Part:2 Welcome to OpenCV

1)

[1]:
```
1 from PIL import Image
2 im = Image.open('image.tif')
3 im
```

t[1]:

2)

```
In [3]:
1 im3 = Image.open('original_color.tif')
2 im3
```

Out[3]:

3)

```
In [2]:
1 im2 = Image.open('opencv_dct.tif')
2 im2
```

Out[2]:

Voilà

4)

```
In [4]:
1 im4 = Image.open('dct_lab_naive.tif')
2 im4
```

Out[4]:

5)

```
In [5]:  1 im5 = Image.open('dct_lab_opt.tif')
         2 im5
```

Out[5]:

Part 2, 2:

Time command results of dct with option 1, 2, 3

S.No	DCT Method	Time Command
1	OpenCV	xilinx@pynq:~/jupyter_notebooks/wes237b_labs/dct$ time ./dct 1 Wrote opencv_dct.tif real 0m0.781s user 0m0.609s sys 0m0.179s xilinx@pynq:~/jupyter_notebooks/wes237b_labs/dct$
2	Naive	xilinx@pynq:~/jupyter_notebooks/wes237b_labs/dct$ time ./dct 2 Wrote dct_lab_naive.tif real 0m6.135s user 0m5.995s sys 0m0.142s xilinx@pynq:~/jupyter_notebooks/wes237b_labs/dct$
3	1D	xilinx@pynq:~/jupyter_notebooks/wes237b_labs/dct$ time ./dct 3 Wrote dct_lab_opt.tif real 0m0.886s user 0m0.719s sys 0m0.171s xilinx@pynq:~/jupyter_notebooks/wes237b_labs/dct$

Part 3: Matrix Multiplication and Performance

Performed square matrix multiplication of sizes 8,16,32,64,128,256,512,1024.
CPU Frequency of PYNQ from documentation: 650 MHZ.
Calculated CPU Cycle through ARM 7 PMU registers done in WES237-A. Perf does not have support on current version of Linux on PYNQ.

Execute: ./matrix <SIZE>

S.No	Performance
1	xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 8 CPU Performance Matrix size = 8 Naive approach, Cycle count = 511 Exec Time 5.03138e-05 Eigen Lib approach, Cycle count = 147 Exec Time 1.44738e-05 OpenCV approach, Cycle count = 20313 Exec Time 0.00200005
2	xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 16 CPU Performance Matrix size = 16 Naive approach, Cycle count = 3440 Exec Time 0.000338708 Eigen Lib approach, Cycle count = 425 Exec Time 4.18462e-05 OpenCV approach, Cycle count = 4097 Exec Time 0.000403397

3	`xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 32`
	`CPU Performance Matrix size = 32`
	`Naive approach, Cycle count = 26596 Exec Time 0.00261868`
	`Eigen Lib approach, Cycle count = 2411 Exec Time 0.000237391`
	`OpenCV approach, Cycle count = 4576 Exec Time 0.00045056`

4	`xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 64`
	`CPU Performance Matrix size = 64`
	`Naive approach, Cycle count = 211413 Exec Time 0.020816`
	`Eigen Lib approach, Cycle count = 15855 Exec Time 0.00156111`
	`OpenCV approach, Cycle count = 22403 Exec Time 0.00220583`

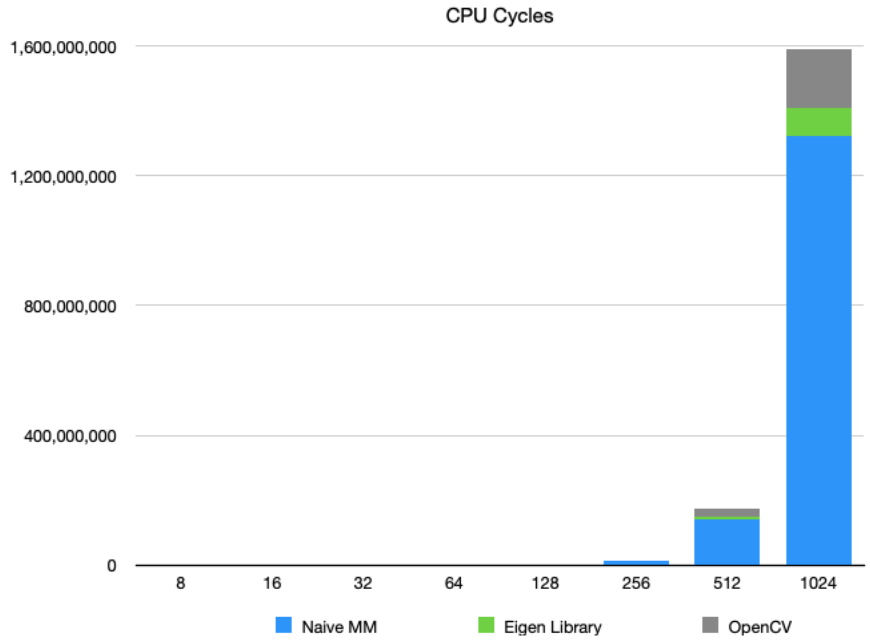
5	`xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 128`
	`CPU Performance Matrix size = 128`
	`Naive approach, Cycle count = 1674470 Exec Time 0.164871`
	`Eigen Lib approach, Cycle count = 150491 Exec Time 0.0148176`
	`OpenCV approach, Cycle count = 270359 Exec Time 0.02662`

6	`xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 256`
	`CPU Performance Matrix size = 256`
	`Naive approach, Cycle count = 14674986 Exec Time 1.44492`
	`Eigen Lib approach, Cycle count = 1358152 Exec Time 0.133726`
	`OpenCV approach, Cycle count = 2746235 Exec Time 0.270399`

7	`xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 512`
	`CPU Performance Matrix size = 512`
	`Naive approach, Cycle count = 139966124 Exec Time 13.7813`
	`Eigen Lib approach, Cycle count = 10787282 Exec Time 1.06213`
	`OpenCV approach, Cycle count = 22398549 Exec Time 2.2054`

8	`xilinx@pynq:~/jupyter_notebooks/wes237b_labs/matrix$ ./matrix 1024`
	`CPU Performance Matrix size = 1024`
	`Naive approach, Cycle count = 1323087283 Exec Time 130.273`
	`Eigen Lib approach, Cycle count = 86047260 Exec Time 8.47235`
	`OpenCV approach, Cycle count = 180772167 Exec Time 17.7991`

Plot



Eigen Library outperforms every time. Naïve approach is slower in every case. OpenCV did not outperform Eigen Library at any testing. It could be seen, for larger matrices involving size of 512 the number of cycles exponentially grows.

Part 4

Used Cycle count and found execution time using cycle count and Frequency of CPU.

Intermediate deliverables
Look up table

Default Naive DCT with LUT (Default Size 64)

```
xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2
WES237B lab 2
LUT is Enabled in Naive Algo
CPU Cycle Count = 2147120 CPU execution Time: = 0.211409
Execute time: 0.211644
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2152899 CPU execution Time: = 0.211978
Execute time: 0.212181
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2156215 CPU execution Time: = 0.212304
Execute time: 0.212516
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2142166 CPU execution Time: = 0.210921
Execute time: 0.211136
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2142350 CPU execution Time: = 0.210939
Execute time: 0.211148
RMSE: 0.0001

 Performance counter stats for './hw2':

          2,863.33 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,082      page-faults:u             #    0.002 M/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

       2.866347337 seconds time elapsed

       2.614521000 seconds user
       0.250433000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Default Naïve DCT with no LUT (Default size 64)

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2
WES237B lab 2
LUT not Enabled in Naive Algo
CPU Cycle Count = 54611573 CPU execution Time: = 5.37714
Execute time: 1.08251
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54620313 CPU execution Time: = 5.378
Execute time: 1.08325
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54622121 CPU execution Time: = 5.37818
Execute time: 1.08344
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54585329 CPU execution Time: = 5.37456
Execute time: 1.07981
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54597212 CPU execution Time: = 5.37573
Execute time: 1.08098
RMSE: 0.0001

 Performance counter stats for './hw2':

         28,676.57 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,078      page-faults:u             #    0.212 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      28.691824302 seconds time elapsed

      28.467767000 seconds user
       0.209836000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

1D-Separable without LUT (Size = 64)

```
xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2
WES237B lab 2
LUT is disabled for 1D Separable algo
CPU Cycle Count = 1661481 CPU execution Time: = 0.163592
Execute time: 0.163845
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 1662149 CPU execution Time: = 0.163658
Execute time: 0.16388
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 1662143 CPU execution Time: = 0.163657
Execute time: 0.163891
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 1660962 CPU execution Time: = 0.163541
Execute time: 0.163761
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 1661062 CPU execution Time: = 0.163551
Execute time: 0.163776
RMSE: 0.0000

 Performance counter stats for './hw2':

          2,631.14 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,086      page-faults:u             #    0.002 M/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

       2.632886096 seconds time elapsed

       2.352510000 seconds user
       0.280299000 seconds sys
```

1D-Separable with LUT (Size 64)

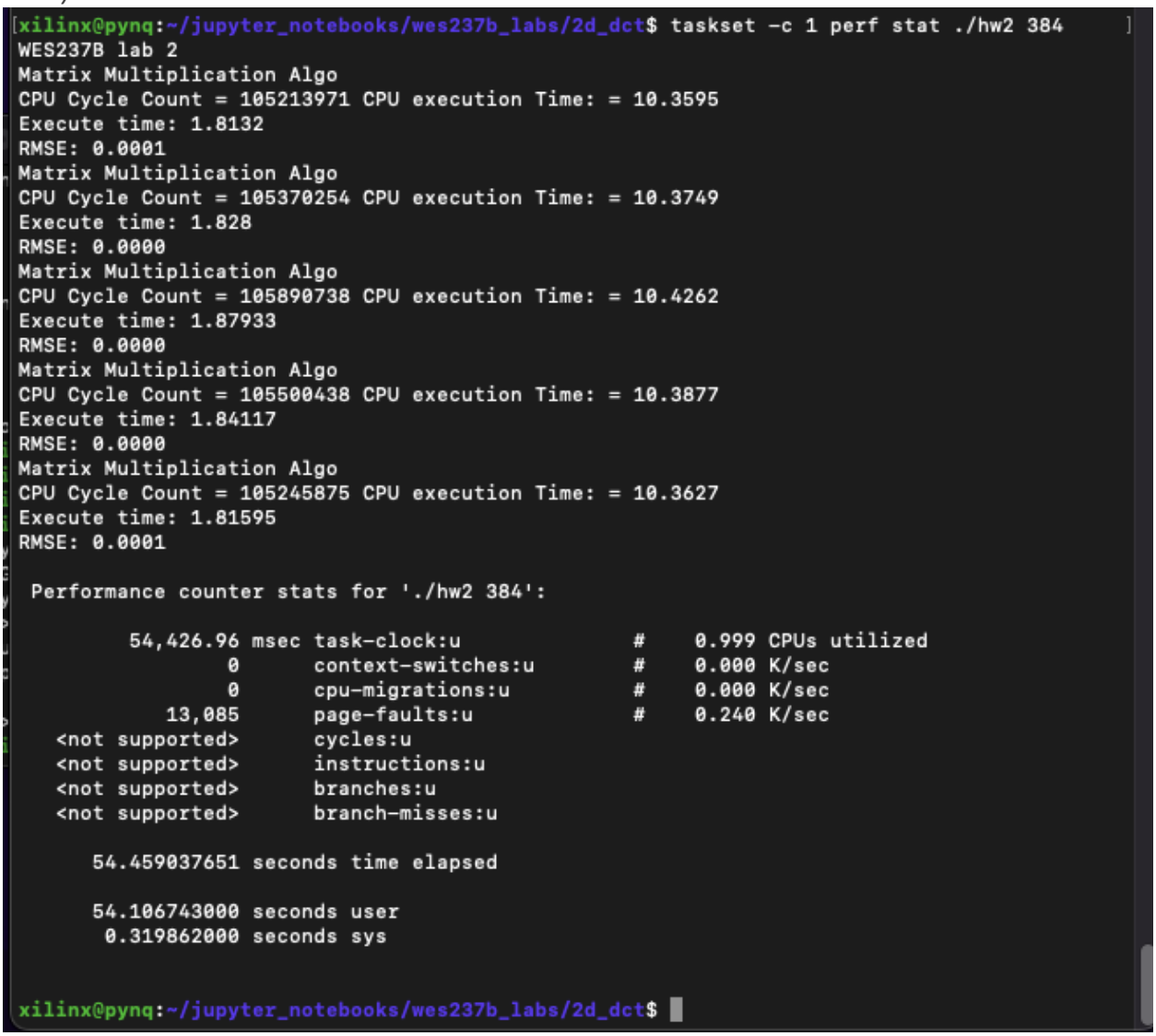
```
xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2
WES237B lab 2
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 46685 CPU execution Time: = 0.00459668
Execute time: 0.00484578
RMSE: 0.0000
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 46720 CPU execution Time: = 0.00460012
Execute time: 0.00480429
RMSE: 0.0000
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 47209 CPU execution Time: = 0.00464827
Execute time: 0.00486974
RMSE: 0.0000
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 46767 CPU execution Time: = 0.00460475
Execute time: 0.00482378
RMSE: 0.0000
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 46680 CPU execution Time: = 0.00459618
Execute time: 0.00481552
RMSE: 0.0000

 Performance counter stats for './hw2':

          1,855.42 msec task-clock:u              #    0.875 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,250      page-faults:u             #    0.003 M/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

       2.120597326 seconds time elapsed

       1.560209000 seconds user
       0.295726000 seconds sys
```

Naïve Matrix Multiplication (Size = 64)

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2
WES237B lab 2
Matrix Multiplication Algo
CPU Cycle Count = 420347 CPU execution Time: = 0.041388
Execute time: 0.0429692
RMSE: 0.0000
Matrix Multiplication Algo
CPU Cycle Count = 419761 CPU execution Time: = 0.0413303
Execute time: 0.0428338
RMSE: 0.0000
Matrix Multiplication Algo
CPU Cycle Count = 419612 CPU execution Time: = 0.0413156
Execute time: 0.0427664
RMSE: 0.0000
Matrix Multiplication Algo
CPU Cycle Count = 420195 CPU execution Time: = 0.041373
Execute time: 0.0428251
RMSE: 0.0000
Matrix Multiplication Algo
CPU Cycle Count = 420224 CPU execution Time: = 0.0413759
Execute time: 0.0428393
RMSE: 0.0000

 Performance counter stats for './hw2':

          2,015.90 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,077      page-faults:u             #    0.003 M/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

       2.018408274 seconds time elapsed

       1.776519000 seconds user
       0.240884000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Block Matrix Multiplication

1) *Naïve MM with size 384*



Find optimal block size on input 384

Block size 8

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
Block Matrix Multiplication Method
CPU Cycle Count = 109585856 CPU execution Time: = 10.79
Execute time: 2.24402
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 109583246 CPU execution Time: = 10.7897
Execute time: 2.24311
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 109588708 CPU execution Time: = 10.7903
Execute time: 2.24382
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 109568016 CPU execution Time: = 10.7882
Execute time: 2.24171
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 109599494 CPU execution Time: = 10.7913
Execute time: 2.2448
RMSE: 0.0001

 Performance counter stats for './hw2 384':

         56,472.93 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            13,095      page-faults:u             #    0.232 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      56.505851057 seconds time elapsed

      56.192685000 seconds user
       0.279863000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Block size 16

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
Block Matrix Multiplication Method
CPU Cycle Count = 107968093 CPU execution Time: = 10.6307
Execute time: 2.08513
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 107962186 CPU execution Time: = 10.6301
Execute time: 2.08322
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107954289 CPU execution Time: = 10.6293
Execute time: 2.08271
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107968343 CPU execution Time: = 10.6307
Execute time: 2.08424
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107964261 CPU execution Time: = 10.6303
Execute time: 2.08383
RMSE: 0.0001

 Performance counter stats for './hw2 384':

         55,668.44 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            13,084      page-faults:u             #    0.235 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      55.700745496 seconds time elapsed

      55.368406000 seconds user
       0.299828000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Block size 32

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
Block Matrix Multiplication Method
CPU Cycle Count = 107846959 CPU execution Time: = 10.6188
Execute time: 2.07271
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 107842535 CPU execution Time: = 10.6183
Execute time: 2.07177
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107841645 CPU execution Time: = 10.6183
Execute time: 2.07162
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107846907 CPU execution Time: = 10.6188
Execute time: 2.07226
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107850323 CPU execution Time: = 10.6191
Execute time: 2.07276
RMSE: 0.0001

 Performance counter stats for './hw2 384':

         55,609.70 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            13,099      page-faults:u             #    0.236 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      55.641572154 seconds time elapsed

      55.309827000 seconds user
       0.299836000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Block size 64

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
Block Matrix Multiplication Method
CPU Cycle Count = 107462983 CPU execution Time: = 10.581
Execute time: 2.03495
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 107457252 CPU execution Time: = 10.5804
Execute time: 2.03363
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107475248 CPU execution Time: = 10.5822
Execute time: 2.03549
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107516236 CPU execution Time: = 10.5862
Execute time: 2.03979
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 107501879 CPU execution Time: = 10.5848
Execute time: 2.03826
RMSE: 0.0001

 Performance counter stats for './hw2 384':

         55,427.10 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            13,096      page-faults:u             #    0.236 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      55.459128665 seconds time elapsed

      55.117019000 seconds user
       0.309870000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Block size 128

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
Block Matrix Multiplication Method
CPU Cycle Count = 111569905 CPU execution Time: = 10.9853
Execute time: 2.43928
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 111591134 CPU execution Time: = 10.9874
Execute time: 2.44079
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 111633946 CPU execution Time: = 10.9916
Execute time: 2.44509
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 111608289 CPU execution Time: = 10.9891
Execute time: 2.44261
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 111611496 CPU execution Time: = 10.9894
Execute time: 2.44294
RMSE: 0.0001

 Performance counter stats for './hw2 384':

         57,466.46 msec task-clock:u              #    1.000 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            13,088      page-faults:u             #    0.228 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      57.493663468 seconds time elapsed

      57.196444000 seconds user
       0.269888000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

From experiments below is the table with summary

S No	Block Size	Execution Time
1	**8**	10.79
2	**16**	10.6307
3	**32**	10.6188
4	**64**	10.581
5	**128**	10.9853

Result: With input image of size 384, the block size taking least CPU execution time is 64

Part 4

1. For each algorithm (Naive and Separable with and without LUTS; Matrix Multiplication, Block Matrix Multiplication) do perf analysis

Input size: 384 for all algorithm, except Naïve DCT as Naïve DCT took exceptionally long to complete for 384, Block Matrix block size = 64 for BMM.

Naïve DCT LUT Enabled (Size 64)

```
xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2
WES237B lab 2
LUT is Enabled in Naive Algo
CPU Cycle Count = 2147120 CPU execution Time: = 0.211409
Execute time: 0.211644
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2152899 CPU execution Time: = 0.211978
Execute time: 0.212181
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2156215 CPU execution Time: = 0.212304
Execute time: 0.212516
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2142166 CPU execution Time: = 0.210921
Execute time: 0.211136
RMSE: 0.0001
LUT is Enabled in Naive Algo
CPU Cycle Count = 2142350 CPU execution Time: = 0.210939
Execute time: 0.211148
RMSE: 0.0001

 Performance counter stats for './hw2':

          2,863.33 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,082      page-faults:u             #    0.002 M/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

       2.866347337 seconds time elapsed

       2.614521000 seconds user
       0.250433000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Avg time: 0.211409

Naïve DCT LUT disabled (Size 64)

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 ]
WES237B lab 2
LUT not Enabled in Naive Algo
CPU Cycle Count = 54611573 CPU execution Time: = 5.37714
Execute time: 1.08251
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54620313 CPU execution Time: = 5.378
Execute time: 1.08325
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54622121 CPU execution Time: = 5.37818
Execute time: 1.08344
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54585329 CPU execution Time: = 5.37456
Execute time: 1.07981
RMSE: 0.0001
LUT not Enabled in Naive Algo
CPU Cycle Count = 54597212 CPU execution Time: = 5.37573
Execute time: 1.08098
RMSE: 0.0001

 Performance counter stats for './hw2':

         28,676.57 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             6,078      page-faults:u             #    0.212 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      28.691824302 seconds time elapsed

      28.467767000 seconds user
       0.209836000 seconds sys


xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$
```

Avg time: 5.37818

1D Separable LUT Disabled (Size 384)

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
LUT is disabled for 1D Separable algo
CPU Cycle Count = 391679005 CPU execution Time: = 38.5653
Execute time: 4.20683
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 391517692 CPU execution Time: = 38.5494
Execute time: 4.19118
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 391576866 CPU execution Time: = 38.5553
Execute time: 4.19701
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 391506263 CPU execution Time: = 38.5483
Execute time: 4.19008
RMSE: 0.0000
LUT is disabled for 1D Separable algo
CPU Cycle Count = 391489141 CPU execution Time: = 38.5466
Execute time: 4.18833
RMSE: 0.0000

 Performance counter stats for './hw2 384':

        195,020.98 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             9,581      page-faults:u             #    0.049 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

     195.123774249 seconds time elapsed

     194.721223000 seconds user
       0.299894000 seconds sys
```

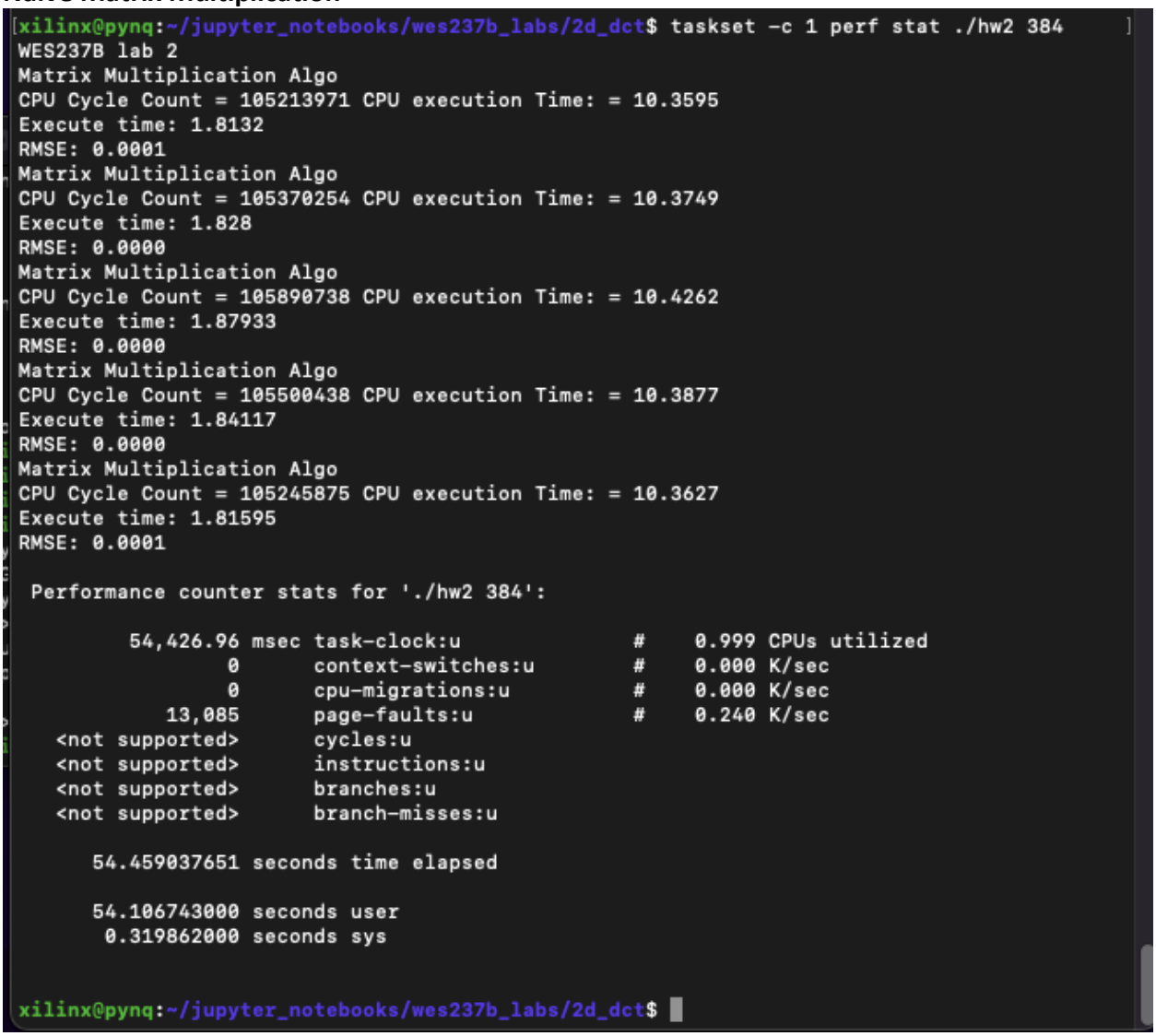
Avg time: 38.56

1D Separable LUT Enabled (Size 384)

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 384
WES237B lab 2
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 27216389 CPU execution Time: = 2.67977
Execute time: 2.68075
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 27277151 CPU execution Time: = 2.68575
Execute time: 2.68694
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 27192479 CPU execution Time: = 2.67741
Execute time: 2.67862
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 27183248 CPU execution Time: = 2.6765
Execute time: 2.67769
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 27270543 CPU execution Time: = 2.6851
Execute time: 2.68628
RMSE: 0.0001

 Performance counter stats for './hw2 384':

         15,726.40 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
             9,559      page-faults:u             #    0.608 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

     15.734773330 seconds time elapsed

     15.507758000 seconds user
      0.219968000 seconds sys
```

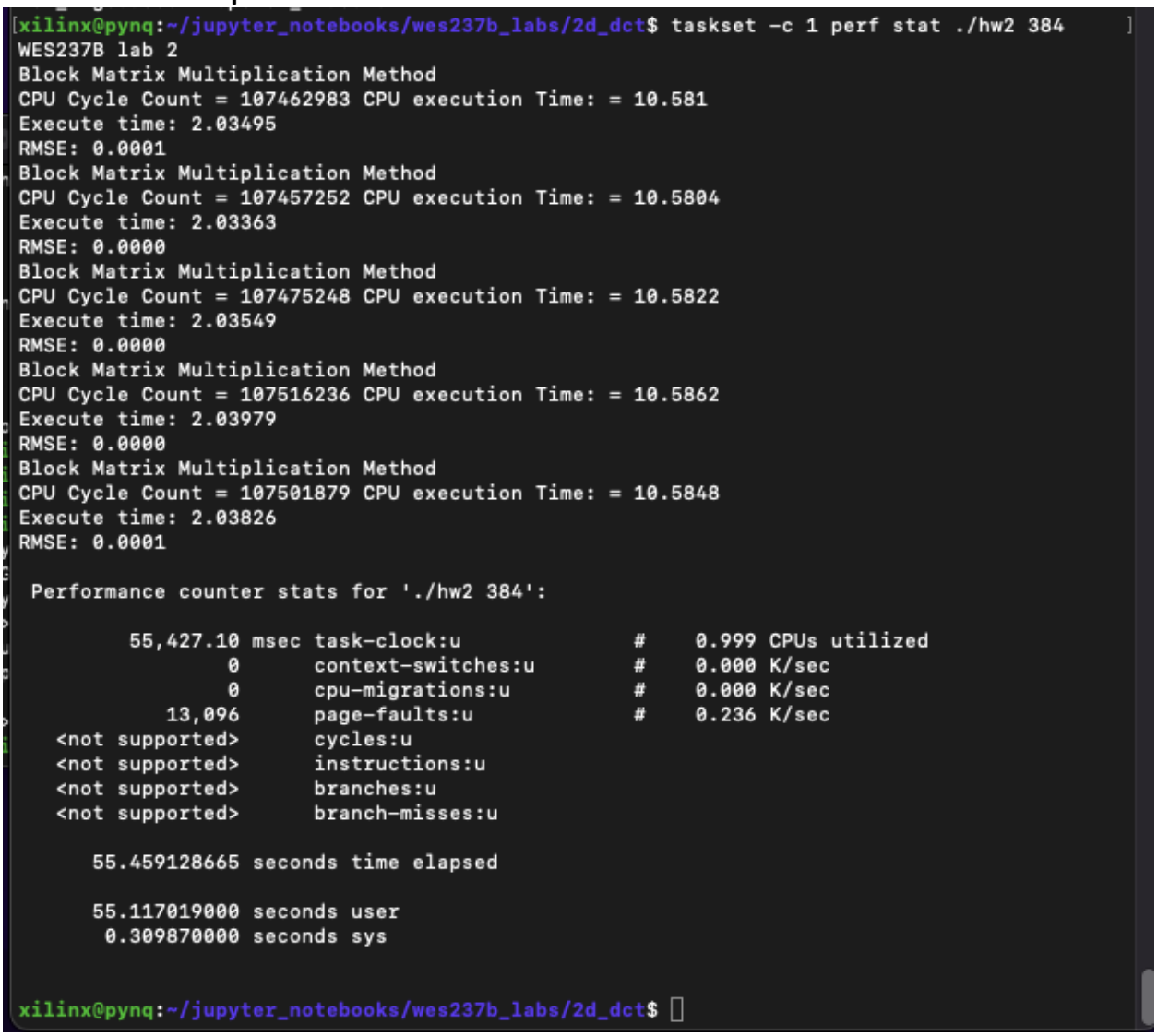
Avg time: 2.68

Naïve Matrix Multiplication



Average time: 10.36

Block Matrix Multiplication



Average Time: 10.581

Part 4:

2. **Setting frame number to 10 and performing the 1-D Separable, Matrix multiplication and BMM on input size of 448**

1D- Separable LUT Enabled:

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 448
WES237B lab 2
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44796813 CPU execution Time: = 4.41076
Execute time: 0.116835
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44695997 CPU execution Time: = 4.40084
Execute time: 0.107284
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44808635 CPU execution Time: = 4.41193
Execute time: 0.118412
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44637629 CPU execution Time: = 4.39509
Execute time: 0.101539
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44806239 CPU execution Time: = 4.41169
Execute time: 0.118169
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44588649 CPU execution Time: = 4.39027
Execute time: 0.0967438
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44748422 CPU execution Time: = 4.406
Execute time: 0.112476
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44582461 CPU execution Time: = 4.38966
Execute time: 0.096126
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44758246 CPU execution Time: = 4.40697
Execute time: 0.113432
RMSE: 0.0001
LUT is Enabled for 1D Separable algo
CPU Cycle Count = 44588403 CPU execution Time: = 4.39024
Execute time: 0.0967236
RMSE: 0.0001

 Performance counter stats for './hw2 448':

         47,585.86 msec task-clock:u              #    0.999 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            14,801      page-faults:u             #    0.311 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

      47.611609477 seconds time elapsed

      47.296557000 seconds user
       0.289917000 seconds sys
```

Avg time: 4.41 sec

Naïve Matrix Multiplication:

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 448
WES237B lab 2
Matrix Multiplication Algo
CPU Cycle Count = 174895609 CPU execution Time: = 17.2205
Execute time: 0.0993764
RMSE: 0.0000
Matrix Multiplication Algo
CPU Cycle Count = 174661586 CPU execution Time: = 17.1974
Execute time: 0.0760358
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 176332521 CPU execution Time: = 17.362
Execute time: 0.240437
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 174555336 CPU execution Time: = 17.187
Execute time: 0.0652392
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 175586231 CPU execution Time: = 17.2885
Execute time: 0.16653
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 174614885 CPU execution Time: = 17.1929
Execute time: 0.0711444
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 174772604 CPU execution Time: = 17.2084
Execute time: 0.0866742
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 174659204 CPU execution Time: = 17.1972
Execute time: 0.0754044
RMSE: 0.0001
Matrix Multiplication Algo
CPU Cycle Count = 174136704 CPU execution Time: = 17.1458
Execute time: 0.0242206
RMSE: 0.0000
Matrix Multiplication Algo
CPU Cycle Count = 174626794 CPU execution Time: = 17.194
Execute time: 0.0722784
RMSE: 0.0000

 Performance counter stats for './hw2 448':

        176,490.71 msec task-clock:u              #    0.986 CPUs utilized
                  0      context-switches:u        #    0.000 K/sec
                  0      cpu-migrations:u          #    0.000 K/sec
             25,535      page-faults:u             #    0.145 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

     179.035137635 seconds time elapsed

     175.963460000 seconds user
       0.519980000 seconds sys
```

Average CPU execution time 17.19

Block Matrix Multiplication

```
[xilinx@pynq:~/jupyter_notebooks/wes237b_labs/2d_dct$ taskset -c 1 perf stat ./hw2 448
WES237B lab 2
Block Matrix Multiplication Method
CPU Cycle Count = 172290886 CPU execution Time: = 16.964
Execute time: 4.138
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 172347033 CPU execution Time: = 16.9696
Execute time: 4.14292
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172333240 CPU execution Time: = 16.9682
Execute time: 4.1414
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172355979 CPU execution Time: = 16.9704
Execute time: 4.14366
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172362404 CPU execution Time: = 16.9711
Execute time: 4.14424
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172313209 CPU execution Time: = 16.9662
Execute time: 4.13952
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172353758 CPU execution Time: = 16.9702
Execute time: 4.14331
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172357984 CPU execution Time: = 16.9706
Execute time: 4.14384
RMSE: 0.0001
Block Matrix Multiplication Method
CPU Cycle Count = 172385419 CPU execution Time: = 16.9733
Execute time: 4.14655
RMSE: 0.0000
Block Matrix Multiplication Method
CPU Cycle Count = 172346332 CPU execution Time: = 16.9695
Execute time: 4.14335
RMSE: 0.0000

 Performance counter stats for './hw2 448':

        173,859.38 msec task-clock:u              #    0.996 CPUs utilized
                 0      context-switches:u        #    0.000 K/sec
                 0      cpu-migrations:u          #    0.000 K/sec
            24,988      page-faults:u             #    0.144 K/sec
   <not supported>      cycles:u
   <not supported>      instructions:u
   <not supported>      branches:u
   <not supported>      branch-misses:u

     174.608835223 seconds time elapsed

     173.405330000 seconds user
       0.449884000 seconds sys
```

Avg time: 16.97