CMSC 714 Assignment 2 Report

I. Program analysis:

    Following steps in instructions to run the serial-version quake.c simulation, with the help of Hatchet, the performance profiling is shown below:

```
66.465 <program root> <unknown file> [libmonitor.so.0.0.0]
`- 66.465 main ./src/homes/jingxie/714assign2/quake.c
   |- 0.173 Loop@quake.c:385 ./src/homes/jingxie/714assign2/quake.c
   | |- 0.018 Loop@quake.c:386 ./src/homes/jingxie/714assign2/quake.c
   | | |- 0.006 quake.c:389 ./src/homes/jingxie/714assign2/quake.c
   | | `- 0.012 Loop@quake.c:390 ./src/homes/jingxie/714assign2/quake.c
   | |   `- 0.012 quake.c:390 ./src/homes/jingxie/714assign2/quake.c
   | |- 0.077 Loop@quake.c:491 ./src/homes/jingxie/714assign2/quake.c
   | | |- 0.006 quake.c:492 ./src/homes/jingxie/714assign2/quake.c
   | | |- 0.006 quake.c:496 ./src/homes/jingxie/714assign2/quake.c
   | | `- 0.065 Loop@quake.c:498 ./src/homes/jingxie/714assign2/quake.c
   | |   |- 0.005 quake.c:498 ./src/homes/jingxie/714assign2/quake.c
   | |   |- 0.030 Loop@quake.c:509 ./src/homes/jingxie/714assign2/quake.c
   | |   | |- 0.006 quake.c:509 ./src/homes/jingxie/714assign2/quake.c
   | |   | `- 0.024 Loop@quake.c:510 ./src/homes/jingxie/714assign2/quake.c
   | |   |   `- 0.024 quake.c:511 ./src/homes/jingxie/714assign2/quake.c
   | |   `- 0.030 quake.c:511 ./src/homes/jingxie/714assign2/quake.c
   | `- 0.078 427:element_matrices ./src/homes/jingxie/714assign2/quake.c
   |   |- 0.012 Loop@quake.c:692 ./src/homes/jingxie/714assign2/quake.c
   |   | |- 0.006 quake.c:692 ./src/homes/jingxie/714assign2/quake.c
   |   | `- 0.006 Loop@quake.c:693 ./src/homes/jingxie/714assign2/quake.c
   |   |   `- 0.006 Loop@quake.c:695 ./src/homes/jingxie/714assign2/quake.c
   |   |     `- 0.006 quake.c:695 ./src/homes/jingxie/714assign2/quake.c
   |   |- 0.006 Loop@quake.c:702 ./src/homes/jingxie/714assign2/quake.c
   |   | `- 0.006 Loop@quake.c:704 ./src/homes/jingxie/714assign2/quake.c
   |   |   `- 0.006 quake.c:704 ./src/homes/jingxie/714assign2/quake.c
   |   |- 0.030 Loop@quake.c:729 ./src/homes/jingxie/714assign2/quake.c
   |   | `- 0.030 Loop@quake.c:730 ./src/homes/jingxie/714assign2/quake.c
   |   |   `- 0.030 Loop@quake.c:733 ./src/homes/jingxie/714assign2/quake.c
   |   |     |- 0.006 quake.c:730 ./src/homes/jingxie/714assign2/quake.c
   |   |     `- 0.024 Loop@quake.c:734 ./src/homes/jingxie/714assign2/quake.c
   |   |       |- 0.006 quake.c:734 ./src/homes/jingxie/714assign2/quake.c
   |   |       |- 0.006 quake.c:738 ./src/homes/jingxie/714assign2/quake.c
   |   |       |- 0.006 quake.c:739 ./src/homes/jingxie/714assign2/quake.c
   |   |       `- 0.006 quake.c:749 ./src/homes/jingxie/714assign2/quake.c
   |   |- 0.012 Loop@quake.c:762 ./src/homes/jingxie/714assign2/quake.c
   |   | `- 0.012 Loop@quake.c:763 ./src/homes/jingxie/714assign2/quake.c
   |   |   |- 0.006 quake.c:763 ./src/homes/jingxie/714assign2/quake.c
   |   |   `- 0.006 quake.c:764 ./src/homes/jingxie/714assign2/quake.c
   |   |- 0.012 700:inv_J ./src/homes/jingxie/714assign2/quake.c
   |   | |- 0.006 quake.c:659 ./src/homes/jingxie/714assign2/quake.c
   |   | `- 0.006 Loop@quake.c:664 ./src/homes/jingxie/714assign2/quake.c
   |   |   `- 0.006 quake.c:666 ./src/homes/jingxie/714assign2/quake.c
   |   `- 0.006 721:get_Enu ./src/homes/jingxie/714assign2/quake.c
   |     `- 0.006 quake.c:635 ./src/homes/jingxie/714assign2/quake.c
   |- 65.983 Loop@quake.c:521 ./src/homes/jingxie/714assign2/quake.c
   | |- 0.395 Loop@quake.c:523 ./src/homes/jingxie/714assign2/quake.c
   | | |- 0.090 quake.c:523 ./src/homes/jingxie/714assign2/quake.c
   | | `- 0.305 quake.c:525 ./src/homes/jingxie/714assign2/quake.c
   | |- 0.006 quake.c:530 ./src/homes/jingxie/714assign2/quake.c
   | |- 14.847 Loop@quake.c:532 ./src/homes/jingxie/714assign2/quake.c
   | | |- 0.078 quake.c:532 ./src/homes/jingxie/714assign2/quake.c
   | | |- 14.208 Loop@quake.c:534 ./src/homes/jingxie/714assign2/quake.c
   | | | |- 0.436 quake.c:534 ./src/homes/jingxie/714assign2/quake.c
   | | | |- 0.394 quake.c:536 ./src/homes/jingxie/714assign2/quake.c
   | | | |- 0.992 quake.c:537 ./src/homes/jingxie/714assign2/quake.c
   | | | |- 1.201 quake.c:538 ./src/homes/jingxie/714assign2/quake.c
   | | | |- 0.000 quake.c:539 ./src/homes/jingxie/714assign2/quake.c
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| | | |- 1.249 quake.c:539 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.777 quake.c:540 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.197 quake.c:541 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.120 quake.c:542 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.568 quake.c:543 ./src/homes/jingxie/714assign2/quake.c
| | | |- 6.050 quake.c:544 ./src/homes/jingxie/714assign2/quake.c
| | | |- 1.058 539:phi2 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.299 quake.c:880 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.000 quake.c:882 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.203 quake.c:887 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.102 quake.c:888 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.096 w_sqrtl_compat.c:882 w_sqrtl_compat.c
| | | | |- 0.006 880:<inline> ./src/homes/jingxie/714assign2/quake.c
| | | | | `- 0.006 quake.c:877 ./src/homes/jingxie/714assign2/quake.c
| | | | `- 0.353 882:__sin_avx w_sqrtl_compat.c
| | | |     `- 0.353 w_sqrtl_compat.c:0 w_sqrtl_compat.c
| | | |- 0.783 540:phi1 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.323 quake.c:860 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.036 quake.c:862 ./src/homes/jingxie/714assign2/quake.c
| | | | `- 0.424 862:__cos_avx w_sqrtl_compat.c
| | | |     `- 0.424 w_sqrtl_compat.c:0 w_sqrtl_compat.c
| | | `- 0.384 541:phi0 ./src/homes/jingxie/714assign2/quake.c
| | |   |- 0.024 quake.c:839 ./src/homes/jingxie/714assign2/quake.c
| | |   |- 0.000 quake.c:841 ./src/homes/jingxie/714assign2/quake.c
| | |   |- 0.060 w_sqrtl_compat.c:841 w_sqrtl_compat.c
| | |   `- 0.300 841:__sin_avx w_sqrtl_compat.c
| | |     `- 0.300 w_sqrtl_compat.c:0 w_sqrtl_compat.c
| | `- 0.562 quake.c:544 ./src/homes/jingxie/714assign2/quake.c
| |- 50.729 527:smvp ./src/homes/jingxie/714assign2/quake.c
| | |- 4.460 Loop@quake.c:1271 ./src/homes/jingxie/714assign2/quake.c
| | | `- 4.460 Loop@quake.c:1272 ./src/homes/jingxie/714assign2/quake.c
| | |   |- 3.773 quake.c:1272 ./src/homes/jingxie/714assign2/quake.c
| | |   `- 0.688 quake.c:1273 ./src/homes/jingxie/714assign2/quake.c
| |- 28.378 Loop@quake.c:1286 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.024 quake.c:1286 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.066 quake.c:1287 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.018 quake.c:1288 ./src/homes/jingxie/714assign2/quake.c
| | |- 1.018 quake.c:1290 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.627 quake.c:1291 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.227 quake.c:1292 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.060 quake.c:1294 ./src/homes/jingxie/714assign2/quake.c
| | |- 24.737 Loop@quake.c:1295 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.395 quake.c:1295 ./src/homes/jingxie/714assign2/quake.c
| | | |- 4.305 quake.c:1298 ./src/homes/jingxie/714assign2/quake.c
| | | |- 4.819 quake.c:1299 ./src/homes/jingxie/714assign2/quake.c
| | | |- 1.963 quake.c:1300 ./src/homes/jingxie/714assign2/quake.c
| | | |- 2.911 quake.c:1302 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.018 quake.c:1303 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.491 quake.c:1304 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.407 quake.c:1305 ./src/homes/jingxie/714assign2/quake.c
| | | |- 0.336 quake.c:1306 ./src/homes/jingxie/714assign2/quake.c
| | | |- 2.883 quake.c:1309 ./src/homes/jingxie/714assign2/quake.c
| | | |- 3.443 quake.c:1310 ./src/homes/jingxie/714assign2/quake.c
| | | `- 2.768 quake.c:1311 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.275 quake.c:1295 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.858 quake.c:1315 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.006 quake.c:1317 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.012 quake.c:1319 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.084 quake.c:1322 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.317 quake.c:1323 ./src/homes/jingxie/714assign2/quake.c
| | `- 0.048 quake.c:1324 ./src/homes/jingxie/714assign2/quake.c
| |- 17.482 Loop@quake.c:1327 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.346 quake.c:1327 ./src/homes/jingxie/714assign2/quake.c
| | |- 17.029 Loop@quake.c:1328 ./src/homes/jingxie/714assign2/quake.c
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| | | | |- 7.115 quake.c:1328 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 8.981 quake.c:1329 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.473 quake.c:1330 ./src/homes/jingxie/714assign2/quake.c
| | | | |- 0.113 quake.c:1331 ./src/homes/jingxie/714assign2/quake.c
| | | | `- 0.346 quake.c:1332 ./src/homes/jingxie/714assign2/quake.c
| | | `- 0.107 quake.c:1328 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.006 quake.c:1336 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.397 1271:GOMP_parallel <unknown file> [libgomp.so.1.0.0]
| | | |- 0.006 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | | |- 0.006 GOMP_doacross_ull_wait <unknown file> [libgomp.so.1.0.0]
| | | | `- 0.006 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | | |- 0.006 omp_in_final <unknown file> [libgomp.so.1.0.0]
| | | | `- 0.006 omp_in_final <unknown file> [libgomp.so.1.0.0]
| | | |    `- 0.006 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | | `- 0.380 omp_in_final <unknown file> [libgomp.so.1.0.0]
| | |   |- 0.018 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | |   |- 0.006 GOMP_single_copy_end <unknown file> [libgomp.so.1.0.0]
| | |   | `- 0.006 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | |   |- 0.012 GOMP_single_copy_end <unknown file> [libgomp.so.1.0.0]
| | |   | `- 0.012 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | |   `- 0.344 omp_get_num_procs <unknown file> [libgomp.so.1.0.0]
| | |     `- 0.344 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| | `- 0.006 1271:omp_in_final <unknown file> [libgomp.so.1.0.0]
| |   `- 0.006 omp_get_num_procs <unknown file> [libgomp.so.1.0.0]
| |     `- 0.006 <unknown file> [libgomp.so.1.0.0]:0 <unknown file> [libgomp.so.1.0.0]
| `- 0.006 553:__GI_fprintf argz-next.c
|   `- 0.006 _IO_vfprintf <unknown file> [libc-2.28.so]
|     `- 0.006 buffered_vfprintf argz-next.c
|       `- 0.006 _IO_new_file_xsputn argz-next.c
|         `- 0.006 new_do_write argz-next.c
|           `- 0.006 _IO_new_file_write argz-next.c
|             `- 0.006 __GI___libc_write argz-next.c
|               `- 0.006 argz-next.c:0 argz-next.c
|- 0.006 Loop@quake.c:578 ./src/homes/jingxie/714assign2/quake.c
| `- 0.006 580:free <unknown file> [libc-2.28.so]
|   `- 0.006 <unknown file> [libc-2.28.so]:0 <unknown file> [libc-2.28.so]
|- 0.237 174:readpackfile ./src/homes/jingxie/714assign2/quake.c
| |- 0.058 Loop@quake.c:1167 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.024 Loop@quake.c:1169 ./src/homes/jingxie/714assign2/quake.c
| | | `- 0.024 1170:__isoc99_fscanf <unknown file> [libc-2.28.so]
| | |   |- 0.006 argz-next.c:0 argz-next.c
| | |   `- 0.018 _IO_vfscanf <unknown file> [libc-2.28.so]
| | |     |- 0.006 argz-next.c:0 argz-next.c
| | |     `- 0.012 ____strtod_l_internal argz-next.c
| | |       |- 0.006 argz-next.c:0 argz-next.c
| | |       `- 0.006 str_to_mpn.isra.0 argz-next.c
| | |         `- 0.006 argz-next.c:0 argz-next.c
| | `- 0.034 1168:__isoc99_fscanf <unknown file> [libc-2.28.so]
| |   `- 0.034 _IO_vfscanf <unknown file> [libc-2.28.so]
| |     |- 0.028 argz-next.c:0 argz-next.c
| |     `- 0.006 __GI_____strtoll_l_internal argz-next.c
| |       `- 0.006 argz-next.c:0 argz-next.c
| |- 0.006 Loop@quake.c:1188 ./src/homes/jingxie/714assign2/quake.c
| | `- 0.006 1189:__malloc argz-next.c
| |   `- 0.006 _int_malloc argz-next.c
| |     `- 0.006 argz-next.c:0 argz-next.c
| |- 0.114 Loop@quake.c:1191 ./src/homes/jingxie/714assign2/quake.c
| | |- 0.090 Loop@quake.c:1193 ./src/homes/jingxie/714assign2/quake.c
| | | `- 0.090 1194:__isoc99_fscanf <unknown file> [libc-2.28.so]
| | |   `- 0.090 _IO_vfscanf <unknown file> [libc-2.28.so]
| | |     |- 0.060 argz-next.c:0 argz-next.c
| | |     |- 0.018 __GI_____strtoll_l_internal argz-next.c
| | |     | `- 0.018 argz-next.c:0 argz-next.c
| | |     `- 0.012 _pthread_cleanup_push_defer <unknown file> [libpthread-2.28.so]
```

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| | |         `- 0.012 <unknown file> [libpthread-2.28.so]:0 <unknown file> [libpthread-2.28.so]
| | `- 0.024 1192:__isoc99_fscanf <unknown file> [libc-2.28.so]
| |   `- 0.024 _IO_vfscanf <unknown file> [libc-2.28.so]
| |     |- 0.012 argz-next.c:0 argz-next.c
| |     |- 0.006 __GI__IO_sputbackc argz-next.c
| |     | `- 0.006 argz-next.c:0 argz-next.c
| |     `- 0.006 __GI_____strtoll_l_internal argz-next.c
| |       `- 0.006 argz-next.c:0 argz-next.c
| `- 0.060 Loop@quake.c:1219 ./src/homes/jingxie/714assign2/quake.c
|   |- 0.048 1220:__isoc99_fscanf <unknown file> [libc-2.28.so]
|   | `- 0.048 _IO_vfscanf <unknown file> [libc-2.28.so]
|   |   |- 0.018 argz-next.c:0 argz-next.c
|   |   |- 0.012 _IO_default_uflow <unknown file> [libc-2.28.so]
|   |   | `- 0.012 _IO_file_underflow@@GLIBC_2.2.5 <unknown file> [libc-2.28.so]
|   |   |   `- 0.012 __GI_read argz-next.c
|   |   |     `- 0.012 argz-next.c:0 argz-next.c
|   |   |- 0.006 __GI__IO_sputbackc argz-next.c
|   |   | `- 0.006 argz-next.c:0 argz-next.c
|   |   `- 0.012 __GI_____strtoll_l_internal argz-next.c
|   |     `- 0.012 argz-next.c:0 argz-next.c
|   `- 0.012 1221:__isoc99_fscanf <unknown file> [libc-2.28.so]
|     `- 0.012 _IO_vfscanf <unknown file> [libc-2.28.so]
|       `- 0.012 <unknown file> [libc-2.28.so]:0 <unknown file> [libc-2.28.so]
|- 0.042 178:mem_init ./src/homes/jingxie/714assign2/quake.c
| |- 0.030 Loop@quake.c:1513 ./src/homes/jingxie/714assign2/quake.c
| | `- 0.030 Loop@quake.c:1514 ./src/homes/jingxie/714assign2/quake.c
| |   `- 0.030 quake.c:1517 ./src/homes/jingxie/714assign2/quake.c
| |- 0.006 Loop@quake.c:1537 ./src/homes/jingxie/714assign2/quake.c
| | `- 0.006 Loop@quake.c:1538 ./src/homes/jingxie/714assign2/quake.c
| |   `- 0.006 quake.c:1538 ./src/homes/jingxie/714assign2/quake.c
| `- 0.006 Loop@quake.c:1586 ./src/homes/jingxie/714assign2/quake.c
|   `- 0.006 quake.c:1586 ./src/homes/jingxie/714assign2/quake.c
|- 0.006 180:arch_readnodevector ./src/homes/jingxie/714assign2/quake.c
| `- 0.006 Loop@quake.c:1072 ./src/homes/jingxie/714assign2/quake.c
|   `- 0.006 1073:__isoc99_fscanf <unknown file> [libc-2.28.so]
|     `- 0.006 _IO_vfscanf <unknown file> [libc-2.28.so]
|       `- 0.006 __GI__IO_sputbackc argz-next.c
|         `- 0.006 argz-next.c:0 argz-next.c
`- 0.018 288:GOMP_parallel <unknown file> [libgomp.so.1.0.0]
  `- 0.018 omp_in_final <unknown file> [libgomp.so.1.0.0]
    `- 0.018 pthread_create <unknown file> [libmonitor.so.0.0.0]
      |- 0.000 dl-minimal.c:0 dl-minimal.c
      `- 0.018 __pthread_create_2_1 pthread_timedjoin.c
        |- 0.012 _dl_allocate_tls_init <unknown file> [ld-2.28.so]
        | `- 0.012 memset dl-minimal.c
        |   `- 0.012 dl-minimal.c:0 dl-minimal.c
        `- 0.006 create_thread pthread_timedjoin.c
          `- 0.006 __GI___clone argz-next.c
            `- 0.006 argz-next.c:0 argz-next.c
```

By investigating the profiling tree, some time-consuming loops are identified, including the loops or the nested loops at line 523, 532, 534, 527 in the main loop, and line 1271 and 1327 in the function smvp that is called in the main loop. Especially the loop at line 532, 1286, and 1327 consumed most of the time. Please note loop at line 521 is the time step simulation main loop, we cannot do parallel to the loop itself. All optimizations are within this main loop. The line number are all referring to the serial version code provided in the instruction.

II. Major optimizations:
     The major optimizations are did to parallelize the code blocks that takes most of time.

     A. Loop at line 532: (optimized file line 556)

```
#pragma omp parallel for private(i, j) collapse(2)
for (i = 0; i < ARCHnodes; i++) nested: for (j = 0; j < 3; j++)
```
i and j are loop iterative variables. They are set privative.
collapse is used to partition the nested loops. Nest loops are also be put into different threads like the parent loop instead of in a same thread. Nested loops have no dependencies on the parent loop, so the collapse works.

B. Loop at line 1286 and 1327 (optimized file line 1301, 1319, and 1363)
```
#pragma omp parallel private(my_cpu_id,i,j,Anext,Alast,col,sum0,sum1,sum2) shared(A,
w1, w2, Aindex, v, Acol) (optimized file line 1301)
```
First spawn the threads and set private and shared variables.

- Loop at line 1286
```
#pragma omp for
    for (i = 0; i < nodes; i++)
```
Then parallel the for loop by dividing the loop iterations among threads.
private and shared variables are set according to the code functionality. All loop iterative variables are set private. Loop accumulative variables are shared.

- Loop at line 1327
```
#pragma omp for collapse(2)
for (i = 0; i < nodes; i++), nested loop: for (j = 0; j < numthreads; j++)
```
private and shared variables are set above. All loop iterative variables are set private. Loop accumulative variables are shared. Because there are nested loops not depending on each other, collapse is used.

III. Minor Optimizations
Besides, some minor optimizations are made to the loops that not taking as much time as the loops optimized above to further reduce the processing time at
line 255, line 301, line 362, line 523, line 1572 Loop: for (i = 0; i < ARCHnodes; i++)
line 578, line 1271, line 1513: for (i = 0; i < numthreads; i++)
line 1586 for (i = 0; i < ARCHelems; i++)
line 1590 for (i = 0; i < ARCHmatrixlen; i++).

IV. Experiment results

Here are the experiment results:

Time (inc) (sec)	1 thread	2 threads	4 threads	8 threads	16 threads
main	19.007	11.020	5.940	3.479	2.770
Loop at line 532 (opt file line 556)	7.927	4.069	2.044	1.150	0.664
Loop at line 1286: Loop at line 1327: (opt file line 1301)	9.574	6.084	3.341	1.904	1.238

Time shown in the table indicates the omp optimization reduce the main function time as well as the most time-consuming loops. The more threads assigned, the less time the program takes.