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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
```

The Original Laplacian_0_10

When we run the original 3D Laplacian stancil without utilizing OpenMP, we get the runtimes as ~880ms and ~50ms. When utilizing OpenMP with 12 threads and an O0 optimization level, the average runtime is about ~140ms. With the same setup, but now with the O3 optimization level, it comes to around ~20ms. The effective memory bandwidth achieved can be deduced by:

(512 * 512 * 512) * 2 * (4 bytes) / (20 ms) => 50 GB/s

which is about 66% of the peak memory bandwidth (76.8%) the machine offers.

```bash
$ export OMP_NUM_THREADS=1
$ g++ -fopenmp main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 1147.75ms]
Running test iteration  2 [Elapsed time : 863.454ms]
Running test iteration  3 [Elapsed time : 873.617ms]
Running test iteration  4 [Elapsed time : 869.885ms]
Running test iteration  5 [Elapsed time : 862.666ms]
Running test iteration  6 [Elapsed time : 861.781ms]
Running test iteration  7 [Elapsed time : 875.017ms]
```

```
Running test iteration  8 [Elapsed time : 876.798ms]
Running test iteration  9 [Elapsed time : 942.534ms]
Running test iteration 10 [Elapsed time : 911.522ms]

$ export OMP_NUM_THREADS=12
$ g++ -fopenmp main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 208.992ms]
Running test iteration  2 [Elapsed time : 149.058ms]
Running test iteration  3 [Elapsed time : 153.368ms]
Running test iteration  4 [Elapsed time : 146.964ms]
Running test iteration  5 [Elapsed time : 134.869ms]
Running test iteration  6 [Elapsed time : 138.985ms]
Running test iteration  7 [Elapsed time : 144.533ms]
Running test iteration  8 [Elapsed time : 136.178ms]
Running test iteration  9 [Elapsed time : 142.118ms]
Running test iteration 10 [Elapsed time : 137.006ms]

$ export OMP_NUM_THREADS=1
$ g++ -fopenmp -O3 main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 211.509ms]
Running test iteration  2 [Elapsed time : 63.2545ms]
Running test iteration  3 [Elapsed time : 51.4643ms]
Running test iteration  4 [Elapsed time : 51.9892ms]
Running test iteration  5 [Elapsed time : 50.9392ms]
Running test iteration  6 [Elapsed time : 51.2919ms]
Running test iteration  7 [Elapsed time : 47.1985ms]
Running test iteration  8 [Elapsed time : 46.6652ms]
Running test iteration  9 [Elapsed time : 49.8423ms]
Running test iteration 10 [Elapsed time : 47.7982ms]

$ export OMP_NUM_THREADS=12
$ g++ -fopenmp -O3 main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 102.865ms]
Running test iteration  2 [Elapsed time : 27.5783ms]
Running test iteration  3 [Elapsed time : 24.4827ms]
Running test iteration  4 [Elapsed time : 20.9801ms]
Running test iteration  5 [Elapsed time : 19.7127ms]
```

```
Running test iteration  6 [Elapsed time : 19.7728ms]
Running test iteration  7 [Elapsed time : 20.7993ms]
Running test iteration  8 [Elapsed time : 21.0341ms]
Running test iteration  9 [Elapsed time : 20.4642ms]
Running test iteration 10 [Elapsed time : 20.1989ms]
```

Laplacian_0_10_k_j_i

When we run this version of 3D Laplacian stancil without utilizing OpenMP, we get the runtimes as ~3500ms and ~2700ms. When utilizing OpenMP with 12 threads and an O0 optimization level, the average runtime is about ~1200ms. With the same setup, but now with the O3 optimization level, it comes to around ~900ms. The reverse loop order makes the row index i to be the fastest. Due to which the memory accesses lack spatial locality which hurts the performance the most, as accessing contiguous memory locations is faster. Lack of temporal locality also contributes to the bad performance as reusing recently accessed data improves cache efficiency. Due to lack of spatial locality, the CPU prefetching also does not work and we see a lot of cache misses.

```bash
$ export OMP_NUM_THREADS=1
$ g++ -fopenmp main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 3057.77ms]
Running test iteration  2 [Elapsed time : 2853.83ms]
Running test iteration  3 [Elapsed time : 3395.51ms]
Running test iteration  4 [Elapsed time : 3694.35ms]
Running test iteration  5 [Elapsed time : 3687.99ms]
Running test iteration  6 [Elapsed time : 3756.47ms]
Running test iteration  7 [Elapsed time : 3558.59ms]
Running test iteration  8 [Elapsed time : 3498.46ms]
Running test iteration  9 [Elapsed time : 3583.48ms]
Running test iteration 10 [Elapsed time : 3681.22ms]

$ export OMP_NUM_THREADS=12
```

```
$ g++ -fopenmp main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 673.235ms]
Running test iteration  2 [Elapsed time : 592.706ms]
Running test iteration  3 [Elapsed time : 1441.84ms]
Running test iteration  4 [Elapsed time : 1333.27ms]
Running test iteration  5 [Elapsed time : 1267.31ms]
Running test iteration  6 [Elapsed time : 1146.56ms]
Running test iteration  7 [Elapsed time : 1164.49ms]
Running test iteration  8 [Elapsed time : 1162.9ms]
Running test iteration  9 [Elapsed time : 1170.88ms]
Running test iteration 10 [Elapsed time : 1190.74ms]

$ export OMP_NUM_THREADS=1
$ g++ -fopenmp -O3 main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 2590.84ms]
Running test iteration  2 [Elapsed time : 2431.09ms]
Running test iteration  3 [Elapsed time : 2596.82ms]
Running test iteration  4 [Elapsed time : 2706.1ms]
Running test iteration  5 [Elapsed time : 2680.12ms]
Running test iteration  6 [Elapsed time : 2782.16ms]
Running test iteration  7 [Elapsed time : 2666.74ms]
Running test iteration  8 [Elapsed time : 2663.05ms]
Running test iteration  9 [Elapsed time : 2671.61ms]
Running test iteration 10 [Elapsed time : 2667.71ms]

$ export OMP_NUM_THREADS=12
$ g++ -fopenmp -O3 main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 670.787ms]
Running test iteration  2 [Elapsed time : 590.447ms]
Running test iteration  3 [Elapsed time : 1209.72ms]
Running test iteration  4 [Elapsed time : 1169.83ms]
Running test iteration  5 [Elapsed time : 953.676ms]
Running test iteration  6 [Elapsed time : 942.214ms]
Running test iteration  7 [Elapsed time : 876.86ms]
Running test iteration  8 [Elapsed time : 906.692ms]
Running test iteration  9 [Elapsed time : 873.619ms]
Running test iteration 10 [Elapsed time : 872.501ms]
```

```

## Laplacian_0_10_i_k_j

**When we run this version of 3D Laplacian stancil without utilizing OpenMP, we get the runtimes as ~1400ms and ~1100ms. When utilizing OpenMP with 12 threads and an O0 optimization level, the average runtime is about ~700ms. With the same setup, but now with the O3 optimization level, it comes to around ~200ms. Again, similar reason may apply to this version as well. The only good thing over here is that the i index moves the slowest(as it is outermost) which corresponds to the row. This gives us better spatial locality than the previous version and hence, does better in terms of runtime with respect to previous one.**

```bash
$ export OMP_NUM_THREADS=1
$ g++ -fopenmp main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 1407.23ms]
Running test iteration  2 [Elapsed time : 1267.08ms]
Running test iteration  3 [Elapsed time : 1183.8ms]
Running test iteration  4 [Elapsed time : 1243.87ms]
Running test iteration  5 [Elapsed time : 1220.7ms]
Running test iteration  6 [Elapsed time : 1321.42ms]
Running test iteration  7 [Elapsed time : 1333.21ms]
Running test iteration  8 [Elapsed time : 1931.56ms]
Running test iteration  9 [Elapsed time : 1924.34ms]
Running test iteration 10 [Elapsed time : 2074.67ms]

$ export OMP_NUM_THREADS=12
$ g++ -fopenmp main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 319.025ms]
Running test iteration  2 [Elapsed time : 246.763ms]
Running test iteration  3 [Elapsed time : 245.948ms]
Running test iteration  4 [Elapsed time : 252.246ms]
Running test iteration  5 [Elapsed time : 263.021ms]
```
```

```
Running test iteration  6 [Elapsed time : 648.498ms]
Running test iteration  7 [Elapsed time : 774.168ms]
Running test iteration  8 [Elapsed time : 730.413ms]
Running test iteration  9 [Elapsed time : 673.438ms]
Running test iteration 10 [Elapsed time : 647.86ms]

$ export OMP_NUM_THREADS=1
$ g++ -fopenmp -O3 main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 1071.04ms]
Running test iteration  2 [Elapsed time : 925.586ms]
Running test iteration  3 [Elapsed time : 921.211ms]
Running test iteration  4 [Elapsed time : 911.208ms]
Running test iteration  5 [Elapsed time : 1168.2ms]
Running test iteration  6 [Elapsed time : 1373.03ms]
Running test iteration  7 [Elapsed time : 1295.81ms]
Running test iteration  8 [Elapsed time : 1634ms]
Running test iteration  9 [Elapsed time : 1538.17ms]
Running test iteration 10 [Elapsed time : 1383.13ms]

$ export OMP_NUM_THREADS=12
$ g++ -fopenmp -O3 main.cpp Laplacian.cpp
$ ./a.out
Running test iteration  1 [Elapsed time : 209.621ms]
Running test iteration  2 [Elapsed time : 185.079ms]
Running test iteration  3 [Elapsed time : 172.729ms]
Running test iteration  4 [Elapsed time : 202.188ms]
Running test iteration  5 [Elapsed time : 172.613ms]
Running test iteration  6 [Elapsed time : 180.068ms]
Running test iteration  7 [Elapsed time : 180.838ms]
Running test iteration  8 [Elapsed time : 182.361ms]
Running test iteration  9 [Elapsed time : 258.07ms]
Running test iteration 10 [Elapsed time : 602.208ms]
```