

Q1) We perform DAXPY operation with formula $X[i] = a*X[i] + Y[i]$. The size of the vector is 65536. The code compares the time taken to complete this operation from 2 to 16 threads. Execution time reduced slightly when increasing threads from 1 to 2, but no consistent improvement was observed beyond 2-4 threads. For higher thread counts (8 and 16), execution time increased and CPU utilization remained close to one core.

With a few threads the work is split and runs faster. After that, the amount of data that can be moved in and out of the memory is already fully used. Adding more threads can't move data any quicker, and it introduces extra work for the processor.

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q1.cpp -O3 -fopenmp -pg -o q1
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q1
Q1 DAXPY | Threads = 2 | Time = 0.034542 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q1
Q1 DAXPY | Threads = 2 | Time = 0.017949 seconds

Performance counter stats for './q1':

      630.93 msec task-clock          #    1.023 CPUs utilized
          3      context-switches      #    4.755 /sec
          0      cpu-migrations       #    0.000 /sec
      65,617  page-faults           # 104.000 K/sec
<not supported>    cycles

 0.616986786 seconds time elapsed

 0.065868000 seconds user
 0.572547000 seconds sys
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q1.cpp -O3 -fopenmp -pg -o q1
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q1
^[[AQ1 DAXPY | Threads = 4 | Time = 0.022226 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q1
Q1 DAXPY | Threads = 4 | Time = 0.019096 seconds

Performance counter stats for './q1':

      726.72 msec task-clock          #    1.153 CPUs utilized
          5      context-switches      #    6.880 /sec
          1      cpu-migrations       #    1.376 /sec
      65,621  page-faults           #  90.298 K/sec
<not supported>    cycles

 0.630063001 seconds time elapsed

 0.124992000 seconds user
 0.605430000 seconds sys
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q1.cpp -O3 -fopenmp -pg -o q1
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q1
Q1 DAXPY | Threads = 8 | Time = 0.024181 seconds
```

Performance counter stats for './q1':

542.42 msec task-clock	# 1.118 CPUs utilized
30 context-switches	# 55.308 /sec
9 cpu-migrations	# 16.592 /sec
65,630 page-faults	# 120.995 K/sec
<not supported> cycles	
0.484982592 seconds time elapsed	
0.089369000 seconds user	
0.459612000 seconds sys	

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q1
Q1 DAXPY | Threads = 8 | Time = 0.029677 seconds
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q1
Q1 DAXPY | Threads = 8 | Time = 0.029677 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q1.cpp -O3 -fopenmp -pg -o q1
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q1
Q1 DAXPY | Threads = 16 | Time = 0.041193 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q1
Q1 DAXPY | Threads = 16 | Time = 0.030265 seconds
```

Performance counter stats for './q1':

589.74 msec task-clock	# 1.163 CPUs utilized
60 context-switches	# 101.739 /sec
13 cpu-migrations	# 22.043 /sec
65,649 page-faults	# 111.318 K/sec
<not supported> cycles	
0.507171349 seconds time elapsed	
0.098761000 seconds user	
0.500620000 seconds sys	

Q2 a) Execution time decreased significantly as threads increased from 1 to 4. Performance improved up to moderate thread counts and then saturated.

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2a.cpp -O3 -fopenmp -pg -o q2a
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2a
Q2 Matrix Multiply 1D | Threads = 1 | Time = 0.895958 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2a
Q2 Matrix Multiply 1D | Threads = 1 | Time = 0.879074 seconds
```

Performance counter stats for './q2a':

915.11 msec task-clock	# 0.995 CPUs utilized
2 context-switches	# 2.186 /sec
0 cpu-migrations	# 0.000 /sec
5,935 page-faults	# 6.486 K/sec
<not supported> cycles	
0.919714676 seconds time elapsed	
0.828089000 seconds user	
0.092869000 seconds sys	

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2a.cpp -O3 -fopenmp -pg -o q2a
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2a
Q2 Matrix Multiply 1D | Threads = 2 | Time = 1.003430 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2a
Q2 Matrix Multiply 1D | Threads = 2 | Time = 0.572035 seconds
```

Performance counter stats for './q2a':

1,207.20 msec task-clock	# 1.849 CPUs utilized
3 context-switches	# 2.485 /sec
0 cpu-migrations	# 0.000 /sec
5,938 page-faults	# 4.919 K/sec
<not supported> cycles	

0.652866752 seconds time elapsed
0.275237000 seconds user
0.946127000 seconds sys

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2a.cpp -O3 -fopenmp -pg -o q2a
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2a
^[[AQ2 Matrix Multiply 1D | Threads = 4 | Time = 0.443487 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2a
Q2 Matrix Multiply 1D | Threads = 4 | Time = 0.510932 seconds
```

Performance counter stats for './q2a':

1,974.68 msec task-clock	# 3.541 CPUs utilized
25 context-switches	# 12.660 /sec
0 cpu-migrations	# 0.000 /sec
5,944 page-faults	# 3.010 K/sec
<not supported> cycles	

0.557670929 seconds time elapsed
1.844093000 seconds user
0.140581000 seconds sys

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2a.cpp -O3 -fopenmp -pg -o q2a
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2a
Q2 Matrix Multiply 1D | Threads = 8 | Time = 0.336697 seconds
```

Performance counter stats for './q2a':

1,493.75 msec task-clock	# 3.556 CPUs utilized
33 context-switches	# 22.092 /sec
7 cpu-migrations	# 4.686 /sec
5,951 page-faults	# 3.984 K/sec
<not supported> cycles	

0.420098504 seconds time elapsed
0.914979000 seconds user
0.614343000 seconds sys

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2a
Q2 Matrix Multiply 1D | Threads = 8 | Time = 0.372289 seconds
```

```

redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2a
Q2 Matrix Multiply 1D | Threads = 8 | Time = 0.372289 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2a.cpp -O3 -fopenmp -pg -o q2a
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2a
^[[AQ2 Matrix Multiply 1D | Threads = 16 | Time = 0.393294 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2a
Q2 Matrix Multiply 1D | Threads = 16 | Time = 0.335762 seconds

Performance counter stats for './q2a':

      1,478.25 msec task-clock          #    3.563 CPUs utilized
          95      context-switches       #   64.265 /sec
          27      cpu-migrations        #   18.265 /sec
         5,968    page-faults           #    4.037 K/sec
<not supported>    cycles

  0.414892115 seconds time elapsed

    1.305208000 seconds user
    0.230070000 seconds sys

```

B) 2D threading showed higher execution time compared to 1D threading for the same number of threads. Improvements with additional threads were limited.

```

redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2b.cpp -O3 -fopenmp -pg -o q2
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2
Q2 Matrix Multiply 2D | Threads = 1 | Time = 2.099976 seconds

Performance counter stats for './q2':

      2,151.16 msec task-clock          #    0.994 CPUs utilized
          15      context-switches       #   6.973 /sec
          1      cpu-migrations        #   0.465 /sec
         5,936    page-faults           #    2.759 K/sec
<not supported>    cycles

  2.163598898 seconds time elapsed

    1.999890000 seconds user
    0.162215000 seconds sys

redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 1 | Time = 2.179143 seconds

```

```

redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 1 | Time = 2.179143 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2b.cpp -O3 -fopenmp -pg -o q2
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
^[[AQ2 Matrix Multiply 2D | Threads = 2 | Time = 1.122255 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2
Q2 Matrix Multiply 2D | Threads = 2 | Time = 1.355466 seconds

Performance counter stats for './q2':

      2,748.69 msec task-clock          #    1.922 CPUs utilized
          17      context-switches       #   6.185 /sec
          2      cpu-migrations        #   0.728 /sec
         5,938    page-faults           #    2.160 K/sec
<not supported>    cycles

  1.430257350 seconds time elapsed

    2.594512000 seconds user
    0.164385000 seconds sys

```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2b.cpp -O3 -fopenmp -pg -o q2
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2
^[[AQ2 Matrix Multiply 2D | Threads = 4 | Time = 0.428263 seconds
```

```
Performance counter stats for './q2':  
  
1,746.34 msec task-clock # 3.643 CPUs utilized  
       6    context-switches # 3.436 /sec  
        0    cpu-migrations # 0.000 /sec  
  5,942    page-faults # 3.403 K/sec  
<not supported>   cycles  
  
0.479371870 seconds time elapsed  
  
0.772179000 seconds user  
0.982773000 seconds sys
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 4 | Time = 0.465501 seconds
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2b.cpp -O3 -fopenmp -pg -o q2
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2
Q2 Matrix Multiply 2D | Threads = 16 | Time = 0.458915 seconds
```

```
Performance counter stats for './q2':  
  
2,225.57 msec task-clock # 4.415 CPUs utilized  
     104    context-switches # 46.730 /sec  
      23    cpu-migrations # 10.334 /sec  
  5,969    page-faults # 2.682 K/sec  
<not supported>   cycles  
  
0.504068843 seconds time elapsed  
  
1.533147000 seconds user  
0.712371000 seconds sys
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 16 | Time = 0.451417 seconds
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 4 | Time = 0.465501 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q2b.cpp -O3 -fopenmp -pg -o q2
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 8 | Time = 0.450777 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q2
Q2 Matrix Multiply 2D | Threads = 8 | Time = 0.455307 seconds
```

```
Performance counter stats for './q2':  
  
1,925.22 msec task-clock # 3.490 CPUs utilized  
     44    context-switches # 22.855 /sec  
      11    cpu-migrations # 5.714 /sec  
  5,951    page-faults # 3.091 K/sec  
<not supported>   cycles  
  
0.551570738 seconds time elapsed  
  
1.484825000 seconds user  
0.481778000 seconds sys
```

Q3) Execution time decreased steadily as thread count increased up to about 8 threads. After this point, performance gains were smaller.

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q2
Q2 Matrix Multiply 2D | Threads = 16 | Time = 0.451417 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q3.cpp -O3 -fopenmp -pg -o q3
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q3
Q3 Pi Calculation | Threads = 1 | Pi = 3.141592653590 | Time = 0.269422 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q3
Q3 Pi Calculation | Threads = 1 | Pi = 3.141592653590 | Time = 0.243761 seconds
```

Performance counter stats for './q3':

248.12 msec task-clock	# 0.971 CPUs utilized
2 context-switches	# 8.061 /sec
0 cpu-migrations	# 0.000 /sec
77 page-faults	# 310.331 /sec
<not supported> cycles	
0.255487540 seconds time elapsed	
0.228110000 seconds user	
0.028013000 seconds sys	

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q3.cpp -O3 -fopenmp -pg -o q3
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q3.cpp -O3 -fopenmp -pg -o q3
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q3
Q3 Pi Calculation | Threads = 2 | Pi = 3.141592653590 | Time = 0.124726 seconds
```

Performance counter stats for './q3':

254.78 msec task-clock	# 1.936 CPUs utilized
1 context-switches	# 3.925 /sec
0 cpu-migrations	# 0.000 /sec
80 page-faults	# 314.002 /sec
<not supported> cycles	
0.131602284 seconds time elapsed	
0.222299000 seconds user	
0.034494000 seconds sys	

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q3
Q3 Pi Calculation | Threads = 2 | Pi = 3.141592653590 | Time = 0.143374 seconds
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q3.cpp -O3 -fopenmp -pg -o q3
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q3
Q3 Pi Calculation | Threads = 4 | Pi = 3.141592653590 | Time = 0.119522 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q3
Q3 Pi Calculation | Threads = 4 | Pi = 3.141592653590 | Time = 0.059925 seconds
```

Performance counter stats for './q3':

255.95 msec task-clock	# 3.367 CPUs utilized
7 context-switches	# 27.349 /sec
1 cpu-migrations	# 3.907 /sec
83 page-faults	# 324.286 /sec
<not supported> cycles	
0.076019116 seconds time elapsed	
0.108235000 seconds user	
0.151529000 seconds sys	

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q3.cpp -O3 -fopenmp -pg -o q3
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q3
Q3 Pi Calculation | Threads = 8 | Pi = 3.141592653590 | Time = 0.060460 seconds
```

Performance counter stats for './q3':

240.04 msec task-clock	# 3.519 CPUs utilized
24 context-switches	# 99.982 /sec
6 cpu-migrations	# 24.995 /sec
92 page-faults	# 383.264 /sec
<not supported> cycles	
0.068214771 seconds time elapsed	
0.061003000 seconds user	
0.183011000 seconds sys	

```
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q3
Q3 Pi Calculation | Threads = 8 | Pi = 3.141592653590 | Time = 0.096657 seconds
```

```
redt@redt-VirtualBox:~/UCS645/Lab1$ g++ q3.cpp -O3 -fopenmp -pg -o q3
redt@redt-VirtualBox:~/UCS645/Lab1$ ./q3
Q3 Pi Calculation | Threads = 16 | Pi = 3.141592653590 | Time = 0.105643 seconds
redt@redt-VirtualBox:~/UCS645/Lab1$ sudo perf stat ./q3
Q3 Pi Calculation | Threads = 16 | Pi = 3.141592653590 | Time = 0.081459 seconds
```

Performance counter stats for './q3':

317.36 msec task-clock	# 3.252 CPUs utilized
64 context-switches	# 201.662 /sec
32 cpu-migrations	# 100.831 /sec
107 page-faults	# 337.153 /sec
<not supported> cycles	
0.097582155 seconds time elapsed	
0.207702000 seconds user	
0.124621000 seconds sys	