

# PC-2020/21 Histogram Equalization

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## Abstract

This project was made as the final work for the “Parallel Programming” exam at the University of Florence. The objective was to create three version of a software to equalize the histogram of a given JPEG image. The first version had to be implemented as a sequential program, while the other two had to be parallel; for the parallel versions one has been implemented using OpenMP on top of the already implemented sequential code and the other is built using CUDA to take advantage of a GPU computing power. The projects has been developed in C on a Ubuntu machine; all tests were made on a Ryzen 7 1700 CPU and a NVIDIA Quadro P2000. The project is hosted on GitHub at <https://github.com/lorenzo-arena/histogram-equalizer>.

## Future Distribution Permission

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## 1. The algorithm

Histogram equalization in image processing can be used to increase an image’s contrast. This is accomplished by spreading the most frequent intensities values across the whole histogram. It works especially well on images which presents foreground and background which are both dark or both bright.

### 1.1. Implementation

We can start by considering a grayscale image of  $n$  pixels, in which  $n_i$  is the number of occurrences of gray level  $i$ . The probability of an occurrence of a pixel of level  $i$  (with  $0 < i < L$ ) in the image is:

$$p_x(i) = \frac{n_i}{n}$$

The histogram is the distribution of the pixel levels in the range  $[0, L - 1]$ .

We can define the *cumulative distribution function* as the cumulative sum of all the probabilities lying in its domain:

$$cdf_x(i) = \sum_{j=0}^i p_x(x = j)$$

To get a linearized *cdf*, which will produce a flatten histogram, we must normalize the *cdf* to the  $[0, L - 1]$  range by using the following formula:

$$cdf_n_x(i) = \frac{cdf(i) - cdf_{min}}{(M \cdot N) - cdf_{min}}$$

where  $M$  and  $N$  are the image’s dimensions. The normalized *cdf* must then be applied to the original histgram:

$$h(v) = round(cdf_n_x(i) \cdot (L - 1))$$

While this can be applied to grayscale images by using the pixel value, for color images applying the equalization process to the R, G and B channels would break the image’s color balance since the relative distribution of the color channels would be changed. Thus, the pixels must be converted to another color space (like HSL) where the algorithm can be applied to the *luminance* channel without creating changes in the *hue* or *saturation* channels.

## 1.2. On HSL color space

HSL (*hue, saturation, lightness*) is an alternative representation of the RGB color space. Instead of describing colors by using the red, green and blue components, it works by using a cylindrical geometry where hue (the angular dimension) gives the description of the perceived color (starting from red at  $0^\circ$ , green at  $120^\circ$  and blue at  $240^\circ$ ). Saturation describes the "colorfulness" of the color, giving the "pure color" at value 1, at the edge of the cylinder, while turning to grayscale as the center of the cylinder is approached. Lightness is used as the vertical axis dimension and ranges from pure white (lightness 1) to pure black (lightness 0).

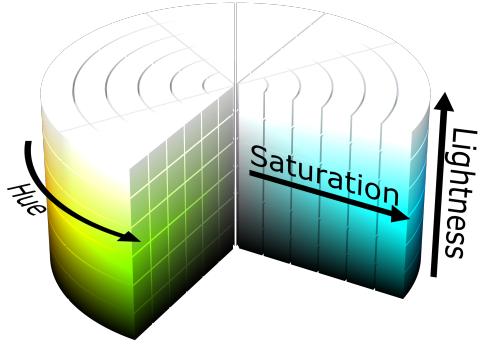


Figure 1. The HSL cilinder

## 2. The sequential implementation

The sequential solution was implemented by applying one by one all the algorithm steps to an image which filename can be read from the command line when running the program. The histogram is computed in 512 bins for the luminance; by using a special command line option it can also be printed out using *gnuplot*. The benchmarks have been made using `clock_gettime` with `CLOCK_MONOTONIC`, both for getting a measure of the complete execution time (including image reading from disk and output writing to disk) and for measuring the algorithm execution time. The function to convert RGB pixels to HSL color space and viceversa has been implemented following the process reported in [4] under the

sections "*From RGB*" and "*To RGB*".

The tests were done on an image with low contrast, showed in Figure 2.

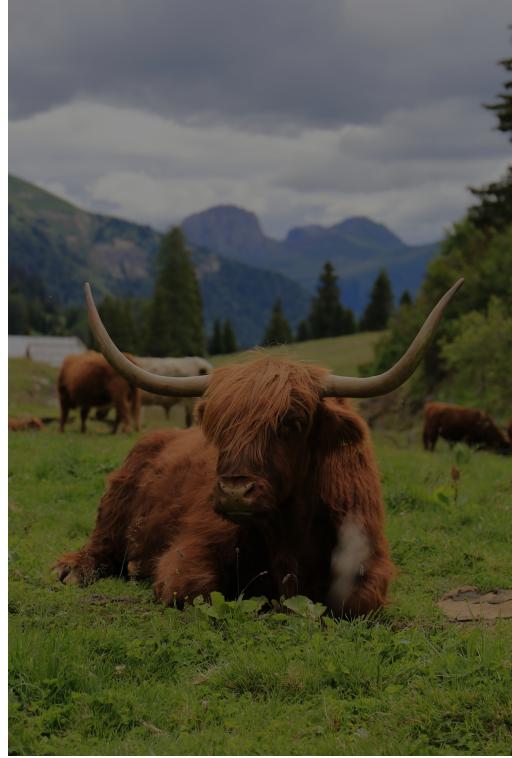


Figure 2. The test input image

The output after the equalization process is showed in Figure 3. The contrast has been increased, making the borders more clear while also darkening the low lights on the animal body and lightening the high lights of the clouds.

## 3. The OpenMP implementation

*OpenMP* is an API consisting of a set of compiler directives, libraries and environment variables which can be used to develop parallel applications. It uses a *fork-join* model, where a primary thread forks a number of sub-threads and divides a task between them. Each section of the code which is meant to be run in a parallel fashion must be marked with a specific compiler directive; during the execution each thread can get its *id*, an integer which univocally identifies it, with the function `omp_get_thread_num`. Each thread executes the parallel section independently, how-



Figure 3. The output image after the equalization process

ever there are a number of directives which allow work sharing between threads, so that each one executes its allocated piece of work. At the start of the program a thread pool is generated using the directive `#pragma omp parallel` (with a clause, or an option, to specify which variables should be shared between the threads). Then, for each of the `for` loops the directive `#pragma omp for` is used to split the work between the threads. During the execution the directive `#pragma omp single` is used to be sure that only one thread executes memory allocations and other specific instructions. Most of the equalization algorithm steps can be parallelized this way; the only exception is the calculation of the cumulative distribution function, which is calculated from a single thread.

The option `-t` can be used when starting the OpenMP version of the program to specify the number of threads which shall be used when performing the equalization. By using that options some measures have been taken: the Figure 4 shows the speedup of this implementation.

Results for a 6MP image		
Implementation	Computation times	Speedup
Sequential:	746ms	1
OpenMP:	114ms	6.54
CUDA:	25ms	29.84

Table 1. CUDA results for 6MP image.

Results for a 20MP image		
Implementation	Computation times	Speedup
Sequential:	2386ms	1
OpenMP:	286ms	8.34
CUDA:	75ms	31.81

Table 2. CUDA results for 20MP image.

#### 4. The CUDA implementation

The second parallel version of the software has been implemented using CUDA, thus being able to take full advantage of a GPU computing power. The first approach was to transpose each step of the algorithm to be run on the GPU; a *kernel* (a routine compiled to be executed on the GPU) has been implemented for each one of the equalization steps. One of the first optimizations was related to the histogram computation: since there could be potentially hundreds of threads writing to the same memory locations (that is, when incrementing a "bin"), *atomic* operations like `atomicAdd` has been used; each thread *block* also works on a separate piece of memory, reducing the risk of collisions. After some tests it has been chosen to use 30 *blocks* of 512 threads each. When the first implementation was completed it was noticed that one of the biggest bottlenecks was the time necessary for the first `cudaMalloc` call, which would take a lot of time while the following CUDA function calls would take a lot less; it was probably relative to the initialization of the runtime, and adding a simple `cudaMalloc` and `cudaFree` for a 0 bytes array call at the start of the program contributed to trim that time. Tables 1 and 2 reports the speedup of the CUDA implementation for two images of different dimensions.

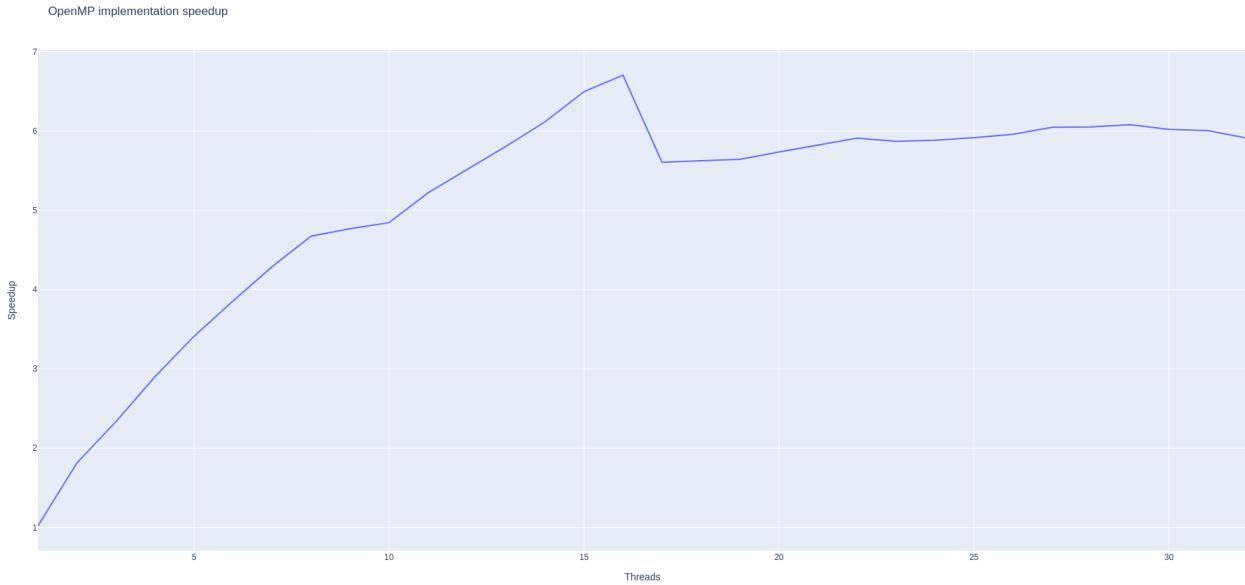


Figure 4. The OpenMP implementation speedup

## 5. Results

By using some utility scripts (which can be found in the repository) both for verifying the correctness of the different solutions and to run them with different thread counts (for the OpenMP implementation) or different input images, the following results are found:

- the OpenMP implementation provides a good speedup over the sequential implementation; however, that stops getting better when the thread count is above the core count on which it is executed (or the virtual thread count in case of *Simultaneous multithreading* enabled CPUs)
- for small images (under 6MP) both the OpenMP and the CUDA implementations provide a good speedup; however with bigger images the amount of parallelized computations grows while the not parallelized or not efficient (i.e. the scan computation) remains the same. This gets translated in an even higher speedup over the sequential implementation.

## References

- [1] CUDA toolkit documentation. <https://docs.nvidia.com/cuda/index.html>. Accessed: 2020-01-12.
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- [3] Wikipedia. Histogram equalization — Wikipedia, the free encyclopedia. <http://en.wikipedia.org/w/index.php?title=Histogram%20equalization&oldid=993129511>, 2021.
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