# Results and Analysis

## Parallelization of a BruteForce Algorithm

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Results, analysis and conclusions from parallelization of a BruteForce algorithm, written in C, using OpenMP and MPI.

# 1 Contents

# 2 Results

All of the runtime results are displayed in the attached spreadsheet “Results.xlsx” There were a total of 334 program runs in various modes eg OMP 3 threads and mean execution times calculated. The total runtime for all the tests was 23540 s (approx. 6.5 hrs).

As the key was known, it was possible to position the first character of the key at different positions within the search alphabet and note execution times accordingly. This was purely for testing purposes, and if user input is taken for the ciphertext, plaintext and IV values, the program would find the relevant key.

The spreadsheet of raw data displays all of the results of the various positions of the first character. Positions 1,2,3,4,8,16, and 36 (the end of the search alphabet) were tested, as well as an exhaustive search where the search alphabet was adjusted to not include the first character.

Due to time constraints for testing, some of the longer searches were only run 2 or 3 times, rather than the planned 5. All program runs executed on UWE cluster 164.11.39.11 from a Lenovo Laptop (4 cores, i7 processor)

*Table 1* shows a summary of the results and the associated speed-up times and efficiencies. The speed up times have been calclulated by dividing the benchmarked serial time by the mean execution time of the relevant program, and the efficiency figure is derived by dividing the speedup by the number of threads/processors.

*Table 1* shows a summary of the results and the associated speed-up times and efficiencies. The speed up times have been calclulated by dividing the benchmarked serial time by the mean execution time of the relevant program, and the efficiency figure is derived by dividing the speedup by the number of threads/processors.

Table 1

| | | **Position of first character of key within search alphabet of length 36** | | | |
|---|---|---|---|---|---|
| Version of program | | **8** | **16** | **36** | **Exhaustive** |
| Serial | Mean Time | 92.31 | 197.69 | 461.21 | 474.45 |
| **OMP 1 thread** | Mean Time | 104.92 | 226.22 | 522.80 | 542.41 |
| | Speed-up | 0.88 | 0.87 | 0.88 | 0.87 |
| | Efficiency | ***0.88*** | ***0.87*** | ***0.88*** | ***0.87*** |
| **MPI 1 proc** | Mean Time | 91.65 | 195.86 | 468.45 | 515.89 |
| | Speed-up | 1.01 | 1.01 | 0.98 | 0.92 |
| | Efficiency | 1.01 | 1.01 | 0.98 | 0.92 |
| **OMP 2 threads** | Mean Time | 68.56 | 168.34 | 384.64 | 411.14 |
| | Speed-up | 1.35 | 1.17 | 1.20 | 1.15 |
| | Efficiency | ***0.67*** | ***0.59*** | ***0.60*** | ***0.58*** |
| **MPI 2 procs** | Mean Time | 40.56 | 94.23 | 228.46 | 245.01 |
| | Speed-up | 2.28 | 2.10 | 2.02 | 1.94 |
| | Efficiency | 1.14 | 1.05 | 1.01 | 0.97 |
| **OMP 3 threads** | Mean Time | 59.40 | 146.09 | 335.75 | 364.01 |
| | Speed-up | 1.55 | 1.35 | 1.37 | 1.30 |
| | Efficiency | ***0.52*** | ***0.45*** | ***0.46*** | ***0.43*** |
| **MPI 3 procs** | Mean Time | 27.68 | 68.21 | 149.70 | 162.55 |
| | Speed-up | 3.33 | 2.90 | 3.08 | 2.92 |
| | Efficiency | 1.11 | 0.97 | 1.03 | 0.97 |
| **OMP 4 threads** | Mean Time | 35.81 | 106.11 | 283.72 | 304.87 |
| | Speed-up | 2.58 | 1.86 | 1.63 | 1.56 |
| | Efficiency | ***0.64*** | ***0.47*** | ***0.41*** | ***0.39*** |
| **MPI 4 procs** | Mean Time | 14.91 | 42.28 | 111.13 | 124.82 |
| | Speed-up | 6.19 | 4.68 | 4.15 | 3.80 |
| | Efficiency | ***1.55*** | ***1.17*** | ***1.04*** | ***0.95*** |
| **MPI 5 procs** | Mean Time | 17.42 | 52.50 | 121.30 | 134.10 |
| | Speed-up | 5.30 | 3.77 | 3.80 | 3.54 |
| | Efficiency | ***1.06*** | ***0.75*** | ***0.76*** | ***0.71*** |
| **MPI 6 procs** | Mean Time | 21.08 | 40.57 | 100.90 | 122.35 |
| | Speed-up | 4.38 | 4.87 | 4.57 | 3.88 |
| | Efficiency | ***0.73*** | ***0.81*** | ***0.76*** | ***0.65*** |
| **MPI 7 procs** | Mean Time | 24.13 | 49.26 | 119.65 | 133.89 |
| | Speed-up | 3.83 | 4.01 | 3.85 | 3.54 |
| | Efficiency | ***0.55*** | ***0.57*** | ***0.55*** | ***0.51*** |
| **MPI 8 procs** | Mean Time | 0.72 | 28.49 | 111.32 | 124.82 |
| | Speed-up | 127.42 | 6.94 | 4.14 | 3.80 |
| | Efficiency | ***15.93*** | ***0.87*** | ***0.52*** | ***0.48*** |

Figure 1 show the results of the various program runs for different positions of the first key character:

**Exhaustive Search** (character not in the alphabet, so key not found).

**End of alphabet** (character is at the end of the search alphabet, in this case position 36).

**Posn 16** (normal position of the first character of the key within the search alphabet).

**Posn 8** (first character positioned towards the beginning of the search alphabet

*Figure 1*

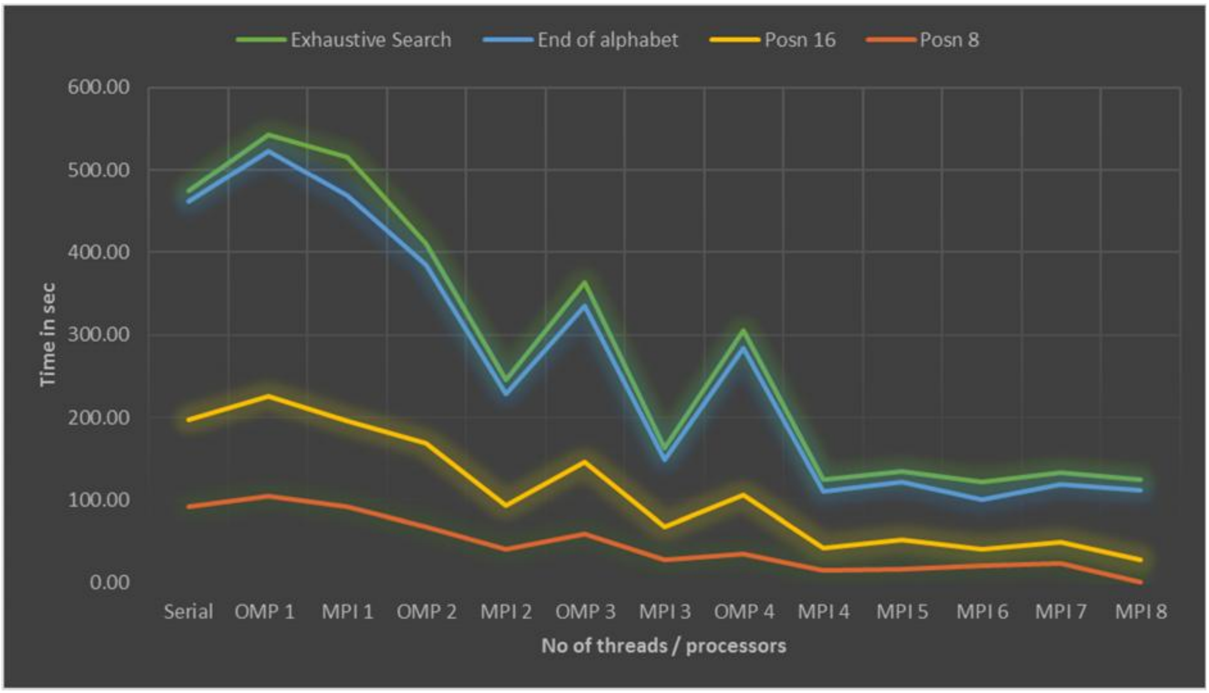


Figure 2 shows a graph of the efficiencies for when the key was at the end of the search space. i.e. “p” was at position 36 in a search alphabet of length 36.

*Figure 2*

## 3.1 Amdahl's Law & Gustafson's Law

It would have been beneficial to analyse the results in terms of Amdahl's law and Gustafson's Law, which both determine the speedup achievable by a parallel program in terms of the proportion of time spent on the serial execution versus the time spent on the execution of the parallel sections of the program. However, in this case, all of the program execution time was within the parallel section, bar that time used for taking user input.

## 3.2 General analysis

### 3.2.1 Mean time and Speedup Factor

It can be seen that there is a general reduction in time for all 3 tests as the number of threads/processors increase. However, there are spikes in the OMP 3 thread and OMP 4 thread results. This is probably due how the search alphabet is distributed among the threads. It is also clear from Figure 1 that there is no significant decrease in time when the number of processors is greater than 4. The exception to this is when the number of processors in the MPI run for the End of Alphabet search was 6. This produced the best overall time for that particular test. MPI parallelization using 8 processes when the first character was positioned at position 8 produced a very quick result (0.72s), which was a speed up of a factor of 127.42 over the serial version. Again, this was because of the way the search alphabet was distributed between the processes. Position 8 would be among the first batch to be processed and hence a very quick result.

### 3.2.2 Efficiency

The efficiencies were calculated for all of the mean speedup factors, and charted for when the key was at the end of the search space. i.e. when p = 36. The theoretical maximum efficiency is 1 (100%). However, some of the efficiencies exceeded this. This was probably due to how the data was distributed in both the MPI and OMP versions.

For example, in the OMP version executed using 4 threads, then all keys beginning with a, b, c, or d would all be generated at the same time. One thread would use "a" as the key starting character, another would use "b", and so on. Thus, batches of 4 are processed together.

If the search space (size of alphabet) is divisible by the no. of threads or processors then each batch will be the same size. If this is not the case, particularly in the MPI version, this may slow the execution time.

# 4 Conclusions

Data distribution was a major factor in the performance of the parallel versions of the BruteForce program. The parallel versions produced the expected results. Overheads, in terms of communication time between the processes in the MPI version also effected the results obtained.

# 5 Raw data

Table 2 displays all the obtained timings.

*Table 2*

| Program Version | No of processors or threads | Posn of p | Run1 | Run2 | Run3 | Run4 | Run5 | Mean Time (s) | Mean Count | Count 1 | Count 2 | Count3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Serial | | 1 | 0.6966 | 0.6948 | 0.7017 | 0.6985 | 0.6973 | 0.70 | 3,166,925 | 3166925 | 3166925 | 3166925 |
| | | 2 | 13.6198 | 16.2965 | 13.4889 | 13.6164 | 13.4662 | 14.10 | 61,953,485 | 61953485 | 61953485 | 61953485 |
| | | 3 | 27.2633 | 26.5803 | 26.8435 | 27.5186 | | 27.05 | 122,419,661 | 122419661 | 122419661 | 122419661 |
| | | 4 | 39.6554 | 39.7008 | 39.7608 | | | 39.71 | 182,885,837 | 182885837 | 182885837 | 182885837 |
| | | 8 | 92.2113 | 92.1902 | 92.5307 | | | 92.31 | 424,750,540 | 424750540 | 424750540 | 424750540 |
| | | 16 | 197.7609 | 197.7441 | 197.5756 | | | 197.69 | 908,479,948 | 908479948 | 908479948 | 908479948 |
| | | 36 | 461.4178 | 461.0027 | | | | 461.21 | 2,117,755,480 | 2117755480 | 2117755480 | |
| | | exhaustive | 474.9618 | 473.9433 | | | | 474.45 | 2,176,782,336 | 2176782336 | 2176782336 | |
| OMP | 1 thread | 1 | 0.79522 | 0.78819 | 0.79262 | 0.7902 | 0.79206 | 0.79 | 3,166,925 | 3,166,925 | 3,166,925 | 3,166,925 |
| | | 2 | 15.296 | 15.343 | 15.324 | 15.321 | 15.734 | 15.40 | 61,953,485 | 61,953,485 | 61,953,485 | 61,953,485 |
| | | 3 | 30.372 | 30.722 | 30.224 | | | 30.44 | 122,419,661 | 122,419,661 | 122,419,661 | 122,419,661 |
| | | 4 | 45.733 | 46.396 | 45.144 | | | 45.76 | 182,885,837 | 182,885,837 | 182,885,837 | 182,885,837 |
| | | 8 | 105.16 | 104.82 | 104.79 | | | 104.92 | 424,750,540 | 424,750,540 | 424,750,540 | 424,750,540 |
| | | 16 | 224.32 | 224.32 | 230.03 | | | 226.22 | 908,479,948 | 908,479,948 | 908,479,948 | 908,479,948 |
| | | 36 | 522.77 | 522.82 | | | | 522.80 | 2,117,755,480 | 2,117,755,480 | 2,117,755,480 | |
| | | exhaustive | 538.8 | 546.02 | | | | 542.41 | 2,176,782,336 | 2,176,782,336 | 2,176,782,336 | |
| | 2 threads | 1 | 1.1859 | 1.1929 | 1.1855 | 1.2123 | 1.1961 | 1.19 | 6,296,407 | 6,333,103 | 6,269,916 | 6,286,202 |
| | | 2 | 0.56475 | 0.55843 | 0.59266 | 0.55906 | 0.5552 | 0.57 | 2,969,535 | 2,968,780 | 2,980,297 | 2,959,527 |
| | | 3 | 22.676 | 22.858 | 22.626 | 22.676 | 23.716 | 22.91 | 123,515,810 | 123,809,635 | 122,918,548 | 123,819,248 |
| | | 4 | 23.06 | 24.635 | 24.01 | 26.987 | 23.304 | 24.40 | 124,190,264 | 123,991,578 | 123,673,718 | 124,905,496 |
| | | 8 | 68.46 | 68.336 | 67.265 | 70.55 | 68.167 | 68.56 | 366,349,425 | 367,150,731 | 365,776,491 | 366,121,053 |
| | | 16 | 172.61 | 160.29 | 172.12 | | | 168.34 | 845,393,634 | 837,478,190 | 852,613,188 | 846,089,525 |
| | | 36 | 386.03 | 385.53 | 382.35 | | | 384.64 | 2,066,682,808 | 2,067,118,832 | 2,071,628,102 | 2,061,301,489 |
| | | exhaustive | 408.9 | 418.15 | 406.38 | | | 411.14 | 2,176,782,336 | 2,176,782,336 | 2,176,782,336 | 2,176,782,336 |
| | 3 threads | 1 | 1.5527 | 1.514 | 1.5503 | 1.4988 | 1.5377 | 1.53 | 8,379,501 | 8,305,977 | 8,110,673 | 8,721,852 |
| | | 2 | 0.75696 | 0.75205 | 0.71733 | 0.72767 | 0.78491 | 0.75 | 4,164,265 | 4,234,331 | 4,014,126 | 4,244,337 |
| | | 3 | 0.71526 | 0.73994 | 0.73239 | 0.7148 | 0.73638 | 0.73 | 4,090,392 | 4,138,107 | 4,305,843 | 3,827,227 |
| | | 4 | 29.388 | 30.274 | 30.391 | 29.404 | 29.859 | 29.86 | 170,531,796 | 173,134,164 | 165,031,163 | 173,430,060 |
| | | 8 | 60.275 | 58.782 | 58.471 | 59.523 | 59.947 | 59.40 | 332,592,350 | 331,538,072 | 341,588,782 | 324,650,197 |
| | | 16 | 145.42 | 147.46 | 146.9 | 145.57 | 145.11 | 146.09 | 846,357,382 | 845,633,622 | 863,397,444 | 830,041,079 |
| | | 36 | 337.23 | 330.68 | 339.35 | | | 335.75 | 1,924,460,726 | 1,921,138,307 | 1,905,044,314 | 1,947,199,556 |
| | | exhaustive | 360.55 | 363.54 | 367.93 | | | 364.01 | 2,176,782,336 | 2,176,782,336 | 2,176,782,336 | 2,176,782,336 |
| | 4 threads | 1 | 1.7315 | 1.7199 | 1.7302 | 1.7335 | 1.7287 | 1.73 | 10,791,724 | | | |
| | | 2 | 0.81446 | 0.99138 | 0.8014 | 0.80708 | 0.81322 | 0.85 | 5,244,124 | | | |
| | | 3 | 0.81854 | 0.79409 | 0.82157 | 0.79433 | 0.77678 | 0.80 | 4,887,542 | | | |
| | | 4 | 0.88126 | 0.80702 | 0.80699 | 0.87651 | 0.87086 | 0.85 | 5,174,164 | | | |
| | | 8 | 35.885 | 34.205 | 36.926 | 37.346 | 34.665 | 35.81 | 221,207,260 | | | |
| | | 16 | 106.26 | 109.42 | 106.5 | 101.57 | 106.8 | 106.11 | 670,777,631 | | | |
| | | 36 | 284.26 | 286.43 | 281.06 | 285.65 | 281.19 | 283.72 | 1,883,212,272 | | | |
| | | exhaustive | 308.84 | 301.52 | 304.26 | | | 304.87 | 2,176,782,336 | | | |
| MPI | 1 proc | 1 | 0.768398 | 0.689645 | 0.68732 | | | 0.72 | 3,166,925 | | | |
| | | 2 | 13.36349 | 14.17904 | 13.36216 | | | 13.63 | 61,953,485 | | | |
| | | 3 | 26.3393 | 26.38305 | 26.40797 | | | 26.38 | 122,419,661 | | | |
| | | 4 | 39.35706 | 39.40234 | 39.56521 | | | 39.44 | 182,885,837 | | | |
| | | 8 | 91.48913 | 91.98718 | 91.47026 | | | 91.65 | 424,750,540 | | | |
| | | 16 | 196.2155 | 195.6466 | 195.7246 | | | 195.86 | 908,479,948 | | | |
| | | 36 | 460.4248 | 476.4738 | | | | 468.45 | 2,117,755,480 | | | |
| | | exhaustive | 515.8911 | | | | | 515.89 | 2,176,782,336 | | | |
| | 2 procs | 1 | 0.706138 | 0.746487 | 0.704952 | | | 0.72 | 3,166,925 | | | |
| | | 2 | 0.332666 | 0.333461 | 0.333499 | | | 0.33 | 1,487,309 | | | |
| | | 3 | 13.75085 | 14.80422 | 13.74726 | | | 14.10 | 61,953,485 | | | |
| | | 4 | 13.74297 | 13.91009 | 13.75808 | | | 13.80 | 61,953,485 | | | |
| | | 8 | 40.59607 | 40.57155 | 40.51024 | | | 40.56 | 182,885,836 | | | |
| | | 16 | 94.21589 | 94.44507 | 94.02402 | | | 94.23 | 424,750,540 | | | |
| | | 36 | 228.638 | 228.2808 | | | | 228.46 | 1,029,364,312 | | | |
| | | exhaustive | 245.0074 | | | | | 245.01 | | | | |
| | 3 procs | 1 | 0.71032 | 0.711189 | 0.714607 | | | 0.71 | 3,166,925 | | | |
| | | 2 | 0.334228 | 0.333145 | 0.33418 | | | 0.33 | 1,487,309 | | | |
| | | 3 | 0.333831 | 0.334199 | 0.334147 | | | 0.33 | 1,487,309 | | | |
| | | 4 | 13.94175 | 13.87485 | 13.90437 | | | 13.91 | 61,953,485 | | | |
| | | 8 | 27.51158 | 28.06831 | 27.4609 | | | 27.68 | 122,419,660 | | | |
| | | 16 | 68.31525 | 68.16699 | 68.15397 | | | 68.21 | 303,818,188 | | | |
| | | 36 | 149.8516 | 149.5476 | | | | 149.70 | 666,567,256 | | | |
| | | exhaustive | 162.5546 | | | | | 162.55 | 725,594,112 | | | |
| | 4 procs | 1 | 0.727761 | 0.750773 | 0.738594 | | | 0.74 | 3,166,925 | | | |
| | | 2 | 0.337682 | 0.34439 | 0.340914 | | | 0.34 | 1,487,309 | | | |
| | | 3 | 0.337645 | 0.337991 | 0.340757 | | | 0.34 | 1,487,309 | | | |
| | | 4 | 0.338109 | 0.35383 | 0.340749 | | | 0.34 | 1,487,309 | | | |
| | | 8 | 14.08414 | 14.57588 | 16.07193 | | | 14.91 | 61,953,484 | | | |
| | | 16 | 41.5167 | 42.69525 | 42.63943 | | | 42.28 | 182,885,836 | | | |
| | | 36 | 112.1576 | 110.1056 | | | | 111.13 | 485,168,728 | | | |
| | | exhaustive | 124.8209 | | | | | 124.82 | 544,195,584 | | | |
| | 5 procs | 1 | 1.204825 | 0.962179 | 1.435989 | | | 1.20 | 3,166,925 | | | |
| | | 2 | 0.345536 | 0.541452 | 0.417733 | | | 0.43 | 1,487,309 | | | |
| | | 3 | 0.457666 | 0.517274 | 0.344432 | | | 0.44 | 1,487,309 | | | |
| | | 4 | 0.425101 | 0.33711 | 0.655874 | | | 0.47 | 1,487,309 | | | |
| | | 8 | 16.15433 | 17.75586 | 18.35608 | | | 17.42 | 61,953,484 | | | |
| | | 16 | 56.79571 | 51.22479 | 49.47918 | | | 52.50 | 182,885,836 | | | |
| | | 36 | 120.3621 | 122.2373 | | | | 121.30 | 424,702,552 | | | |
| | | exhaustive | 134.0972 | | | | | 134.10 | 483,729,408 | | | |
| | 6 procs | 1 | 1.16992 | 0.995297 | 1.105558 | | | 1.09 | 3,166,925 | | | |
| | | 2 | 0.422131 | 0.61605 | 0.66695 | | | 0.57 | 1,487,309 | | | |
| | | 3 | 0.402147 | 0.668302 | 0.423609 | | | 0.50 | 1,487,309 | | | |
| | | 4 | 0.415148 | 0.66035 | 0.4909 | | | 0.52 | 1,487,309 | | | |
| | | 8 | 21.58406 | 20.86207 | 20.79847 | | | 21.08 | 61,953,484 | | | |
| | | 16 | 40.55182 | 40.45869 | 40.71363 | | | 40.57 | 122,419,660 | | | |
| | | 36 | 100.9222 | 100.8817 | | | | 100.90 | 303,770,200 | | | |
| | | exhaustive | 122.3512 | | | | | 122.35 | 362,797,056 | | | |
| | 7 procs | 1 | 1.058003 | 0.987399 | 1.499253 | | | 1.18 | 3,166,925 | | | |
| | | 2 | 0.68131 | 0.697367 | 0.68555 | | | 0.69 | 1,487,309 | | | |
| | | 3 | 0.71069 | 0.689936 | 0.444216 | | | 0.61 | 1,487,309 | | | |
| | | 4 | 0.384869 | 0.696285 | 0.692383 | | | 0.59 | 1,487,309 | | | |
| | | 8 | 23.50498 | 24.24896 | 24.63445 | | | 24.13 | 61,953,484 | | | |
| | | 16 | 50.01321 | 49.61092 | 48.15976 | | | 49.26 | 122,419,660 | | | |
| | | 36 | 119.1086 | 120.187 | | | | 119.65 | 303,770,200 | | | |
| | | exhaustive | 133.8863 | | | | | 133.89 | 362,797,056 | | | |
| | 8 procs | 1 | 1.497889 | 1.52364 | 1.446222 | | | 1.49 | 3,166,925 | | | |
| | | 2 | 0.728921 | 0.701961 | 0.695412 | | | 0.71 | 1,487,309 | | | |
| | | 3 | 0.700729 | 0.688372 | 0.759351 | | | 0.72 | 1,487,309 | | | |
| | | 4 | 0.601441 | 0.713404 | 0.708346 | | | 0.67 | 1,487,309 | | | |
| | | 8 | 0.697114 | 0.696355 | 0.77999 | | | 0.72 | 1,487,308 | | | |
| | | 16 | 28.22435 | 28.54018 | 28.70439 | | | 28.49 | 61,953,484 | | | |
| | | 36 | 111.3138 | 111.3317 | | | | 111.32 | 243,304,024 | | | |
| | | exhaustive | 124.8243 | | | | | 124.82 | 302,330,880 | | | |