**ECE569 -Homework 3**

**Matrix Multiplication**

1. **Objective**

The purpose of this lab is to implement two versions of the dense matrix multiplication routine and perform experiments to study the impact of array size, block size (tile size), and tiling.

**Note:** This assignment emphasizes experimental analysis. Please refer to the grading criteria.

1. **Logistics**

In the Assignment3 package you will find the “hw3” folder along with the “CmakeLists.txt”. Place them into your “labs” folder.

1. **Task 1: Instructions for basic matrix multiplication**

You will implement a basic dense matrix multiplication routine for arbitrary but legitimate size inputs. Optimizations such as tiling and usage of shared memory are not required for this version. You will find the temple source code named “solution.cu” in the folder named: hw3/BasicMatrixMultiplication

Edit this file to perform the following:

* Allocate device memory
* Copy host memory to device
* Initialize thread block and kernel grid dimensions
* Invoke CUDA kernel
* Copy results from device to host
* Free device memory
* Write the CUDA kernel

The code handles the import and export as well as the checking of the solution. Instructions about where to place each part of the code is demarcated by the **//@@**. You should keep all other parts of the template code unchanged.

**Compiling and Execution Instructions**

You will need to compile your code from the “build-dir” folder similar to the process described earlier assignments.

Change your home directory to ece569/build\_dir

**$ cd ece569/build\_dir**

Then run the following commands:

**$module load cuda11/11.0**

**$CC=gcc cmake3 ../labs**

**$make**

The makefile compiles and generates the executable “BasicMatrixMultiplication\_Solution” in the “build-dir” directory. The executable generated as a result of compiling the lab can be run using the following command:

**./BasicMatrixMultiplication\_Solution -e <expected.raw> -i <input0.raw>,<input1.raw> -t matrix > output.txt**

where <expected.raw> is the expected output, <input0.raw>,<input1.raw> is the input dataset, and output.txt stores the results.

The datasets can be generated using the dataset generator built as part of the compilation process.

BasicMatrixMultiplication\_DatasetGenerator in the build-dir generates the data set.

**$./BasicMatrixMultiplication\_DatasetGenerator**

then go into the MatrixMultiplication folder to access the test files.

* Dataset generator has routines to print transposed matrix for convenience.
  + If you want to test your code with small non-square matrix, printing the first one in transpose is convenient. You can then copy paste into excel and do column wise multiplication of the two inputs to check your results.
  + Refer to lines #107 and #110 in MatrixMultiplication/dataset\_generator.cpp
* **When grading square and non-square matrices will be used. Refer to grading criteria.**

Example test run:

**Before running your slurm script (run\_hw3.slurm provided in Assignment 3) ,**

**create the following folder in your “build\_dir” directory:**

**$mkdir BasicMatrixMultiplication\_output**

**In the slurm script, you should comment out the test runs related to the TiledMatrixMultiplication (lines 60-76)**

**Then launch your jobs**

**$srun run\_hw3.slurm**

**Outputs for each test case will be written into the “BasicMatrixMultiplication\_output” folder.**

1. **Task 2: Instructions for tiled matrix multiplication**

You will implement a tiled dense matrix multiplication routine using shared memory. Before starting this task, make sure that you have completed "Basic Matrix Multiplication".

**Instructions**

You will find the temple source code named “solution.cu” in hw3/TiledMatrixMultiplication

Edit the code to perform the following:

* 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

Instructions about where to place each part of the code is demarcated by the **//@@** lines.

You will need to compile your code from the “build-dir” folder. In your “build\_dir” type the following command to compile:

**$make**

The datasets can be generated using the dataset generator built as part of the compilation process.

**TiledMatrixMultiplication\_DatasetGenerator** in the build-dir generates the data set.

**$./TiledMatrixMultiplication\_DatasetGenerator**

then go into the **TiledMatrixMultiplication** folder to access the test files.

* You should test your code with all the files in the data set. You can modify the “dataset\_generator.cpp” modules to test your code for various sizes.
* Dataset generator has routines to print transposed matrix for convenience.
  + If you want to test your code with small non-square matrix, printing the first one in transpose is convenient. You can then copy paste into excel and do column wise multiplication of the two inputs to check your results.
  + Refer to line #99 in TiledMatrixMultiplication/dataset\_generator.cpp
* **When grading square and non-square matrices will be used. Refer to grading criteria.**

The executable generated as a result of compiling the lab can be run using the following command:

**./TiledMatrixMultiplication\_Solution -e <expected.raw> -i <input0.raw>,<input1.raw> -t matrix > output.txt**

where <expected.raw> is the expected output, <input0.raw>,<input1.raw> is the input dataset, and output.txt stores the results.

Example test run:

**Before running your pbs script (run\_hw3.slurm provided in Assignment 3) ,**

**create the following folder in your “build\_dir” directory:**

**$mkdir TiledMatrixMultiplication\_output**

**In the slurm script, make sure that lines 38-56 are uncommented from task1 before running the jobs.**

**Then launch your jobs**

**$srun run\_hw3.slurm**

**Outputs for each test case will be written into the “TiledMatrixMultiplication\_output” folder.**

1. **Task 3: Performance Analysis**

**Objective:** Practice running configuration sweeping experiments and data collection

**Modify the dataset\_generator.cpp for both basic and tiled versions to include the following test cases:**

Case 1: A is 2048x2048, B is 2048x2048

Case 2: A is 2051x2051, B is 2051x2051

Case 3: A is 4096x2048, B is 2048x4096

Case4: A is 4096x2047, B is 2047x4095

For each **version** (basic and tiled matrix multiplication)

For each **test case** ( 4 cases)

For each **thread block** configuration of 4x4, 8x8, 16x16 and 32x32

* Run each experiment configuration 10 times
* Collect average computation time (time spent on kernels excluding time spent on memory allocations, data transfer from host to device and device to host) data across 10 experiments
* Fill the timing table below for each test case and thread block configuration.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Execution Time Data | | | | | |
|  |  | Thread block configuration | | | |
|  | Test case | 4x4 | 8x8 | 16x16 | 32x32 |
| Basic Matrix Multiply Kernel | Case 1 |  |  |  |  |
| Case 2 |  |  |  |  |
| Case 3 |  |  |  |  |
| Case 4 |  |  |  |  |
| Tiled Matrix Multiply Kernel | Case 1 |  |  |  |  |
| Case 2 |  |  |  |  |
| Case 3 |  |  |  |  |
| Case 4 |  |  |  |  |

**Analysis Required**

Perform performance comparison based on timing table given above. For this analysis, plot the following line and bar charts to visualize the data and trends.

Plot1: Line chart for basic version

Execution time (y-axis) with respect to problem size (x-axis) where each line in the chart shows the trend for a given block size.

Plot2: Line chart for tiled version

Execution time with respect to problem size where each line in the chart shows the trend for a given block size.

Plot3: Basic and Tiled version performance with respect to block size

For the largest input size plot bar chart on execution time with respect to thread block configuration (Two bars per thread block configuration representing basic and tiled versions respectively).

You need to include at least the following discussions with a root cause analysis.

1. Fix input size, discuss execution time trends with respect to change in thread block configuration for basic and tiled solutions individually. What is the optimal thread block configuration for each version? Discuss why a specific block size results with best/worst performance for each version? Does optimal block size depend on the input size?
2. Discuss execution time trends among square matrices only for basic and tiled versions individually.
3. Discuss execution time trends among square and non-square matrices for basic and tiled versions individually.
4. Discuss performance of basic and tiled solution versions for a given problem size and across different problem sizes. Include any additional plot that will help your claims.
5. Can basic version execute faster than the tiled version for the same problem size? You need to use dataset\_generator to change the problem size and show execution time performance.
6. Can basic version run faster than the tiled version for the same block size? Your discussions need to be based on your experimental results.

**Suggested approach**:

In the CMakeLists.txt, if you have enabled, you should turn off all debugging related flags. You may observe noisy timing for the same testcase for various runs. For this, running each test case for 10 times and taking the average should help. You will need to modify your slurm script.

For this experiment it might save you time to run through all configurations. You may also prefer to use your own timer function for computation time analysis. For both needs, there is a template in “BasicMatrixMultiplication” folder “solution\_template\_with\_timer\_utility\_without\_wb\_library”. The main function has all wb calls commented out except functional verification. For a given test case, once filled in with kernel code, it will run for all four thread block configurations and generate an output similar to the following:

Total execution time (ms) ??? for block size 4 x 4 matrix size of 128 x 128 and 128 x 128

{"data": {"correctq": true, "message": "The solution is correct"}, "type": "solution"}

Total execution time (ms) ??? for block size 8 x 8 matrix size of 128 x 128 and 128 x 128

{"data": {"correctq": true, "message": "The solution is correct"}, "type": "solution"}

Total execution time (ms) ???for block size 16 x 16 matrix size of 128 x 128 and 128 x 128

{"data": {"correctq": true, "message": "The solution is correct"}, "type": "solution"}

Total execution time (ms) ??? for block size 32 x 32 matrix size of 128 x 128 and 128 x 128

{"data": {"correctq": true, "message": "The solution is correct"}, "type": "solution"}

1. **Submission Instructions**

**It is critical that you follow the following steps for submission. Please refer to penalty points.**

1. **Rename your solution.cu files from parts C and D as basic\_solution.cu** and **tiled\_solution.cu** for global and tiled versions respectively**.** 
   1. **Make sure that these are the versions implemented using the solution templates given for each in the BasicMatrixMultiplication (solution.cu) and TiledMatrixMultiplication (solution.cu) folders. Testing and validation process relies on the wb library.**
   2. **“**solution\_template\_with\_timer\_utility\_without\_wb\_library.cu” is provided for helping you with automating the testing of block size variations. It is a suggested method. You can use any method you prefer. **Do not** submit any code built based on this template.
2. Create a folder and name it as your “net id”.
   1. Include **basic\_solution.cu** and **tiled\_solution.cu** in the **“netid”** folder
3. Zip your **netid** folder **(netid.zip)**
4. Create a **hw3\_netid** folder
   1. Include **netid.zip**
   2. Include **ECE569\_hw3.docx** or **ECE\_hw3.pdf** file with part E (data and analysis)
   3. Create “**BasicMatrixMultiplication\_output** ” folder and include output files for the 10 public test cases
   4. Create “**TiledMatrixMultiplication\_output** ” folder and include output files for the 10 public test cases
5. Zip **hw3\_netid** folder
6. Submit **hw3\_netid.zip** to the designated D2L hw3 folde**r.**
7. **Grading**
8. basic\_solution.cu coding style and commenting 10pts
9. tiled\_solution.cu coding style and commenting 10pts
10. **BasicMatrixMultiplication\_output**

**(folder that contains all output files for the public test cases)** 20pts

1. **TiledMatrixMultiplication\_output**

**(folder that contains all output files for the public test cases)** 30pts

1. ECE569\_hw3.docx file with part E 100pts
2. basic\_solution.cu (based on private test cases) 20 pts
3. tiled\_solution.cu (based on private test cases) 60 pts

Total 250 points

Penalty Conditions (20% each):

* Incompatible submission (file naming/folder structure issue that makes submission incomparable to compile/test
* Missing output files
* Late submission per day

**Optional Analysis If you have access to your own GPU - Profiling based analysis:**

Refer to the template given in the “Content🡺Demo🡺Profiling” for setting up hw3 for profiling.

**Include profile.txt file that is showing the execution time analysis and correlate to timing measurements in your sweeping experiments.**

What are the improvements observed for the tiled solution compared to the basic solution? What are the performance issues regarding the execution of the tiled solution?

Perform memory, compute and latency analysis

* 1. Execution time
  2. Memory bandwidth utilization: Traffic to/from each memory subsystem relative to peak (L1/shared memory, L2, device memory)
  3. Compute resource utilization: divergent branches, warp execution efficiency,
     1. Occupancy analysis
     2. upper bound analysis based on threads/block, shared memory usage/block, register usage per thread,
     3. Achieved occupancy – (active warps/active cycles)/ Maximum warps per SM
     4. Warps per SM with respect to varying block size (threads per block)
     5. Instruction and memory latency

Support your claims referring to several performance metrics related to memory, thread behavior, utilization and efficiency factors. You should connect your arguments with the nature of the input data (square, non-square, matrix dimension).