COMP SCI 557 Assignment 2

Environment

- CPU: `AMD Ryzen 7 7735HS with Radeon Graphics`
- Memory: `Configured Memory Speed: 4800 MT/s, dual channel`
- Compiler: `g++ (Ubuntu 13.3.0-6ubuntu2~24.04) 13.3.0`
- OS: `Ubuntu 24.04.2 LTS (Noble Numbat)`
- Compile commands:

```
$ make -j
g++ -O3 -g -std=c++20 -Wall -fopenmp -c main.cpp -o main.o
g++ -O3 -g -std=c++20 -Wall -fopenmp -c ConjugateGradients.cpp -o
ConjugateGradients.o
g++ -O3 -g -std=c++20 -Wall -fopenmp -c Laplacian.cpp -o Laplacian.o
g++ -O3 -g -std=c++20 -Wall -fopenmp -c PointwiseOps.cpp -o
PointwiseOps.o
g++ -O3 -g -std=c++20 -Wall -fopenmp -c Reductions.cpp -o Reductions.o
g++ -O3 -g -std=c++20 -Wall -fopenmp -c Utilities.cpp -o Utilities.o
g++ -O3 -g -std=c++20 -Wall -fopenmp -fno-strict-aliasing -c
MergedOp.cpp -o MergedOp.o
g++ main.o ConjugateGradients.o Laplacian.o PointwiseOps.o
Reductions.o Utilities.o MergedOp.o -o solver -fopenmp
```

Task 1

Changes Made to Collect Timing Info

1. In `ConjugateGradients.cpp`, I did the following
   - Declared lots of `extern Timer`
   - Wrapped each kernel function around a independent `Timer`
   - Disabled the `WriteAsImage` function to remove image output
2. In `main.cpp`, I did the following
   - Declared lots of `Timer` in global section
   - For each of the `Timer`, their address is pushed to a `std::vector<Timer *>` for management
   - Created a `std::vector<std::string>` to store information about each `Timer` pointer in the `std::vector<Timer *>`
   - Reset the timer before calling the conjugate gradients algorithm
   - Wrapped `ConjugateGradients` function around a timer to get total runtime
   - Print per kernel cumulative runtime
   - Print per kernel average runtime

As can been seen in below diagram, the sum is almost equal to the total time taken, verifying that this step is done correctly.

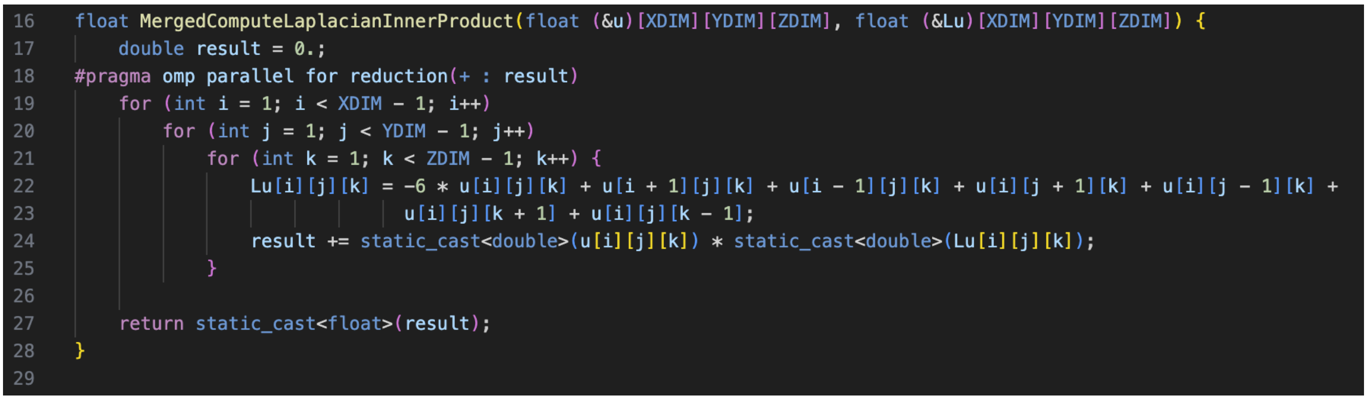
Timing Info

Line	Operation	1-Thread Cumulative (ms)	1-Thread Per Avg. (ms)	16-Thread Cumulative (ms)	16-Thread Avg. (ms)
2	ComputeLaplacian(x, z)	46.5141	0.181696	13.634	0.053258
6	ComputeLaplacian(p, z)	2349.49	9.17771	1765.05	6.89471
4	Copy(r, p)	37.8532	0.147864	6.09127	0.023794
13	Copy(r, z)	1600.19	6.25075	1320.03	5.15637
4	InnerProduct(p, r)	16.4926	0.0644242	3.56605	0.0139299
6	InnerProduct(p, z)	2883.99	11.2656	989.452	3.86505
13	InnerProduct(z, r)	2854.33	11.1497	952.401	3.72031
2	Norm(r)	6.58686	0.0257299	2.02624	0.00791502
8	Norm(r)	1153.37	4.50534	516.433	2.01731
2	Saxpy(z, f, r, -1)	40.7673	0.159247	47.1377	0.184132
8	Saxpy(z, r, r, -alpha)	1664.2	6.50079	1717.37	6.70848
9-12	Saxpy(p, x, x, alpha)	6.85812	0.0267895	7.11839	0.0278062
16	Saxpy(p, x, x, alpha)	1772.35	6.92325	1761.47	6.88073
16	Saxpy(p, r, p, beta)	1673.02	6.53522	1724.05	6.73458
1-18	**Conjugate Gradients Sum**	**16106.01218**	-	**10825.82965**	-
1-18	**Conjugate Gradients Total**	**16112.5**	-	**10833**	-

Task 2

Implementation of Kernel Function

Merging Line 6



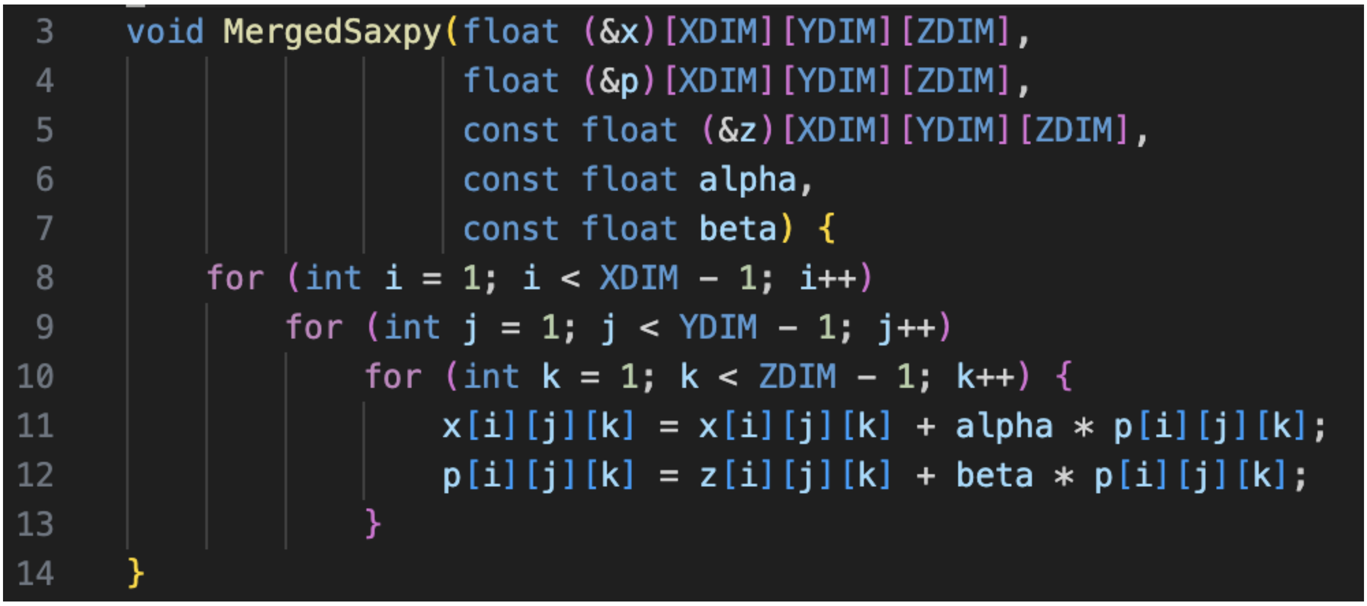
```
float MergedComputeLaplacianInnerProduct(float (&u)[XDIM][YDIM][ZDIM], float (&Lu)[XDIM][YDIM][ZDIM]) {
    double result = 0.;
#pragma omp parallel for reduction(+ : result)
    for (int i = 1; i < XDIM - 1; i++)
        for (int j = 1; j < YDIM - 1; j++)
            for (int k = 1; k < ZDIM - 1; k++) {
                Lu[i][j][k] = -6 * u[i][j][k] + u[i + 1][j][k] + u[i - 1][j][k] + u[i][j + 1][k] + u[i][j - 1][k] +
                              u[i][j][k + 1] + u[i][j][k - 1];
                result += static_cast<double>(u[i][j][k]) * static_cast<double>(Lu[i][j][k]);
            }

    return static_cast<float>(result);
}

```

Implementation can be found at `./task_2/MergedOp.cpp` at `line 16-28`

As can be seen in the above and below timing info, for running with a single thread, before merging line 6, it takes `2349.49 + 2883.99 = 5233.48 ms` to complete; after merging, it takes `5062.44 ms` to complete. We can see a boost of `3.27%`.

For running with all threads (16 threads), before merging line 6, it takes `1765.05 + 989.452 = 2754.502 ms` to complete; after merging, it takes `1895.96 ms` to complete. We can see a boost of `36.17%`.

Merging Line 16



```
 3  void MergedSaxpy(float (&x)[XDIM][YDIM][ZDIM],
 4                   float (&p)[XDIM][YDIM][ZDIM],
 5                   const float (&z)[XDIM][YDIM][ZDIM],
 6                   const float alpha,
 7                   const float beta) {
 8      for (int i = 1; i < XDIM - 1; i++)
 9          for (int j = 1; j < YDIM - 1; j++)
10              for (int k = 1; k < ZDIM - 1; k++) {
11                  x[i][j][k] = x[i][j][k] + alpha * p[i][j][k];
12                  p[i][j][k] = z[i][j][k] + beta * p[i][j][k];
13              }
14  }
```

Implementation can be found at `./task_2/MergedOp.cpp` at `line 3-14`

As can be seen in the above and below timing info, for running with a single thread, before merging line 16, it takes `1772.35 + 1673.02 = 3445.37 ms` to complete; after merging, it takes `2724.3 ms` to complete. We can see a boost of `20.93%`.

For running with all threads (16 threads), before merging line 16, it takes `1761.47 + 1724.05 = 3485.52 ms` to complete; after merging, it takes `2829.22` to complete. We can see a boost of `18.83%`.

How I Linked the File

I included the header file `MergedOp.h` in `main.cpp`, and using the `Makefile`, `MergedOp.cpp` is compiled into an object file `MergedOp.o`. Then, `MergedOp.o` is linked to the final executable `solver`

Timing Info with Line 6 and 16 merged

Line	Operation	1-Thread Cumulative (ms)	1-Thread Per Avg. (ms)	16-Thread Cumulative (ms)	16-Thread Avg. (ms)
2	ComputeLaplacian(x, z)	46.8384	0.182963	14.2677	0.0557334

Line	Operation	1-Thread Cumulative (ms)	1-Thread Per Avg. (ms)	16-Thread Cumulative (ms)	16-Thread Avg. (ms)
6	MergedComputeLaplacianInnerProduct(p, z)	5062.44	19.7752	1895.96	7.4061
4	Copy(r, p)	36.7851	0.143692	5.0267	0.0196355
13	Copy(r, z)	1644.48	6.42376	1331.44	5.20093
4	InnerProduct(p, r)	16.4903	0.0644151	3.60943	0.0140993
13	InnerProduct(z, r)	2848.12	11.1255	997.232	3.89544
2	Norm(r)	6.72545	0.0262713	2.77454	0.010838
8	Norm(r)	1153.96	4.50766	618.402	2.41563
2	Saxpy(z, f, r, -1)	39.0947	0.152714	43.7447	0.170878
8	Saxpy(z, r, r, -alpha)	1742.07	6.80495	1930.35	7.54042
9-12	Saxpy(p, x, x, alpha)	6.69216	0.0261413	8.07225	0.0315322
16	MergedSaxpy(p, x, r, x, alpha, beta)	2724.3	10.6418	2829.22	11.0516
1-18	**Conjugate Gradients Total**	**15334.5**	-	**9687.6**	-

Comments

In the implementation process, I ensure the merged version behaves like the original version by comparing their output image file using the following command:

```
for file in task_1/x.*.pgm; do
    fname=$(basename "$file")
    cmp "$file" "task_2/$fname"
done
```

With line 6 and 16 being merged, the performance of the application with single-core and multi-core both have an upgrade of `4.8%` and `10.6%`, respectively. Having only line 6 or only line 16 merged also shows a performance boost.

The performance might be able to enhance if `OpenMP` is used in the `Saxpy` function, or in line 16. Also, some call of `Saxpy` has its pointer aliased, which prevents us from adding `-fno-strict-aliasing` flags to the files for more aggressive optimization, even though in the Merged version, I have tried to use `-fno-strict-aliasing` flag and do **NOT** see any performance improvements.

In summary, the performance boost is likely due to less function calls, less memory access and better cache locality. We do **NOT** need to access the same place twice because they're already in the cache.