Name: Rohan Jhaveri
CSU ID: 830962238

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1a) GCC Version

```
[adminuser@localhost ~]$ gcc --version
gcc (GCC) 4.8.5 20150623 (Red Hat 4.8.5-11)
Copyright (C) 2015 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.
```

1b) Code Compilation Statement

```
[adminuser@localhost ~]$ cd Downloads/
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
All done.
```

2a) Information about execution time

The information about the execution time calculation was found on stack-overflow. (https://stackoverflow.com/questions/5248915/execution-time-of-c-program)

2b) Code changes

```
#include <time.h>    //Included this header file to calculate the execution time of the kernel
double time_spent; //Initialized a variable to store the execution time of the kernel
clock_t begin,end; //Initialized two variables to store the start and end time of the kernel execution
begin = clock(); //function call to calculate the start time of kernel execution
dgemm_kernel (ni, nj, nk, alpha, beta, *C, *A, *B);
end = clock(); //function call to calculate the end time of kernel execution
time_spent = ((double) (end – begin)); //calculate the kernel execution time
time_spent = time_spent/CLOCKS_PER_SEC; // convert the execution time from  number of clock cycles to seconds
printf ("time spent = %f\n", time_spent); // print the execution time in seconds
```

2c) Time taken by the dgemm_kernel

```
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.680000
All done.
```

2d) GigaFlops/s achieved by dgemm_kernel

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((2000 * 2000 * 1) + (2000 * 2000 * 2000 * 3)) *10^-9)/41.68
= 0.576 GigaFlops/s

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3a) Optimization method used

To optimize the kernel, loop transformation specifically loop unrolling method was used. The advantage of using loop unrolling is that it reduces the branching in the code. Hence branch penalty is minimized. This is because the compiler can pre calculate the next memory location at compile time rather then calculating it at run-time which is the reason for performance optimization.
But unrolling it by more number of iterations could result into increased code size, which is undesirable. Also, the cache may not be able to hold large amount of data, which could lead to cache miss and miss penalty and hence decrease performance. So, loop unrolling should not increase the code size by much in order to get optimization as in our case.

3b) Time taken by the optimized dgemm_kernel

```
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 4.980000
All done.
```

3c) GigaFlops/s achieved by dgemm_kernel

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((1000 * 1000 * 2) + (1000 * 1000 * 1000 * 6)) *10^-9)/4.98
= 1.205 GigaFlops/s

3d) Optimized C code attached in the email

4) For N = 512

1st run

```
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.670000
All done.
```

2nd run

```
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.680000
All done.
```

3rd run

```
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.660000
All done.
```

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4th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.660000
All done.

5th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.690000
All done.

6th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.660000
All done.

7th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.640000
All done.

8th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.670000
All done.

9th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.680000
All done.

10th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 0.700000
All done.

4a) Time
Min Time = 0.640000
Max Time = 0.700000
Avg. Time = (0.670000 + 0.680000 + 0.660000 + 0.660000 + 0.690000 + 0.660000 + 0.640000 + 0.670000 + 0.680000 + 0.700000) / 10 = 0.671000

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4b) Best GigaFlop/s achieved for N = 512

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((512 * 512 * 1) + (512 * 512 * 512 * 3)) *10^-9)/0.640000
= 0.629 GigaFlops/s

4) For N = 1000

1st run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 4.870000
All done.

2nd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 4.970000
All done.

3rd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.000000
All done.

4th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.100000
All done.

5th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 4.990000
All done.

6th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.150000
All done.

7th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.080000
All done.

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8th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 4.920000
All done.

9th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.080000
All done.

10th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.080000
All done.

4a) Time
Min Time = 4.870000
Max Time = 5.100000
Avg. Time = (4.870000 + 4.970000 + 5.000000 + 5.100000 + 4.990000 + 5.150000 + 5.080000 + 4.920000 + 5.080000 + 5.080000)/10 = 5.024000

4b) Best GigaFlop/s achieved for N = 1000

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((1000 * 1000 * 1) + (1000 * 1000 * 1000 * 3)) *10^-9)/4.870000
= 0.616 GigaFlops/s

4) For N = 1024

1st run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.500000
All done.

2nd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.420000
All done.

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3rd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.470000
All done.

4th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.610000
All done.

5th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.440000
All done.

6th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.500000
All done.

7th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.400000
All done.

8th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.470000
All done.

9th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.520000
All done.

10th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 5.530000
All done.

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4a) Time
Min Time = 5.420000
Max Time = 5.610000
Avg. Time = (5.500000 + 5.420000 + 5.470000 + 5.610000 + 5.440000 + 5.500000 + 5.400000 + 5.470000 + 5.520000 + 5.530000)/10 = 5.486000

4b) Best GigaFlop/s achieved for N = 1024

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((1024* 1024* 1) + (1024* 1024* 1024* 3)) *10^-9)/5.420000
= 0.595 GigaFlops/s

4) For N = 2000

1st run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.070000
All done.

2nd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.210000
All done.

3rd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 42.230000
All done.

4th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.350000
All done.

5th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.920000
All done.

6th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.090000
All done.

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7th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 42.170000
All done.

8th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 40.710000
All done.

9th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 41.350000
All done.

10th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 42.170000
All done.

4a) Time
Min Time = 40.710000
Max Time = 42.230000
Avg. Time = (42.170000 + 41.350000 + 40.710000 + 42.170000 + 41.920000 + 41.090000 + 41.350000 + 42.230000 + 41.210000 + 41.070000)/10 = 41.527000

4b) Best GigaFlop/s achieved for N = 2000

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((2000 * 2000 * 1) + (2000 * 2000 * 2000 * 3)) *10^-9)/40.710000
= 0.589 GigaFlops/s

4) For N = 2048

1st run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 42.490000
All done.

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2nd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 43.500000
All done.

3rd run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 44.870000
All done.

4th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 44.100000
All done.

5th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 44.010000
All done.

6th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 43.600000
All done.

7th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 43.560000
All done.

8th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 43.380000
All done.

9th run
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 43.000000
All done.

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10^{th} run

```
[adminuser@localhost Downloads]$ gcc dgemm.c -o dgemm
[adminuser@localhost Downloads]$ ./dgemm
time spent = 44.140000
All done.
```

4a) Time

Min Time = 42.490000

Max Time = 44.870000

Avg. Time = (42.490000 + 43.500000 + 44.870000 + 44.100000 + 44.010000 + 43.600000 + 43.560000 + 43.380000 + 43.000000 + 44.140000)/10 = 43.665000

4b) Best GigaFlop/s achieved for N = 2048

GigaFlops/s = (number of iterations * number of floating point operations*10^-9)/(Execution time)
= (((2048 * 2048 * 1) + (2048 * 2048 * 2048 * 3)) *10^-9)/42.490000
= 0.607 GigaFlops/s

4c) Reason for change of execution time for each run

The execution time changes every time a program is executed. This is because the operating system can schedule program run-times and wait times as it sees fit. Most of the times, on user centric OS they try to make things fair, so that a program doesn't get totally forgotten about i.e. the scheduling technique used by OS is preemptive. Hence the execution time of the program changes every time the we run it.

4d) Yes, the program was SIMD vectorized by the compiler.