- CS Login: **dspatel6**

- Wisc ID: **9085310937**

- Email: **dspatel6@wisc.edu /** [**dspatel6@cs.wisc.edu**](mailto:dspatel6@cs.wisc.edu)

**CPU Specifications**

**- Processor 13th Gen Intel(R) Core(TM) i5-1350P 1.90 GHz**

**- Installed RAM 16.0 GB (15.4 GB usable)**

**- Total Cores 12**

**- Performance-cores 4**

**- Efficient-cores 8**

**- Total Threads 16**

**- Max Turbo Frequency 4.70 GHz**

**- Performance-core Max Turbo Frequency 4.70 GHz**

**- Efficient-core Max Turbo Frequency 3.50 GHz**

**Memory bandwidth**

**DDR5-4800 (Dual-Channel)**

**Memory speed: 4800 MT/s**

**Bus width per DIMM: 64 bits (8 bytes)**

**Channels: 2 (dual-channel)**

**4800 × 8 × 2 = 76.8 GB/s**

**Compiler**

**```bash**

**$ g++ --version**

**g++ (Ubuntu 14.2.0-16ubuntu1) 14.2.0**

**Copyright (C) 2024 Free Software Foundation, Inc.**

**This is free software; see the source for copying conditions. There is NO**

**warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.**

**```**

**OS**

**```bash**

**$ cat /etc/os-release**

**PRETTY\_NAME="Ubuntu Plucky Puffin (development branch)"**

**NAME="Ubuntu"**

**VERSION\_ID="25.04"**

**```**

**Compilation command**

**```bash**

**$ g++ -fopenmp main.cpp Laplacian.cpp**

**```**

**LaplaceSolver\_0\_3 serial execution**

**```bash**

**$ export OMP\_NUM\_THREADS=1**

**$ make**

**$ ./laplace\_solver**

**...**

**...**

**Conjugate Gradients terminated after 256 iterations; residual norm (nu) = 0.000975892**

**-----------------------------------------------------**

**[Line-2 Laplacian Time : 29.1459ms]**

**[Line-6 Laplacian Time : 4052.18ms]**

**[Line-6 Average Laplacian Time : 15.7672ms]**

**Aggregated Laplacian Time : 4081ms**

**-----------------------------------------------------**

**[Line-2 Saxpy Time : 35.5474ms]**

**[Line-8 Saxpy Time : 2987.49ms]**

**[Line-8 Average Saxpy Time : 11.6245ms]**

**[Line-9-12 Saxpy Time : 14.9098ms]**

**[Line-9-12 Average Saxpy Time : 14.9098ms]**

**[Line-16 Saxpy Time : 5667.91ms]**

**[Line-16 Average Saxpy Time : 22.1403ms]**

**Aggregated Saxpy Time : 8703ms**

**-----------------------------------------------------**

**[Line-4 InnerProduct Time : 14.2709ms]**

**[Line-6 InnerProduct Time : 3934ms]**

**[Line-6 Average InnerProduct Time : 15.3074ms]**

**[Line-13 InnerProduct Time : 3819.27ms]**

**[Line-13 Average InnerProduct Time : 14.919ms]**

**Aggregated InnerProduct Time : 7766ms**

**-----------------------------------------------------**

**[Line-2 Norm Time : 18.8318ms]**

**[Line-8 Norm Time : 6603.5ms]**

**[Line-8 Average Norm Time : 25.6945ms]**

**Aggregated Norm Time : 6621ms**

**-----------------------------------------------------**

**[Line-4 Copy Time : 34.1096ms]**

**[Line-13 Copy Time : 2141.6ms]**

**[Line-13 Average Copy Time : 8.36563ms]**

**Aggregated Copy Time : 2175ms**

**-----------------------------------------------------**

**[WriteAsImage Time : 0ms]**

**WriteAsImage Time : 0ms**

**-----------------------------------------------------**

**Total time : 29346ms**

**-----------------------------------------------------**

**[Conjugate Gradients Time : 29381.6ms]**

**-----------------------------------------------------**

**```**

**LaplaceSolver\_0\_3 parallel execution**

**```bash**

**$ export OMP\_NUM\_THREADS=12**

**$ make**

**$ ./laplace\_solver**

**...**

**...**

**Conjugate Gradients terminated after 256 iterations; residual norm (nu) = 0.000975892**

**-----------------------------------------------------**

**[Line-2 Laplacian Time : 15.5547ms]**

**[Line-6 Laplacian Time : 4987.46ms]**

**[Line-6 Average Laplacian Time : 19.4065ms]**

**Aggregated Laplacian Time : 5002ms**

**-----------------------------------------------------**

**[Line-2 Saxpy Time : 30.5737ms]**

**[Line-8 Saxpy Time : 5030.09ms]**

**[Line-8 Average Saxpy Time : 19.5723ms]**

**[Line-9-12 Saxpy Time : 35.5049ms]**

**[Line-9-12 Average Saxpy Time : 35.5049ms]**

**[Line-16 Saxpy Time : 7732.92ms]**

**[Line-16 Average Saxpy Time : 30.2067ms]**

**Aggregated Saxpy Time : 12827ms**

**-----------------------------------------------------**

**[Line-4 InnerProduct Time : 10.7883ms]**

**[Line-6 InnerProduct Time : 1444.16ms]**

**[Line-6 Average InnerProduct Time : 5.61929ms]**

**[Line-13 InnerProduct Time : 1315.97ms]**

**[Line-13 Average InnerProduct Time : 5.1405ms]**

**Aggregated InnerProduct Time : 2769ms**

**-----------------------------------------------------**

**[Line-2 Norm Time : 8.45493ms]**

**[Line-8 Norm Time : 1224.5ms]**

**[Line-8 Average Norm Time : 4.76458ms]**

**Aggregated Norm Time : 1232ms**

**-----------------------------------------------------**

**[Line-4 Copy Time : 18.3264ms]**

**[Line-13 Copy Time : 1307.69ms]**

**[Line-13 Average Copy Time : 5.10816ms]**

**Aggregated Copy Time : 1325ms**

**-----------------------------------------------------**

**[WriteAsImage Time : 0ms]**

**WriteAsImage Time : 0ms**

**-----------------------------------------------------**

**Total time : 23155ms**

**-----------------------------------------------------**

**[Conjugate Gradients Time : 23187.2ms]**

**-----------------------------------------------------**

**```**

**In the kernels merged implementation of the LaplaceSolver, I have merged the kernels at Line 13 which are Copy() and InnerProduct() kernels in the files MergedLine13.cpp MergedLine13.h. Also I have merged the Line 16 kernels which are two Saxpy() kernel calls in the files MergedSaxpysLine16.cpp and MergedSaxpysLine16.h. I have also added make file to the respective directories for easy compilation. Below are latency numbers for the serial and parallel execution of the Merged kernel's implementation.**

**float MergedLine13(const float (&x)[XDIM][YDIM][ZDIM], float (&z)[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++) {**

**z[i][j][k] = x[i][j][k];**

**result += (double) x[i][j][k] \* (double) x[i][j][k];**

**}**

**}**

**}**

**return (float) result;**

**}**

**void MergedSaxpysLine16(float (&p)[XDIM][YDIM][ZDIM], float (&x)[XDIM][YDIM][ZDIM],**

**float (&z)[XDIM][YDIM][ZDIM], const float alpha, const float beta)**

**{**

**// Should we use OpenMP parallel for here?**

**for (int i = 1; i < XDIM-1; i++) {**

**for (int j = 1; j < YDIM-1; j++) {**

**for (int k = 1; k < ZDIM-1; k++) {**

**x[i][j][k] = x[i][j][k] + alpha \* p[i][j][k];**

**p[i][j][k] = z[i][j][k] + beta \* p[i][j][k];**

**}**

**}**

**}**

**}**

**LaplaceSolver\_0\_3 Merged serial execution**

**```bash**

**$ export OMP\_NUM\_THREADS=1**

**$ make**

**$ ./laplace\_solver**

**...**

**...**

**Conjugate Gradients terminated after 256 iterations; residual norm (nu) = 0.000975892**

**-----------------------------------------------------**

**[Line-2 Laplacian Time : 27.428ms]**

**[Line-6 Laplacian Time : 2971.38ms]**

**[Line-6 Average Laplacian Time : 11.5618ms]**

**Aggregated Laplacian Time : 2998ms**

**-----------------------------------------------------**

**[Line-2 Saxpy Time : 30.1041ms]**

**[Line-8 Saxpy Time : 2290.66ms]**

**[Line-8 Average Saxpy Time : 8.91306ms]**

**[Line-9-12 Saxpy Time : 8.45638ms]**

**[Line-9-12 Average Saxpy Time : 8.45638ms]**

**[Line-16 Saxpy Time : 3491.99ms]**

**[Line-16 Average Saxpy Time : 13.6406ms]**

**Aggregated Saxpy Time : 5819ms**

**-----------------------------------------------------**

**[Line-4 InnerProduct Time : 12.61ms]**

**[Line-6 InnerProduct Time : 2984.67ms]**

**[Line-6 Average InnerProduct Time : 11.6135ms]**

**Aggregated InnerProduct Time : 2996ms**

**-----------------------------------------------------**

**[Line-2 Norm Time : 14.8673ms]**

**[Line-8 Norm Time : 4431.27ms]**

**[Line-8 Average Norm Time : 17.2423ms]**

**Aggregated Norm Time : 4445ms**

**-----------------------------------------------------**

**[Line-4 Copy Time : 31.2045ms]**

**Aggregated Copy Time : 31ms**

**-----------------------------------------------------**

**[Merged Line-13 Time : 2937.03ms]**

**[Merged Line-13 Average Time : 11.4728ms]**

**-----------------------------------------------------**

**[WriteAsImage Time : 0ms]**

**WriteAsImage Time : 0ms**

**-----------------------------------------------------**

**Total time : 19226ms**

**-----------------------------------------------------**

**[Conjugate Gradients Time : 19594.6ms]**

**-----------------------------------------------------**

**```**

**LaplaceSolver\_0\_3 Merged serial execution**

**```bash**

**$ export OMP\_NUM\_THREADS=12**

**$ make**

**$ ./laplace\_solver**

**...**

**...**

**Conjugate Gradients terminated after 256 iterations; residual norm (nu) = 0.000975892**

**-----------------------------------------------------**

**[Line-2 Laplacian Time : 13.9378ms]**

**[Line-6 Laplacian Time : 3745.64ms]**

**[Line-6 Average Laplacian Time : 14.5745ms]**

**Aggregated Laplacian Time : 3758ms**

**-----------------------------------------------------**

**[Line-2 Saxpy Time : 48.0553ms]**

**[Line-8 Saxpy Time : 3872.32ms]**

**[Line-8 Average Saxpy Time : 15.0674ms]**

**[Line-9-12 Saxpy Time : 43.2465ms]**

**[Line-9-12 Average Saxpy Time : 43.2465ms]**

**[Line-16 Saxpy Time : 4627.62ms]**

**[Line-16 Average Saxpy Time : 18.0767ms]**

**Aggregated Saxpy Time : 8590ms**

**-----------------------------------------------------**

**[Line-4 InnerProduct Time : 15.3389ms]**

**[Line-6 InnerProduct Time : 1074.53ms]**

**[Line-6 Average InnerProduct Time : 4.18104ms]**

**Aggregated InnerProduct Time : 1089ms**

**-----------------------------------------------------**

**[Line-2 Norm Time : 9.66278ms]**

**[Line-8 Norm Time : 670.698ms]**

**[Line-8 Average Norm Time : 2.60972ms]**

**Aggregated Norm Time : 679ms**

**-----------------------------------------------------**

**[Line-4 Copy Time : 25.7142ms]**

**Aggregated Copy Time : 25ms**

**-----------------------------------------------------**

**[Merged Line-13 Time : 1063.42ms]**

**[Merged Line-13 Average Time : 4.154ms]**

**-----------------------------------------------------**

**[WriteAsImage Time : 0ms]**

**WriteAsImage Time : 0ms**

**-----------------------------------------------------**

**Total time : 15204ms**

**-----------------------------------------------------**

**[Conjugate Gradients Time : 15228.4ms]**

**-----------------------------------------------------**

**```**

**### LaplaceSolver\_0\_3 Merged parallel execution**

**```bash**

**$ export OMP\_NUM\_THREADS=12**

**$ make**

**$ ./laplace\_solver**

**...**

**...**

**Conjugate Gradients terminated after 256 iterations; residual norm (nu) = 0.000975892**

**-----------------------------------------------------**

**[Line-2 Laplacian Time : 13.9378ms]**

**[Line-6 Laplacian Time : 3745.64ms]**

**[Line-6 Average Laplacian Time : 14.5745ms]**

**Aggregated Laplacian Time : 3758ms**

**-----------------------------------------------------**

**[Line-2 Saxpy Time : 48.0553ms]**

**[Line-8 Saxpy Time : 3872.32ms]**

**[Line-8 Average Saxpy Time : 15.0674ms]**

**[Line-9-12 Saxpy Time : 43.2465ms]**

**[Line-9-12 Average Saxpy Time : 43.2465ms]**

**[Line-16 Saxpy Time : 4627.62ms]**

**[Line-16 Average Saxpy Time : 18.0767ms]**

**Aggregated Saxpy Time : 8590ms**

**-----------------------------------------------------**

**[Line-4 InnerProduct Time : 15.3389ms]**

**[Line-6 InnerProduct Time : 1074.53ms]**

**[Line-6 Average InnerProduct Time : 4.18104ms]**

**Aggregated InnerProduct Time : 1089ms**

**-----------------------------------------------------**

**[Line-2 Norm Time : 9.66278ms]**

**[Line-8 Norm Time : 670.698ms]**

**[Line-8 Average Norm Time : 2.60972ms]**

**Aggregated Norm Time : 679ms**

**-----------------------------------------------------**

**[Line-4 Copy Time : 25.7142ms]**

**Aggregated Copy Time : 25ms**

**-----------------------------------------------------**

**[Merged Line-13 Time : 1063.42ms]**

**[Merged Line-13 Average Time : 4.154ms]**

**-----------------------------------------------------**

**[WriteAsImage Time : 0ms]**

**WriteAsImage Time : 0ms**

**-----------------------------------------------------**

**Total time : 15204ms**

**-----------------------------------------------------**

**[Conjugate Gradients Time : 15228.4ms]**

**-----------------------------------------------------**

**```**