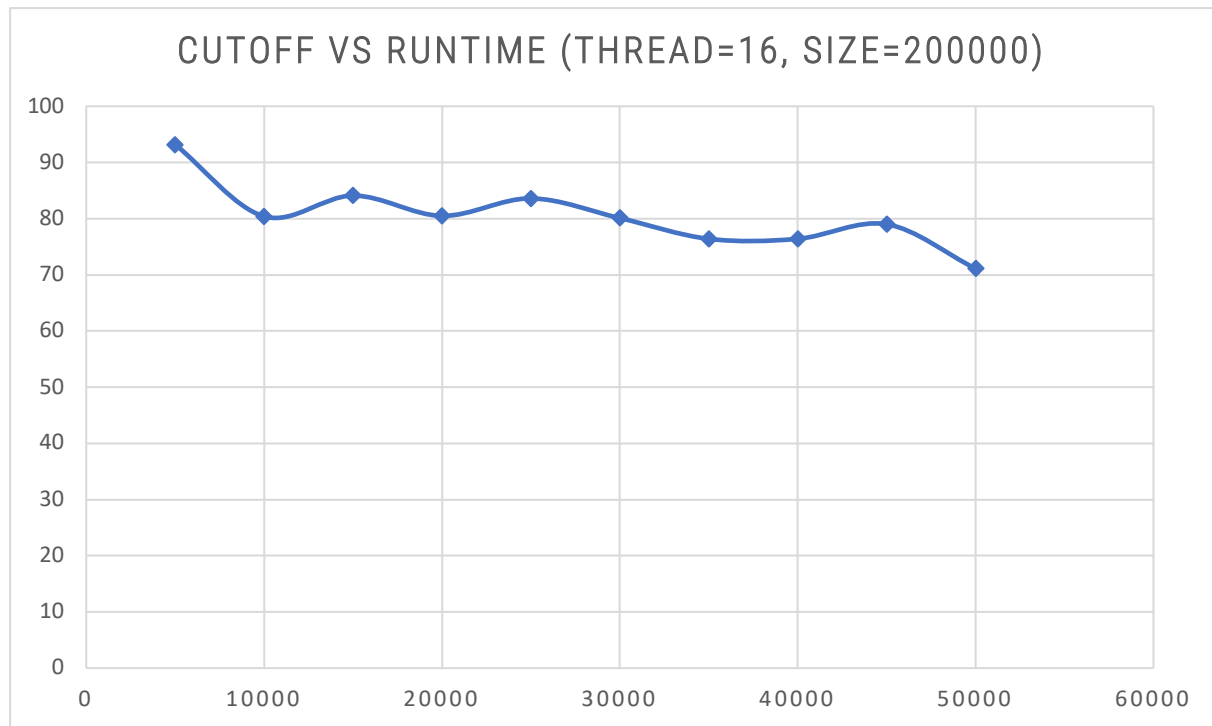
| Cutoff | Runtime |
|--------|---------|
| 5000   | 102.9   |
| 10000  | 80.2    |
| 15000  | 81.4    |
| 20000  | 80.7    |
| 25000  | 76.7    |
| 30000  | 81.1    |
| 35000  | 71.1    |
| 40000  | 75.8    |
| 45000  | 76.8    |
| 50000  | 75.9    |

Thread=16

| Cutoff | Runtime |
|--------|---------|
| 5000   | 93.2    |
| 10000  | 80.4    |
| 15000  | 84.1    |
| 20000  | 80.5    |
| 25000  | 83.6    |
| 30000  | 80.1    |
| 35000  | 76.4    |
| 40000  | 76.4    |
| 45000  | 79      |
| 50000  | 71.1    |

Thread=32

| Cutoff | Runtime |
|--------|---------|
| 5000   | 88.3    |
| 10000  | 78.2    |
| 15000  | 78.3    |
| 20000  | 79.1    |
| 25000  | 87.4    |
| 30000  | 80.8    |
| 35000  | 70.6    |
| 40000  | 75.2    |
| 45000  | 81.8    |
| 50000  | 76.6    |





## Console Output:

```
Degree of parallelism: 2
cutoff: 5000      10times Time:712ms
cutoff: 10000     10times Time:516ms
cutoff: 15000     10times Time:288ms
cutoff: 20000     10times Time:216ms
cutoff: 25000     10times Time:206ms
cutoff: 30000     10times Time:195ms
cutoff: 35000     10times Time:240ms
cutoff: 40000     10times Time:201ms
cutoff: 45000     10times Time:205ms
cutoff: 50000     10times Time:200ms
Degree of parallelism: 4
cutoff: 5000      10times Time:222ms
cutoff: 10000     10times Time:174ms
cutoff: 15000     10times Time:169ms
cutoff: 20000     10times Time:161ms
cutoff: 25000     10times Time:171ms
cutoff: 30000     10times Time:188ms
cutoff: 35000     10times Time:181ms
cutoff: 40000     10times Time:181ms
cutoff: 45000     10times Time:186ms
cutoff: 50000     10times Time:172ms
Degree of parallelism: 8
cutoff: 5000      10times Time:227ms
cutoff: 10000     10times Time:170ms
cutoff: 15000     10times Time:165ms
cutoff: 20000     10times Time:161ms
cutoff: 25000     10times Time:167ms
cutoff: 30000     10times Time:195ms
cutoff: 35000     10times Time:185ms
cutoff: 40000     10times Time:157ms
cutoff: 45000     10times Time:163ms
cutoff: 50000     10times Time:155ms
Degree of parallelism: 16
cutoff: 5000      10times Time:207ms
cutoff: 10000     10times Time:187ms
cutoff: 15000     10times Time:181ms
cutoff: 20000     10times Time:159ms
cutoff: 25000     10times Time:190ms
cutoff: 30000     10times Time:152ms
cutoff: 35000     10times Time:180ms
cutoff: 40000     10times Time:176ms
cutoff: 45000     10times Time:173ms
```

Size of Array: 50000

Degree of parallelism: 2

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:712ms |
| cutoff : 10000 | 10times Time:516ms |
| cutoff : 15000 | 10times Time:288ms |
| cutoff : 20000 | 10times Time:216ms |
| cutoff : 25000 | 10times Time:206ms |
| cutoff : 30000 | 10times Time:195ms |
| cutoff : 35000 | 10times Time:240ms |
| cutoff : 40000 | 10times Time:201ms |
| cutoff : 45000 | 10times Time:205ms |
| cutoff : 50000 | 10times Time:200ms |

Degree of parallelism: 4

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:222ms |
| cutoff : 10000 | 10times Time:174ms |
| cutoff : 15000 | 10times Time:169ms |
| cutoff : 20000 | 10times Time:161ms |
| cutoff : 25000 | 10times Time:171ms |
| cutoff : 30000 | 10times Time:188ms |
| cutoff : 35000 | 10times Time:181ms |
| cutoff : 40000 | 10times Time:181ms |
| cutoff : 45000 | 10times Time:186ms |
| cutoff : 50000 | 10times Time:172ms |

Degree of parallelism: 8

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:227ms |
| cutoff : 10000 | 10times Time:170ms |
| cutoff : 15000 | 10times Time:165ms |
| cutoff : 20000 | 10times Time:161ms |
| cutoff : 25000 | 10times Time:167ms |
| cutoff : 30000 | 10times Time:195ms |
| cutoff : 35000 | 10times Time:185ms |
| cutoff : 40000 | 10times Time:157ms |
| cutoff : 45000 | 10times Time:163ms |
| cutoff : 50000 | 10times Time:155ms |

Degree of parallelism: 16

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:207ms |
| cutoff : 10000 | 10times Time:187ms |
| cutoff : 15000 | 10times Time:181ms |
| cutoff : 20000 | 10times Time:159ms |
| cutoff : 25000 | 10times Time:190ms |
| cutoff : 30000 | 10times Time:152ms |
| cutoff : 35000 | 10times Time:180ms |
| cutoff : 40000 | 10times Time:176ms |
| cutoff : 45000 | 10times Time:173ms |

|                           |                    |
|---------------------------|--------------------|
| cutoff : 50000            | 10times Time:157ms |
| Degree of parallelism: 32 |                    |
| cutoff : 5000             | 10times Time:197ms |
| cutoff : 10000            | 10times Time:154ms |
| cutoff : 15000            | 10times Time:163ms |
| cutoff : 20000            | 10times Time:177ms |
| cutoff : 25000            | 10times Time:186ms |
| cutoff : 30000            | 10times Time:171ms |
| cutoff : 35000            | 10times Time:172ms |
| cutoff : 40000            | 10times Time:157ms |
| cutoff : 45000            | 10times Time:163ms |
| cutoff : 50000            | 10times Time:158ms |
| Degree of parallelism: 64 |                    |
| cutoff : 5000             | 10times Time:202ms |
| cutoff : 10000            | 10times Time:155ms |
| cutoff : 15000            | 10times Time:197ms |
| cutoff : 20000            | 10times Time:212ms |
| cutoff : 25000            | 10times Time:254ms |
| cutoff : 30000            | 10times Time:236ms |
| cutoff : 35000            | 10times Time:168ms |
| cutoff : 40000            | 10times Time:181ms |
| cutoff : 45000            | 10times Time:170ms |
| cutoff : 50000            | 10times Time:196ms |

Process finished with exit code 0

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Size of Array: 100000  
Degree of parallelism: 2

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:854ms |
| cutoff : 10000 | 10times Time:686ms |
| cutoff : 15000 | 10times Time:413ms |
| cutoff : 20000 | 10times Time:406ms |
| cutoff : 25000 | 10times Time:385ms |
| cutoff : 30000 | 10times Time:458ms |
| cutoff : 35000 | 10times Time:481ms |
| cutoff : 40000 | 10times Time:414ms |
| cutoff : 45000 | 10times Time:373ms |
| cutoff : 50000 | 10times Time:363ms |

Degree of parallelism: 4

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:600ms |
| cutoff : 10000 | 10times Time:460ms |
| cutoff : 15000 | 10times Time:615ms |
| cutoff : 20000 | 10times Time:503ms |
| cutoff : 25000 | 10times Time:474ms |

|                |                    |
|----------------|--------------------|
| cutoff : 30000 | 10times Time:470ms |
| cutoff : 35000 | 10times Time:449ms |
| cutoff : 40000 | 10times Time:498ms |
| cutoff : 45000 | 10times Time:507ms |
| cutoff : 50000 | 10times Time:488ms |

Degree of parallelism: 8

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:586ms |
| cutoff : 10000 | 10times Time:434ms |
| cutoff : 15000 | 10times Time:479ms |
| cutoff : 20000 | 10times Time:503ms |
| cutoff : 25000 | 10times Time:656ms |
| cutoff : 30000 | 10times Time:602ms |
| cutoff : 35000 | 10times Time:504ms |
| cutoff : 40000 | 10times Time:574ms |
| cutoff : 45000 | 10times Time:389ms |
| cutoff : 50000 | 10times Time:436ms |

Degree of parallelism: 16

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:496ms |
| cutoff : 10000 | 10times Time:508ms |
| cutoff : 15000 | 10times Time:474ms |
| cutoff : 20000 | 10times Time:571ms |
| cutoff : 25000 | 10times Time:563ms |
| cutoff : 30000 | 10times Time:515ms |
| cutoff : 35000 | 10times Time:511ms |
| cutoff : 40000 | 10times Time:405ms |
| cutoff : 45000 | 10times Time:390ms |
| cutoff : 50000 | 10times Time:412ms |

Degree of parallelism: 32

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:524ms |
| cutoff : 10000 | 10times Time:380ms |
| cutoff : 15000 | 10times Time:384ms |
| cutoff : 20000 | 10times Time:371ms |
| cutoff : 25000 | 10times Time:404ms |
| cutoff : 30000 | 10times Time:382ms |
| cutoff : 35000 | 10times Time:417ms |
| cutoff : 40000 | 10times Time:355ms |
| cutoff : 45000 | 10times Time:363ms |
| cutoff : 50000 | 10times Time:392ms |

Degree of parallelism: 64

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:417ms |
| cutoff : 10000 | 10times Time:388ms |
| cutoff : 15000 | 10times Time:389ms |
| cutoff : 20000 | 10times Time:444ms |
| cutoff : 25000 | 10times Time:432ms |
| cutoff : 30000 | 10times Time:417ms |

|                |                    |
|----------------|--------------------|
| cutoff : 35000 | 10times Time:403ms |
| cutoff : 40000 | 10times Time:368ms |
| cutoff : 45000 | 10times Time:400ms |
| cutoff : 50000 | 10times Time:357ms |

Process finished with exit code 0

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Size of Array: 200000

Degree of parallelism: 2

|                |                     |
|----------------|---------------------|
| cutoff : 5000  | 10times Time:1708ms |
| cutoff : 10000 | 10times Time:1551ms |
| cutoff : 15000 | 10times Time:928ms  |
| cutoff : 20000 | 10times Time:885ms  |
| cutoff : 25000 | 10times Time:929ms  |
| cutoff : 30000 | 10times Time:962ms  |
| cutoff : 35000 | 10times Time:931ms  |
| cutoff : 40000 | 10times Time:942ms  |
| cutoff : 45000 | 10times Time:911ms  |
| cutoff : 50000 | 10times Time:965ms  |

Degree of parallelism: 4

|                |                     |
|----------------|---------------------|
| cutoff : 5000  | 10times Time:1065ms |
| cutoff : 10000 | 10times Time:851ms  |
| cutoff : 15000 | 10times Time:936ms  |
| cutoff : 20000 | 10times Time:936ms  |
| cutoff : 25000 | 10times Time:1004ms |
| cutoff : 30000 | 10times Time:970ms  |
| cutoff : 35000 | 10times Time:1067ms |
| cutoff : 40000 | 10times Time:1007ms |
| cutoff : 45000 | 10times Time:1012ms |
| cutoff : 50000 | 10times Time:937ms  |

Degree of parallelism: 8

|                |                     |
|----------------|---------------------|
| cutoff : 5000  | 10times Time:1029ms |
| cutoff : 10000 | 10times Time:802ms  |
| cutoff : 15000 | 10times Time:814ms  |
| cutoff : 20000 | 10times Time:807ms  |
| cutoff : 25000 | 10times Time:767ms  |
| cutoff : 30000 | 10times Time:811ms  |
| cutoff : 35000 | 10times Time:711ms  |
| cutoff : 40000 | 10times Time:758ms  |
| cutoff : 45000 | 10times Time:768ms  |
| cutoff : 50000 | 10times Time:759ms  |

Degree of parallelism: 16

|                |                     |
|----------------|---------------------|
| cutoff : 5000  | 10times Time:1006ms |
| cutoff : 10000 | 10times Time:837ms  |

|                |                    |
|----------------|--------------------|
| cutoff : 15000 | 10times Time:846ms |
| cutoff : 20000 | 10times Time:828ms |
| cutoff : 25000 | 10times Time:810ms |
| cutoff : 30000 | 10times Time:862ms |
| cutoff : 35000 | 10times Time:740ms |
| cutoff : 40000 | 10times Time:768ms |
| cutoff : 45000 | 10times Time:789ms |
| cutoff : 50000 | 10times Time:727ms |

Degree of parallelism: 32

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:932ms |
| cutoff : 10000 | 10times Time:804ms |
| cutoff : 15000 | 10times Time:841ms |
| cutoff : 20000 | 10times Time:805ms |
| cutoff : 25000 | 10times Time:836ms |
| cutoff : 30000 | 10times Time:801ms |
| cutoff : 35000 | 10times Time:764ms |
| cutoff : 40000 | 10times Time:764ms |
| cutoff : 45000 | 10times Time:790ms |
| cutoff : 50000 | 10times Time:711ms |

Degree of parallelism: 64

|                |                    |
|----------------|--------------------|
| cutoff : 5000  | 10times Time:883ms |
| cutoff : 10000 | 10times Time:782ms |
| cutoff : 15000 | 10times Time:783ms |
| cutoff : 20000 | 10times Time:791ms |
| cutoff : 25000 | 10times Time:874ms |
| cutoff : 30000 | 10times Time:808ms |
| cutoff : 35000 | 10times Time:706ms |
| cutoff : 40000 | 10times Time:752ms |
| cutoff : 45000 | 10times Time:818ms |
| cutoff : 50000 | 10times Time:766ms |

Process finished with exit code 0

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