Project 1: Embarrassingly Parallel Programming

This project weights 12.5% for your final grade (4 Projects for 50%)

Release Date:

September 22nd, 2023 (Beijing Time, UTC+8)

Deadline (Submit on BlackBoard):

11:59 P.M., October 10th, 2023 (Beijing Time, UTC+8)

Prologue

As the first programming project, students are required to solve embarrassingly parallel problem with six different parallel programming languages to get an intuitive understanding and hands-on experience on how the simplest parallel programming works. A very popular and representative application of embarrassingly parallel problem is image processing since the computation of each pixel is completely or nearly independent with each other.

This programming project consists of two parts:

Part-A: RGB to Grayscale

Note: You do not need to modify the codes in this part. Just compile and execute them on the cluster to get the experiment results, and include that in your report.

In this part, students are provided with ready-to-use source programs in a properly configured CMake project. Students need to download the source programs, compile them, and execute them on the cluster to get the experiment results. During the process, they need to have a brief understanding about how each parallel programming model is designed and implemented to do computation in

parallel (for example, do computations on multiple data with one instruction, multiple processes with message passing in between, or multiple threads with shared memory).

Problem Description

What is RGB Image?

RGB image can be viewed as three different images(a red scale image, a green scale image and a blue scale image) stacked on top of each other, and when fed into the red, green and blue inputs of a color monitor, it produces a color image on the screen.

Reference: https://www.geeksforgeeks.org/matlab-rgb-image-representation/

What is Grayscale Image?

A grayscale (or graylevel) image is simply one in which the only colors are shades of gray. The reason for differentiating such images from any other sort of color image is that less information needs to be provided for each pixel. In fact a `gray' color is one in which the red, green and blue components all have equal intensity in RGB space, and so it is only necessary to specify a single intensity value for each pixel, as opposed to the three intensities needed to specify each pixel in a full color image.

Reference: https://homepages.inf.ed.ac.uk/rbf/HIPR2/gryimage.htm (Glossary of University of Edinburgh)

RGB to Grayscale as a Point Operation

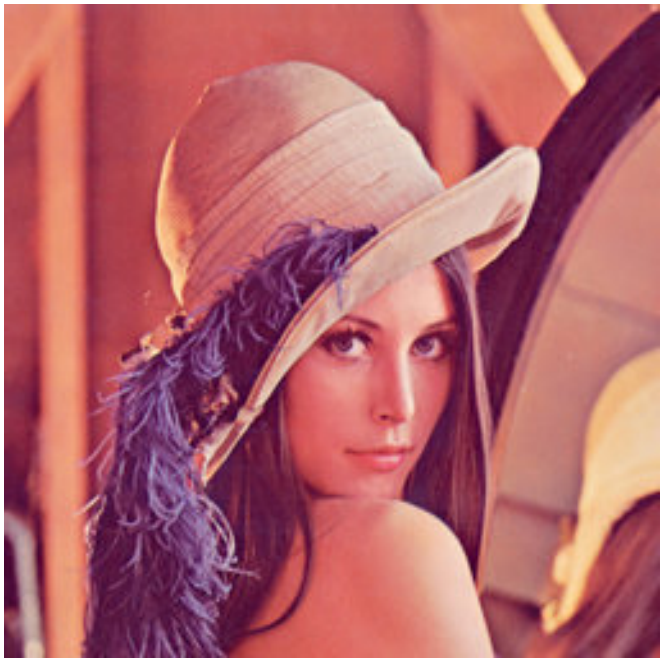
Transferring an image from RGB to grayscale belongs to point operation, which means a function is applied to every pixel in an image or in a selection. The key point is that the function operates only on the pixel's current value, which makes it completely embarrassingly parallel.

In this project, we use NTSC formula to be the function applied to the RGB image.

$$Gray = 0.299 * Red + 0.587 * Green + 0.114 * Blue$$

Reference:
https://support.ptc.com/help/mathcad/r9.0/en/index.html#page/PTC_Mathcad_Help/example_grayscale_and_color_in_images.html

Example



Convert Lena JPEG image (256x256) from RGB to Grayscale

Convert 4K JPEG image (3840x2599) from RGB to Grayscale

Part-B: Image Filtering (Soften with Equal Weight Filter)

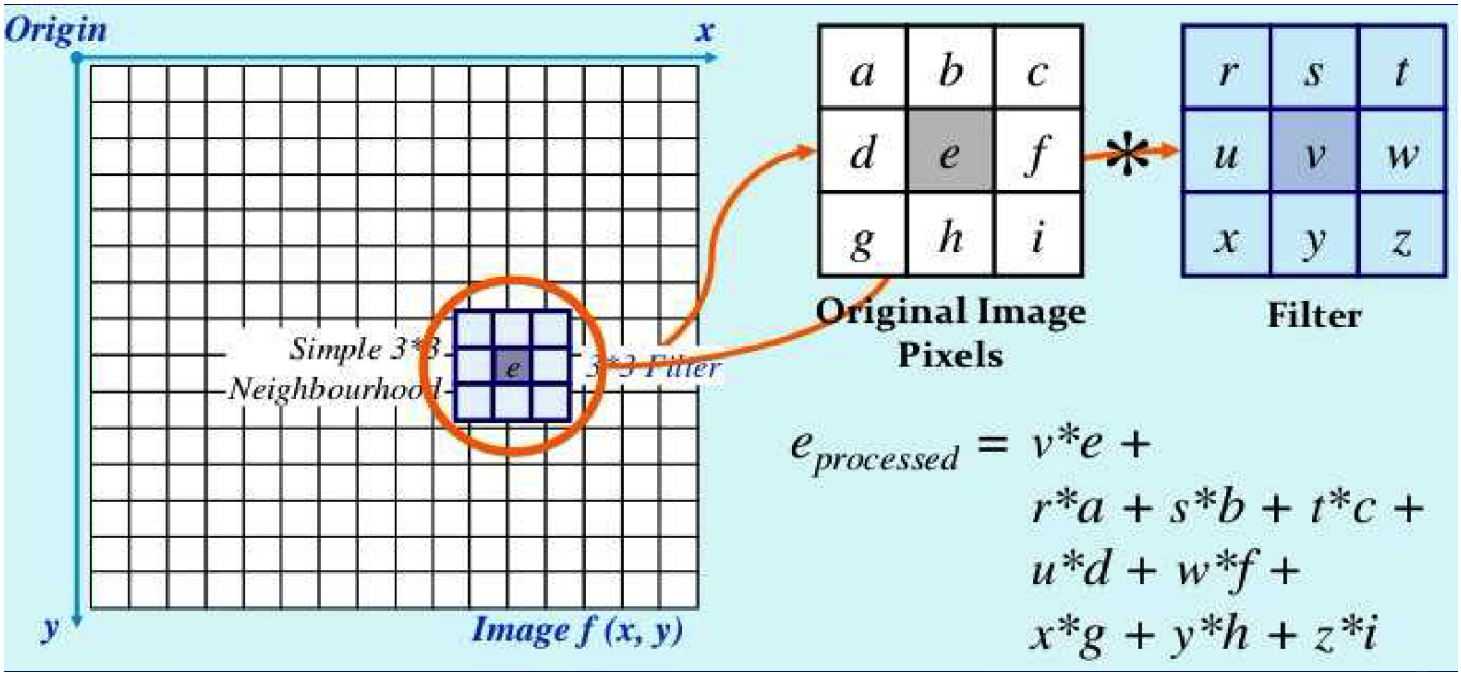
In part B, students are asked to implement parallel programs by themselves do embarrassingly parallel image filtering, which is slightly harder than PartA. This time, they need to take the information of the pixel's neighbors into consideration instead of doing computation on the pixel itself. Although two pixels may share the same neighbors, the read-only property still makes the computation embarrassingly parallel.

Problem Description

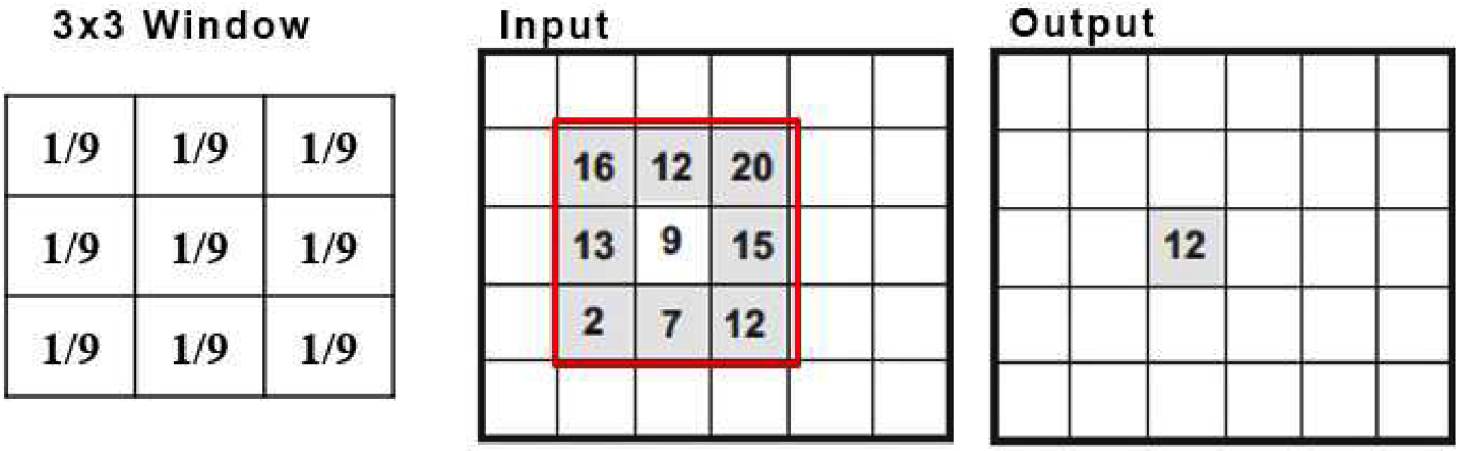
Image Filtering involves applying a function to every pixel in an image or selection but where the function utilizes not only the pixels current value but the value of neighboring pixels. Some of the filtering functions are listed below, and the famous convolutional kernel computation is also a kind of image filtering.

- blur
- sharpen
- soften
- distort

Two images below demostrate in detail how the image filtering is done. Basically, we have a filter matrix of given size (3 for example), and we slide that filter matrix across the image to compute the filtered value by element-wise multipling and summation.



How to do image filtering with filter matrix



An example of image filtering of size 3

In this project, students are required to apply the simplest size-3 low-pass filter with equal weights to smooth the input JPEG image, which is shown below. Note that your program should also work for other filter matrices of size 3 with different weights, that means you should not do specific optimization on the 1 / 9 weight, such as replacing multiplication with addition.

1 / 9	1 / 9	1 / 9
1 / 9	1 / 9	1 / 9
1 / 9	1 / 9	1 / 9

Reference: Lecture-04 slides of course CSC3185: Introduction to Multimedia Systems, CUHKSZ

Reminders of Implementation

1. The pixels on the boundary of the image do not have all 8 neighbor pixels. For these pixels, you can either use padding (set value as 0 for those missed neighbors) or simply ignore them, which means you can handle the (width - 2) * (height - 2) inner image only. In this way, all the pixels should have all 8 neighbors.
2. Check the correctness of your program with the Lena RGB image. The 4K image has high resolution and the effect of smooth operation is hardly to tell.

Examples

Lena RGB Original and Smooth from left to right

Benchmark Image

The image used for performance evaluation is a 20K JPEG image with around 250 million pixels (19200 x 12995) retrieved by doing upper sampling on the 4K image, and the image has been uploaded to BlackBoard. Please download that image to your docker container or on the cluster. Do not use Lena or the 4K image to do the performance evaluation on your report, because the problem size is too small to get the parallel speedup.

Requirements

- **Six parallel programming implementations for PartB (60%)**

- SIMD (10%)
- MPI (10%)
- Pthread (10%)
- OpenMP (10%)
- CUDA (10%)
- OpenACC (10%)

As long as your programs can compile and execute to get the expected output image by the command you give in the report, you can get full mark.

- **Performance of Your Program (30%)**
  Try your best to do optimization on your parallel programs for higher speedup.If your programs shows similar performance to the sample solutions provided by the teaching stuff, then you can get full mark. Points will be deduted if your parallel programs perform poor while no justification can be found in the report. (Target Peformance will be released soon).
  Some hints to optimize your program are listed below:
  - Try to avoid nested for loop, which often leads to bad parallelism.
  - Change the way that image data or filter matrix are storred for more efficient memory access.
  - Try to avoid expensive arithmetic operations (for example, double-precision floating point division is very expensive, and takes a few dozens of cycles to finish).
  - Partition your data for computation in a proper way for balanced workload when doing parallelism.
- **One Report in PDF (10%, No Page Limit)**
  The report does not have to be very long and beautiful to help you get good grade, but you need to include what you have done and what you have learned in this project.
  The following components should be included in the report:
  - How to compile and execute your program to get the expected output on the cluster.
  - Briefly explain how does each parallel programming model do computation in parallel? What are the similarities and differences between them. Explain these with what you have learned from the lectures (like different types of parallelism, ILP, DLP, TLP, etc).
  - What kinds of optimizations have you tried to speed up your parallel program for PartB, and how does them work?
  - Show the experiment results you get for **both PartA and PartB**, and do some numerical analysis, such as calculating the speedup and efficiency, demonstrated with tables and figures.
  - What have you found from the experiment results? Is there any difference between the experiment resutls of PartA and PartB? If so, what may cause the differences.
- **Extra Credits (10%)**
  If you can use any other methods to achieve a higher speedup than the sample solutions provided

by the TA (Baseline peformance to be released).

Some possible ways are listed below:

- A combination of multiple parallel programming models, like combining MPI and OpenMP together.
- Try to bind program to a specific CPU core for better performance. Refer to: https://slurm.schedmd.com/mc_support.html
- For SIMD, maybe you can have a try with different ISA (Instruction Set Architecture) to do ILP (Instruction-Level-Parallelism).

The Extra Credit Policy

According to the professor, the extra credits in project 1 cannot be added to other projects to make them full mark. The credits are the honor you received from the professor and the teaching stuff, and the professor may help raise you to a higher grade level if you are at the boundary of two grade levels and he think you deserve a better grade with your extra credits. For example, if you are the top students with B+ grade, and get enough extra credits, the professor may raise you to A- grade.

How to execute the sample programs in PartA?

Dependency Installation

Libjpeg

Libjpeg is a tool that we use to manipulate JPEG images. You need to install its packages with yum in your docker container instead of your host OS (Windows or MacOS). This package has been installed on the cluster, so feel free to use it there.

```
# Check the ligjpeg packages that are going to be installed
yum list libjpeg*

# Install libjpeg-turbo-devel.x86_64 with yum
yum install libjpeg-turbo-devel.x86_64 -y

# Check that you have installed libjpeg packages correctly
yum list libjpeg*
```

The terminal output for `yum list libjpeg*` after the installation should be as follows:

```
[root@cf49d1025aff bin]# yum list libjpeg*
Loaded plugins: fastestmirror, ovl
Loading mirror speeds from cached hostfile
 * base: mirrors.aliyun.com
 * epel: ftp.riken.jp
 * extras: mirrors.aliyun.com
 * updates: mirrors.aliyun.com
Installed Packages
libjpeg-turbo.x86_64                                                    1.2.90-8.
libjpeg-turbo-devel.x86_64                                              1.2.90-8.
Available Packages
libjpeg-turbo.i686                                                      1.2.90-8.
libjpeg-turbo-devel.i686                                                1.2.90-8.
libjpeg-turbo-static.i686                                               1.2.90-8.
libjpeg-turbo-static.x86_64                                             1.2.90-8.
libjpeg-turbo-utils.x86_64                                              1.2.90-8.
```

Upgrade to CMake3 and GCC-7 (In docker container only)

The programs need `cmake3` and `gcc-7` for compilation and execution. These upgrades have been done on the cluster, which means you can compile and execute the programs directly on the cluster with no problem. If you need to develop programs on your docker container, like for PartB implementation, you need to upgrade your `cmake` and `gcc` by yourself.

```
# Install cmake3 with yum
yum install cmake3 -y
cmake --version # output should be 3.17.5

# Install gcc/g++-7 with yum
yum install -y centos-release-scl*
yum install -y devtoolset-7-gcc*
scl -l
scl enable devtoolset-7 bash
gcc -v # output should be 7.3.1
```

How to compile the programs?

```
cd /path/to/project1
mkdir build && cd build
# Change to -DCMAKE_BUILD_TYPE=Debug for debug build error message logging
# Here, use cmake on the cluster and cmake3 in your docker container
cmake ..
make -j4
```

Compilation with `cmake` may fail in docker container, if so, please compile with `gcc`, `mpic++`, `nvcc` and `pgc++` in the terminal with the correct optimization options.

How to execute the programs?

In Your Docker Container

```
cd /path/to/project1/build
# Sequential
./src/cpu/sequential_PartA /path/to/input.jpg /path/to/output.jpg
# MPI
mpirun -np {Num of Processes} ./src/cpu/mpi_PartA /path/to/input.jpg /path/to/output.jpg
# Pthread
./src/cpu/pthread_PartA /path/to/input.jpg /path/to/output.jpg {Num of Threads}
# OpenMP
./src/cpu/openmp_PartA /path/to/input.jpg /path/to/output.jpg
# CUDA
./src/gpu/cuda_PartA /path/to/input.jpg /path/to/output.jpg
# OpenACC
./src/gpu/openacc_PartA /path/to/input.jpg /path/to/output.jpg
```

On the Cluster

Important: Change the directory of output file in sbatch.sh first

```
# Use sbatch
cd /path/to/project1
sbatch ./src/scripts/sbatch_PartA.sh
```

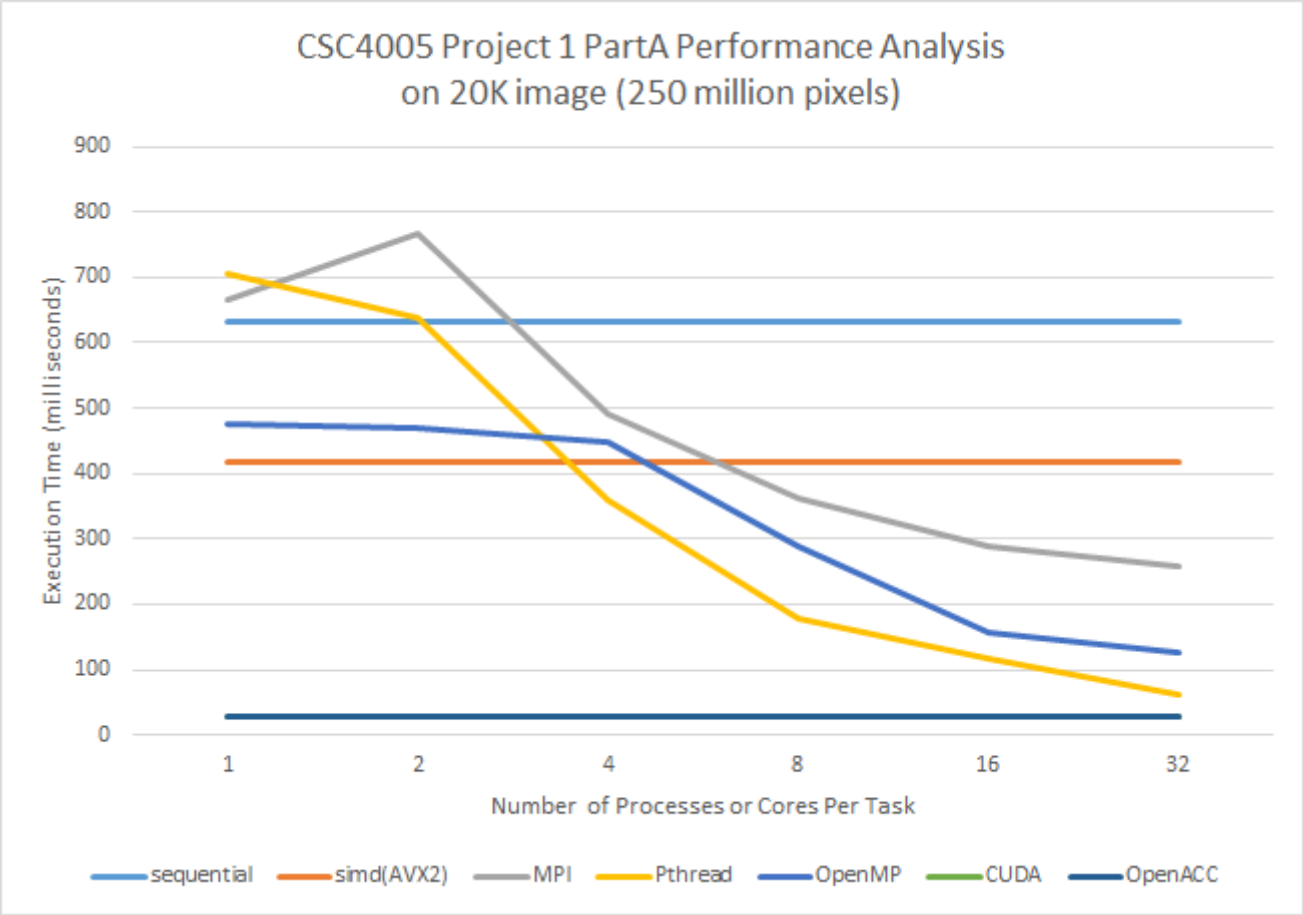
Performance Evaluation

PartA: RGB to Grayscale

Experiment Setup

- On the cluster, allocated with 32 cores
- Experiment on a 20K JPEG image (19200 x 12995 = 250 million pixels)
- sbatch file for PartA
- Performance measured as execution time in milliseconds

Number of Processes / Cores	Sequential	SIMD (AVX2)	MPI	Pthread	OpenMP	CUDA	OpenACC
1	632	416	665	704	475	27	28
2	N/A	N/A	767	638	471	N/A	N/A
4	N/A	N/A	490	358	448	N/A	N/A
8	N/A	N/A	361	178	288	N/A	N/A
16	N/A	N/A	288	116	158	N/A	N/A
32	N/A	N/A	257	62	126	N/A	N/A



Performance Evaluation of PartA (numbers refer to execution time in milliseconds)

Appendix

Appendix A: GCC Optimization Options

You can list all the supported optimization options for gcc either by terminal or through online documentations

```
# Execute on your docker container or on the cluster
gcc --help=optimizers
```

Online
documentation: Options That Control Optimization for gcc-7.3

You can find a lot of useful options to let gcc compiler to do optimization for your program, like doing tree
vectorization.

- **-ftree-vectorize**
  Perform vectorization on trees. This flag enables -ftree-loop-vectorize and -ftree-slp-vectorize if not explicitly
  specified.
- **-ftree-loop-vectorize**
  Perform loop vectorization on trees. This flag is enabled by default at -O3 and when -ftree-vectorize is enabled.
- **-ftree-slp-vectorize**
  Perform basic block vectorization on trees. This flag is enabled by default at -O3 and when -ftree-vectorize is
  enabled.

Appendix B: Tutorials of the Six Parallel Programing Languages

- **SIMD**
  - https://users.ece.cmu.edu/~franzf/teaching/slides-18-645-simd.pdf
- **MPI**
  - https://mpitutorial.com/tutorials/
- **OpenMP**
  - https://www.openmp.org/resources/tutorials-articles/
  - https://engineering.purdue.edu/~smidkiff/ece563/files/ECE563OpenMPTutorial.pdf

- **Pthread**
  - https://www.cs.cmu.edu/afs/cs/academic/class/15492-f07/www/pthreads.html
  - https://hpc-tutorials.llnl.gov/posix/
- **CUDA**
  - https://newfrontiers.illinois.edu/news-and-events/introduction-to-parallel-programming-with-cuda/
  - https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html
- **OpenACC**
  - https://ulhpc-tutorials.readthedocs.io/en/latest/gpu/openacc/basics/
  - https://www.openacc.org/sites/default/files/inline-files/OpenACC_Programming_Guide_0_0.pdf