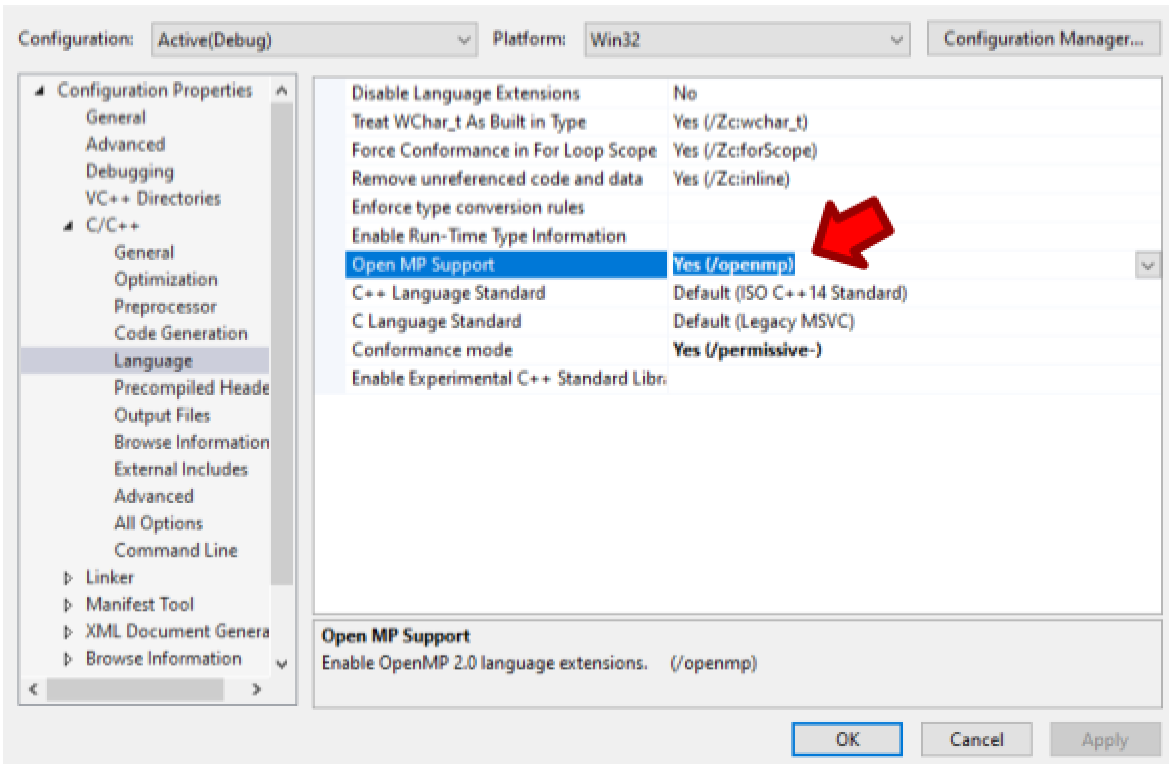
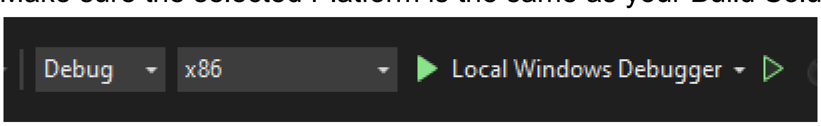
Resources: OpenMP - Official Website

Tutorial from OpenMP: OpenMP 101 (ACF Spring Training Workshop)
Official OpenMP in Visual C++ Documentation: MSDN Documentation on OpenMP

Pre-configuration in Visual Studio, in your Project Properties > Configuration Properties > C/C++ > Language > Open MP Support > select **Yes (/openmp)**



Make sure the selected Platform is the same as your Build Solution selected Platform:



Hints: **Win32** is the same as **x86**

Question 1:

Write a program, named P3Q1.cpp that displays Hello World with OpenMP. This is to check whether you have OpenMP configured.

```
#include "omp.h"

int main()
{
#pragma omp parallel
    {
        int ID = omp_get_thread_num();
        printf("hello(%d)", ID);
        printf("world(%d)\n", ID);
    }
    return 0;
}
```

Output:

```
hello(1)world(1)
hello(0)world(0)
hello(2)world(2)
hello(5)world(5)
hello(3)world(3)
hello(4)world(4)
hello(7)world(7)
hello(6)world(6)
```

OpenMP topic: Controlling thread data

In a parallel region there are two types of data: private and shared. In this section, we will see the various ways you can control what category your data falls under; for private data items we also discuss how their values relate to shared data.

Shared Data

In a parallel region, any data declared outside it will be shared: any thread using a variable x will access the same memory location associated with that variable.

Example:

```
int x = 5;
#pragma omp parallel
{
      x = x+1;
      printf("shared: x is %d\n",x);
}
```

Output:

```
Microsoft Visual Studio Debug Console
Shared: x is 8
Shared: x is 6
Shared: x is 7
Shared: x is 9
Shared: x is 9
Shared: x is 10
Shared: x is 11
Shared: x is 12
```

All threads increment the same variable, so after the loop it will have a value of five plus the number of threads; or maybe less because of the data races involved.

Sometimes this global update is what you want; in other cases the variable is intended only for intermediate results in a computation. In that case there are various ways of creating data that is local to a thread, and therefore invisible to other threads.

Private Data

In the C/C++ language it is possible to declare variables inside a *lexical scope* ; roughly: inside curly braces. This concept extends to OpenMP parallel regions and directives: any variable declared in a block following an OpenMP directive will be local to the executing thread.

Example:

```
int x = 5;
#pragma omp parallel
{
      int x; x = 3;
      printf("local: x is %d\n",x);
}
```

Output:

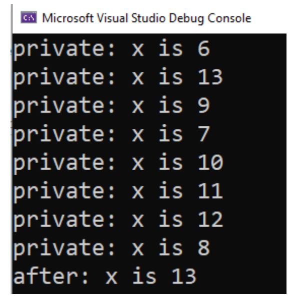
```
Microsoft Visual Studio Debug Console
Local: x is 3
Local: x is 3
Local: x is 3
Local: x is 3
Local: x is 3
Local: x is 3
Local: x is 3
Local: x is 3
```

After the parallel region the outer variable x will still have the value 5 : there is no *storage association* between the private variable and global one.

The private directive declares data to have a separate copy in the memory of each thread. Such private variables are initialized as they would be in a main program. Any computed value goes away at the end of the parallel region. (However, see below.) Thus, you should not rely on any initial value, or on the value of the outer variable after the region.

Example: Output:

```
int x = 5;
#pragma omp parallel
{
      x = x+1; // dangerous
      printf("private: x is %d\n",x);
}
printf("after: x is %d\n",x); // also dangerous
```



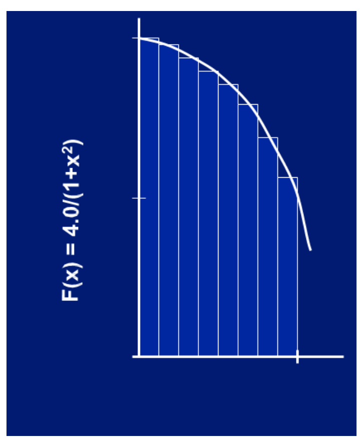
Question 2:
Write a program that computes the numerical integration below:
Mathematically, we know that,

$$F(x) = \int_0^1 \frac{4.0}{(1+x^2)} dx = \pi$$

We can approximate the sum of rectangles

$$\sum_{i=0}^{N} \Delta x F(x_i) \approx \pi$$

Where each rectangle has width Δx and height $F(x_i)$ at the middle of the interval i as shown in the figure.



The serial code is shown as below and obtained from here [P3Q2](P3Q2):

```
#include "stdafx.h"
#include "omp.h"

static long num_steps = 100000;
double step;

int main()
{
     int i; double x, pi, sum = 0.0;
     step = 1.0 / (double)num_steps;

     for (i = 0; i < num_steps; i++) {
          x = (i + 0.5)*step;
          sum = sum + 4.0 / (1.0 + x * x);
     }
     pi = step * sum;
     printf("%f", pi);
    return 0;
}
```

a) Create a parallel version of the pi program using a parallel construct.
   Use runtime library routines such as the followings:
   int omp_get_num_threads();
   Number of threads in the team

   Int omp_get_thread_num();
   Thread ID or rank

   Double omp_get_wtime();
   Time in seconds since a fixed point in the past

b) While the code in a) is correct, it may be inefficient because of a phenomenon called **false sharing**. Even though the threads write to separate variables, those variables are likely to be on the same cache line. This means that the cores will be wasting a lot of time and bandwidth updating each other's copy of this cache line.

   False sharing can be prevented by giving each thread its own cache line, modify the code using padding as shown in the example below:

   sum[i][pad]

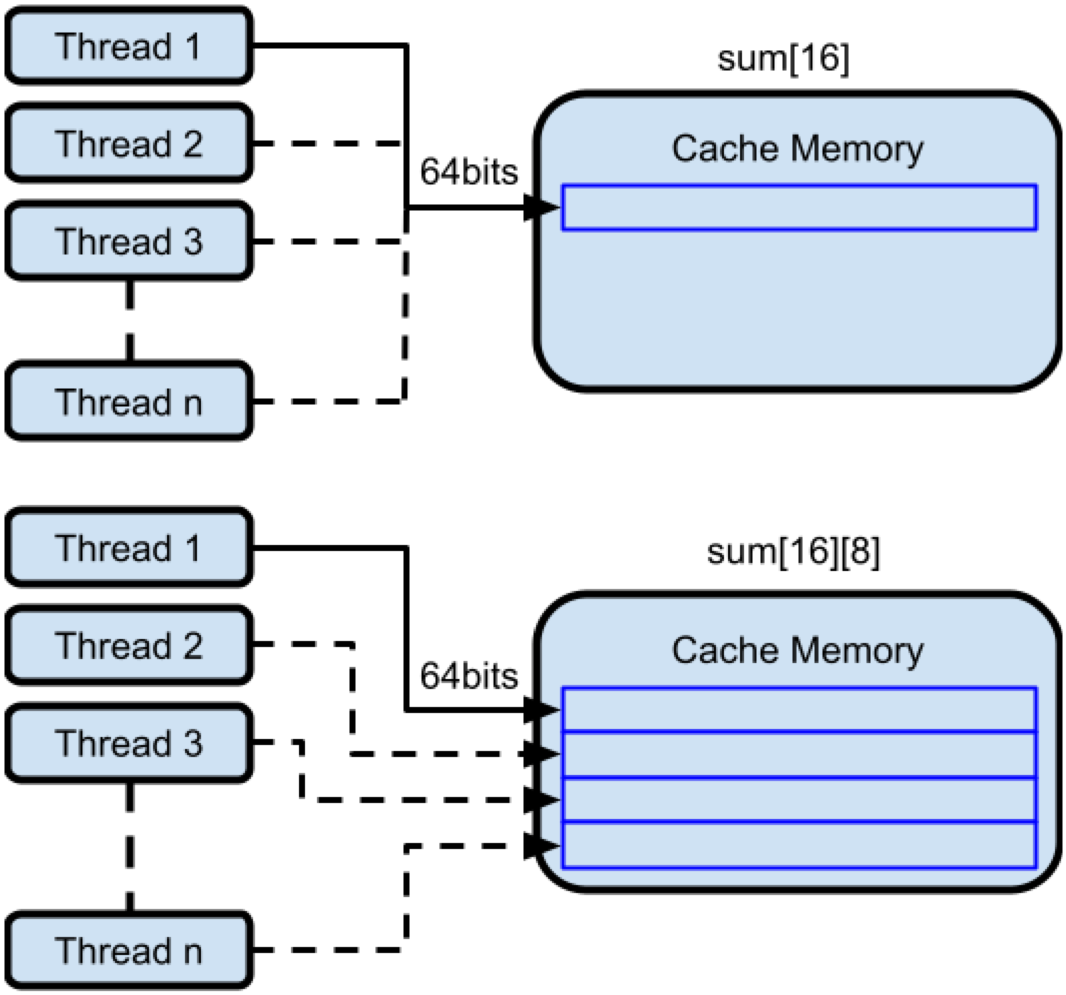


Illustration on Cache line(s)

* Compare the results between non-PAD and PAD, with
thread number = `8` and num_steps = `10000000` .

c) The OpenMP reduction clause lets you specify one or more thread-private variables that are subject to a reduction operation at the end of the parallel region. OpenMP pre defines a set of reduction operators. Each reduction variable must be a scalar (for example, int, long, and float). OpenMP also defines several restrictions on how reduction variables are used in a parallel region.

Modify the code using #pragma omp for reduction(+:sum).
Reference:
https://docs.microsoft.com/en-us/cpp/parallel/concrt/convert-an-openmp-loop-that-uses-a-reduction-variable?view=msvc-170

Output:

```
C:\WINDOWS\system32\cmd.exe
num_threads = 1
pi is 3.141593 in 0.907559 seconds and 1 threads
num_threads = 2
pi is 3.142932 in 0.636558 seconds and 2 threads
num_threads = 3
pi is 3.142014 in 0.625026 seconds and 3 threads
num_threads = 4
pi is 3.141898 in 0.621494 seconds and 4 threads
num_threads = 5
pi is 3.142028 in 0.770418 seconds and 5 threads
num_threads = 6
pi is 3.142065 in 0.718954 seconds and 6 threads
num_threads = 7
pi is 3.142139 in 0.715128 seconds and 7 threads
num_threads = 8
pi is 3.142018 in 0.648263 seconds and 8 threads
Press any key to continue . . .
```

* Discuss why the pi value is different with different numbers of thread.

Question 3.

Parallelize the matrix multiplication program in the file P3Q3.c. Then evaluate the time required to execute the program.

(Hints: Use #pragma omp parallel for private(.....))

Reference:
https://docs.microsoft.com/en-us/cpp/parallel/openmp/reference/openmp-clauses?view=msvc-170

Example answer

```
Microsoft Visual Studio Debug Console
Order 1000 multiplication in 0.491261 seconds
Order 1000 multiplication at 4071.151515 mflops

Hey, it worked
all done
```

* Compare the results with no having #pragma omp parallel for private(.....)

Compute Unified Device Architecture (CUDA)

* If CUDA is not installed properly, may need to download the latest version from here:
https://developer.nvidia.com/cuda-downloads

* For latest Visual Studio 2022 (Community Version), download from here
https://visualstudio.microsoft.com/vs/

[OPTIONAL] Setting up CUDA project in Visual Studio 2019 *only if you are using VS2019
https://medium.com/@aviatorx/c-and-cuda-project-visual-studio-d07c6ad771e3

Memory Allocation in CUDA
To compute on the GPU, you need to allocate memory accessible by the GPU. Unified Memory in CUDA makes this easy by providing a single memory space accessible by all GPUs and CPUs in your system. To allocate data in unified memory, call cudaMallocManaged(), which returns a pointer that you can access from host (CPU) code or device (GPU) code. To free the data, just pass the pointer to cudaFree().

Launch the functionCall() kernel, which invokes it on the GPU. CUDA kernel launches are specified using the triple angle bracket syntax << < > >>.

Call cudaDeviceSynchronize() before doing the final error checking on the CPU.
Save this code in a file called FileName.cu and compile it with nvcc, the CUDA C++ compiler.

In summary, the steps to allocate memory, implement program parallelization and free memory are as follows:

- allocate device memory
- copy host memory to device
- initialize thread block and kernel grid dimensions
- invoke CUDA kernel
- copy results from device to host
- deallocate device memory

Question 4:

Perform the above steps for Vector Addition, then use *nvprof* (Nvidia Profiler) to evaluate the performance for the codes below:

(i) Serial Vector Addition
(ii) Parallel Vector Addition

* To run *nvprof* and *nvcc* in command prompt, we may need to include the following two paths in Run (or Windows+R), type *sysdm.cpl* and press Enter,

System Properties > Advanced > Environment Variable> System Variable > Paths > Add New

```
C:\Program Files [OR (x86)]\Microsoft Visual Studio\[ANY VS YEAR]\Professional\VC\Tools\MSVC\[ANY NEWER VERSION]\bin\Hostx64\x64
```

- To get *cl.exe* when running nvcc (NVIDIA CUDA Compiler)

  We can run `nvcc [your *.cu]` file to generate `*.exe` file, without using Visual Studio.

```
C:\Program Files [OR (x86)]\NVIDIA GPU Computing Toolkit\CUDA\[ANY CUDA Version]\extras\CUPTI\lib64
```

- To get *cupti64_XXXX.dll* when running nvprof

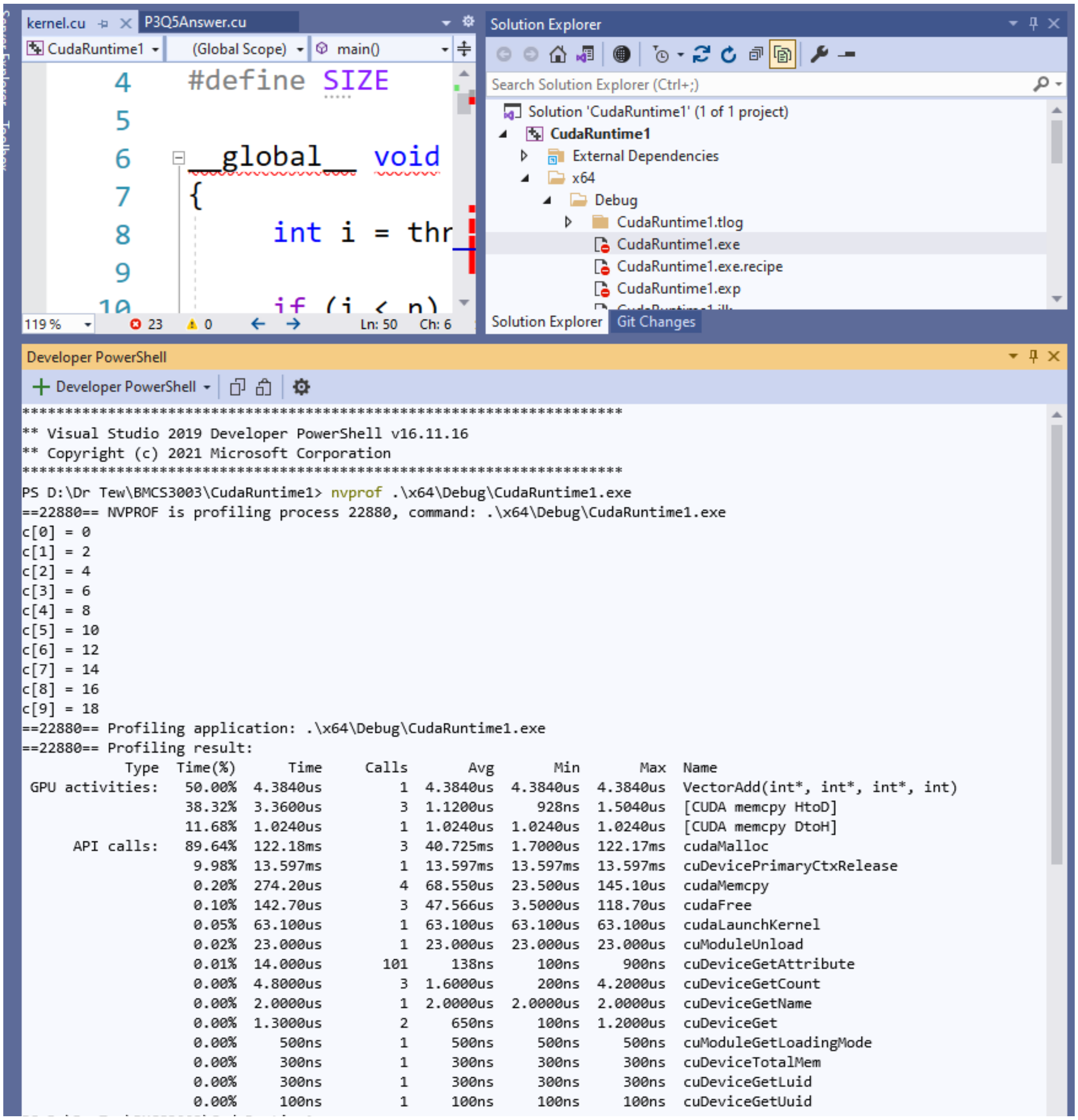
Output:
In powershell, type:

```
nvprof YOUR_COMPILED_PROJECT_EXE_PATH.exe
```

```
==6100== NVPROF is profiling process 6100, command: VectorAdd
c[0] = 0
c[1] = 2
c[2] = 4
c[3] = 6
c[4] = 8
c[5] = 10
c[6] = 12
c[7] = 14
c[8] = 16
c[9] = 18
==6100== Profiling application: VectorAdd
==6100== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   46.65%  5.1200us         3  1.7060us  1.5680us  1.9200us  [CUDA memcpy HtoD]
                   44.02%  4.8320us         1  4.8320us  4.8320us  4.8320us  VectorAdd(int*, int*, int*, int)
                    9.33%  1.0240us         1  1.0240us  1.0240us  1.0240us  [CUDA memcpy DtoH]
      API calls:   81.54%  260.76ms         3  86.919ms  3.9000us  260.74ms  cudaMalloc
                   17.82%  56.983ms         1  56.983ms  56.983ms  56.983ms  cuDevicePrimaryCtxRelease
                    0.32%  1.0088ms         1  1.0088ms  1.0088ms  1.0088ms  cuModuleUnload
                    0.09%  293.00us         3  97.666us  5.5000us  262.80us  cudaFree
                    0.09%  291.40us         4  72.850us  52.900us  87.300us  cudaMemcpy
                    0.08%  269.80us         1  269.80us  269.80us  269.80us  cuDeviceGetPCIBusId
                    0.02%  63.900us         1  63.900us  63.900us  63.900us  cudaLaunchKernel
                    0.02%  55.300us         1  55.300us  55.300us  55.300us  cuDeviceTotalMem
                    0.01%  41.700us        97     429ns     100ns  18.100us  cuDeviceGetAttribute
                    0.00%  4.2000us         3  1.4000us     500ns  3.2000us  cuDeviceGetCount
                    0.00%  2.3000us         1  2.3000us  2.3000us  2.3000us  cuDeviceGetName
                    0.00%  1.9000us         2     950ns     200ns  1.7000us  cuDeviceGet
                    0.00%     400ns         1     400ns     400ns     400ns  cuDeviceGetLuid
                    0.00%     300ns         1     300ns     300ns     300ns  cuDeviceGetUuid
```

OR
In visual studio terminal, type:

```
nvprof .\x64\Debug\YOUR_PROJECT_NAME.exe
```



If your computer generate the following result after running the nvprof:

```
PS C:\Users\TARUMT> nvprof
======== Error: no application specified.
PS C:\Users\TARUMT> nvprof "C:\Users\TARUMT\Desktop\CudaRuntime1\x64\Debug\CudaRuntime1.exe"
======== Warning: nvprof is not supported on devices with compute capability 8.0 and higher.
                  Use NVIDIA Nsight Systems for GPU tracing and CPU sampling and NVIDIA Nsight Compute for GPU profiling.
                  Refer https://developer.nvidia.com/tools-overview for more details.

PS C:\Users\TARUMT>
```

It is possible due to the NVIDIA graphic card compatibility issue, with the legacy nvprof application.

According to the official NVIDIA guideline, we are suggested to use the NVIDIA NSight System for executing the profiler. In the System Properties > Advanced > Environment Variable> System Variable > Paths > Add New:

C:\Program Files\NVIDIA Corporation\Nsight Systems 2022.1.3\target-windows-x64

To run nsys.exe profile function on the exe file

```
PS C:\Users\TARUMT> nsys profile "C:\Users\TARUMT\Desktop\CudaRuntime1\x64\Debug\CudaRuntime1.exe"
WARNING: CPU context switches trace requires administrative privileges, disabling.
WARNING: CPU sampling requires administrative privileges, disabling.
Generating 'C:\Users\TARUMT\AppData\Local\Temp\nsys-report-affd.qdstrm'
[1/1] [========================100%] report2.nsys-rep
Generated:
    C:\Users\TARUMT\report2.nsys-rep
```

To run analysis on the generated report nsys-rep file, double click the file and open using NVIDIA NSight System viewer,

OR

Run the nsys.exe **analyze** function on this generated report file:

```
PS C:\Users\TARUMT> nsys analyze C:\Users\TARUMT\report2.nsys-rep
Generating SQLite file C:\Users\TARUMT\report2.sqlite from C:\Users\TARUMT\report2.nsys-rep
Exporting 63 events: [=================================================100%]
Using C:\Users\TARUMT\report2.sqlite for SQL queries.
Running [C:/Program Files\NVIDIA Corporation\Nsight Systems 2022.1.3\target-windows-x64\rules\cuda-async-memcpy.py C:\Users
TARUMT\report2.sqlite]...

There were no problems detected related to memcpy operations using pageable
memory.

Running [C:/Program Files\NVIDIA Corporation\Nsight Systems 2022.1.3\target-windows-x64\rules\cuda-sync-memcpy.py C:\Users\
ARUMT\report2.sqlite]...

The following are synchronous memory transfers that block the host. This does
not include host to device transfers of a memory block of 64 KB or less.

Suggestion: Use cudaMemcpy*Async() APIs instead.

 Duration (ns)  Start (ns)  Src Kind  Dst Kind  Bytes (MB)   PID   Device ID  Context ID  Stream ID      API Name
 -------------  ----------  --------  --------  ----------  -----  ---------  ----------  ---------  ----------------
          1375   781303212  Device    Pageable       0.000  22380          0           1          7  cudaMemcpy_v3020

Running [C:/Program Files\NVIDIA Corporation\Nsight Systems 2022.1.3\target-windows-x64\rules\cuda-sync-memset.py C:\Users\
ARUMT\report2.sqlite]... SKIPPED: C:\Users\TARUMT\report2.sqlite could not be analyzed because it does not contain the requ
red CUDA data. Does the application use CUDA memset APIs?

Running [C:/Program Files\NVIDIA Corporation\Nsight Systems 2022.1.3\target-windows-x64\rules\cuda-sync-api.py C:\Users\TAR
MT\report2.sqlite]...

The following are synchronization APIs that block the host until all issued
CUDA calls are complete.
```

Question 5:

Using the same steps, modify the code for Matrix Multiplication that can be obtained here P3Q5.

- allocate device memory
  cudaMalloc((void **)&device_memory, MAX_BYTES);

- copy host memory to device
  cudaMemcpy(device_memory,host_memory,MAX_BYTES, cudaMemcpyHostToDevice);

- initialize thread block and kernel grid dimensions, and invoke CUDA kernel
  matrix_mul << < CEIL(MAX_SIZE, 1024), 1024 >> >(source, source, destination);

- copy results from device to host
  cudaMemcpy(host_memory,device_memory,MAX_BYTES, cudaMemcpyDeviceToHost);

- free the memories at the correct location

  Note: Adapt the variables that are highlighted in RED.
  Output:

```
The solution is correct
```