Program Structure & Algorithms
INFO6205
Assignment .05

Name: Srikanth Nandikonda

NUID: 002737724

Task:

- Find the appropriate cutoff length.
- Find the appropriate recursion depth(thread count).
- Combination of these

Relationship Conclusion:

By conducting simulations of experiments with various combinations of cutoff values, threads, and array sizes, we have gathered sufficient data to draw a conclusion on the optimal number of threads for our algorithm. Based on the analysis of the runtimes, we have determined that utilizing four threads offers the best performance, and any additional threads are unlikely to result in a significant improvement as the overhead of thread creation and synchronization will start to outweigh the benefits of parallelism. In other words, increasing the number of threads beyond **four** would not provide a substantial boost to the efficiency of the algorithm.

On an average, the lowest runtime is achieved when the cutoff value is 30% of the array size.

Relation between Thread count (t) and recursion depth(d)

$$t=2^d$$

This means that for each additional level of recursion, the number of threads required doubles.

Evidence to the Conclusion

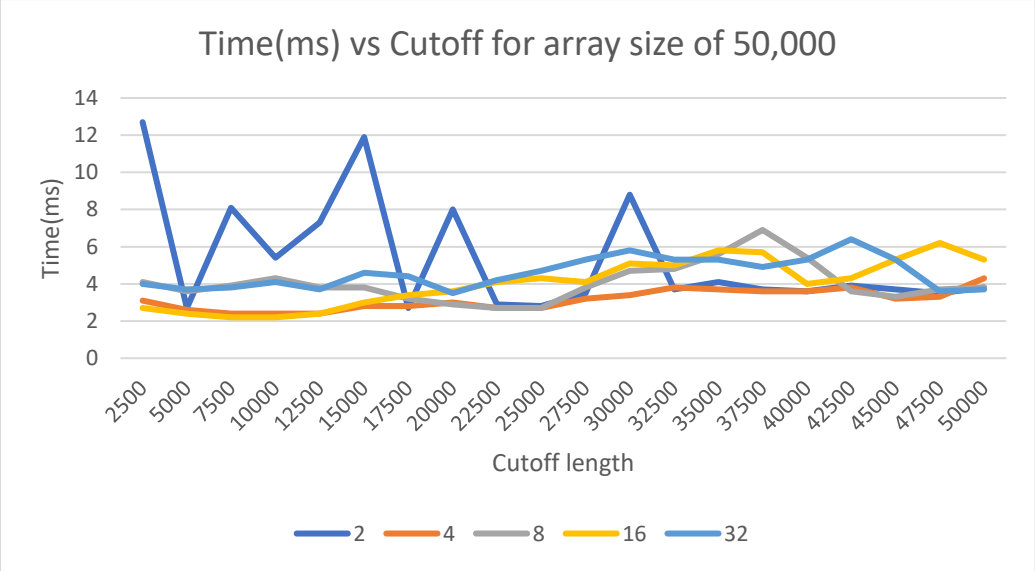
Below are the runtimes in ‘ms’ for different combinations of Array size, threads, and cutoffs.

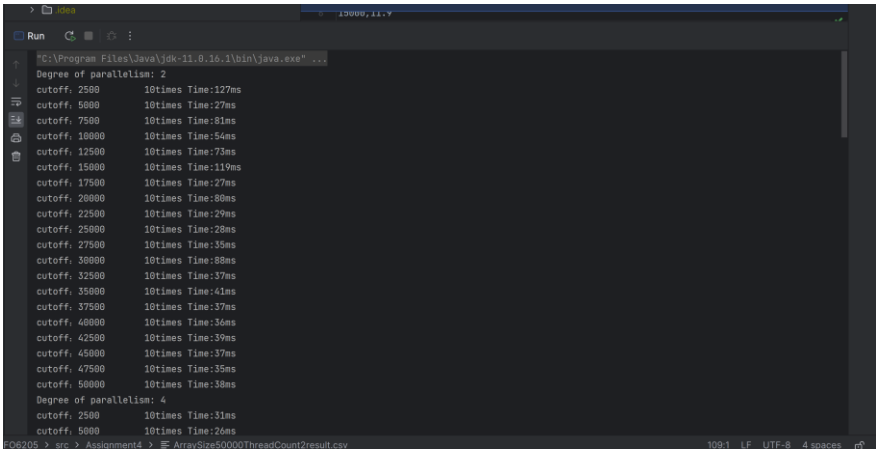
Array Size: 50,0000

2,4,6,8,16,32 -> Thread Count

2500,5000 … -> Cutoff length

50,000					
	2	4	8	16	32
2500	12.7	3.1	4.1	2.7	4
5000	2.7	2.6	3.6	2.4	3.7
7500	8.1	2.4	3.9	2.2	3.8
10000	5.4	2.4	4.3	2.2	4.1
12500	7.3	2.4	3.8	2.4	3.7
15000	11.9	2.8	3.8	3	4.6
17500	2.7	2.8	3.2	3.4	4.4
20000	8	3	2.9	3.6	3.5
22500	2.9	2.7	2.7	4.1	4.2
25000	2.8	2.7	2.7	4.3	4.7
27500	3.5	3.2	3.8	4.1	5.3
30000	8.8	3.4	4.7	5.1	5.8
32500	3.7	3.8	4.8	5	5.3
35000	4.1	3.7	5.6	5.8	5.3
37500	3.7	3.6	6.9	5.7	4.9
40000	3.6	3.6	5.4	4	5.3
42500	3.9	3.8	3.6	4.3	6.4
45000	3.7	3.2	3.3	5.3	5.3
47500	3.5	3.3	3.7	6.2	3.6
50000	3.8	4.3	3.8	5.3	3.7





.idea

Run

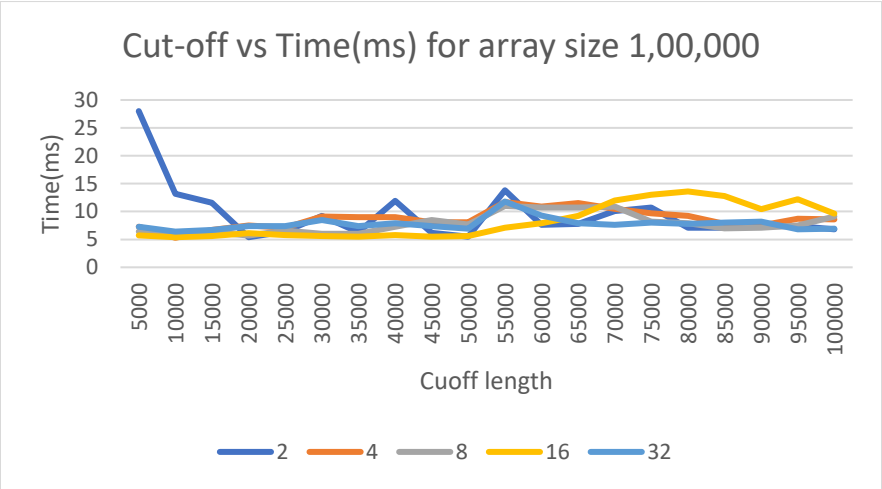
```
cutoff: 50000       10times Time:53ms
Degree of parallelism: 32
cutoff: 2500        10times Time:40ms
cutoff: 5000        10times Time:37ms
cutoff: 7500        10times Time:38ms
cutoff: 10000       10times Time:41ms
cutoff: 12500       10times Time:37ms
cutoff: 15000       10times Time:46ms
cutoff: 17500       10times Time:44ms
cutoff: 20000       10times Time:35ms
cutoff: 22500       10times Time:42ms
cutoff: 25000       10times Time:47ms
cutoff: 27500       10times Time:53ms
cutoff: 30000       10times Time:58ms
cutoff: 32500       10times Time:53ms
cutoff: 35000       10times Time:53ms
cutoff: 37500       10times Time:49ms
cutoff: 40000       10times Time:53ms
cutoff: 42500       10times Time:64ms
cutoff: 45000       10times Time:53ms
cutoff: 47500       10times Time:36ms
cutoff: 50000       10times Time:37ms

Process finished with exit code 0
```

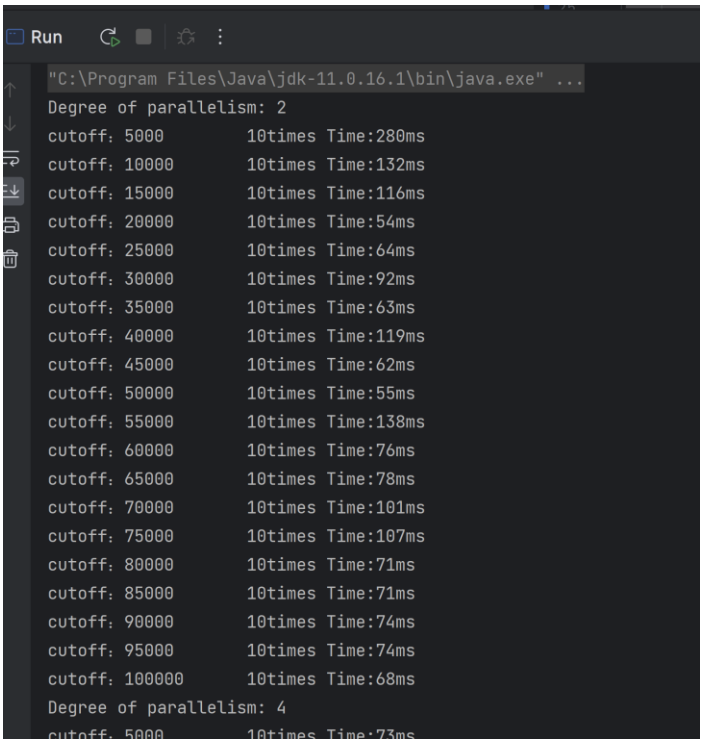
Array Size : 1,00,000

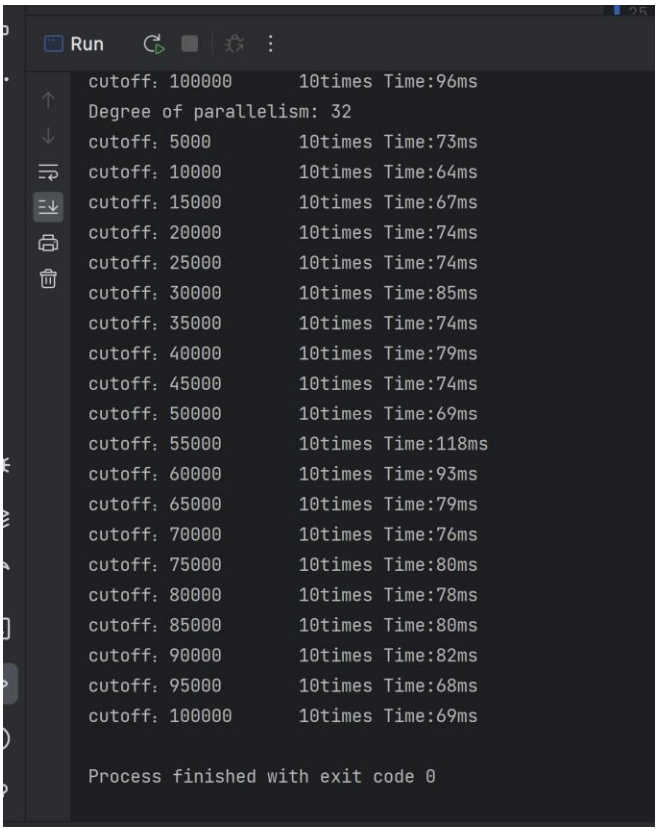
2,4,6,8,16,32 -> Thread Count

5000,10000 … -> Cutoff length

Array Size :1,00,000					
	2	4	8	16	32
5000	28	7.3	6.4	5.7	7.3
10000	13.2	5.3	5.8	5.4	6.4
15000	11.6	6.7	6.3	5.6	6.7
20000	5.4	7.5	5.7	6.1	7.4
25000	6.4	7.1	6.6	5.8	7.4
30000	9.2	9.1	6	5.6	8.5
35000	6.3	9	6	5.5	7.4
40000	11.9	9	7.3	5.8	7.9
45000	6.2	8.1	8.5	5.5	7.4
50000	5.5	8.1	7.7	5.6	6.9
55000	13.8	11.7	11	7.1	11.8
60000	7.6	10.9	10.7	7.9	9.3
65000	7.8	11.5	10.7	9.2	7.9
70000	10.1	10.5	10.9	12	7.6
75000	10.7	9.7	8.2	13	8
80000	7.1	9.2	7.9	13.6	7.8
85000	7.1	7.8	7	12.8	8
90000	7.4	7.5	7.1	10.4	8.2
95000	7.4	8.7	7.5	12.2	6.8
100000	6.8	8.6	9.1	9.6	6.9




Run
"C:\Program Files\Java\jdk-11.0.16.1\bin\java.exe" ...
Degree of parallelism: 2
cutoff: 5000 10times Time:280ms
cutoff: 10000 10times Time:132ms
cutoff: 15000 10times Time:116ms
cutoff: 20000 10times Time:54ms
cutoff: 25000 10times Time:64ms
cutoff: 30000 10times Time:92ms
cutoff: 35000 10times Time:63ms
cutoff: 40000 10times Time:119ms
cutoff: 45000 10times Time:62ms
cutoff: 50000 10times Time:55ms
cutoff: 55000 10times Time:138ms
cutoff: 60000 10times Time:76ms
cutoff: 65000 10times Time:78ms
cutoff: 70000 10times Time:101ms
cutoff: 75000 10times Time:107ms
cutoff: 80000 10times Time:71ms
cutoff: 85000 10times Time:71ms
cutoff: 90000 10times Time:74ms
cutoff: 95000 10times Time:74ms
cutoff: 100000 10times Time:68ms
Degree of parallelism: 4

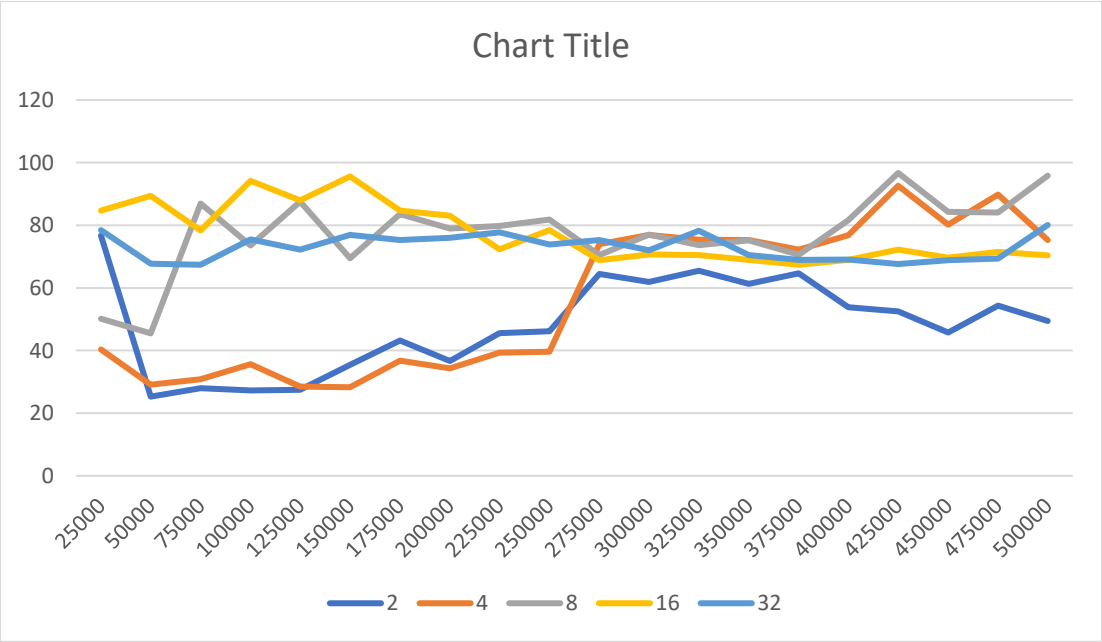

Run
cutoff: 100000 10times Time:96ms
Degree of parallelism: 32
cutoff: 5000 10times Time:73ms
cutoff: 10000 10times Time:64ms
cutoff: 15000 10times Time:67ms
cutoff: 20000 10times Time:74ms
cutoff: 25000 10times Time:74ms
cutoff: 30000 10times Time:85ms
cutoff: 35000 10times Time:74ms
cutoff: 40000 10times Time:79ms
cutoff: 45000 10times Time:74ms
cutoff: 50000 10times Time:69ms
cutoff: 55000 10times Time:118ms
cutoff: 60000 10times Time:93ms
cutoff: 65000 10times Time:79ms
cutoff: 70000 10times Time:76ms
cutoff: 75000 10times Time:80ms
cutoff: 80000 10times Time:78ms
cutoff: 85000 10times Time:80ms
cutoff: 90000 10times Time:82ms
cutoff: 95000 10times Time:68ms
cutoff: 100000 10times Time:69ms
Process finished with exit code 0

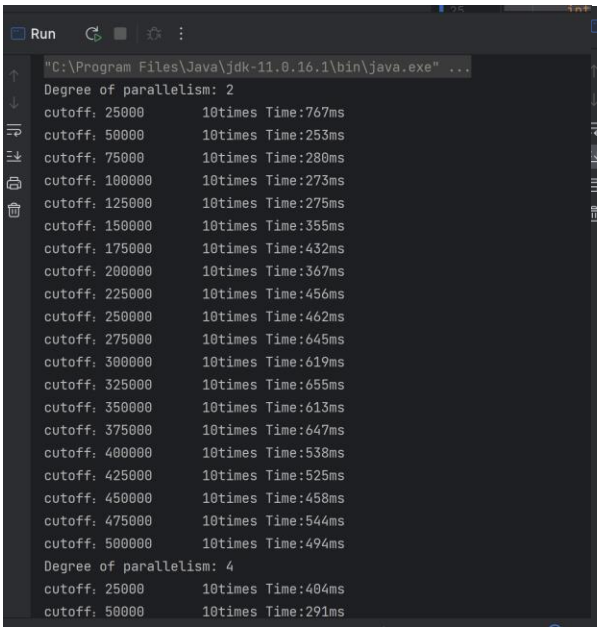
Array size: 5,00,000

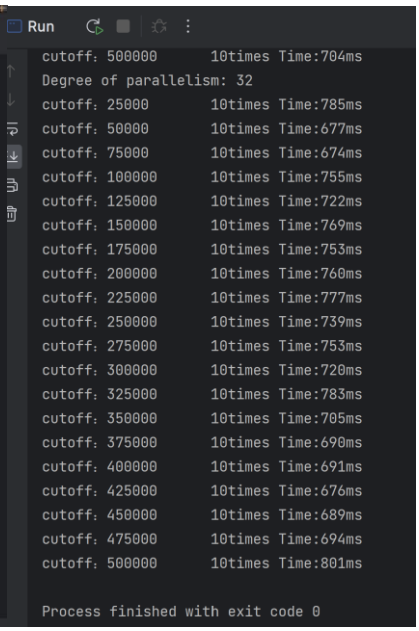
2,4,6,8,16,32 -> Thread Count

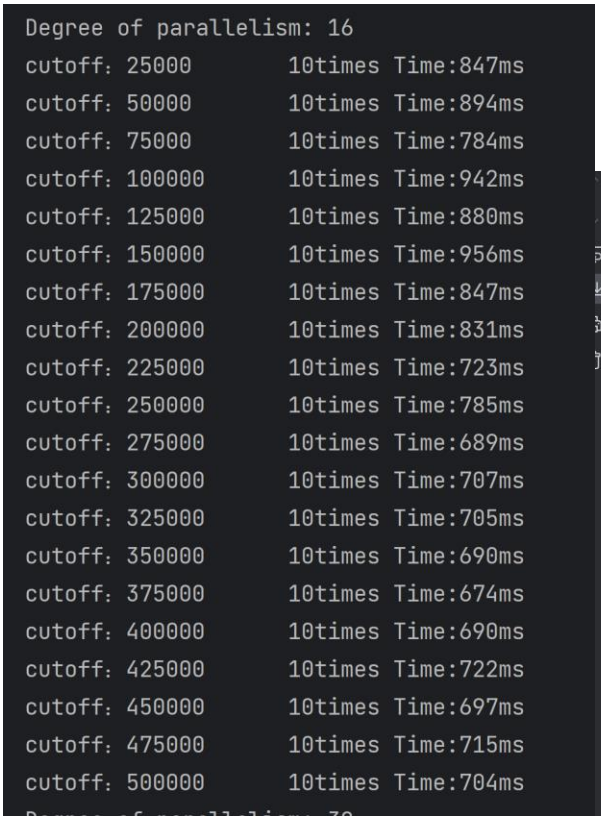
25000,50000 … -> Cutoff length

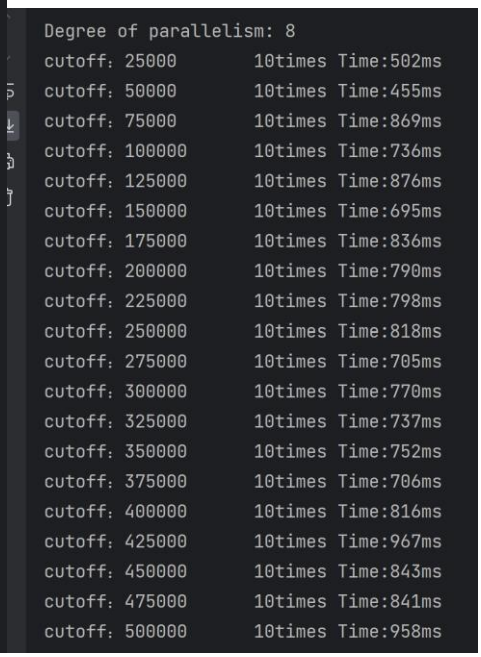
Array Size : 5,00,000					
	2	4	8	16	32
25000	76.7	40.4	50.2	84.7	78.5
50000	25.3	29.1	45.5	89.4	67.7
75000	28	30.9	86.9	78.4	67.4
100000	27.3	35.7	73.6	94.2	75.5
125000	27.5	28.5	87.6	88	72.2
150000	35.5	28.3	69.5	95.6	76.9
175000	43.2	36.8	83.6	84.7	75.3
200000	36.7	34.3	79	83.1	76
225000	45.6	39.3	79.8	72.3	77.7
250000	46.2	39.6	81.8	78.5	73.9
275000	64.5	74	70.5	68.9	75.3
300000	61.9	76.9	77	70.7	72
325000	65.5	75.4	73.7	70.5	78.3
350000	61.3	75.3	75.2	69	70.5
375000	64.7	72.2	70.6	67.4	69
400000	53.8	76.8	81.6	69	69.1
425000	52.5	92.6	96.7	72.2	67.6
450000	45.8	80.2	84.3	69.7	68.9
475000	54.4	89.8	84.1	71.5	69.4
500000	49.4	75.3	95.8	70.4	80.1




Run
"C:\Program Files\Java\jdk-11.0.16.1\bin\java.exe" ...
Degree of parallelism: 2
cutoff: 25000 10times Time:767ms
cutoff: 50000 10times Time:253ms
cutoff: 75000 10times Time:280ms
cutoff: 100000 10times Time:273ms
cutoff: 125000 10times Time:275ms
cutoff: 150000 10times Time:355ms
cutoff: 175000 10times Time:432ms
cutoff: 200000 10times Time:367ms
cutoff: 225000 10times Time:456ms
cutoff: 250000 10times Time:462ms
cutoff: 275000 10times Time:645ms
cutoff: 300000 10times Time:619ms
cutoff: 325000 10times Time:655ms
cutoff: 350000 10times Time:613ms
cutoff: 375000 10times Time:647ms
cutoff: 400000 10times Time:538ms
cutoff: 425000 10times Time:525ms
cutoff: 450000 10times Time:458ms
cutoff: 475000 10times Time:544ms
cutoff: 500000 10times Time:494ms
Degree of parallelism: 4
cutoff: 25000 10times Time:404ms
cutoff: 50000 10times Time:291ms


Run
cutoff: 500000 10times Time:704ms
Degree of parallelism: 32
cutoff: 25000 10times Time:785ms
cutoff: 50000 10times Time:677ms
cutoff: 75000 10times Time:674ms
cutoff: 100000 10times Time:755ms
cutoff: 125000 10times Time:722ms
cutoff: 150000 10times Time:769ms
cutoff: 175000 10times Time:753ms
cutoff: 200000 10times Time:760ms
cutoff: 225000 10times Time:777ms
cutoff: 250000 10times Time:739ms
cutoff: 275000 10times Time:753ms
cutoff: 300000 10times Time:720ms
cutoff: 325000 10times Time:783ms
cutoff: 350000 10times Time:705ms
cutoff: 375000 10times Time:690ms
cutoff: 400000 10times Time:691ms
cutoff: 425000 10times Time:676ms
cutoff: 450000 10times Time:689ms
cutoff: 475000 10times Time:694ms
cutoff: 500000 10times Time:801ms
Process finished with exit code 0


Degree of parallelism: 16
cutoff: 25000 10times Time:847ms
cutoff: 50000 10times Time:894ms
cutoff: 75000 10times Time:784ms
cutoff: 100000 10times Time:942ms
cutoff: 125000 10times Time:880ms
cutoff: 150000 10times Time:956ms
cutoff: 175000 10times Time:847ms
cutoff: 200000 10times Time:831ms
cutoff: 225000 10times Time:723ms
cutoff: 250000 10times Time:785ms
cutoff: 275000 10times Time:689ms
cutoff: 300000 10times Time:707ms
cutoff: 325000 10times Time:705ms
cutoff: 350000 10times Time:690ms
cutoff: 375000 10times Time:674ms
cutoff: 400000 10times Time:690ms
cutoff: 425000 10times Time:722ms
cutoff: 450000 10times Time:697ms
cutoff: 475000 10times Time:715ms
cutoff: 500000 10times Time:704ms

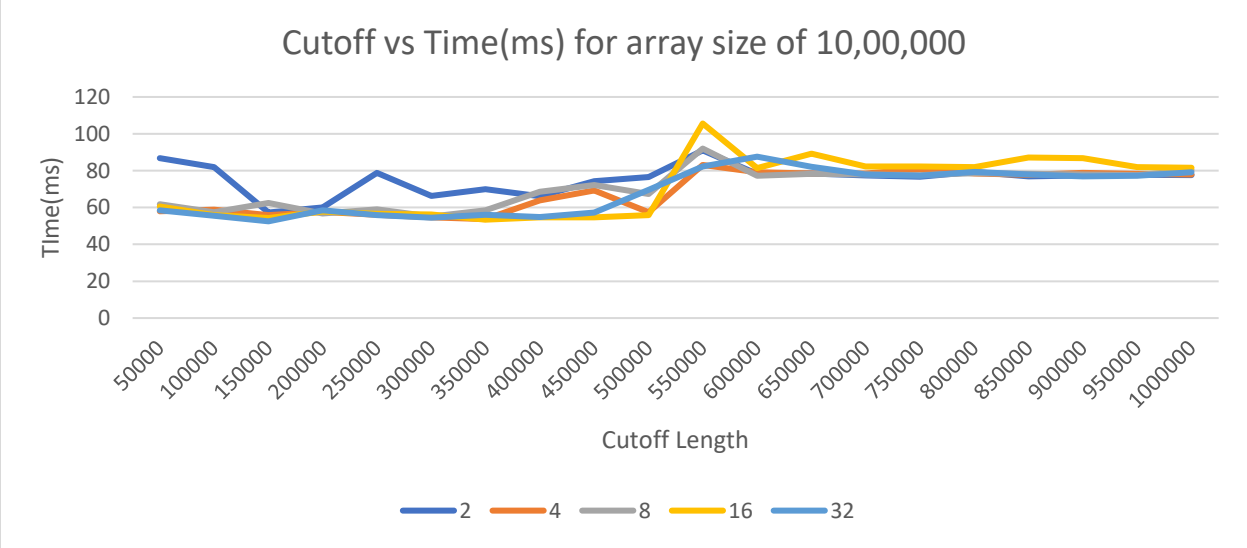

Degree of parallelism: 8
cutoff: 25000 10times Time:502ms
cutoff: 50000 10times Time:455ms
cutoff: 75000 10times Time:869ms
cutoff: 100000 10times Time:736ms
cutoff: 125000 10times Time:876ms
cutoff: 150000 10times Time:695ms
cutoff: 175000 10times Time:836ms
cutoff: 200000 10times Time:790ms
cutoff: 225000 10times Time:798ms
cutoff: 250000 10times Time:818ms
cutoff: 275000 10times Time:705ms
cutoff: 300000 10times Time:770ms
cutoff: 325000 10times Time:737ms
cutoff: 350000 10times Time:752ms
cutoff: 375000 10times Time:706ms
cutoff: 400000 10times Time:816ms
cutoff: 425000 10times Time:967ms
cutoff: 450000 10times Time:843ms
cutoff: 475000 10times Time:841ms
cutoff: 500000 10times Time:958ms

Array size: 10,00,000

2,4,6,8,16,32 -> Thread Count

50000,100000 … -> Cutoff length

10,00,000					
	2	4	8	16	32
50000	86.7	58	61.8	60.5	58.4
100000	82	58.9	57.4	55.9	55.5
150000	57.3	55.9	62.5	54.4	52.5
200000	60	57.7	56.7	57.8	58.5
250000	78.8	56	59	56.6	55.9
300000	66.3	54.6	55.1	56.2	54.5
350000	70	53.7	58.5	53.4	56
400000	66.2	63.9	68.6	54.7	54.9
450000	74.2	69.3	72.2	54.7	57.3
500000	76.6	57.4	67.4	55.8	69.6
550000	91	83.1	92	105.6	82.2
600000	78.2	79.1	77.2	81.4	87.6
650000	78.5	78.5	78.2	89.3	82.1
700000	77.4	78.5	77.9	82.2	77.9
750000	76.7	80.9	77.5	82.3	77.2
800000	79.4	78.5	78.7	82	79.4
850000	76.9	77.7	78.2	87.2	78
900000	77.4	78.8	78	86.8	76.9
950000	77.7	78.2	77.5	81.9	77.2
1000000	77.6	78	80.3	81.5	79.1



```
Degree of parallelism: 2
cutoff: 50000       10times Time:867ms
cutoff: 100000      10times Time:820ms
cutoff: 150000      10times Time:573ms
cutoff: 200000      10times Time:600ms
cutoff: 250000      10times Time:788ms
cutoff: 300000      10times Time:663ms
cutoff: 350000      10times Time:700ms
cutoff: 400000      10times Time:662ms
cutoff: 450000      10times Time:742ms
cutoff: 500000      10times Time:766ms
cutoff: 550000      10times Time:910ms
cutoff: 600000      10times Time:782ms
cutoff: 650000      10times Time:785ms
cutoff: 700000      10times Time:774ms
cutoff: 750000      10times Time:767ms
cutoff: 800000      10times Time:794ms
cutoff: 850000      10times Time:769ms
cutoff: 900000      10times Time:774ms
cutoff: 950000      10times Time:777ms
cutoff: 1000000     10times Time:776ms
```

```
Degree of parallelism: 4
cutoff: 50000       10times Time:580ms
cutoff: 100000      10times Time:589ms
cutoff: 150000      10times Time:559ms
cutoff: 200000      10times Time:577ms
cutoff: 250000      10times Time:560ms
cutoff: 300000      10times Time:546ms
cutoff: 350000      10times Time:537ms
cutoff: 400000      10times Time:639ms
cutoff: 450000      10times Time:693ms
cutoff: 500000      10times Time:574ms
cutoff: 550000      10times Time:831ms
cutoff: 600000      10times Time:791ms
cutoff: 650000      10times Time:785ms
cutoff: 700000      10times Time:785ms
cutoff: 750000      10times Time:809ms
cutoff: 800000      10times Time:785ms
cutoff: 850000      10times Time:777ms
cutoff: 900000      10times Time:788ms
cutoff: 950000      10times Time:782ms
cutoff: 1000000     10times Time:780ms
```

```
Degree of parallelism: 8
cutoff: 50000       10times Time:618ms
cutoff: 100000      10times Time:574ms
cutoff: 150000      10times Time:625ms
cutoff: 200000      10times Time:567ms
cutoff: 250000      10times Time:590ms
cutoff: 300000      10times Time:551ms
cutoff: 350000      10times Time:585ms
cutoff: 400000      10times Time:686ms
cutoff: 450000      10times Time:722ms
cutoff: 500000      10times Time:674ms
cutoff: 550000      10times Time:920ms
cutoff: 600000      10times Time:772ms
cutoff: 650000      10times Time:782ms
cutoff: 700000      10times Time:779ms
cutoff: 750000      10times Time:775ms
cutoff: 800000      10times Time:787ms
cutoff: 850000      10times Time:782ms
cutoff: 900000      10times Time:780ms
cutoff: 950000      10times Time:775ms
cutoff: 1000000     10times Time:803ms
```

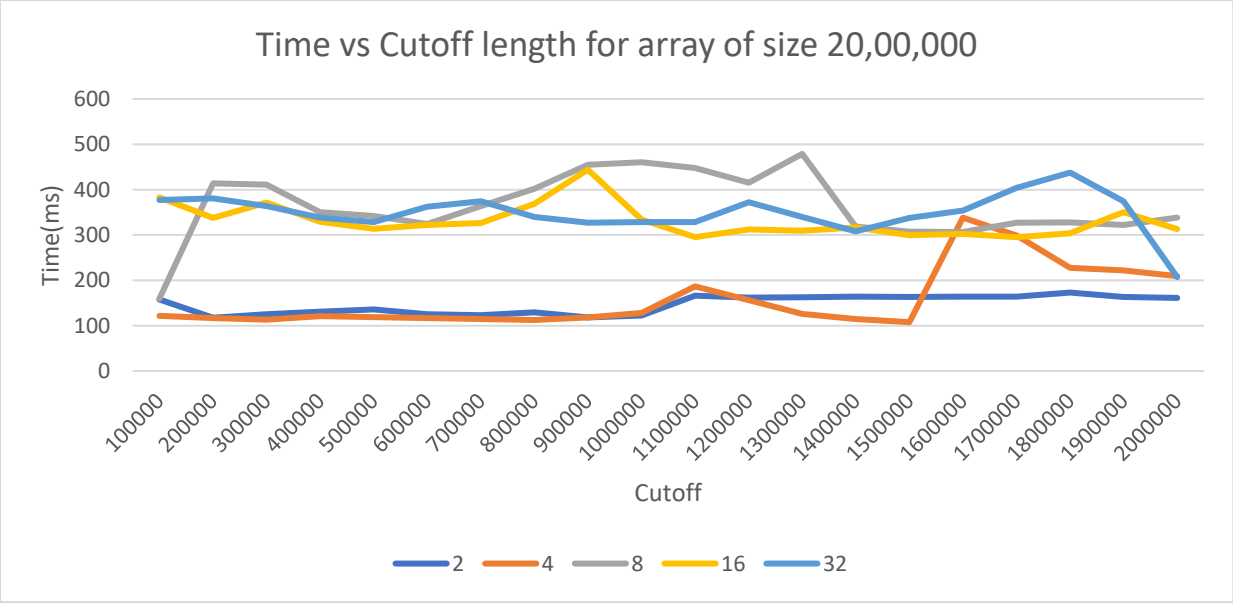
```
Degree of parallelism: 16
cutoff: 50000       10times Time:605ms
cutoff: 100000      10times Time:559ms
cutoff: 150000      10times Time:544ms
cutoff: 200000      10times Time:578ms
cutoff: 250000      10times Time:566ms
cutoff: 300000      10times Time:562ms
cutoff: 350000      10times Time:534ms
cutoff: 400000      10times Time:547ms
cutoff: 450000      10times Time:547ms
cutoff: 500000      10times Time:558ms
cutoff: 550000      10times Time:1056ms
cutoff: 600000      10times Time:814ms
cutoff: 650000      10times Time:893ms
cutoff: 700000      10times Time:822ms
cutoff: 750000      10times Time:823ms
cutoff: 800000      10times Time:820ms
cutoff: 850000      10times Time:872ms
cutoff: 900000      10times Time:868ms
cutoff: 950000      10times Time:819ms
cutoff: 1000000     10times Time:815ms
```

Array size: 20,00,000

2,4,6,8,16,32 -> Thread Count

100000,200000 … -> Cutoff length

	20,00,000				
	2	4	8	16	32
100000	158	121.6	159.6	382.8	377.2
200000	117.6	117	413.8	337.8	380.5
300000	125	113.1	411.3	371.3	363.7
400000	130.7	121.2	350.2	329.4	338.4
500000	135.8	118.7	341.9	313.7	328.4
600000	125.2	116.6	324.3	322.2	362.6
700000	122.9	115	363.7	326.6	374.2
800000	129.3	112.5	401.6	369	339.7
900000	117.9	118.1	454.6	444.1	326.9
1000000	122.6	128.3	460.2	334.1	328.7
1100000	166.4	186.4	448	295.3	328.4
1200000	161.8	156.1	415.5	312	372.3
1300000	163	126.1	478.9	309.5	339.9
1400000	164	114.8	318.6	316.3	308
1500000	163.6	107.8	307.7	299.6	337.7
1600000	164.1	338.2	306.4	302.2	353.9
1700000	164	298.6	327.4	295.2	403.9
1800000	173.1	227.3	327.7	303.5	437.6
1900000	163.1	221.8	322.1	350.2	374.2
2000000	161.1	209	338.4	312.9	207.2



```
Degree of parallelism: 2
cutoff: 100000      10times Time:1580ms
cutoff: 200000      10times Time:1176ms
cutoff: 300000      10times Time:1250ms
cutoff: 400000      10times Time:1307ms
cutoff: 500000      10times Time:1358ms
cutoff: 600000      10times Time:1252ms
cutoff: 700000      10times Time:1229ms
cutoff: 800000      10times Time:1293ms
cutoff: 900000      10times Time:1179ms
cutoff: 1000000     10times Time:1226ms
cutoff: 1100000     10times Time:1664ms
cutoff: 1200000     10times Time:1618ms
cutoff: 1300000     10times Time:1630ms
cutoff: 1400000     10times Time:1640ms
cutoff: 1500000     10times Time:1636ms
cutoff: 1600000     10times Time:1641ms
cutoff: 1700000     10times Time:1640ms
cutoff: 1800000     10times Time:1731ms
cutoff: 1900000     10times Time:1631ms
cutoff: 2000000     10times Time:1611ms
```

```
Degree of parallelism: 4
cutoff: 100000      10times Time:1216ms
cutoff: 200000      10times Time:1170ms
cutoff: 300000      10times Time:1131ms
cutoff: 400000      10times Time:1212ms
cutoff: 500000      10times Time:1187ms
cutoff: 600000      10times Time:1166ms
cutoff: 700000      10times Time:1150ms
cutoff: 800000      10times Time:1125ms
cutoff: 900000      10times Time:1181ms
cutoff: 1000000     10times Time:1283ms
cutoff: 1100000     10times Time:1864ms
cutoff: 1200000     10times Time:191486ms
cutoff: 1300000     10times Time:1261ms
cutoff: 1400000     10times Time:1148ms
cutoff: 1500000     10times Time:1078ms
cutoff: 1600000     10times Time:3382ms
cutoff: 1700000     10times Time:2986ms
cutoff: 1800000     10times Time:2273ms
cutoff: 1900000     10times Time:2218ms
cutoff: 2000000     10times Time:2090ms
```

```
Degree of parallelism: 8
cutoff: 100000      10times Time:1596ms
cutoff: 200000      10times Time:4138ms
cutoff: 300000      10times Time:4113ms
cutoff: 400000      10times Time:3502ms
cutoff: 500000      10times Time:3419ms
cutoff: 600000      10times Time:3243ms
cutoff: 700000      10times Time:3637ms
cutoff: 800000      10times Time:4016ms
cutoff: 900000      10times Time:4546ms
cutoff: 1000000     10times Time:4602ms
cutoff: 1100000     10times Time:4480ms
cutoff: 1200000     10times Time:4155ms
cutoff: 1300000     10times Time:4789ms
cutoff: 1400000     10times Time:3186ms
cutoff: 1500000     10times Time:3077ms
cutoff: 1600000     10times Time:3064ms
cutoff: 1700000     10times Time:3274ms
cutoff: 1800000     10times Time:3277ms
cutoff: 1900000     10times Time:3221ms
cutoff: 2000000     10times Time:3384ms
```

```
Degree of parallelism: 16
cutoff: 100000      10times Time:3828ms
cutoff: 200000      10times Time:3378ms
cutoff: 300000      10times Time:3713ms
cutoff: 400000      10times Time:3294ms
cutoff: 500000      10times Time:3137ms
cutoff: 600000      10times Time:3222ms
cutoff: 700000      10times Time:3266ms
cutoff: 800000      10times Time:3690ms
cutoff: 900000      10times Time:4441ms
cutoff: 1000000     10times Time:3341ms
cutoff: 1100000     10times Time:2953ms
cutoff: 1200000     10times Time:3120ms
cutoff: 1300000     10times Time:3095ms
cutoff: 1400000     10times Time:3163ms
cutoff: 1500000     10times Time:2996ms
cutoff: 1600000     10times Time:3022ms
cutoff: 1700000     10times Time:2952ms
cutoff: 1800000     10times Time:3035ms
cutoff: 1900000     10times Time:3502ms
cutoff: 2000000     10times Time:3129ms
```

The graphs show that changing the thread count does not significantly affect the time taken to sort. The optimal results were obtained when the thread count was set to 4 for all test cases. Increasing the thread count beyond 4 would require more memory to maintain the threads, and therefore 4 is the best thread count for parallel sorting.

When the thread count is set to 4, the time taken to sort for arrays of different sizes and cutoff percentages is shown in the table. The cells marked in red represent the lowest time taken to sort for each array length.

For 50K its 25%, 1L its 10%, 5L -> 30%, 10L -> 35%, 20L -> 40%

So we can consider the ideal cutoff time should be in the range of 10 -40%, average value if around 30%

Ideal cutoff length as the percentage of length should be 30%.

	Thread count 4				
	50,000	1,00,000	5,00,000	10,00,000	20,00,000
5	3.1	7.3	40.4	58	121.6
10	2.6	5.3	29.1	58.9	117
15	2.4	6.7	30.9	55.9	113.1
20	2.4	7.5	35.7	57.7	121.2
25	2.4	7.1	28.5	56	118.7
30	2.8	9.1	28.3	54.6	116.6
35	2.8	9	36.8	53.7	115
40	3	9	34.3	63.9	112.5
45	2.7	8.1	39.3	69.3	118.1
50	2.7	8.1	39.6	57.4	128.3
55	3.2	11.7	74	83.1	186.4
60	3.4	10.9	76.9	79.1	156.1
65	3.8	11.5	75.4	78.5	126.1
70	3.7	10.5	75.3	78.5	114.8
75	3.6	9.7	72.2	80.9	107.8
80	3.6	9.2	76.8	78.5	338.2
85	3.8	7.8	92.6	77.7	298.6
90	3.2	7.5	80.2	78.8	227.3
95	3.3	8.7	89.8	78.2	221.8
100	4.3	8.6	75.3	78	209

CSV generated for Each array size and thread count