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Histogram Equalization

Parallel Computing Second Project

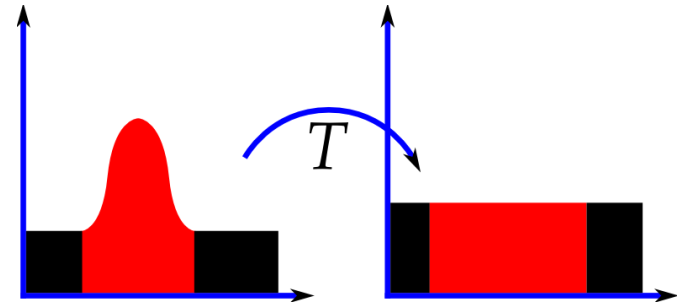
Implementation and Performance
Analysis of Sequential and Parallel
Version in CUDA

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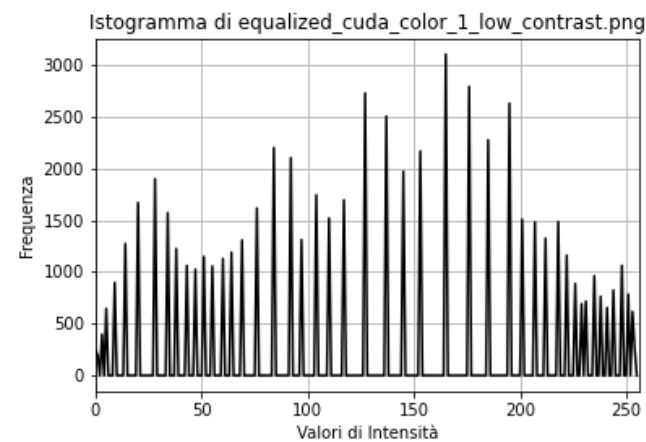
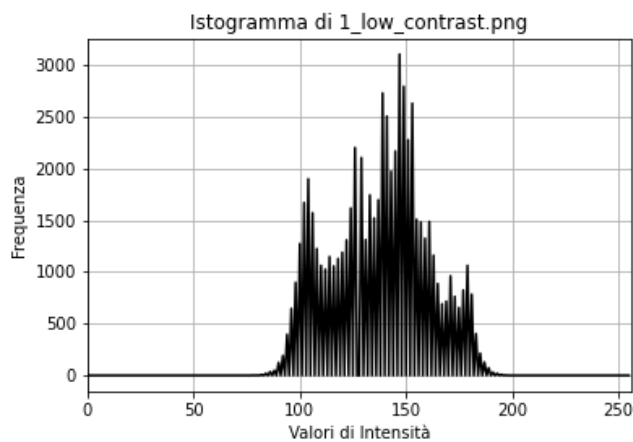
Firenze 2024-2025

Introduction

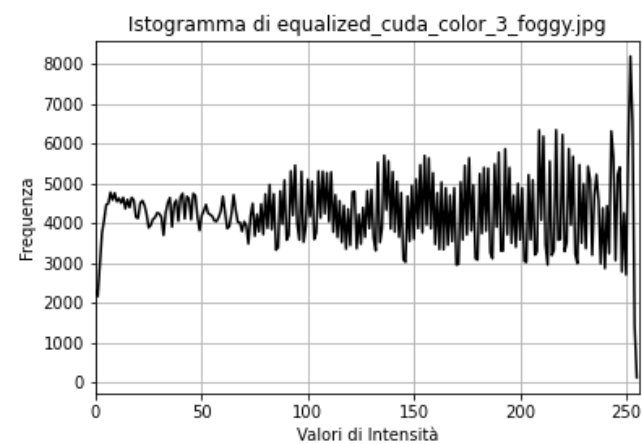
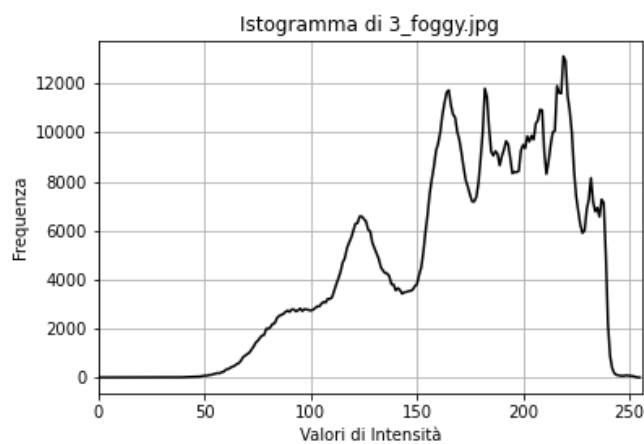
Histogram Equalization



- **Histogram Equalization** is a technique for **enhancing image contrast**.
- It **redistributes the intensity levels** of an image's histogram to achieve a more uniform distribution.
- It uses the **Cumulative Distribution Function (CDF)** to remap intensity values.
- Applicable to both **grayscale** and **color images**.
- Useful in the preprocessing of **low-contrast** images to improve visual quality.



Grayscale image equalization result



Color image equalization result

Implementation

Sequential version

- Sequential version implemented in **C++** with **OpenCV**.
- **Main steps** of the sequential algorithm:
 - **Input:** Image (grayscale or color).
 - Check if the image is grayscale; otherwise, convert it to grayscale.
 1. Compute **histogram**.
 2. Compute **CDF**.
 3. **Normalize CDF** to obtain new pixel values.
 4. Apply **transformation** (pixel remapping).
 - **Output:** Equalized grayscale image.



Observations

Sequential version

- **Slow for large images** due to **nested loops over rows and columns** for *histogram computation* (step 1) and *transformation application* (step 4).
- **CDF computation** (step 3) is well-suited for parallel **reduction**, as it is obtained by progressively summing the histogram values.
- Therefore, a **parallel CUDA implementation** can improve efficiency by using **three kernels** to replace the corresponding steps of the sequential version.

Implementation

Parallel version CUDA

- Parallel version implemented in **CUDA** to exploit the GPU.
- Parallelized algorithm using **3 kernels**:
 1. **computeHistogram**: computes **histogram** using tiling.
 2. **computeCDF**: computes **CDF** using reduction.
 3. **applyTransformation**: applies **transformation** using tiling.
- The parallel code includes **memory management** (CPU-GPU), **pinned memory allocation** to speed up data transfers, and **execution time measurement**.
- CDF normalization is performed on **CPU**.



Implementation

Memory Management CUDA

- Some objects are allocated using ***cudaMalloc*** in the GPU global memory:
 - A buffer for **input image**, with ***cudaMemcpy*** used to transfer the image from host to device.
 - A buffer for **output image**, with ***cudaMemcpy*** used to transfer the image from device to host.
 - An integer array of size 256 for **histogram**.
 - An integer array of size 256 for **CDF**.
 - A buffer of size 256 for **lookup table**.
- Some objects are allocated using ***cudaHostAlloc*** in the CPU memory:
 - An integer array of size 256 for **CDF**, with ***cudaMemcpyAsync*** used to copy values from GPU to CPU.
 - A buffer of size 256 for **lookup table**, with ***cudaMemcpyAsync*** used to copy values from GPU to CPU.

Implementation

First Kernel CUDA: computeHistogram

- Its purpose is to **compute histogram** in parallel.
- **Main steps:**
 1. **Initialize** local histogram to zero.
 2. **Load pixels** from global memory into shared memory (`__shared__ uchar tile[16][16]`).
 3. **Update local histogram** using atomic operations.
 4. **Merge with global histogram** using `'atomicAdd()'`.
- **Strategy:**
 - **Shared memory:** each thread block has shared memory for a local histogram, reducing access latency. The drawback is that local copies must be merged.
 - **Tiling:** Reduces global memory traffic by enabling **coalesced access**, improving efficiency.

Implementation

Second Kernel CUDA: computeCDF

- Its purpose is to **compute Cumulative Distribution Function (CDF)** in parallel.
- **Main steps:**
 1. Load **histogram into shared memory**.
 2. Use **parallel reduction** to progressively sum the values. Each value is updated by adding the previous one with an offset that doubles at each iteration.
 3. Write the result to global memory.
- **Strategy:**
 - **Shared memory:** for fast access.
 - **Parallel reduce:** computing CDF requires **$O(\log N)$** operations instead of **$O(N)$** .



Implementation

Third Kernel CUDA: applyTransformation

- Its purpose is to **apply pixel transformation** using precomputed lookup table.
- **Main steps:**

After CDF normalization by the CPU, the lookup table is obtained.

 1. Load **data into shared memory** using **tiling** for fast access.
 2. **Each thread reads a pixel** and replaces it with the corresponding value from the lookup table.
- **Strategy:**
 - **Shared memory:** each thread block has shared memory for a local histogram, reducing access latency. The drawback is that local copies must be merged.
 - **Tiling:** enables **coalesced memory access**, maximizing GPU efficiency.



Experiments

Technical Specifications

- **Hardware:**
 - CPU: Intel Core i7-7700HQ (2.8 GHz)
 - **GPU: NVIDIA GeForce GTX 1050**
 - RAM: 16 GB
 - **Compute Capability: 6.1**
- **Software:**
 - SO: Microsoft Windows 10 Home
 - **CUDA Compiler: nvcc 12.8.61**
 - **Host Compiler: MSVC 1942**
 - IDE: CLion 2024.2.2



Experiments

Analysis Metrics

- **Execution time**, measured with `std::chrono` for **total parallel execution time** (T_{cuda}) and `cudaEventElapsedTime` for **kernel execution time** (T_{kernel}).

- $$\text{Speedup} = \frac{T_{\text{sequenziale}}}{T_{\text{parallelo}}}$$

- **Theoretical Speedup** (S_{kernel}):

- Calculated considering only **CUDA kernel execution time** (T_{kernel}).
- **Excludes data transfer costs** between CPU and GPU.
- Measures the **efficiency of parallel computing** on the GPU.

- **Actual Speedup** (S_{cuda}):

- Based on **total parallel execution time** (T_{cuda}), **including data transfer**.
- Provides a **realistic** evaluation of overall performance.

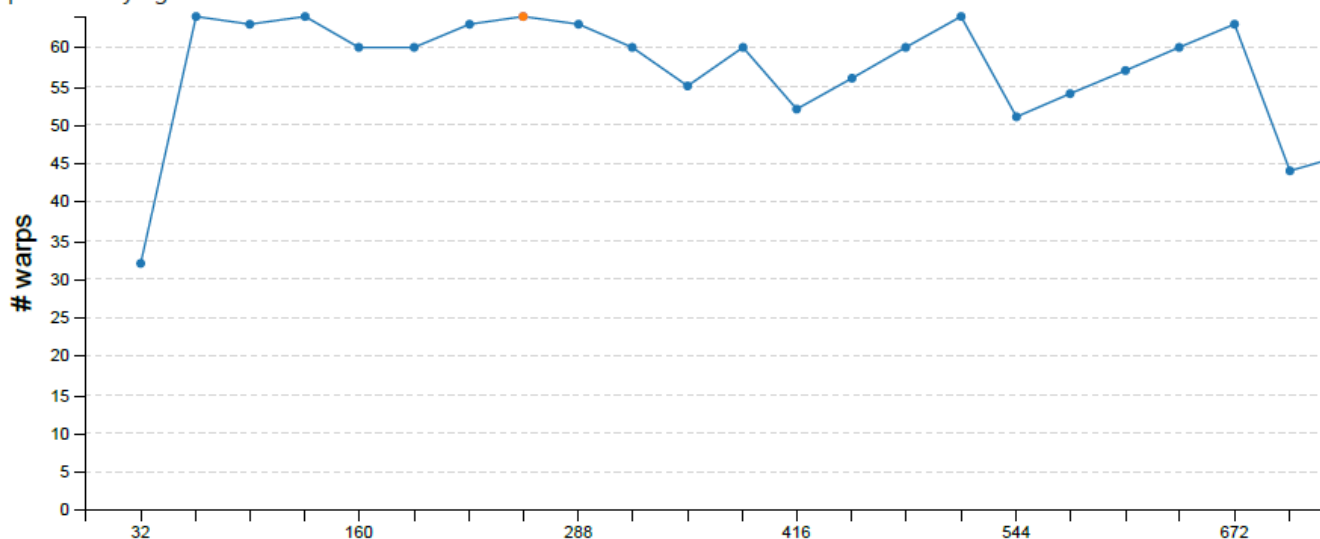
Experiments

Technical Choices

- Analyzing **occupancy** and based on experiments, the following dimensions were chosen:
 - blockSize: 16x16**, to have **256 threads per block**.
 - gridSize**: depends on the image dimensions:

$$[(width + blockSize.x - 1) / blockSize.x], [(height + blockSize.y - 1) / blockSize.y]$$

Impact of Varying Block Size



Experiments

Images used

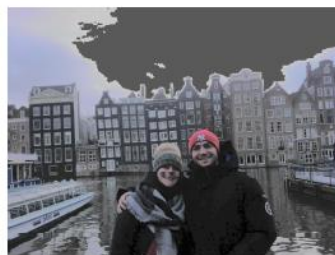
- Test **images** were selected to analyze **speedup** and **effectiveness** based on different **resolutions** and **lighting conditions**.



Results

Sequential images

- Visual result obtained with **sequential** Histogram Equalization, **excellent** for **low resolution** images, **terrible** for **high resolution** images.



Results

CUDA Images

- Visual result obtained with **CUDA parallel** Histogram Equalization, **great** for **low resolution** images as well as **high resolution** images.



Results

Execution Times

- For parallel version, the **kernel execution time** (T_{kernel}) and the **total parallel execution time** (T_{cuda}) are reported, including data transfer times between CPU and GPU.

Immagine	$T_{sequenziale}$ (ms)	T_{kernel} (ms)	T_{cuda} (ms)
lc 256x256	2.1704	0.233248	89.3771
di 1344x768	34.5987	0.580288	78.435
f 1280x813	36.0089	0.575712	91.6379
o 608x406	8.3431	0.450464	89.9615
u 1024x683	22.8673	0.63056	89.523
o 3680x2760	359.179	3.46342	599.038
u 3680x2760	335.684	3.52854	636.197
hr 3072x4096	421.064	4.29763	564.916

Results

Speedup Analysis

- Notice how **Theoretical Speedup** (S_{kernel}) and **Actual Speedup** (S_{cuda}) vary.

Immagine	S_{kernel}	S_{cuda}
lc 256x256	9.31	0.024
di 1344x768	59.6	0.44
f 1280x813	62.5	0.39
o 608x406	18.5	0.093
u 1024x683	36.3	0.26
o 3680x2760	103.7	0.6
u 3680x2760	95.13	0.53
hr 3072x4096	97.99	0.75

- Theoretical Speedup** (S_{kernel}): up to 100x for high resolution images.
- Actual Speedup** (S_{cuda}): lower due to data transfer.

Conclusions

Analysis of results

- The **CUDA kernel** offers **high efficiency**, with speedups between 9x and 100x compared to the CPU, demonstrating the **superiority and scalability of parallel computing**, especially for high-resolution images.
- Images processed with CUDA look **visually better**.
- However, the **total execution time increases** significantly **due to the data transfer overhead between CPU and GPU**, which particularly affects small images.
- For larger images, such as 3680x2760 or 3072x4096, the overhead impact is reduced, allowing for an overall performance improvement. So, the **GPU** really becomes **advantageous for large images**.