Question 1: (I'm using my own laptop with an nvidia gpu)

a How many GPUs are attached to mcu?
Two GPUs are attached to mcu

b What is the complete product name of each GPU?
GPU 0: NVIDIA GeForce RTX 2080 Ti (UUID: GPU-cca6f7c7-a959-b848-3875-e5eddaabd222)
GPU 1: NVIDIA GeForce RTX 2080 Ti (UUID: GPU-b3c99acd-d0c0-a736-b04e-1be9c8801078)

c What are the minimum, maximum, and default power limits?
nvidia-smi -q -d power

```
GPU 00000000:03:00.0
    Power Readings
        Power Management            : Supported
        Power Draw                  : 39.61 W
        Power Limit                 : 260.00 W
        Default Power Limit         : 260.00 W
        Enforced Power Limit        : 260.00 W
        Min Power Limit             : 100.00 W
        Max Power Limit             : 320.00 W
    Power Samples
        Duration                    : 0.60 sec
        Number of Samples           : 31
        Max                         : 40.43 W
        Min                         : 17.26 W
        Avg                         : 36.06 W

GPU 00000000:04:00.0
    Power Readings
        Power Management            : Supported
        Power Draw                  : 24.29 W
        Power Limit                 : 260.00 W
        Default Power Limit         : 260.00 W
        Enforced Power Limit        : 260.00 W
        Min Power Limit             : 100.00 W
        Max Power Limit             : 320.00 W
    Power Samples
        Duration                    : 0.07 sec
        Number of Samples           : 4
        Max                         : 33.52 W
        Min                         : 22.45 W
        Avg                         : 27.41 W
```

d What power limit is currently set?
Power Limit : 260.00 W

e What is the GPU shutdown temperature?
nvidia-smi -q -d temperature

GPU 00000000:03:00.0
Temperature
GPU Current Temp : 36 C
GPU Shutdown Temp : 94 C
GPU Slowdown Temp : 91 C
GPU Max Operating Temp : 89 C
GPU Target Temperature : 84 C
Memory Current Temp : N/A
Memory Max Operating Temp : N/A

GPU 00000000:04:00.0
Temperature
GPU Current Temp : 35 C
GPU Shutdown Temp : 94 C
GPU Slowdown Temp : 91 C
GPU Max Operating Temp : 89 C
GPU Target Temperature : 84 C
Memory Current Temp : N/A
Memory Max Operating Temp : N/A

f What is the maximum SM clock?
nvidia-smi -q -d CLOCK

GPU 00000000:03:00.0
Temperature
GPU Current Temp : 36 C
GPU Shutdown Temp : 94 C
GPU Slowdown Temp : 91 C
GPU Max Operating Temp : 89 C
GPU Target Temperature : 84 C
Memory Current Temp : N/A
Memory Max Operating Temp : N/A

GPU 00000000:04:00.0
Temperature
GPU Current Temp : 35 C
GPU Shutdown Temp : 94 C

```
        GPU Slowdown Temp               : 91 C
        GPU Max Operating Temp          : 89 C
        GPU Target Temperature          : 84 C
        Memory Current Temp             : N/A
        Memory Max Operating Temp       : N/A

[tyao0625@mcu ~]$ clear
[tyao0625@mcu ~]$ nvidia-smi -q -d CLOCK

==============NVSMI LOG==============

Timestamp                           : Thu Mar 10 22:45:23 2022
Driver Version                      : 470.63.01
CUDA Version                        : 11.4

Attached GPUs                       : 2
GPU 00000000:03:00.0
    Clocks
        Graphics                    : 1350 MHz
        SM                          : 1350 MHz
        Memory                      : 7000 MHz
        Video                       : 1245 MHz
    Applications Clocks
        Graphics                    : N/A
        Memory                      : N/A
    Default Applications Clocks
        Graphics                    : N/A
        Memory                      : N/A
    Max Clocks
        Graphics                    : 2160 MHz
        SM                          : 2160 MHz
        Memory                      : 7000 MHz
        Video                       : 1950 MHz
    Max Customer Boost Clocks
        Graphics                    : N/A
    SM Clock Samples
        Duration                    : Not Found
        Number of Samples           : Not Found
        Max                         : Not Found
        Min                         : Not Found
        Avg                         : Not Found
    Memory Clock Samples
        Duration                    : Not Found
        Number of Samples           : Not Found
```

```
        Max                 : Not Found
        Min                 : Not Found
        Avg                 : Not Found
    Clock Policy
        Auto Boost          : N/A
        Auto Boost Default  : N/A

GPU 00000000:04:00.0
    Clocks
        Graphics            : 1350 MHz
        SM                  : 1350 MHz
        Memory              : 7000 MHz
        Video               : 1245 MHz
    Applications Clocks
        Graphics            : N/A
        Memory              : N/A
    Default Applications Clocks
        Graphics            : N/A
        Memory              : N/A
    Max Clocks
        Graphics            : 2160 MHz
        SM                  : 2160 MHz
        Memory              : 7000 MHz
        Video               : 1950 MHz
    Max Customer Boost Clocks
        Graphics            : N/A
    SM Clock Samples
        Duration            : Not Found
        Number of Samples   : Not Found
        Max                 : Not Found
        Min                 : Not Found
        Avg                 : Not Found
    Memory Clock Samples
        Duration            : Not Found
        Number of Samples   : Not Found
        Max                 : Not Found
        Min                 : Not Found
        Avg                 : Not Found
    Clock Policy
        Auto Boost          : N/A
        Auto Boost Default  : N/A
```

Question 2:

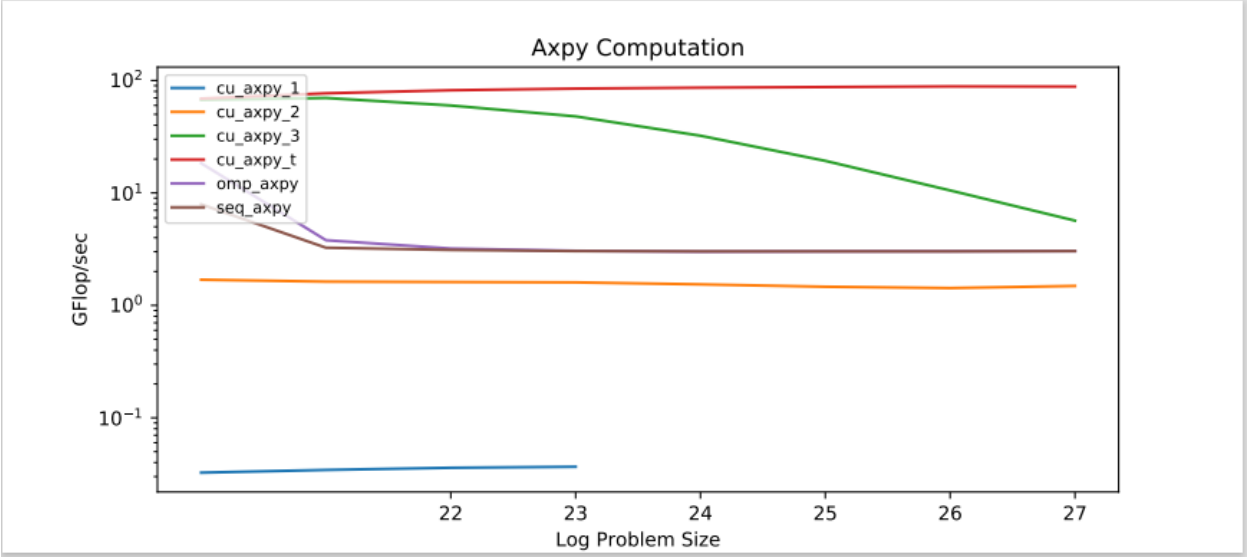
a How many total cores are available on each GPU?
(068) Multiprocessors, (064) CUDA Cores/MP: 4352 CUDA Cores
Each GPU has 4352 CUDA Cores

b What is the maximum dimension size of a thread block?
Max dimension size of a thread block (x,y,z): (1024, 1024, 64)

c What is the maximum dimension size of a grid size?
Max dimension size of a grid size (x,y,z): (2147483647, 65535, 65535)

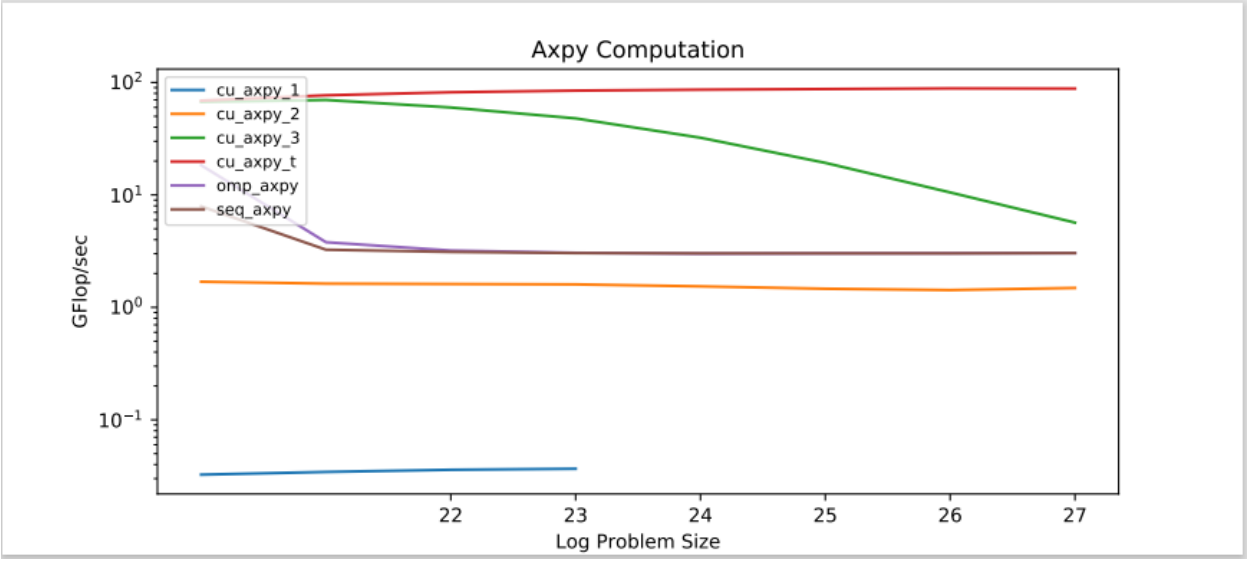
d What is the CUDA capability level of the GPUs?
CUDA Capability Major/Minor version number: 7.5

Question 3:
Cu_axpy_1 is only invoking 1 block per grid and 1 thread per block, whereas Cu_axpy_2 invokes 1 block per grid and 256 threads per block. So there're 255 more threads running in version 2 comparing to version 1. Under the most optimum assumption, based on the output reading of version 1, we assume it's the performance of exactly 1 thread per second, that is, 0.0375 glops / sec per thread. Because version 2 has 256 more threads, we times the per thread performance with 256 and the result is 9.6 gflps. But in reality we only got 2.5 gflps on version 2. There're two floating operations per madd function and N is 2^16 by default, which means there're 2*2^16=float operation, the expected speedup = expected axpy_1 time / expected axpy_2 time = (2*2^16 / 0.0375 gflops) / (2*2^16 / 2.5 gflops) = 26.6 / 0.4 = 66.5. But in reality speedup = 116ms/169ms = 0.69. This is also what I saw from my plot shown as follow:



Question 4:

Cu_axpy_3 has 256 blocks per grid and 256 threads per block, so that's 255*256 = 65280 more threads than cu_axpy_2. The version 2 has 2.5 gflps as we've already know. Version 3 on average has close to 23.5 gflops. This is not as close to what we'd expect. The expected speedup = expected axpy_2 time / expected axpy_3 time = (2*2^16 / 2.5 gflops) / (2*2^16 / 23.5 gflops) = 4 / 0.0425 = 94. But in reality speedup = 169ms / 71 ms = 2.38. The following is the axpy_cuda plot:



Question 5:
Based on my observations the block size give the best performance when block size = 128, output shown as follow:
[tyao0625@mcu axpy_cuda]$ ./cu_axpy_3.exe 24 128
elapsed time [cuda_malloc]: 1240 ms
elapsed time [cuda_call]: 54 ms
gflops / sec [madd]: 31.0689
elapsed time [cuda_free]: 6 ms

Which makes a lot of sense, because based on deviceQuery, the warp size of the gpu is 32, and 128 is 4 times more than the warp size. Which mean each core has to deal with 4 threads, 2 float operation, store 3 float values at a time. And from the device query we also know that the memory bus width is 352-bit. To reduce memory traffic, we need to make the 4 threads operations data stored as close to that number as possible. We need to store 3 float values, each float is 32 bits and we have 4 threads per core, which is 3*4*32 = 384 in total. So this way we maximized the usage of each core while also reduce to the least amount of memory traffic or make use the most amount of memory usage.

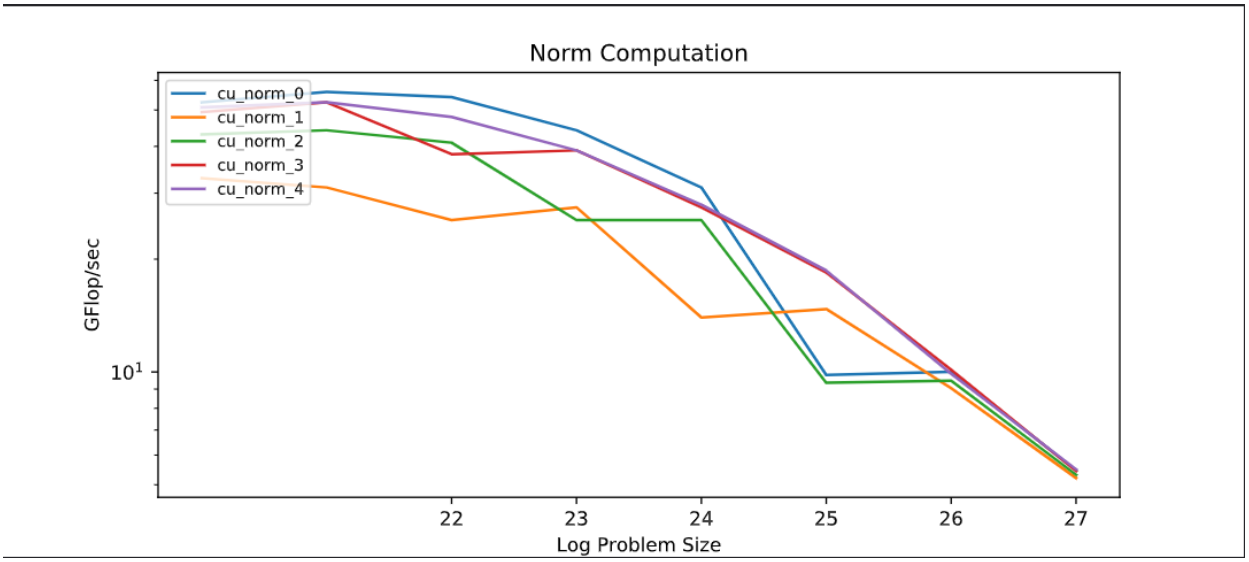
Question 6:
Because the latter case GPU has a lot more cores and bigger shared memories than CPU. The data being transferred from host to the device is much bigger than the former CPU case, which reduced the memory traffic memory significantly. Each SM contained multiple cores which they will all retrieve entries from the shared memory on the device. When the memory traffic gets resolved, which was the

biggest issue that caused stride solution being slow, the speed is no longer affected by and therefore significantly increased.

Question 7:
The max number of Gflops I was able to achieve from the GPU was around 55 Gflops. The following are the outputs from the seq and omp executable:

```
[tyao0625@mcu norm_cuda]$ ./norm_seq.exe
        N  Sequential   1 thread  2 threads  4 threads  8 threads
  1048576    12.7864    12.7178     12.752     12.752     12.752
  2097152    10.6644    11.2178    11.3246    11.2443    11.2709
  4194304    8.50802    8.56901    8.44789    8.61533    8.59983
  8388608    8.20346    8.13441    8.25955    8.24546    8.23141
 16777216    8.11267    8.17994    8.24833    8.16639    8.22084
 33554432      8.213    8.09567    8.17352     8.1998    8.09567
[tyao0625@mcu norm_cuda]$ ./norm_parfor.exe
        N  Sequential   1 thread  2 threads  4 threads  8 threads
  1048576    12.0706    12.1014     23.838    47.4376    87.8474
  2097152    11.0356     11.087    22.4356    39.3086    35.4951
  4194304    8.47785    8.67787    10.4628    13.3562    9.48712
  8388608    8.21741    8.10711    9.70249    10.4134    8.98111
 16777216    8.09935    8.22084    9.44924    9.80617    8.16639
 33554432     8.1998     8.1998    9.32408    9.80822    9.18968
```

The cuda performance is much faster with bigger Gflops across implementations. Especially when the problem sizes are bigger. The following is my norm_cuda.pdf plot:



Question 8:

The following are the outputs from my norm_thrust.exe

Float

N	Sequential	First	Second	First	Second
1048576	2.05736	12.1941	12.2687	1	1
2097152	2.05641	21.3954	21.5098	1	1
4194304	1.98201	33.9774	33.9774	1	1
8388608	1.97474	48.1605	48.1605	1	1
16777216	1.97286	60.787	61.6809	1	1
33554432	1.9729	70.3561	70.3561	1	1
67108864	1.97213	75.7681	77.0102	1	1
134217728	1.97162	80.13	80.13	nan	nan

Double

N	Sequential	First	Second	First	Second
1048576	2.04582	10.5298	10.6134	1	1
2097152	1.89376	16.9719	16.9719	1	1
4194304	1.86499	24.0673	24.0673	1	1
8388608	1.85484	30.3233	30.5496	1	1
16777216	1.85097	35.2463	35.2463	1	1
33554432	1.85148	38.2638	38.2638	1	1
67108864	1.85019	39.8103	39.8103	1	1
134217728	1.84937	40.672	40.9825	1	1

The highest performance I achieved was 80 Gflops for Float and 41 Gflops for double. When problem sizes are small, the performances of float and double are very similar. With float being just a little higher than double. But I started to see a more drastic performance when the problem sizes are bigger. In the biggest problem size, the float's Gflops almost doubled comparing to double. The following is a listing of my norm_thrust:

```
template<typename T>
T norm_thrust(const thrust::device_vector<T>& x) {
  T sum = thrust::reduce(x.begin(), x.end(), 0);
  return std::sqrt(sum);
}
```