# COL 380 A0 Report

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# 1 Experiment - I

## 1.1 Plot of Execution Time v/s Matrix size

A plot was created for each of the permutations (IJK, IKJ, JIK, JKI, KIJ, KJI) by varying the matrix size (shown on the x-axis) and recording the corresponding execution time (in seconds, as measured by the driver script provided) on the y axis.

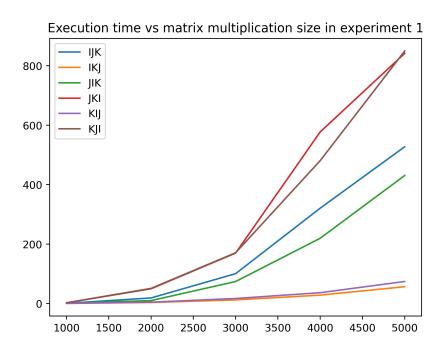


Figure 1: Experiment - I plot.

## 2 Experiment - II

#### 2.1 Plot of User Time v/s Matrix size

Similar to the above plot but Execution time along the y-axis replaced by the user time provided by perf.

#### Comparsion with plot in section 1

Before comparing the plots, let us define the Execution time and User time.

- Execution Time: It represents the total time a program takes to execute from start to finish. It includes User Time, System Time, and Waiting Time.
- User Time: It is the time spent executing instructions in user mode, which is the non-privileged mode where application-level code runs.



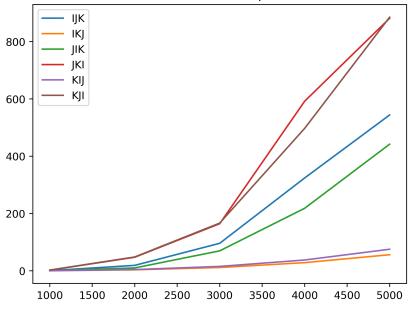


Figure 2: Experiment - II(a) plot.

- System Time: It is time spent in the kernel mode handling system calls (e.g., I/O operations).
- Waiting Time: It is time spent waiting for other processes, such as disk I/O or network responses.

By noticing the output from the perf command, it was evident that the system time and waiting time vary from a few milliseconds to seconds. Following this, we can say most of the execution time is indeed the user time, which is the reason the graphs have similar trends.

## 2.2 Plot of User Time for Matrix Multiplication v/s Matrix size

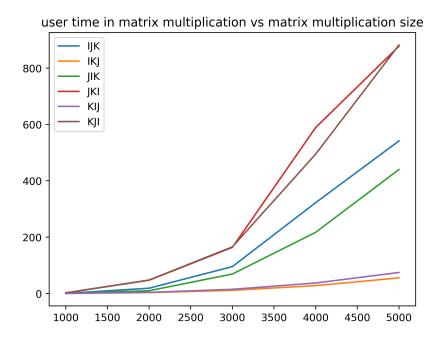


Figure 3: Experiment - II(b) plot.

Here we have considered plotting the self-time of matrix multiplication from the perf report against the matrix size. As the readMatrix and writeMatrix functions take a very small percentage of time in comparison to the matrixMultiplication function, which consists of 95% to 99% of userTime, this is the reason we observe a similar graph to the above one.

#### Understanding the Trends of Execution/User Time

To understand the trends we first need to look into memory access patterns of each of these permutations; based on this, we can classify them into the following types:

- Type: IJK & JIK In both of these cases we access the elements of A in row-major order and that of B in column-major order. It has moderate performance, by understanding below two categories it will be clear why this trend falls in between.
- Type: KIJ & IKJ In these cases we access the elements of both A & B in row major order. The result in this case is also stored in row-major order. It is the most favorable case in terms of performance because of proximity in memory accesses due to which we observe their trends to be at the bottom of the graph.
- Type: JKI & KJI In these cases the elements of A are accessed in row-major order. But the thing that makes it worst performing among all the three types in terms of performance is the fact the elements of C are being stored in column major order due to which there are frequent write backs to update the dirty cache lines while replacing the cache line with new data from next column ordered element (which is farther away in memory). This is the reason observe these permutations' curve lie above all other curves in the graph.

### 2.3 Plot of Cache Hit Rate v/s Matrix size

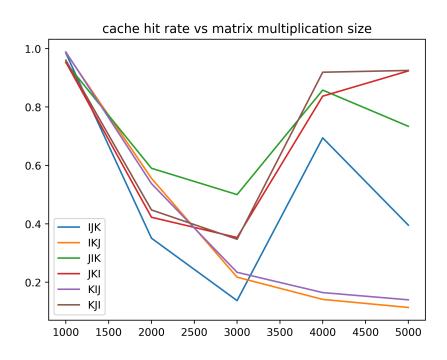


Figure 4: Experiment - II(c) plot.

#### Understanding the Trends of Cache Hit Rate

From the above discussion, it was clear that the IKJ and KIJ groups had optimal cache access patterns. However, we observed these to be at the bottom of the cache hit rate graphs. The reason could be the spatial proximity of data in the IKJ, causing the data from the cache to be moved to registers in a parallelized way, reducing the total number of cache accesses and hence giving a lower cache hit rate.

Permutation	Avg cache hit rate across matrix sizes
IJK	0.5124
IKJ	0.4029
JIK	0.7266
JKI	0.6978
KIJ	0.4129
KJI	0.7197

Table 1: Average cache hit rate for each permutation.

Permutation	Avg execution time across matrix sizes (sec)
IJK	196.66
IKJ	19.9376
JIK	148.0268
JKI	337.4176
KIJ	26.5836
KJI	319.879

Table 2: Average execution time for each permutation.

#### 2.4 Optimal Permutation and Disscussions

By analyzing Table-2, it is clear that IKJ is the optimal permutation in terms of average execution time across various sizes. This aligns with our explanation mentioned under the section 'Understanding the Trends of Execution/User Time'. If we look at Table-1, we can see that the permutations JIK, KJI, and JKI have one of the highest cache hit rates. The reason for this is not very clear and seems to have some relation with cache register interaction (as mentioned under section 'Understanding the Trends of Cache Hit Rate') and the sequential nature of the test we conducted.

# 2.5 Comparison of Reports from perf and gprof for time spent by each individual function

The table on the next page shows that both perf and gprof indicate a similar distribution of user time spent in individual functions (namely main, readMatrix, writeMatrix, and multiplyMatrix). However, perf provides a more realistic and accurate profiling. This was expected because, while gprof can show the exact function call count for a single program, it cannot resolve the call stack accurately and only provides an approximation. In contrast, perf is a modern, Linux-only tool for statistical profiling. It leverages hardware performance monitoring units and supports both single-program profiling and system-wide profiling. [Note that in the table below, for the performance data, we provided the percentages of user time for each function, including its child processes. However, in the raw data csv, we provided the self-time for the function involved.]

tiply 97.95 100.0 93.23 100.0 97.62 100.0 99.45 rix 0.34 0.0 1.04 0.0 0.79 0.0 0.04 0.0 0.04  0.00 0.17  0.34 0.0 2.08 0.0 0.79 0.0 0.17  0.00, 1JK 2000, 1KJ 2000, JIK 3000, JI			1000	1000, IJK	1000	1000, IKJ	1000	1000, JIK	1000	1000, JKI	1000, KIJ	, KIJ	1000	1000, KJI
matrixMultiply         97.95         100.0         93.23         100.0         97.62         100.0         99.45           readMatrix         0.34         0.0         1.04         0.0         0.4         0.0         0.04           writeMatrix         0.34         0.0         2.08         0.0         0.79         0.0         0.04           main         98.81         N/A         96.88         N/A         98.81         N/A         99.66           matrixMultiply         99.76         100         98.31         100         99.46         100         90.07           writeMatrix         0.06         0         0         0         0         0         0         0           matrixMultiply         99.89         100         99.91         N/A         99.97         N/A         99.99         0         0.05         0         0.01           matrixMultiply         99.93<			perf	gprof	$_{ m perf}$	gprof	$\mathbf{perf}$	$_{ m gprof}$	perf	gprof	perf	gprof	perf	gprof
PeadMatrix   0.34   0.0   1.04   0.0   0.4   0.0   0.04   0.04   0.04   0.04   0.04   0.04   0.05	%age of time spent in	matrixMultiply	97.95	100.0	93.23	100.0	97.62	100.0	99.45	100.0	95.36	100.0	99.51	100.0
writeMatrix         0.34         0.0         2.08         0.0         0.79         0.0         0.17           main         98.81         N/A         96.88         N/A         98.81         N/A         99.66           main         2000, IJK         2000, IKJ         2000, JIK         00.07         0         0.02         0         0.07         0         0.02         0         0.07         0         0.02         0         0.04         0         0.02         0         0.02         0         0.02         0         0.02         0         0.02         0         0.02         0         0.02         0         0.04         0         0.02         0         0.01         0         0.04         0         0.02         0         0.01         0         0.01         0         0.01         0         0.01         0         0.01         0         0.01         0         0         0         0         0         0         0         0         0		readMatrix	0.34	0.0	1.04	0.0	0.4	0.0	0.04	0.0	0.71	0.0	0.07	0.0
Perf   Sprof   Sprof   Perf   Sprof   Spro		writeMatrix	0.34	0.0	2.08	0.0	0.79	0.0	0.17	0.0	1.07	0.0	0.11	0.0
Perf   Sprof   Perf		main	98.81		88.96	N/A	98.81	N/A	99.66	N/A	97.5	N/A	99.74	N/A
matrixMultiply         99.76         perf         gprof         perf         gprof         perf         gprof         perf         gprof         perf         gprof         perf         gprof         99.46         100         99.88           readMatrix         0.04         0         0.2         0         0.07         0         0.02           writeMatrix         0.06         0         0.5         0         0.16         0         0.04           matrixMultiply         99.89         100         98.92         100         99.80         100         99.93           readMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.16         0         0.03         0         0.01           matrixMultiply         99.94         N/A         99.94         N/A         99.89         100         99.95           readMatrix         0.01         0         0.24         0         0.01         0         0           main         99.94         100 </td <td></td> <td></td> <td>2000</td> <td>, IJK</td> <td>2000</td> <td></td> <td>2000</td> <td>, JIK</td> <td>2000</td> <td>), JKI</td> <td>2000,</td> <td>, KIJ</td> <td>2000, KJ</td> <td>KJI</td>			2000	, IJK	2000		2000	, JIK	2000	), JKI	2000,	, KIJ	2000, KJ	KJI
matrixMultiply         99.76         100         98.31         100         99.46         100         99.88           readMatrix         0.04         0         0.2         0         0.07         0         0.02           writeMatrix         0.06         0         0.5         0         0.16         0         0.04           main         99.87         N/A         99.21         N/A         99.72         N/A         99.94           matrixMultiply         99.89         100         98.92         100         99.80         100         99.93           writeMatrix         0.02         0         0.16         0         0.05         0         0.01           matrixMultiply         99.94         N/A         99.44         N/A         99.92         N/A         99.95           matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           main         99.97         N/A         99.63         N/A         99.95         N/A         99.95           main         99.97         N/A         99.63         N/A         99.95         N/A         99.95           main         99.97			perf	gprof	$_{ m perf}$	gprof	$_{ m perf}$	gprof	perf	gprof	perf	gprof	perf	gprof
readMatrix         0.04         0         0.2         0         0.07         0         0.02           writeMatrix         0.06         0         0.5         0         0.16         0         0.04           main         99.87         N/A         99.21         N/A         99.72         N/A         99.94           matrixMultiply         99.89         100         98.92         100         99.80         100         99.93           readMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.31         0         0.05         0         0.02           main         99.94         N/A         99.44         N/A         99.92         N/A         99.96           matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           main         99.97         N/A         99.63         N/A         99.95         N/A         99.96           main         99.97         N/A         99.63         N/A         99.95         N/A         99.98           main         99.97         N/A	%age of time spent in	matrixMultiply	99.76	100	98.31	100	99.46	100	88.66	100	98.73	100	68.66	100
writeMatrix         0.06         0         0.5         0         0.16         0         0.04           main         99.87         N/A         99.21         N/A         99.72         N/A         99.94           matrixMultiply         99.87         100         98.92         100         99.80         100         99.93           readMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.31         0         0.05         0         0.02           main         99.94         N/A         99.44         N/A         99.92         N/A         99.96           matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           readMatrix         0.01         0         0.11         0         0.01         0         0.01         0         0.01         0         0           main         99.97         N/A         99.63         N/A         99.95         N/A         99.95         0         0         0           matrixMultiply         99.94         100         90.91         100 <t< td=""><td></td><td>readMatrix</td><td>0.04</td><td>0</td><td>0.2</td><td>0</td><td>0.07</td><td>0</td><td>0.02</td><td>0</td><td>0.16</td><td>0</td><td>0.01</td><td>0</td></t<>		readMatrix	0.04	0	0.2	0	0.07	0	0.02	0	0.16	0	0.01	0
main         99.87         N/A         99.21         N/A         99.72         N/A         99.94           matrixMultiply         perf         gprof         perf         gprof         perf         gprof         perf         perf         perf         gprof         perf         perf         gprof         perf         perf         perf         gprof         perf         perf <td></td> <td>writeMatrix</td> <td>90.0</td> <td>0</td> <td>0.5</td> <td>0</td> <td>0.16</td> <td>0</td> <td>0.04</td> <td>0</td> <td>0.39</td> <td>0</td> <td>0.03</td> <td>0</td>		writeMatrix	90.0	0	0.5	0	0.16	0	0.04	0	0.39	0	0.03	0
MatrixMultiply   99.87   90.0, IKJ   3000, JIK   3000, JIC   30.01   30.89   100   98.92   100   99.80   30.01   30.01   30.02   30.01   30.02   30.02   30.03   30.		main	28.66	N/A	99.21		99.72	N/A	99.94	N/A	99.38	N/A	99.94	N/A
matrixMultiply         99.89         100         98.92         100         99.80         100         99.93           readMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.31         0         0.03         0         0.01           main         99.94         N/A         99.44         N/A         99.92         N/A         99.96           matrixMultiply         99.93         100         99.24         N/A         99.93         100         99.95           readMatrix         0.01         0         0.11         0         0.01         0         0         0         0           matrixMultiply         99.97         N/A         99.63         N/A         99.95         N/A         99.98           matrixMultiply         99.94         100         99.41         100         99.95         N/A         99.95           matrixMultiply         99.94         100         99.91         0         0         0           writeMatrix         0.01         0         0         0         0         0         0           writeMatrix         0.0			3000	, IJK	3000	_	3000		3000	), JKI	3000,	, KIJ	3000	3000, KJI
matrixMultiply         99.89         100         98.92         100         99.80         100         99.93           readMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.31         0         0.05         0         0.01           main         99.94         N/A         99.44         N/A         99.92         N/A         99.96           matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           readMatrix         0.01         0         0.11         0         0.01         0         0         0         0           matrixMultiply         99.97         N/A         99.63         N/A         99.95         N/A         99.98           matrixMultiply         99.94         100         99.41         100         99.95         N/A         99.95           readMatrix         0.01         0         0.09         0         0.01         0         0         0           writeMatrix         0.01         0         0.09         0         0         0         0         0			perf	gprof	perf	gprof	$_{ m perf}$	gprof	perf	gprof	perf	gprof	perf	gprof
readMatrix         0.02         0         0.16         0         0.03         0         0.01           writeMatrix         0.02         0         0.31         0         0.05         0         0.02           main         99.94         N/A         99.92         N/A         99.96         N/A         99.96           matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           readMatrix         0.01         0         0.11         0         0.01         0         0         0         0           writeMatrix         0.01         0         0.24         0         0.03         0         0         0           main         99.97         N/A         99.63         N/A         99.95         N/A         99.98           matrixMultiply         99.94         100         99.91         100         99.95           readMatrix         0.01         0         0         0         0         0           writeMatrix         0.01         0         0         0         0         0         0           writeMatrix         0.01         0         0         0 <td>%age of time spent in</td> <td>matrixMultiply</td> <td>68.66</td> <td>100</td> <td>98.92</td> <td>100</td> <td>99.80</td> <td>100</td> <td>99.93</td> <td>100</td> <td>99.13</td> <td>100</td> <td>99.95</td> <td>100</td>	%age of time spent in	matrixMultiply	68.66	100	98.92	100	99.80	100	99.93	100	99.13	100	99.95	100
writeMatrix         0.02         0         0.31         0         0.05         0         0.02           main         99.94         N/A         99.44         N/A         99.92         N/A         99.96           matrixMultiply         99.94         N/A         99.92         N/A         99.96           matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           writeMatrix         0.01         0         0.11         0         0.01         0         0.01           writeMatrix         0.01         0         0.24         0         0.03         0         0.01           main         99.97         N/A         99.63         N/A         99.98         100         99.98           matrixMultiply         99.94         100         99.41         100         99.9         100         99.95           readMatrix         0.01         0         0.09         0         0.01         0         0.01           writeMatrix         0.01         0         0.07         0         0         0         0         0		readMatrix	0.02	0	0.16	0	0.03	0	0.01	0	0.12	0	0.01	0
main         99.94         N/A         99.44         N/A         99.92         N/A         99.96           matrixMultiply         perf         gprof         perf         gprof         perf         gprof         perf         perf         perf         4000, JIK         4		writeMatrix	0.02	0	0.31	0	0.05	0	0.02	0	0.25	0	0.02	0
MatrixMultiply   99.93   100   99.24   100   99.89   100   99.95   100   99.24   100   99.89   100   99.95   100		main	99.94	N/A	99.44	N/A	99.92	N/A	96.66	N/A	99.59	N/A	96.66	N/A
matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           readMatrix         0.01         0         0.11         0         0.01         0			4000	, IJK	4000	, IKJ	4000	, JIK	4000	), JKI	4000,	, KIJ	4000,	KJI
matrixMultiply         99.93         100         99.24         100         99.89         100         99.95           readMatrix         0.01         0         0.11         0         0.01         0			perf	gprof	$\mathbf{perf}$	gprof	$_{ m perf}$	gprof	perf	gprof	perf	gprof	perf	gprof
readMatrix         0.01         0         0.11         0         0.01         0           writeMatrix         0.01         0         0.24         0         0.03         0         0.01           main         99.97         N/A         99.63         N/A         99.95         N/A         99.98           perf         gprof         perf         gprof         perf         gprof         perf           matrixMultiply         99.94         100         99.41         100         99.9         100         99.95           readMatrix         0.01         0         0.09         0         0.01         0         0.01           writeMatrix         0.01         0         0.17         0         0.02         0         0.01	%age of time spent in	matrixMultiply	99.93	100	99.24	100	68.66	100	99.95	100	99.32	100	99.94	100
writeMatrix         0.01         0         0.24         0         0.03         0         0.01           main         99.97         N/A         99.63         N/A         99.95         N/A         99.98           5000, IJK         5000, IKJ         5000, JIK		readMatrix	0.01	0	0.11	0	0.01	0	0	0	0.08	0	0.01	0
main         99.97         N/A         99.63         N/A         99.95         N/A         99.98           fono, LJK         fono, LJK         fono, IKJ         fono, JIK         fono, JIK         fono, fono, fono, JIK         fono, fon		writeMatrix	0.01	0	0.24	0	0.03	0	0.01	0	0.21	0	0.01	0
5000, 1JK   5000, 1KJ   5000, JIK   5000, M		main	26.66	N/A	99.63	N/A	99.95	N/A	86.66	N/A	99.71	N/A	86.66	N/A
matrixMultiply         99.94         100         99.41         100         99.91         100         99.95           readMatrix         0.01         0         0.09         0         0.01         0         0.01           writeMatrix         0.01         0         0.17         0         0.02         0         0.01			2000	, IJK	5000	, IKJ	5000	, JIK	5000	, JKI	5000,	, KIJ	5000, KJI	KJI
matrixMultiply         99.94         100         99.41         100         99.9         100         99.95           readMatrix         0.01         0         0.09         0         0.01         0         0.01           writeMatrix         0.01         0         0.17         0         0.02         0         0.01			perf	$_{ m gprof}$	$_{ m perf}$	$_{ m gprof}$	$_{ m perf}$	gprof	perf	gprof	perf	gprof	perf	gprof
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	%age of time spent in	matrixMultiply	99.94	100	99.41	100	666	100	99.95	100	99.54	100	99.95	100
0.01 0 0.17 0 0.02 0 0.01		readMatrix	0.01	0	0.09	0	0.01	0	0.01	0	90.0	0	0.01	0
00 00   1/15   00 00   1/15   100   1/15   10 00		writeMatrix	0.01	0	0.17	0	0.02	0	0.01	0	0.14	0	0.01	0
$\mid 99.97 \mid { m N/A} \mid 99.71 \mid { m N/A} \mid 99.96 \mid { m N/A} \mid 99.98 \mid$		main	26.66	N/A	99.71	N/A	96.66	N/A	99.98	N/A	22.66	N/A	86.66	N/A

Table 3: Comparison of Perf and Gprof data for matrix sizes 1000 to 5000.