Recap of the previous lesson

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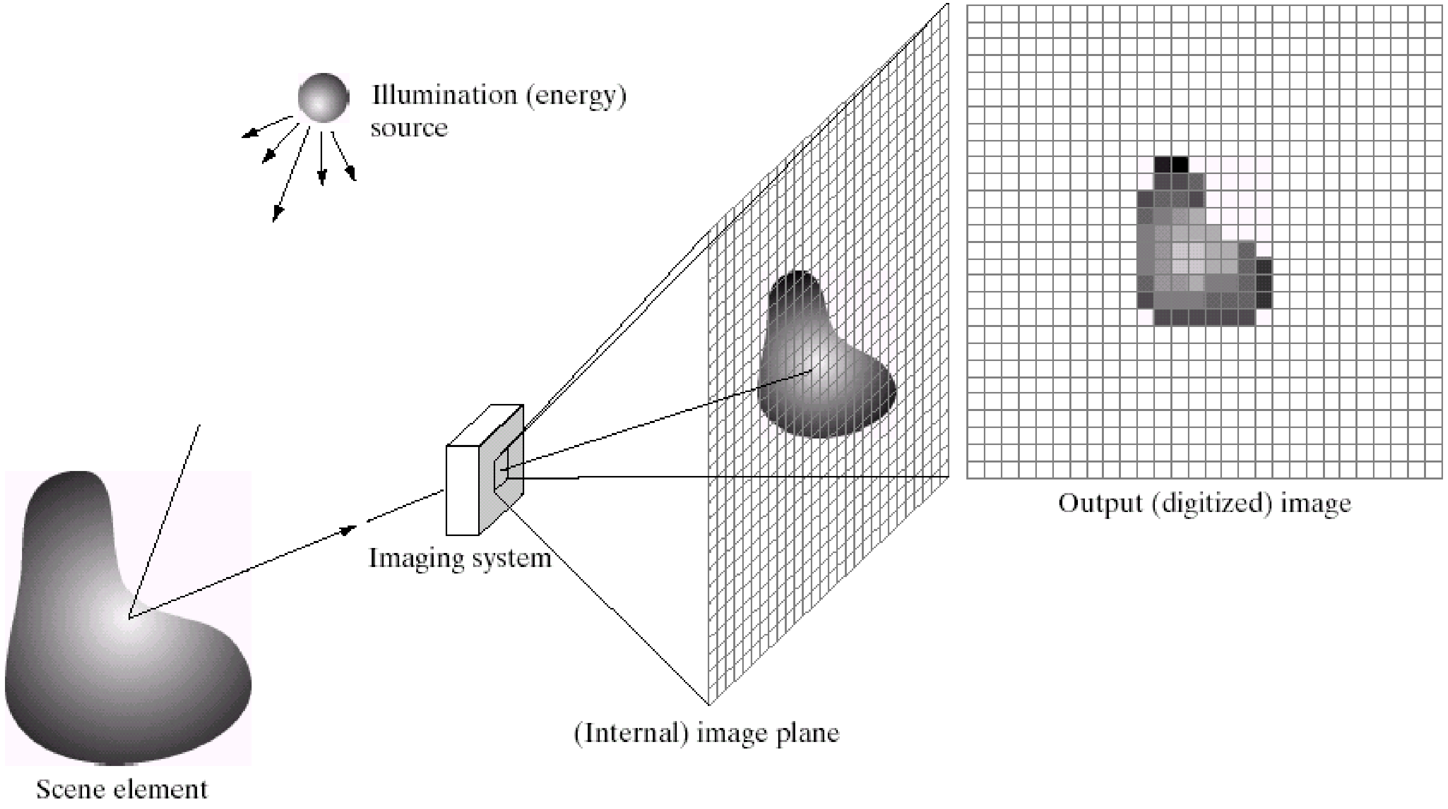
How to capture an image

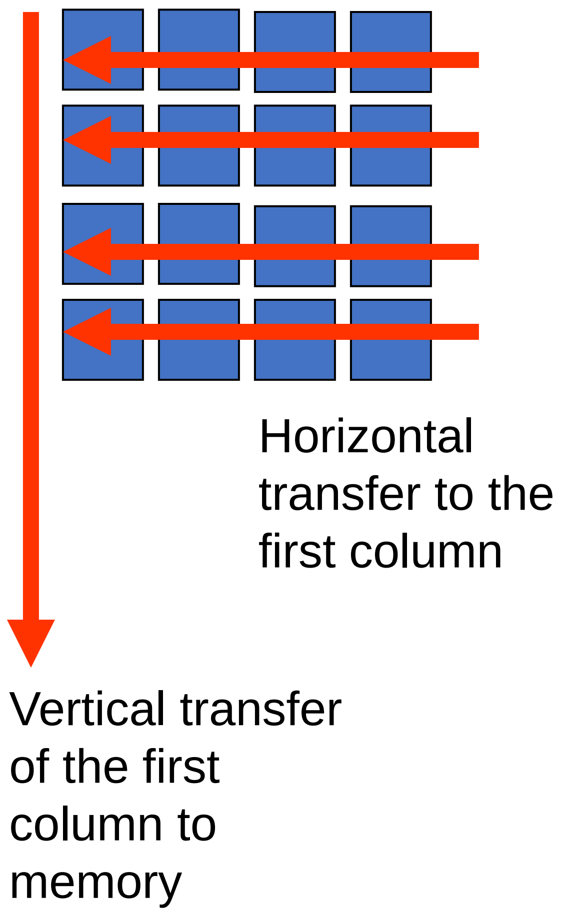
- When light hits an object, part of it is absorbed and part of it is reflected.
- That which is reflected gives rise to the perceived color.
- To create a digital image, it is essential that such reflected light be captured by a sensor and processed.



CCD: the measurement scheme

After charges have been acquired from an array of cells they must be transferred to a digital memory. The scanning is done in C phases, one phase for each column of the matrix.

At each stage the first column of the matrix is transferred to memory, at the same time all elements (from the second column onward) are transferred from their column to the previous one.

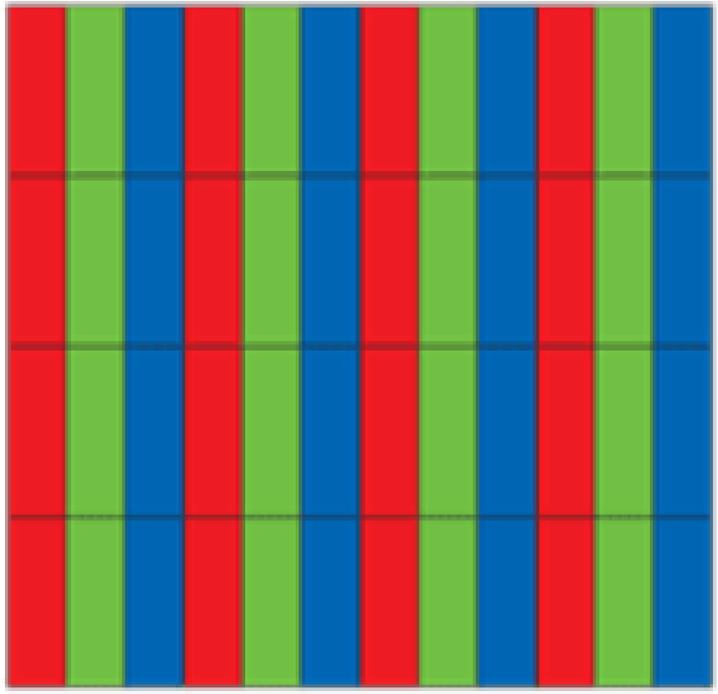


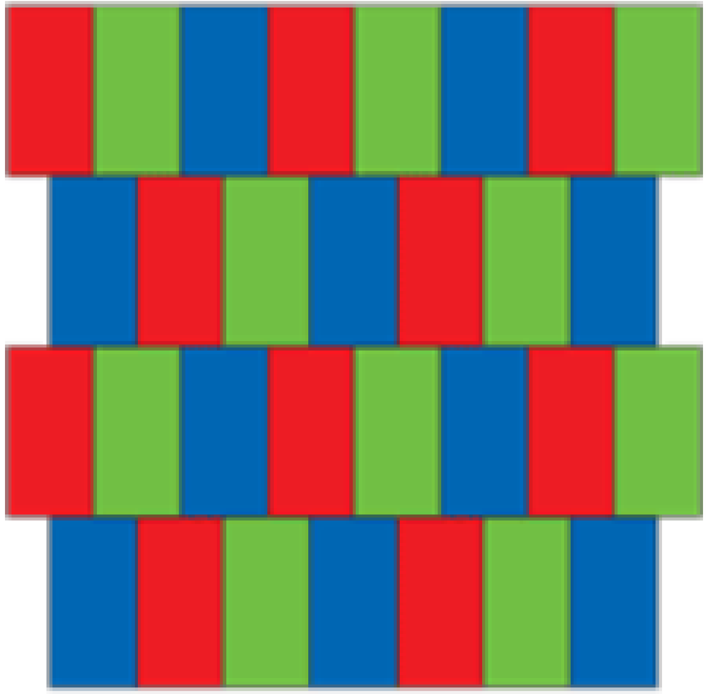
This is considered the first official photo taken with the "Kodak."

CFA: Color Filter Array

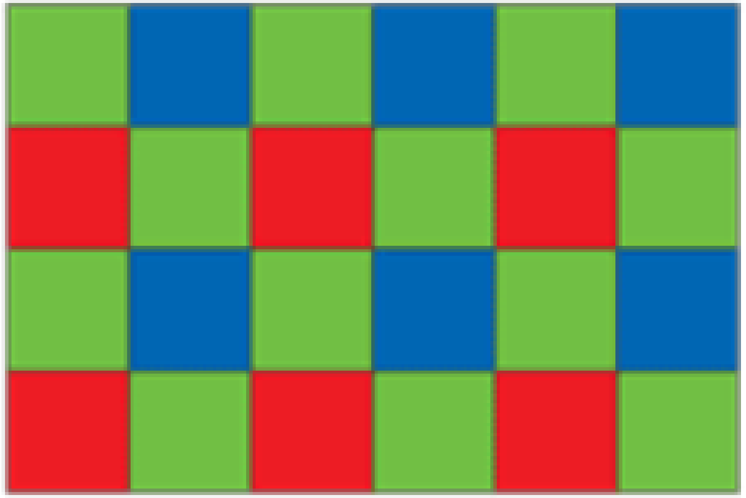
- Since each cell will store **only one color** at a time and not a triad, it is necessary to choose what is the optimal storage pattern (CFA).
- The two missing colors to complete the triad will be obtained by interpolation from neighboring pixels (Color Interpolation).
- The degree of accuracy of the result depends on how sophisticated the interpolation method is.

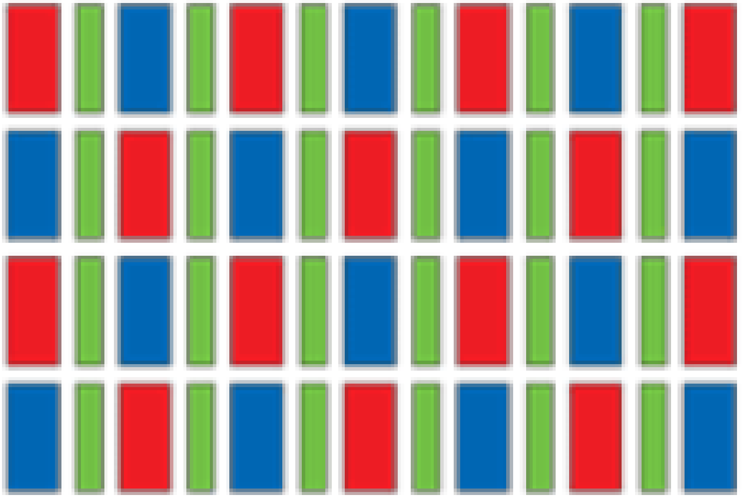
Possible models of CFA



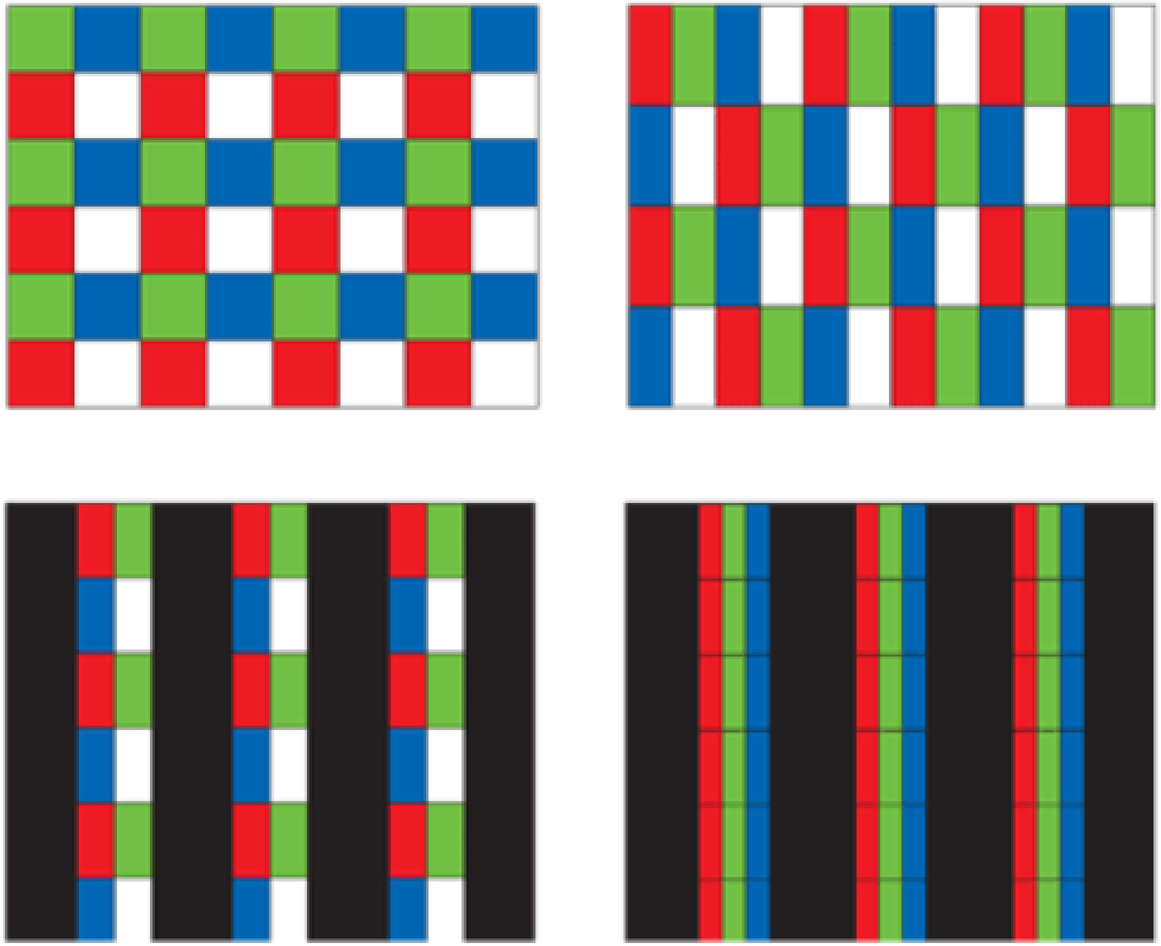


Possible models of CFA



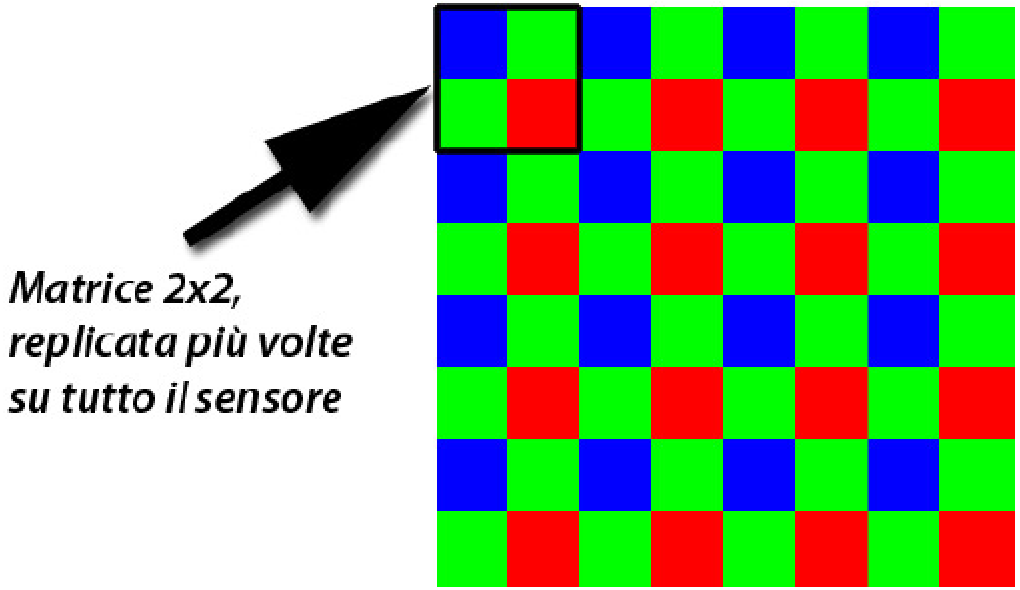


Possible models of CFA

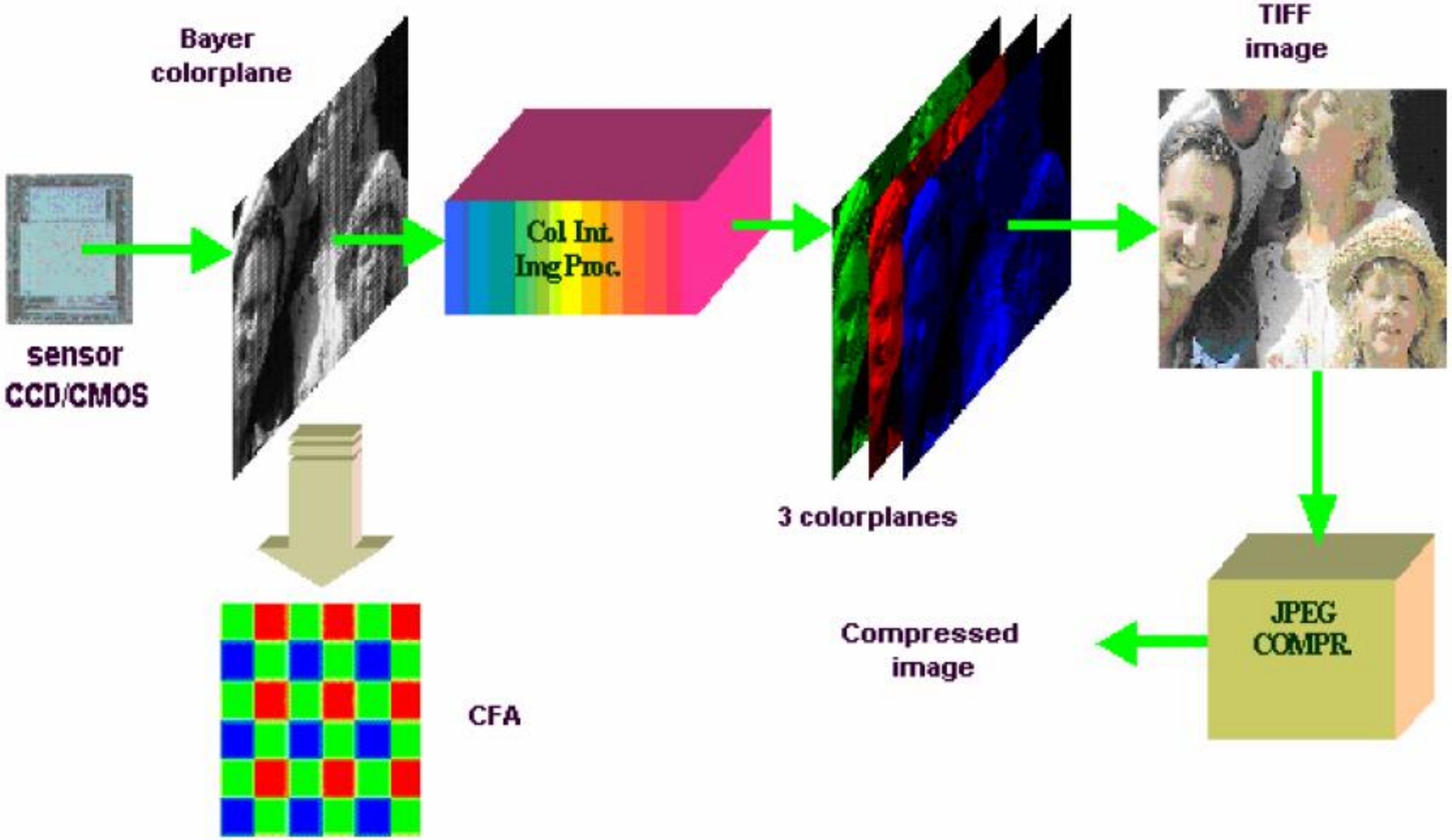


Which one is the best? The Bayer Pattern

- The most widely used scheme is the BAYER PATTERN. It was proposed in 1976 by Byce Bayer and used since 1980 in all electronic devices.
- It has a 1:2:1 ratio for R:G:B, where the green pixels are arranged on "diagonals.“
- It favors measurements in the green channel because it is the most important for human perception.
- A Bayer Pattern image is stored in the "raw" format.

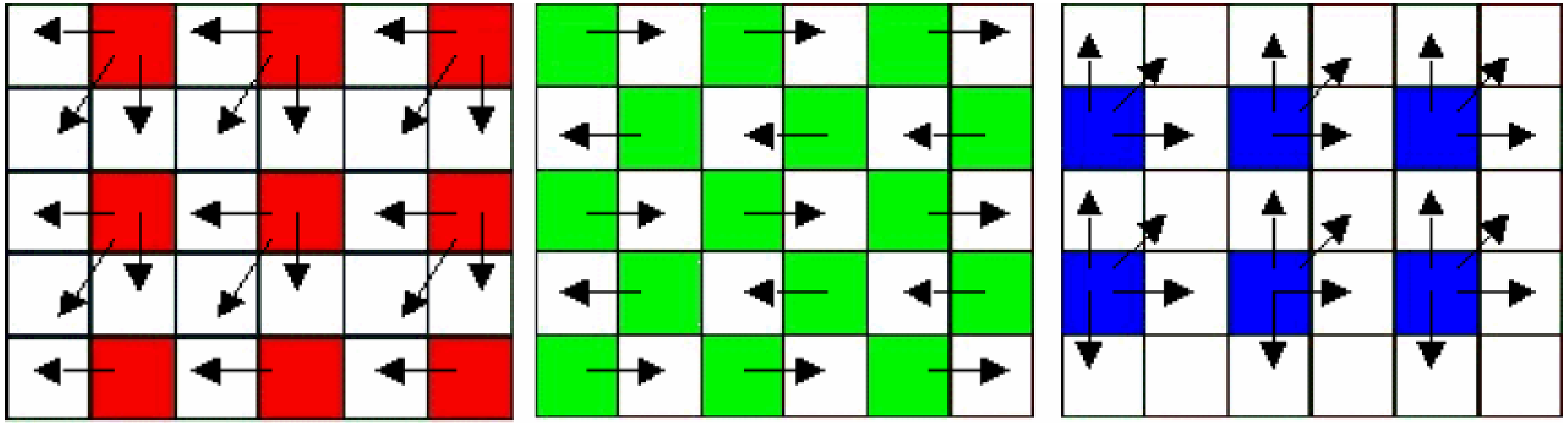


In more detail



Color interpolation: replication

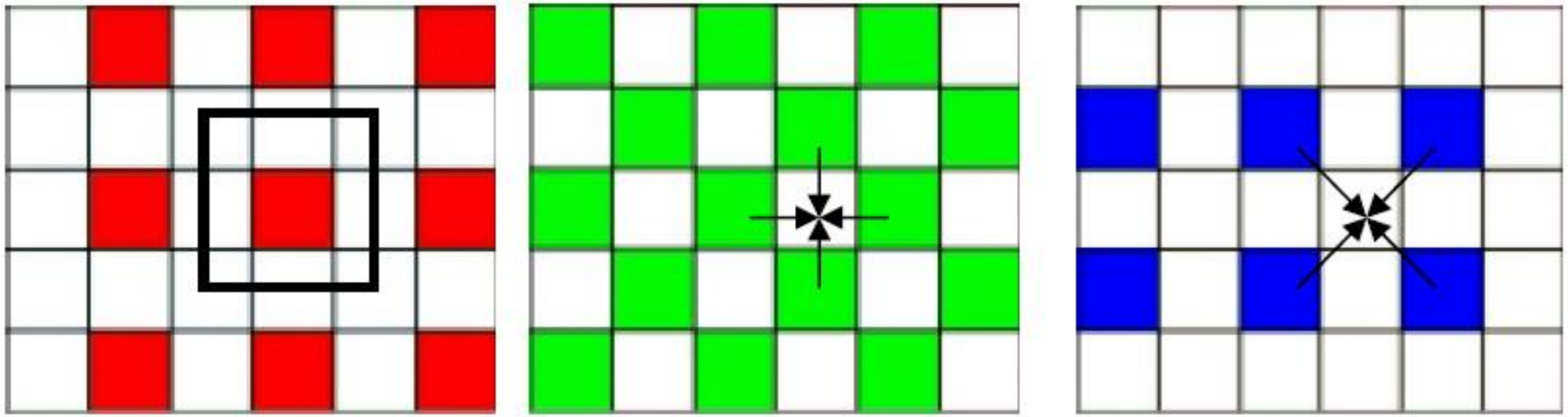
- For each individual pixel, the missing elements of the triad are copied from the surroundings.
- This technique is also called **"Nearest-neighbor interpolation."**



Color interpolation: bilinear
about the information of R and missing G and B

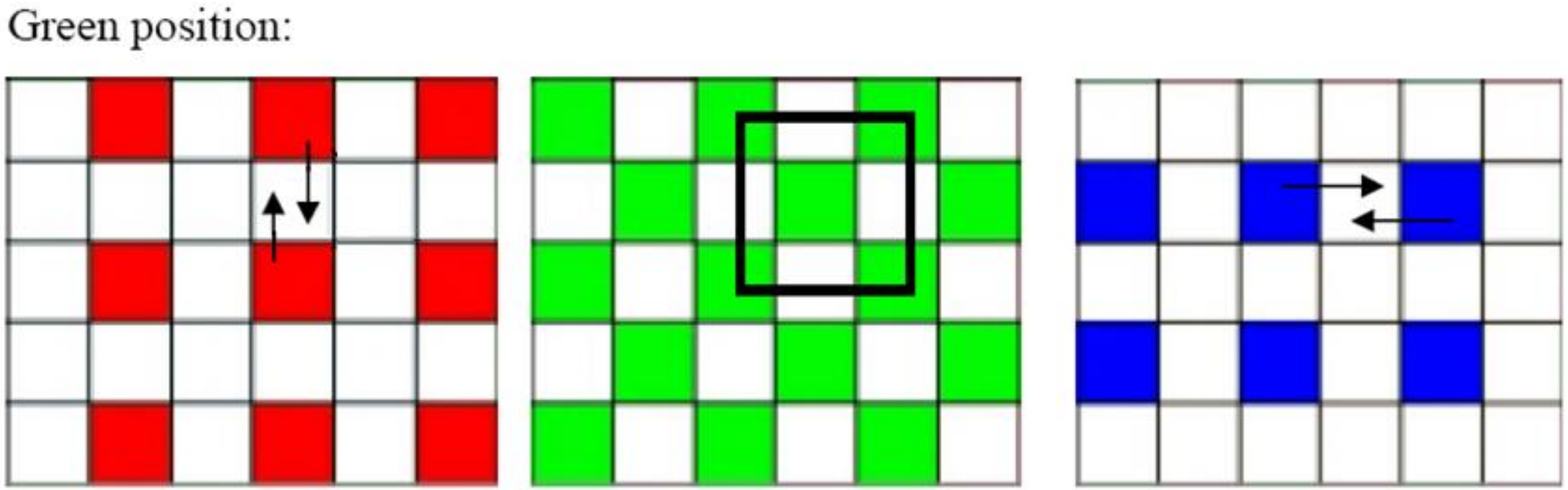
- In the matrix of R, nothing needs to be done.
- In G it is necessary to derive data from a neighborhood by selecting the 4 values released by the sensor.
- In B it is necessary to derive data from a neighborhood by selecting the 4 values released by the sensor.

Red position:



Color interpolation: bilinear
about the information of G and missing R and B

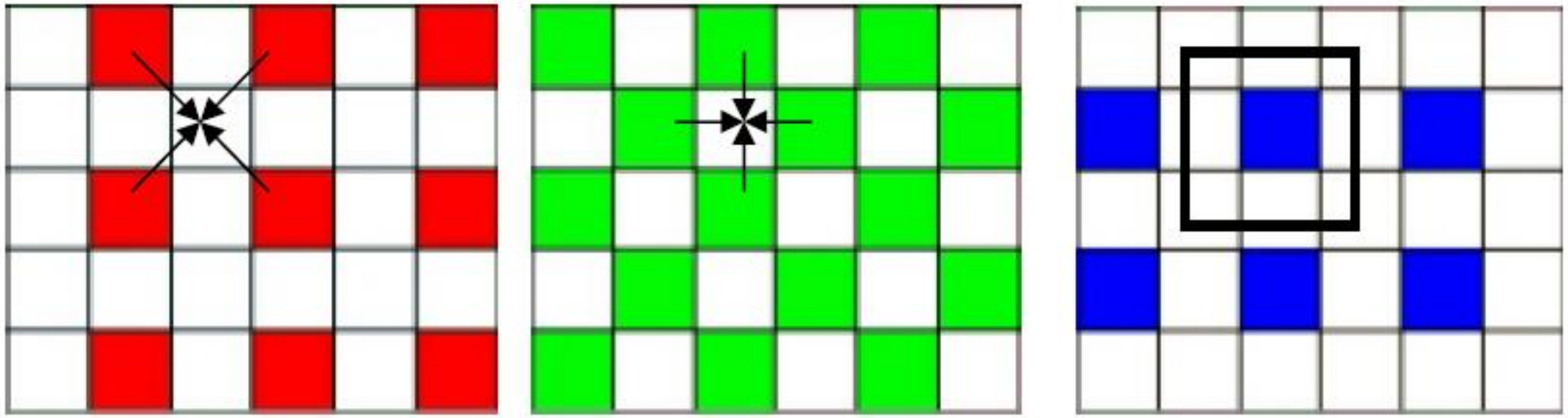
- In the matrix of G nothing has to be done.
- In R it is necessary to derive data from a neighborhood by selecting the 2 values released by the sensor.
- In B it is necessary to derive data from a neighborhood by selecting the 2 values released by the sensor.



Color interpolation: bilinear
about the information of B and missing R and G

- In the matrix of B, nothing needs to be done.
- In R it is necessary to derive data from a neighborhood by selecting the 4 values released by the sensor.
- In G one needs to derive data from a neighborhood by selecting the 4 values released by the sensor.

Blue position:



Results obtained using different color interpolation

Ideale

Bayer Pattern

Replication

Bilineare

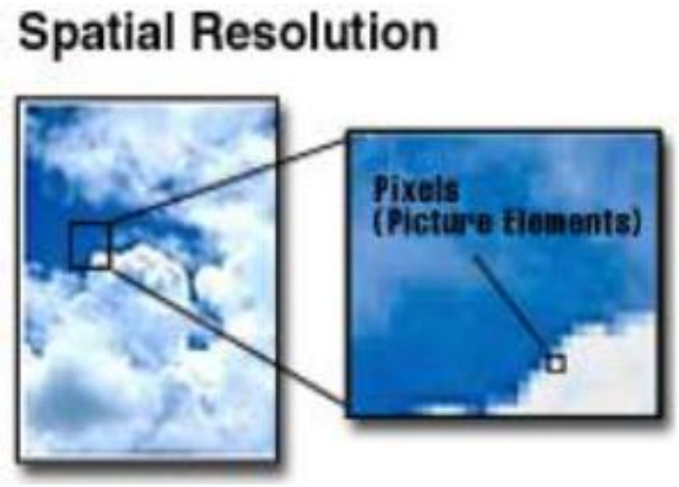
Bicubico

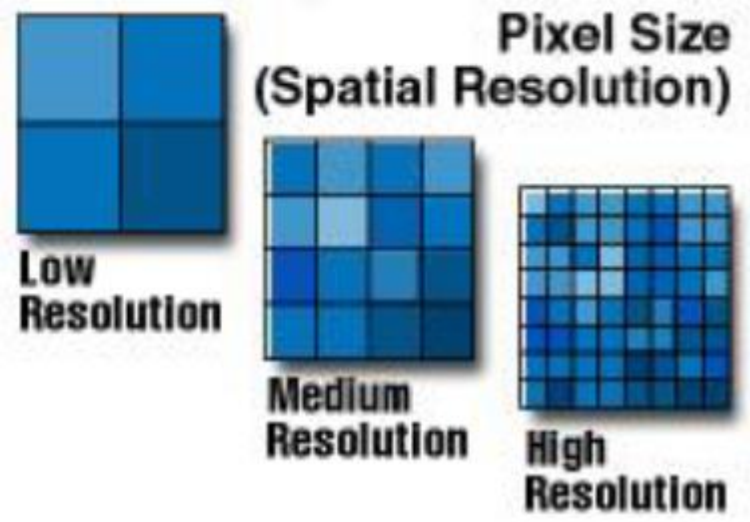
Altro

Spatial Resolution

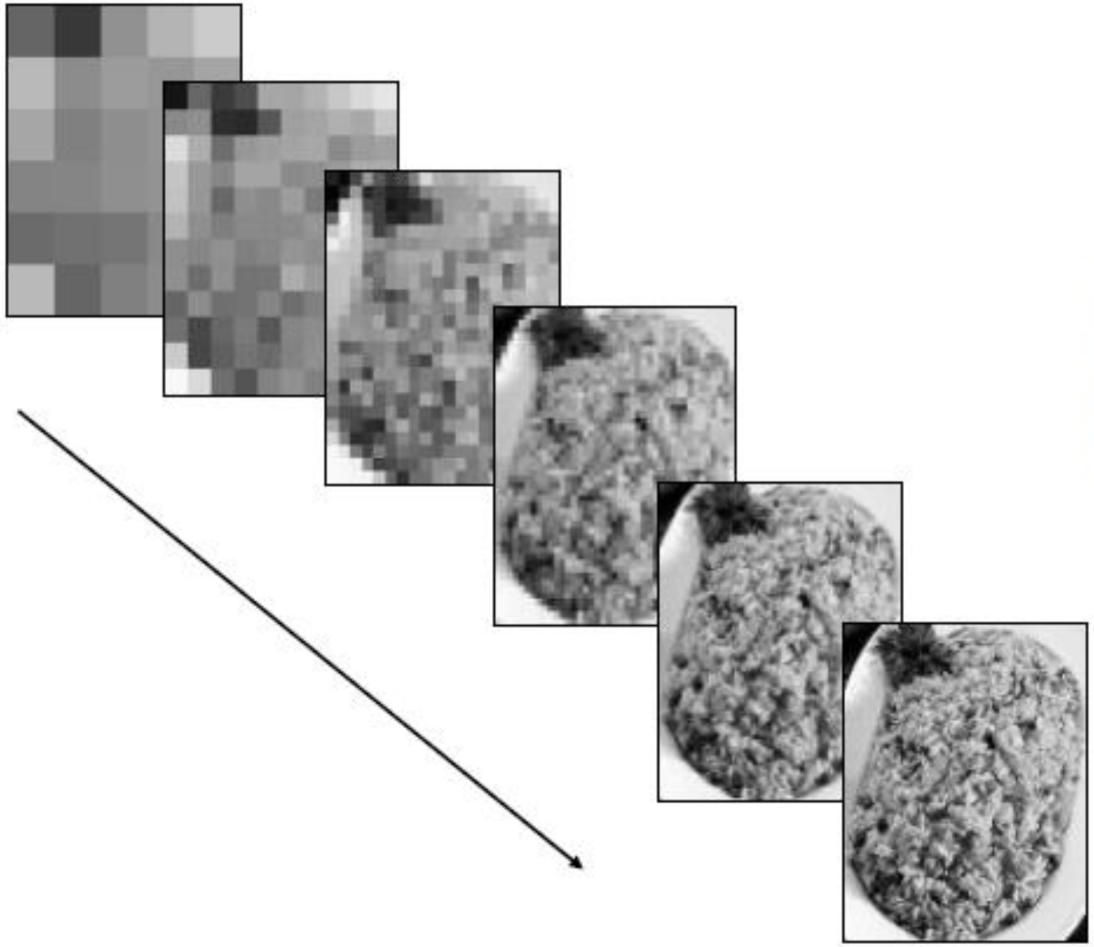
Definition

Spatial resolution refers to the specific number of information points (pixels - Picture Element) in an 'image.





Spatial Resolution



Histogram

Luca Guarnera, Ph.D.

Research Fellow
luca.guarnera@unict.it

University of Catania
Dipartimento di Economia e Impresa

Histogram

- The pixels of an image are a "population" on which we can calculate all the descriptive statistical quantities that are normally used: mean, median, variance, standard deviation, quartiles, percentiles ...

- Particularly important is knowledge of the frequency distribution of gray levels: the histogram.

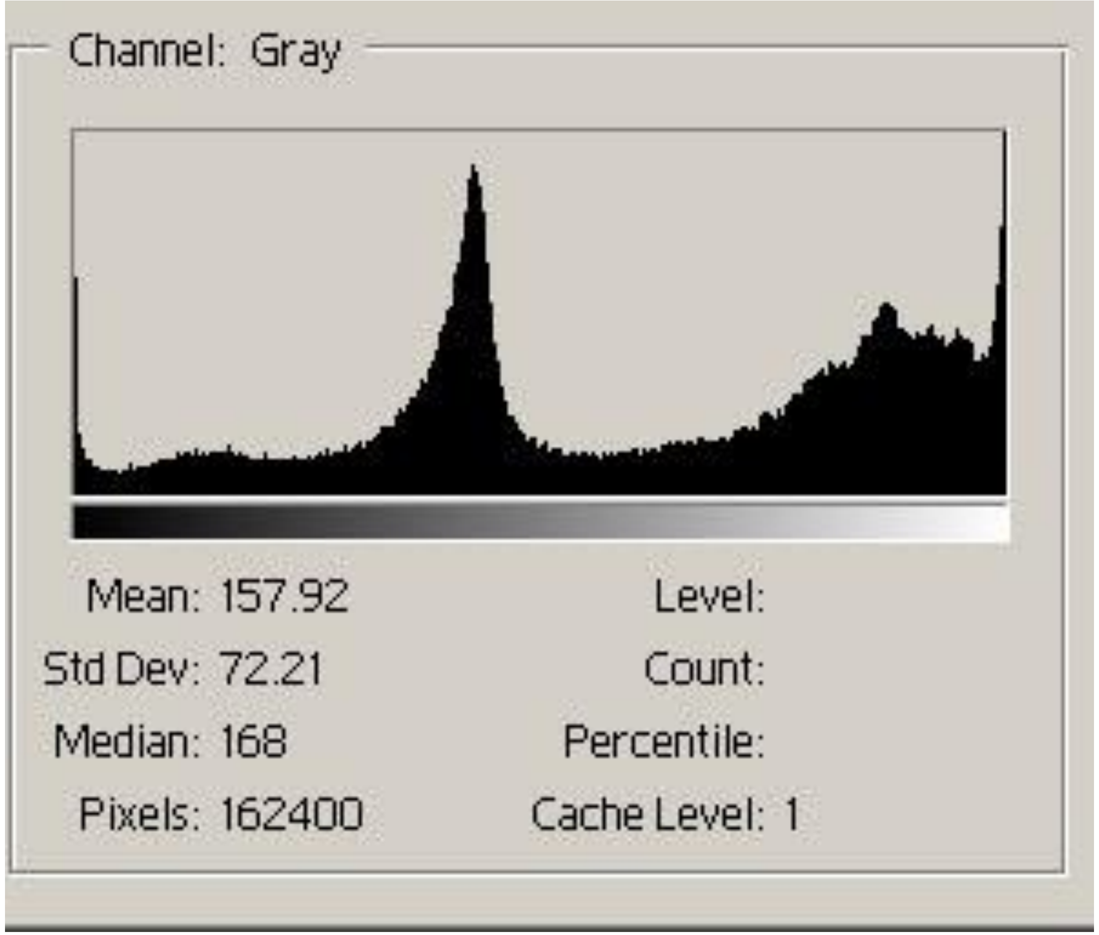
Histogram

- For each gray level, it reports the number of pixels of that color.
- For an image I[m,n] we have

H(k) = number of pixels of value k

- And the sum of all H is exactly *mxn*
- The histogram is useful for an immediate understanding of the characteristics of the image.

Histogram



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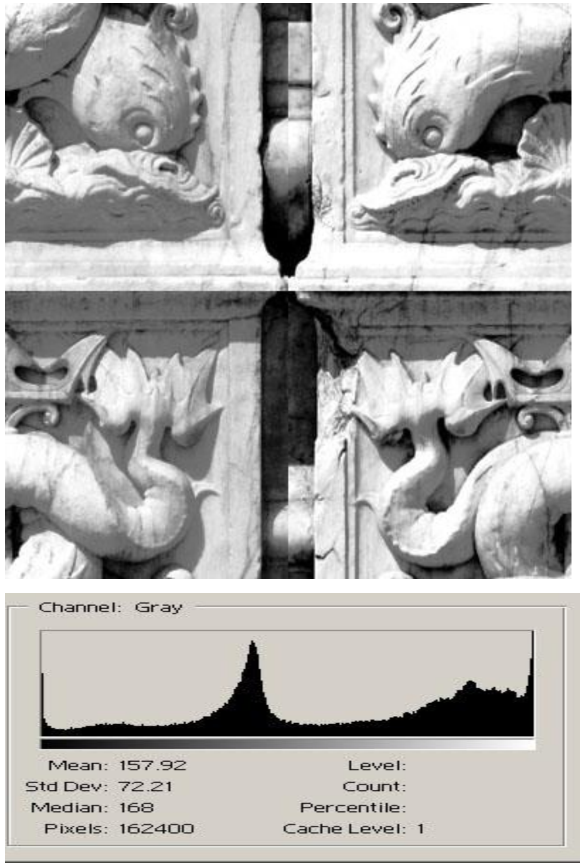
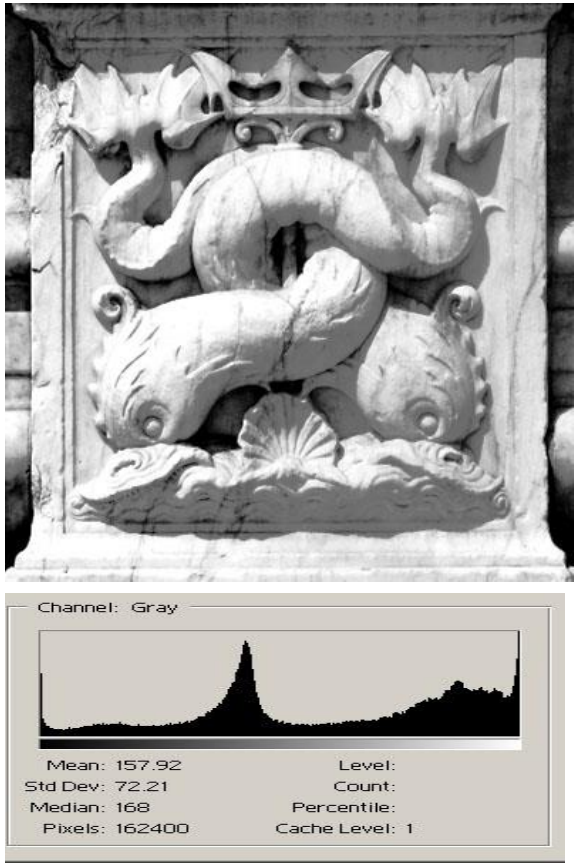
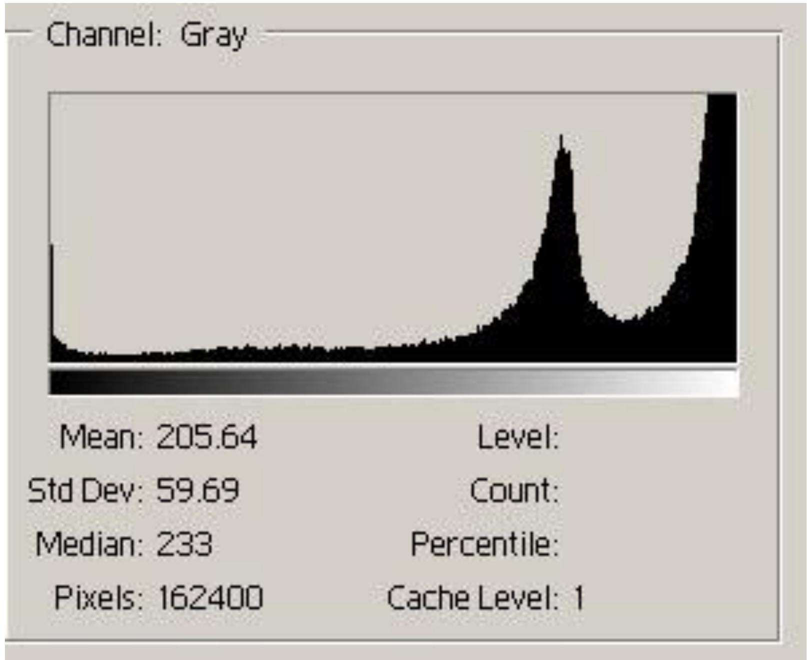
Different images may have similar histograms!





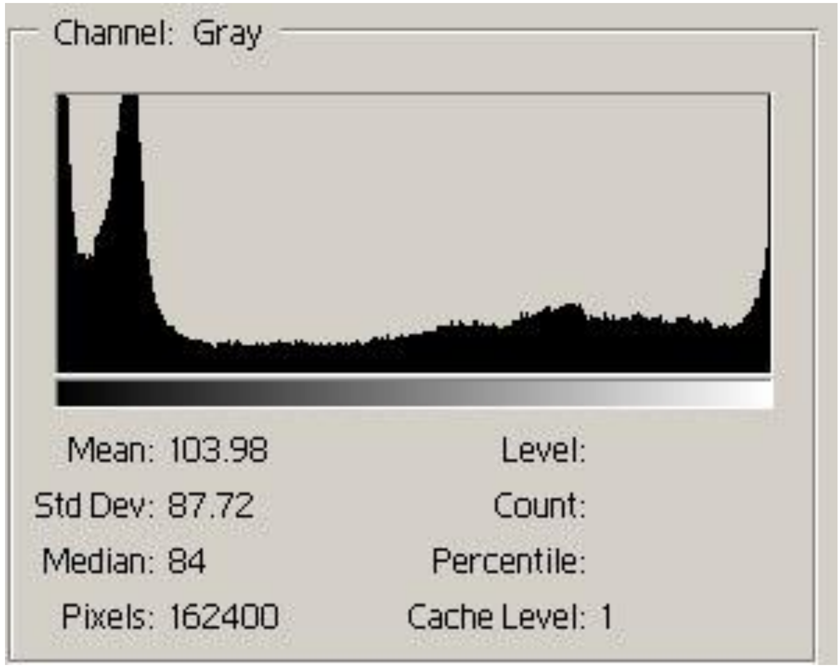
The histogram does not take into account the spatial distribution of pixels!

Clear image: denser histogram on the right



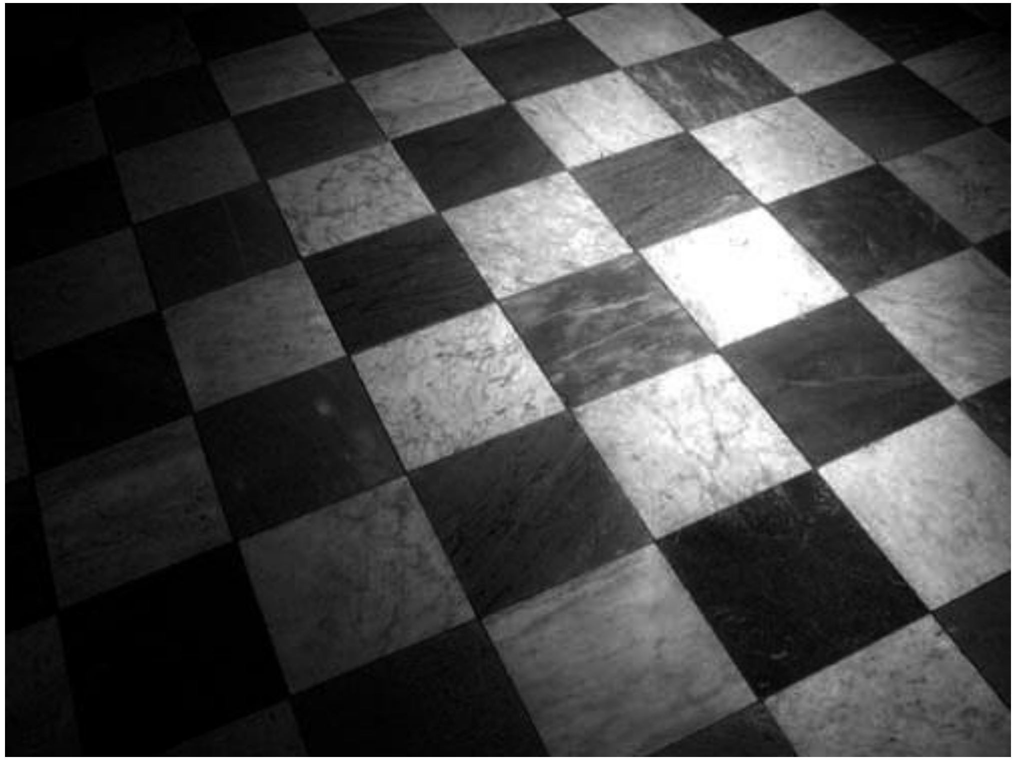
A **clear image** is a photograph or digital image that is sharp, well-lit, and free from blurriness or noise, making details easy to distinguish. In a clear image, both the subject and the background are well-defined, with accurate colors, appropriate contrast, and balanced exposure.

Dark image: denser histogram on the left



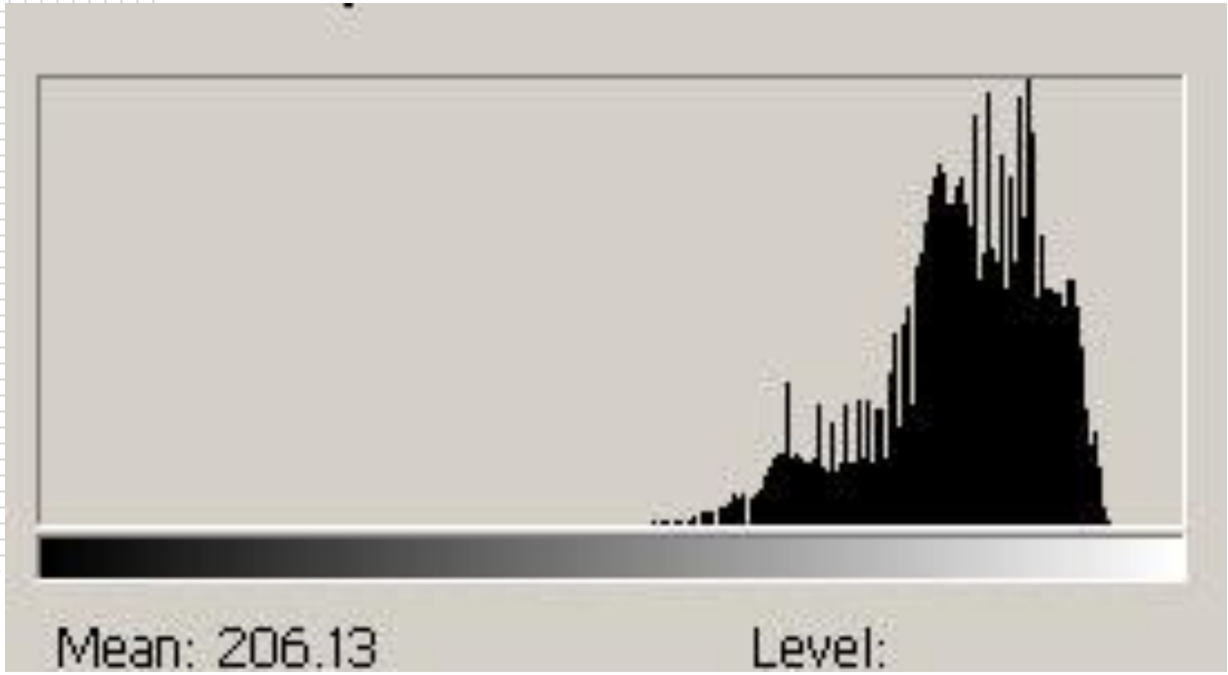
A **dark image** refers to a photograph or digital image that appears overly dim or lacks sufficient brightness, making details difficult to discern, especially in shadowed or low-light areas.

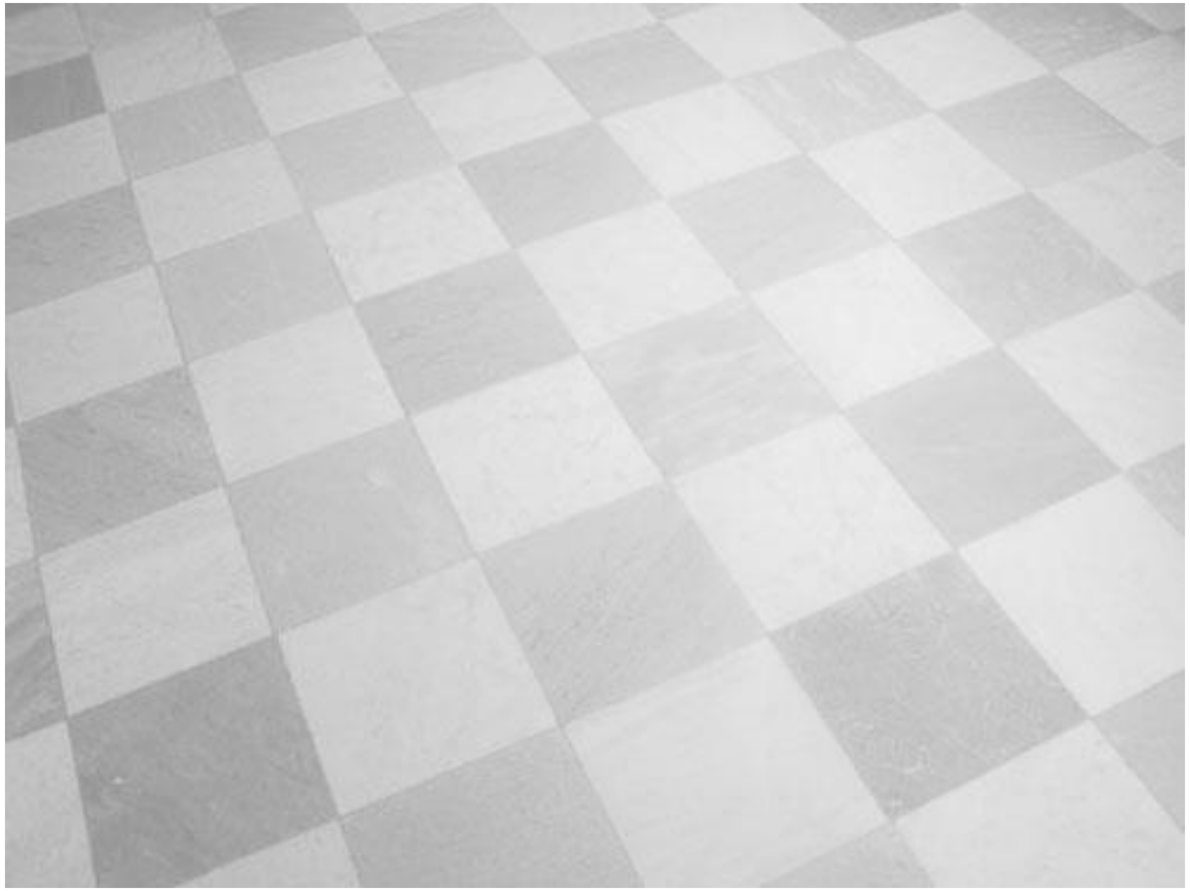
Under-exposed image



An **under-exposed image** is one that has received insufficient light during capture, resulting in a darker-than-expected outcome. Details in shadowed areas may be lost, and the overall image can appear overly dim or lack contrast.

Over-exposed image





An **over-exposed image** is one that has received too much light during capture, resulting in an excessively bright image where details in the highlighted or bright areas are lost.

Contrast expansion (contrast stretching)

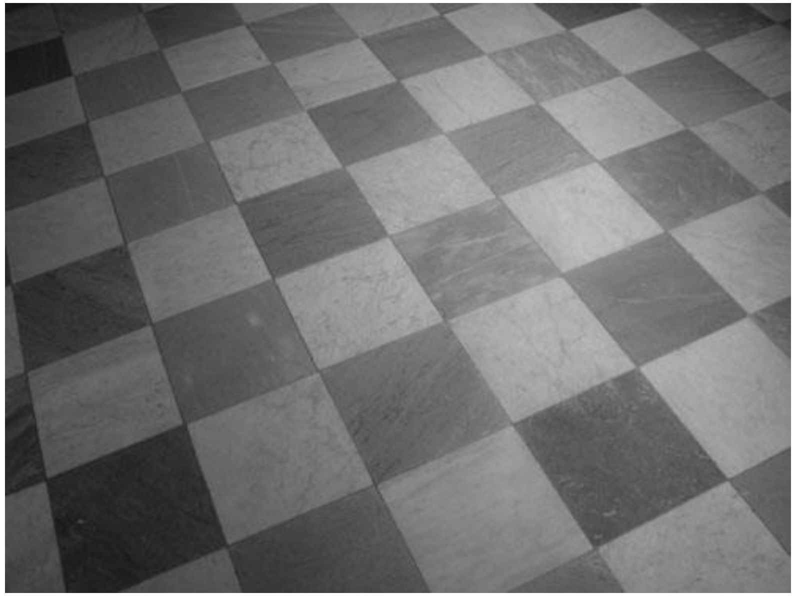
- It is used to increase the dynamics of an image whose histogram is focused on a limited range of possible values.

- It is achieved by shifting (with special algorithms) the values of one bin of the histogram to another unused bin.

- The histogram will appear differently. This is done to emphasize that the missing bins have been distributed along other levels.

Contrast stretching

Immagine originale



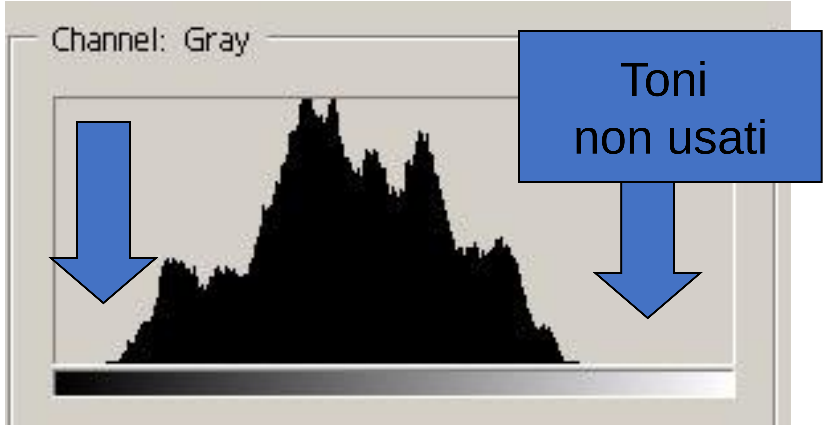
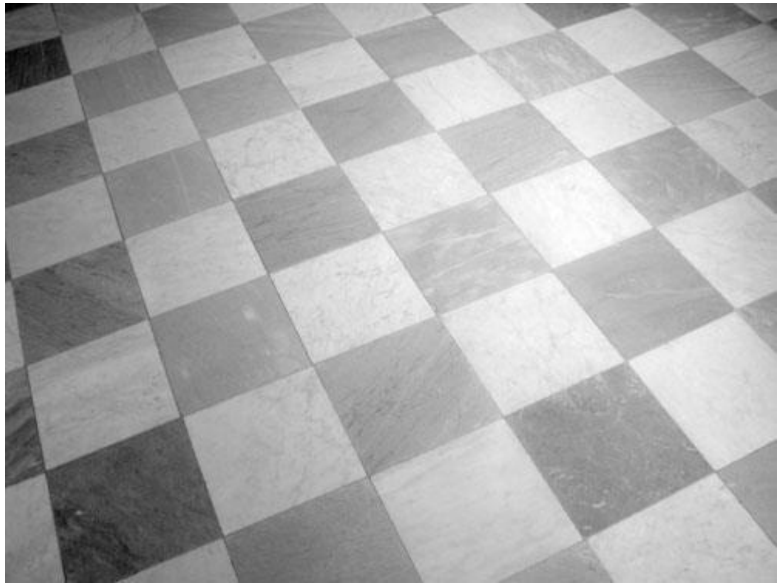
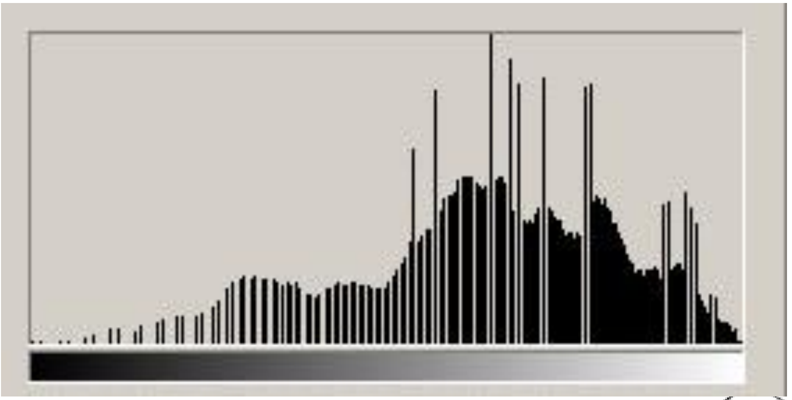
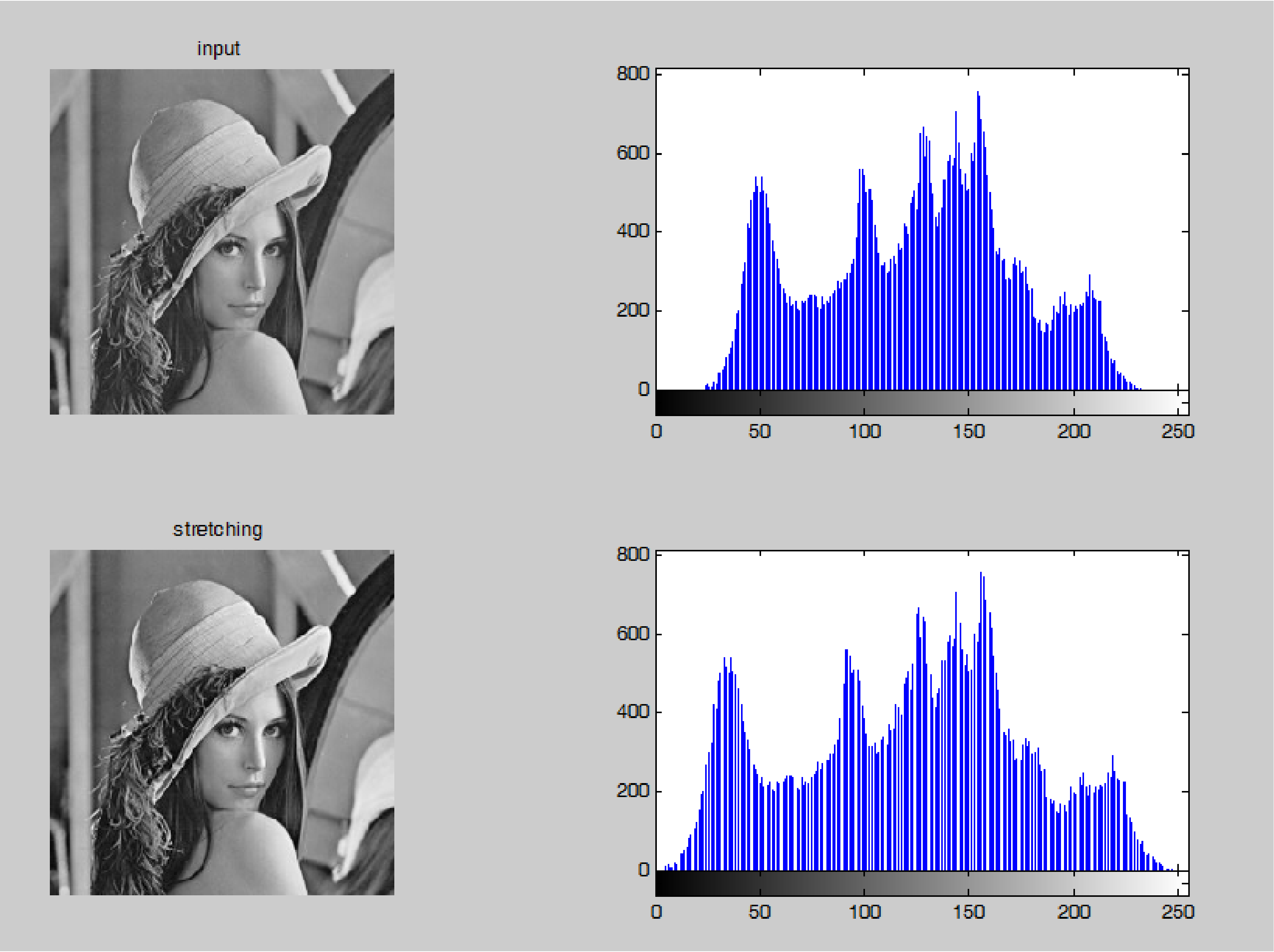


Immagine “corretta”






input
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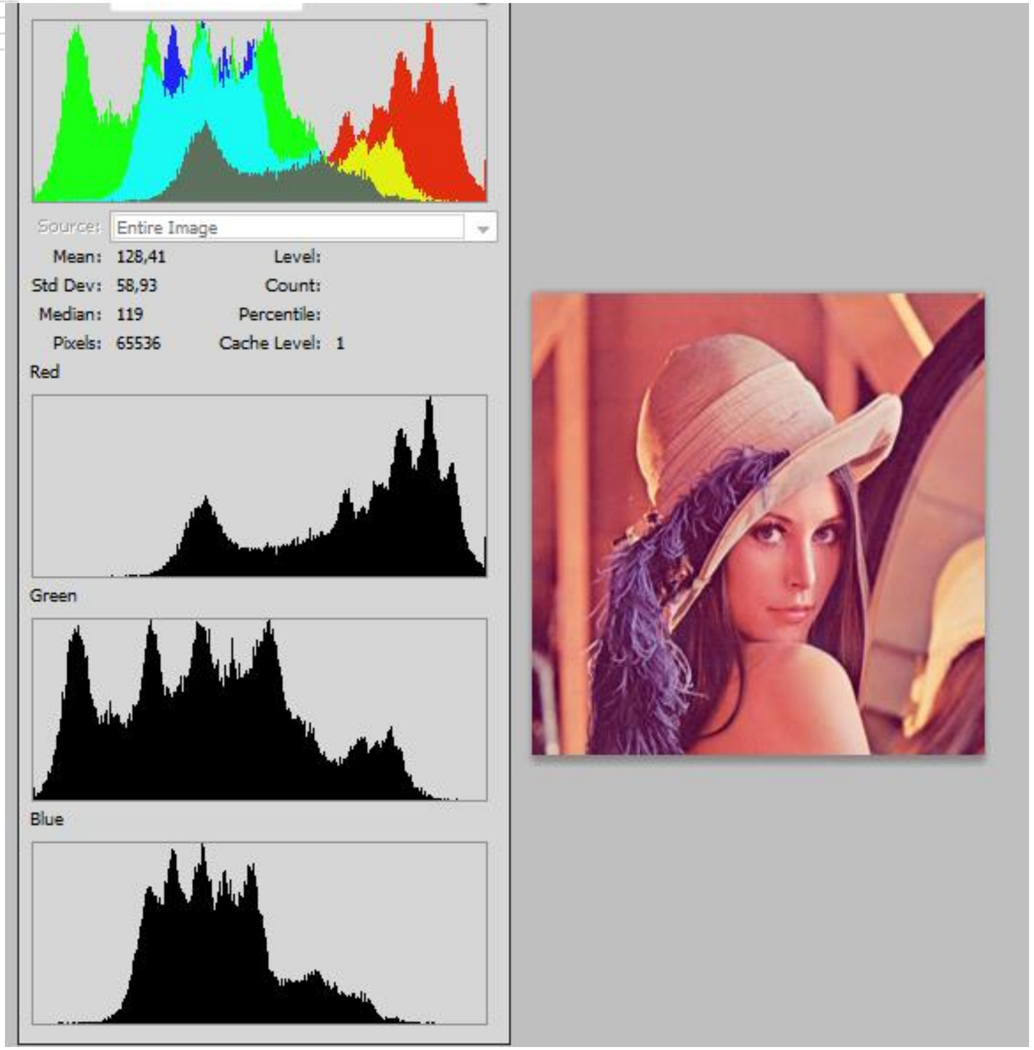
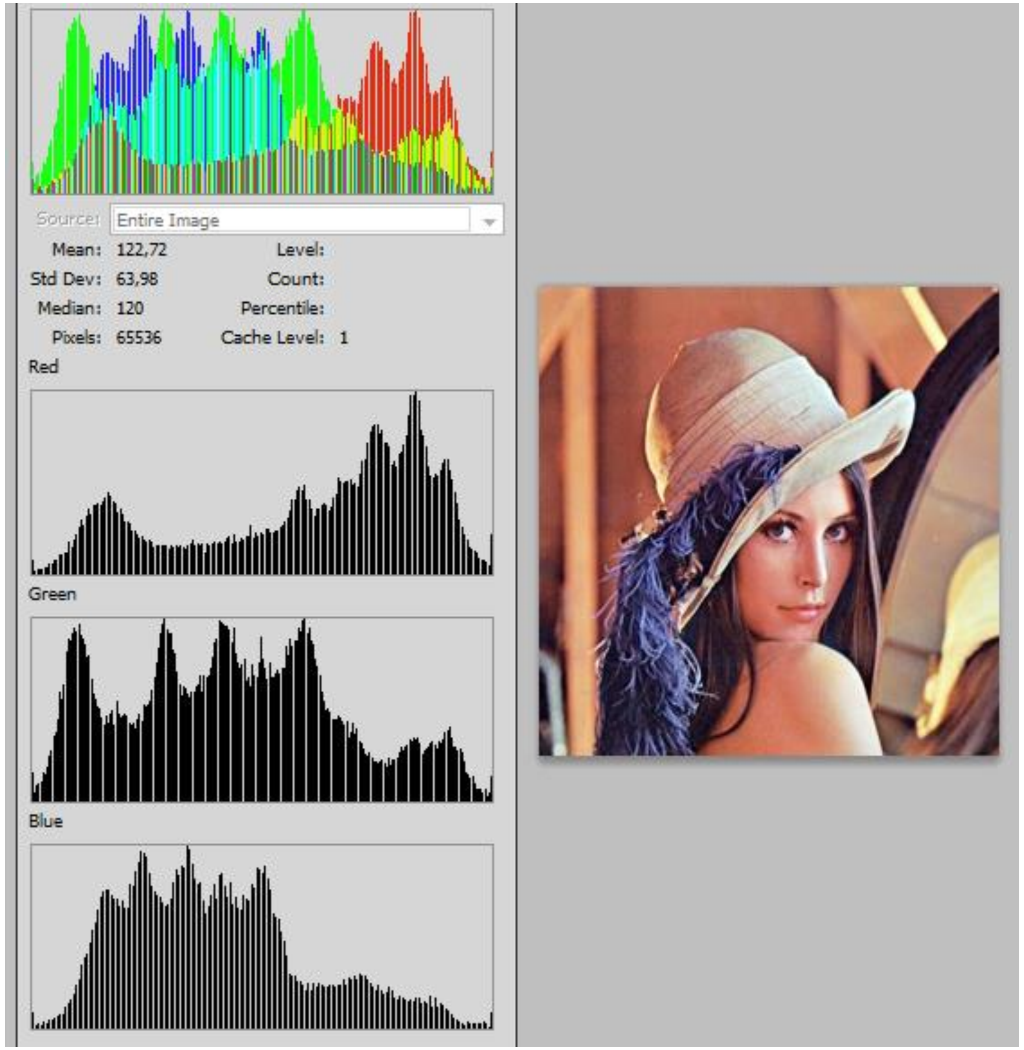
Lena's Stretching





Arithmetic on images

Operating arithmetically, it may happen that a pixel has:

a) A negative value;

b) A value greater than the maximum (typically 255);

c) A non-integer value (easily solved by approximation or truncation);

Normalization

Problems (a) and (b) on the previous slide are called range problems.

Two are the most common solutions:

- Set negative values to 0 (black) and values greater than 255 to 255 (white).
- Re-normalize the range by transforming each value according to the equation:

$$v_{new} = \underbrace{255}_{\text{Max value}} * \frac{v_{old} - min_{observed}}{max_{observed} - min_{observed}} \underbrace{+ 0}_{\text{Min value}}$$

Python Exercize!

- Write a Python program that creates a numpy matrix of NxM of random values between [-500, 500].

  - Normalize the matrix values between [0,255].
  - Normalize the matrix values between [10,255].
  - Normalize the matrix values between [500,900].

$$v_{new} = (MAX - MIN) * \frac{v_{old} - min_{observed}}{max_{observed} - min_{observed}} + MIN$$

Generic Formula

- Normalize in the range [MIN, MAX]

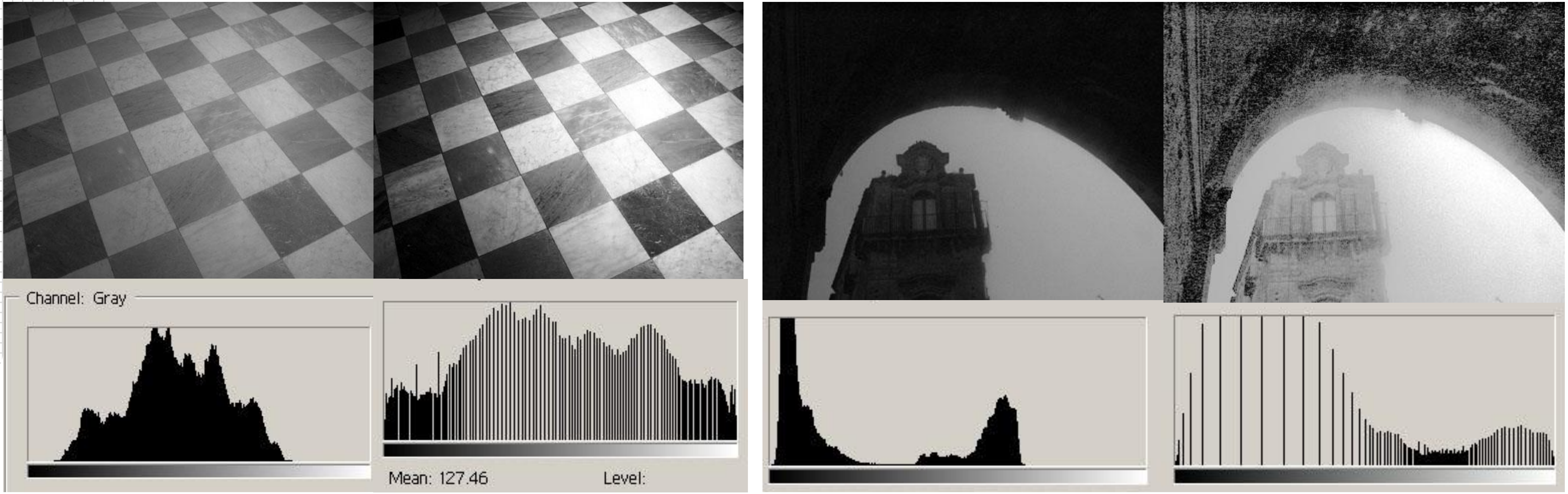
$$v_{new} = (MAX - MIN) * \frac{v_{old} - min_{observed}}{max_{observed} - min_{observed}} + MIN$$

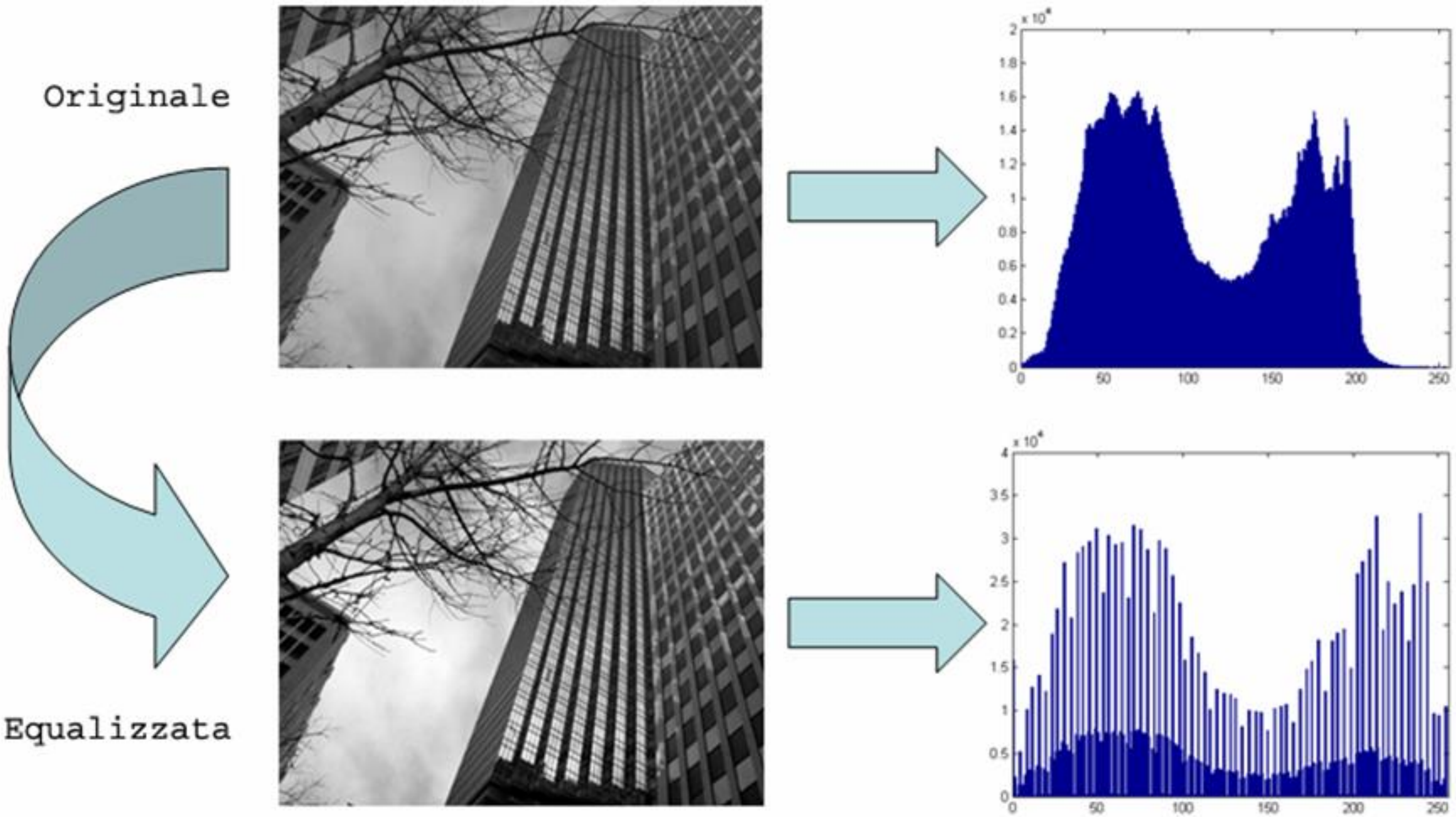
Equalization

An equalized image is defined when the contribution of each different grey level is approximately equal.

- It is also referred to as a uniform or flattened "histogram”.
- Equalization is achieved using special algorithms
- Beware that equalization does not always improve the image!

Equalized image




Originale
Equalizzata

Equalization Algorithm

- If r_k is a gray level and n_k the number of pixels in the image MxN of that gray level, we can define

$$p_r(r_k) = \frac{n_k}{MN}, \qquad k = 0,1,2, \dots, L-1$$

- If we plot r_k versus $\mathrm{p_r}(r_k)$ what we get is the histogram of the image.

Equalization Algorithm

- The new gray values of the histogram are defined as follows:

$$s(k) = T(r_k) = (L-1)\sum_{j=0}^{k} p_r(r_j) = \frac{(L-1)}{MN}\sum_{j=0}^{k} n_j \qquad k = 0,1,2,\dots,L-1$$

Equalization Algorithm: Example

- Let there be a 3-bit image (L=8) with 64x64 pixels (MN=4096) with the following intensity distribution:

r_k	n_k	$p_r(r_k) = n_k/MN$
$r_0 = 0$	790	0.19
$r_1 = 1$	1023	0.25
$r_2 = 2$	850	0.21
$r_3 = 3$	656	0.16
$r_4 = 4$	329	0.08
$r_5 = 5$	245	0.06
$r_6 = 6$	122	0.03
$r_7 = 7$	81	0.02

Equalization Algorithm: Example

- Applying the formula gives:

$$s(k) = T(r_k) = (L-1)\sum_{j=0}^{k} p_r(r_j) = \frac{(L-1)}{MN}\sum_{j=0}^{k} n_j \qquad k = 0, 1, 2, \dots, L-1$$

r_k	n_k	$p_r(r_k) = n_k/MN$
$r_0 = 0$	790	0.19
$r_1 = 1$	1023	0.25
$r_2 = 2$	850	0.21
$r_3 = 3$	656	0.16
$r_4 = 4$	329	0.08
$r_5 = 5$	245	0.06
$r_6 = 6$	122	0.03
$r_7 = 7$	81	0.02

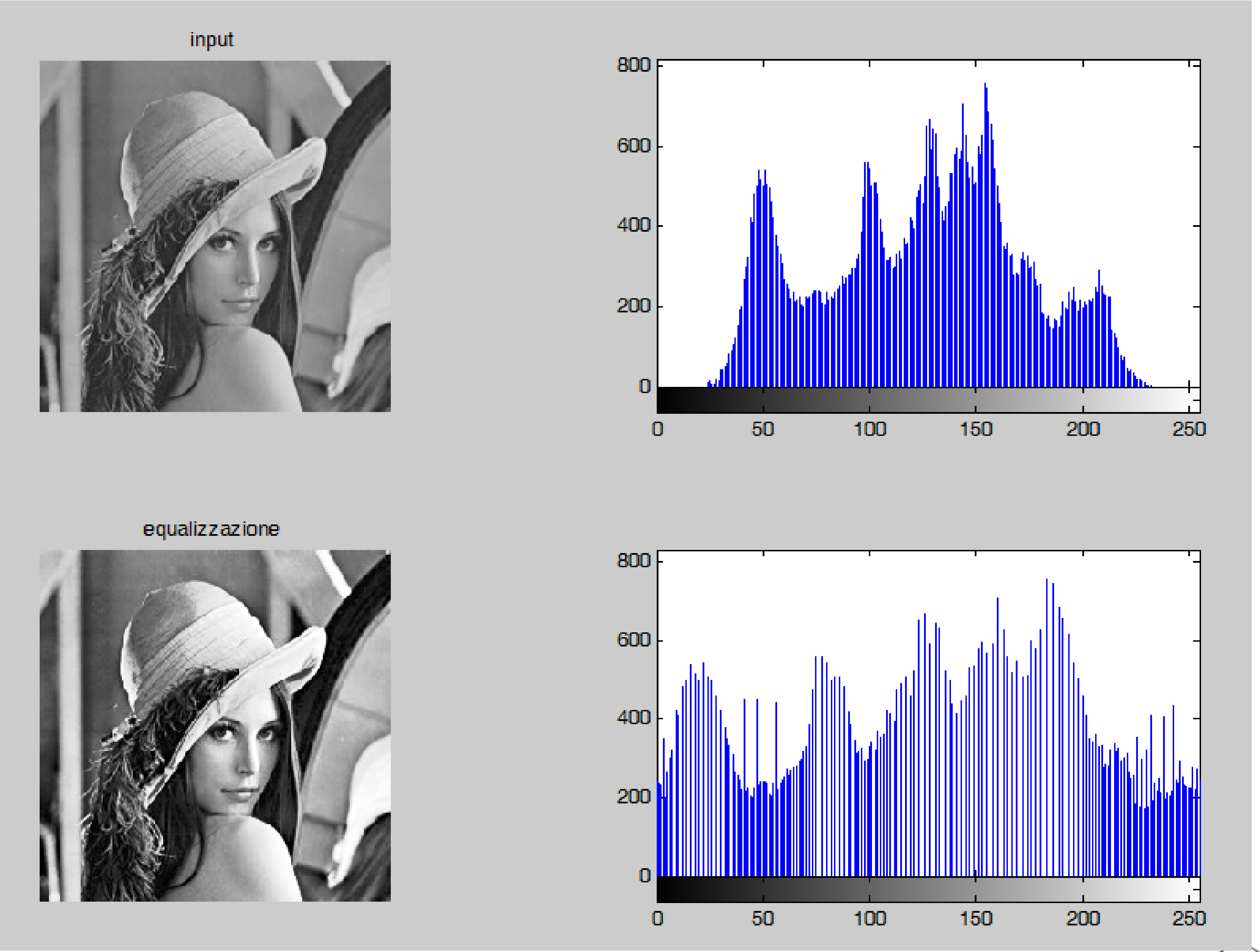
$$s(0) = T(r_0) = 7\sum_{j=0}^{0} p_r(r_j) = 7p_r(r_0) = 7 * 0,19 = 1.33$$

$$s(1) = T(r_1) = 7\sum_{j=0}^{1} p_r(r_j) = 7p_r(r_0) + 7p_r(r_1) = 3.08$$

$$s(2) = 4,55; \quad s_3 = 5,67; \quad s_4 = 6,23; \quad s_5 = 6,65; \quad s_6 = 6,86; \quad s_7 = 7.00$$

Rounding up :

$$s_0 = 1.33 \rightarrow 1 \qquad s_4 = 6.23 \rightarrow 6$$
$$s_1 = 3.08 \rightarrow 3 \qquad s_5 = 6.65 \rightarrow 7$$
$$s_2 = 4.55 \rightarrow 5 \qquad s_6 = 6.86 \rightarrow 7$$
$$s_3 = 5.67 \rightarrow 6 \qquad s_7 = 7.00 \rightarrow 7$$


input
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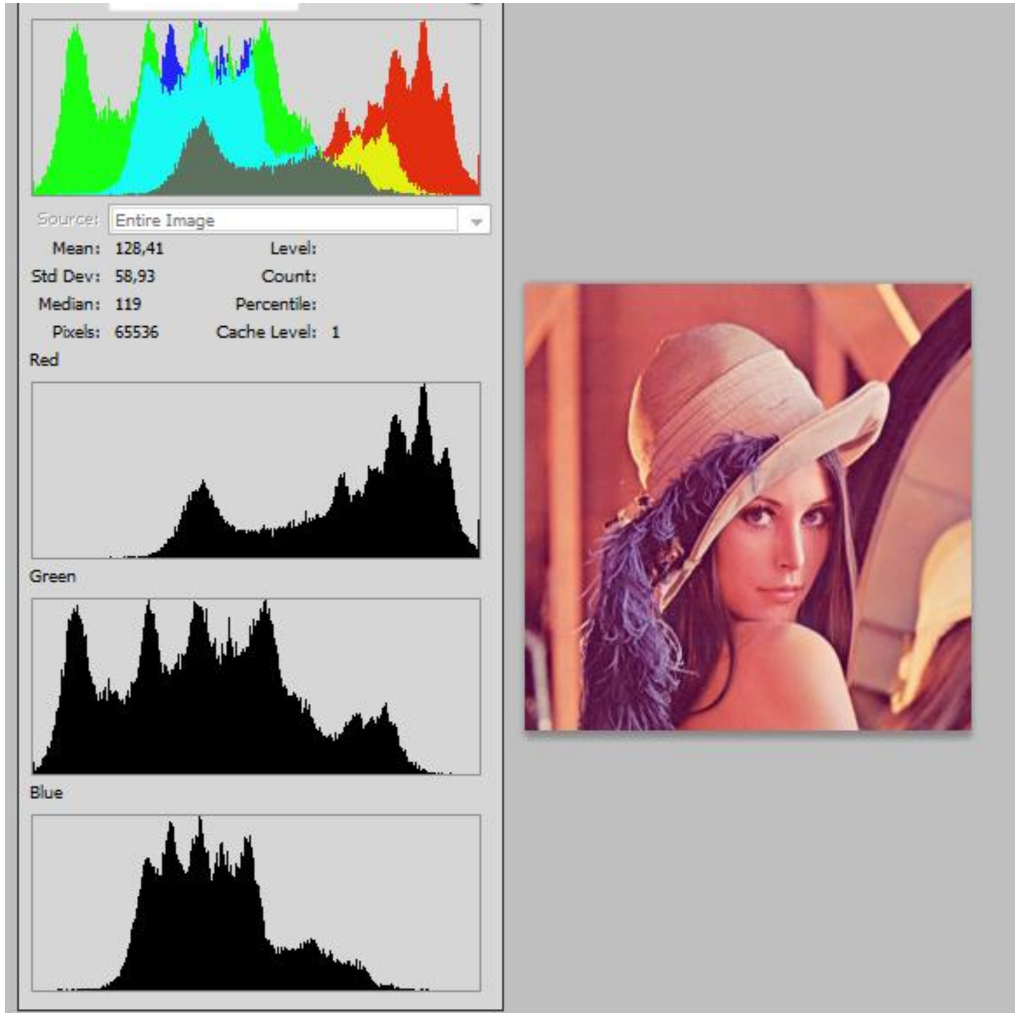
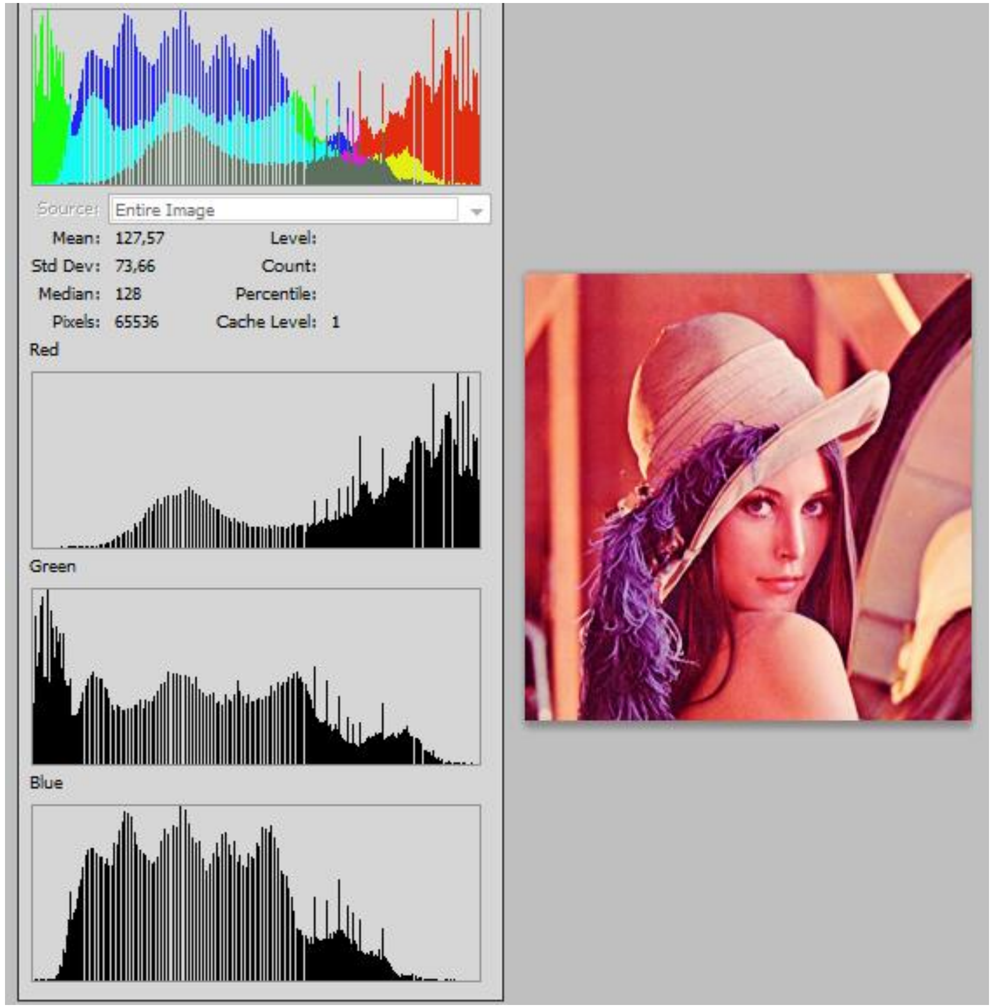
Equalization of Lena





Python Exercize!

- Write a Python program that creates a numpy matrix of NxM of random values between [30, 150].

$$p_r(r_k) = \frac{n_k}{MN},$$
$$k = 0,1,2, \dots, L-1$$

  - Showing the histogram
  - Creating the equalized image representation
  - Showing the equalized histogram

$$\boldsymbol{s(k) = T(r_k) = (L-1)\sum_{j=0}^{k} p_r(r_j) = \frac{(L-1)}{MN}\sum_{j=0}^{k} n_j \quad k = 0, 1, 2, \dots, L-1}$$

Operations on images

Image Processing Laboratory

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Simplification: gray levels

- To simplify the treatment of the problem we will work only on gray-tone images.

- The same operations described for such images are extended to RGB images by operating separately on the three channels (planes) R, G and B and treating each of them as a gray-level image independent of the other channels (a solution not always appreciated in research).

Operations on images

These are operations alter the pixel values of an image.

The final image will appear different from the original one.

These operators work on both color and gray-tone images.

Operations on images

Processing in the spatial domain can be expressed as:

$$g(x,y) = T[f(x,y)]$$

f being the input image to the processing, ***g*** being the output image, and ***T*** being an operator on ***f*** defined in a neighborhood of ***(x,y)***.

Types of operations

The size of the neighborhood of (x,y) defines the character of the processing:

- punctual (the neighborhood coincides with the pixel itself);
- local (for example, a small square region centered on the pixel);
- global (the neighborhood coincides with the entire f).

Punctual Operators

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Punctual operators

- A point operator is said to be an operator that taken as input the value of a pixel returns a changed one that depends solely on the value of the input pixel.

Typical point operations:

- addition or subtraction of a constant to all pixels (to compensate for underexposure or overexposure);
- gray scale inversion (negative);
- contrast expansion;
- changing (equalizing or specifying) the histogram;

Point operators

- A point operator can be represented by a function that taken as input a value ***f(x,y)*** changes it to a value ***g(x,y)=T(f(x,y))*** with **f(x,y)** and **g(x,y)** belonging to the same range of definition (e.g., both between 0 and 255).

- Since a point operator depends only on the pixel value it is completely described by a table such as the following:

IN	0	1	2	3	4	5	6	7	…
OUT	T(0)	T(1)	T(2)	T(3)	T(4)	T(5)	T(6)	T(7)	…

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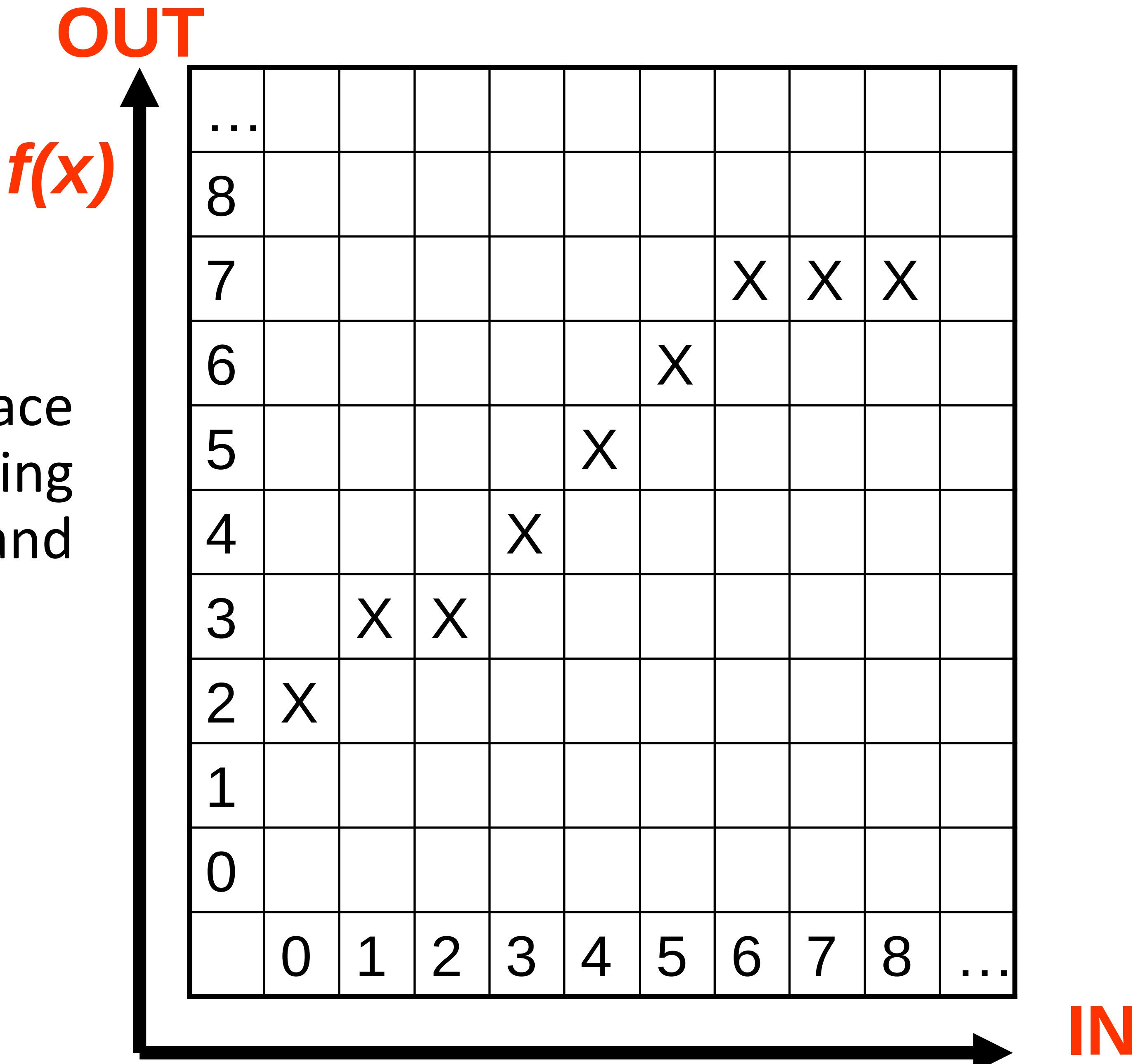
This is universally the interface that all commercial imaging programs offer for viewing and managing point operations



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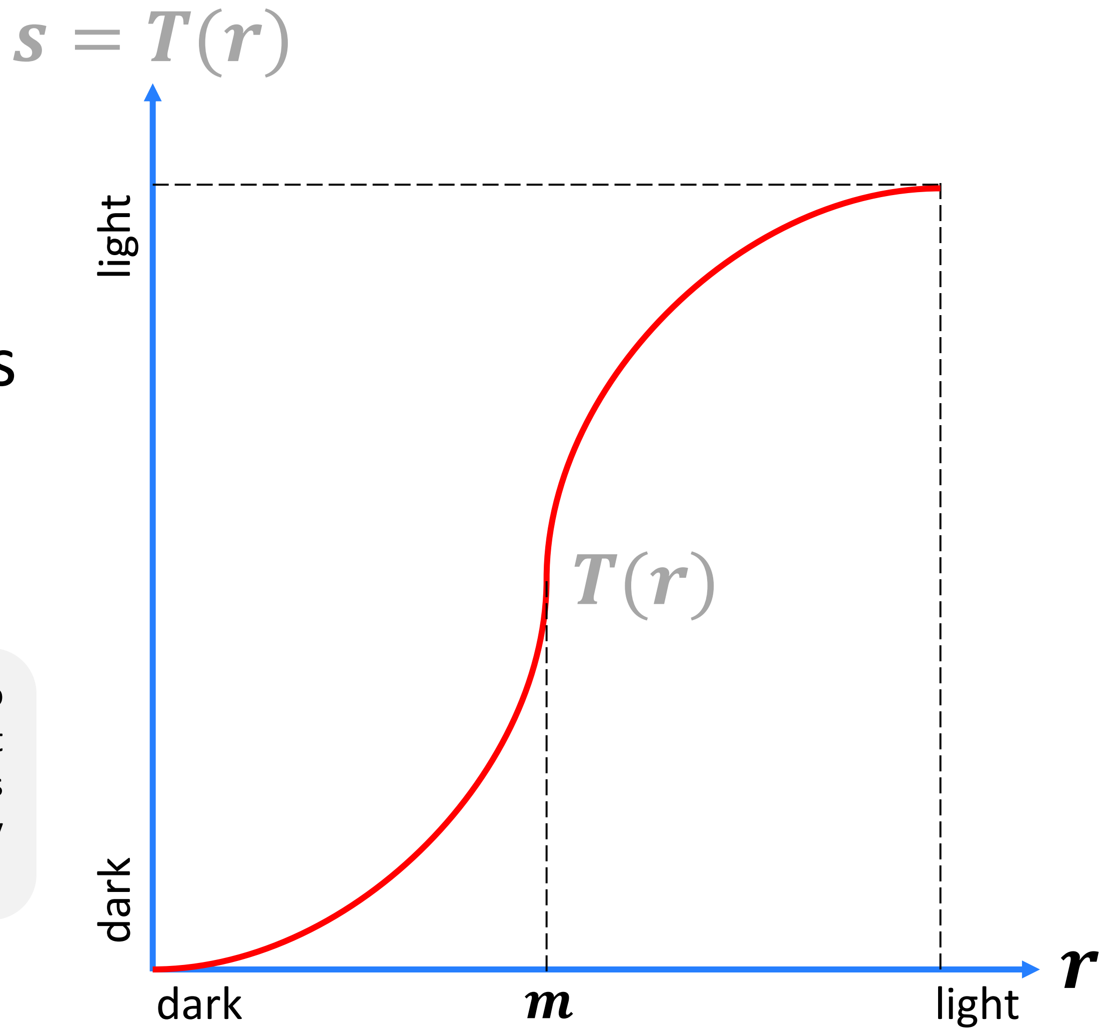
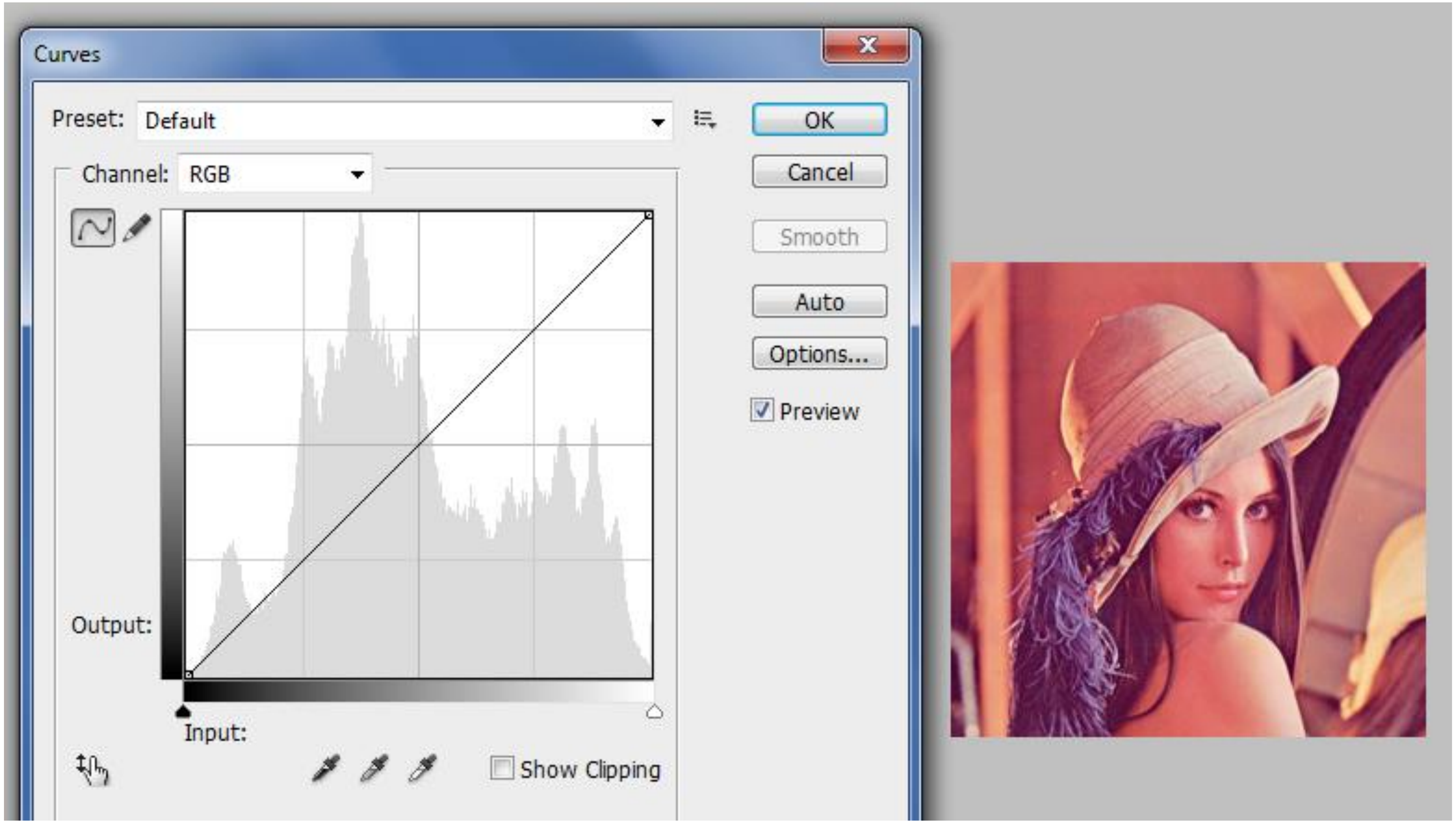
Look-up Tables (LUT)

- This type of chart is called look-up tables (LUT).

A **Look-Up Table (LUT)** is a mathematical table used to transform input values into desired output values. In image processing, LUTs are commonly applied to adjust colors, brightness, contrast, or tone within an image. By mapping each pixel's original value to a new value based on predefined settings, LUTs can quickly apply complex color grading or correction without requiring extensive calculations.



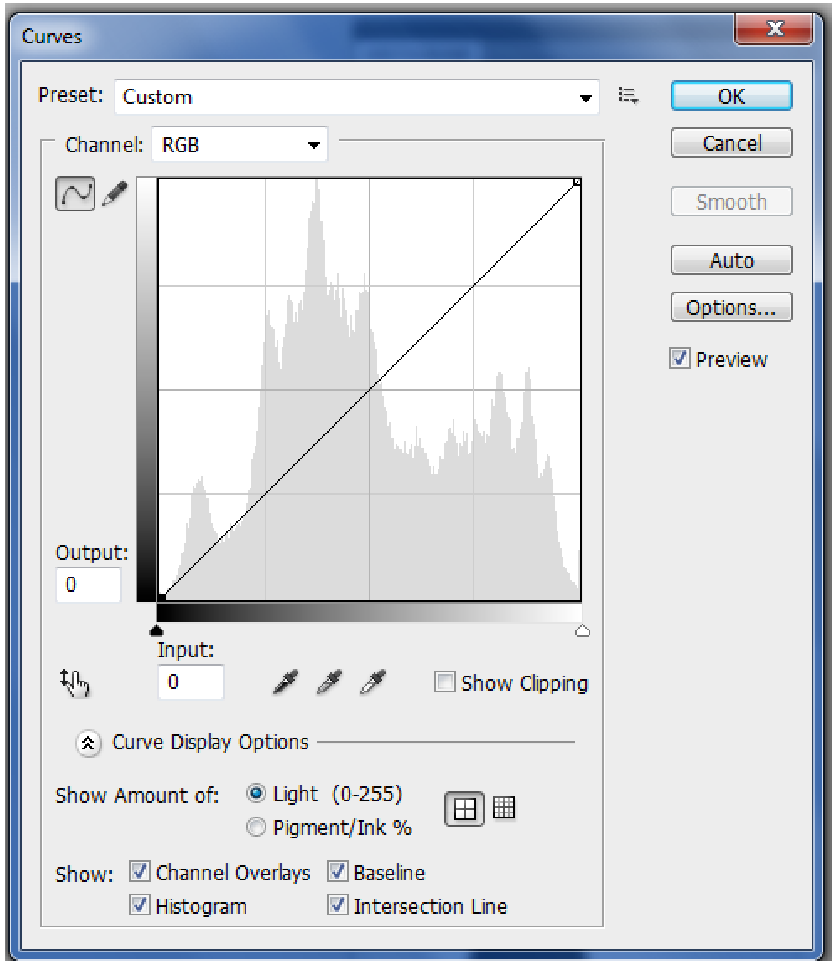
In Photoshop: "adjust curves"

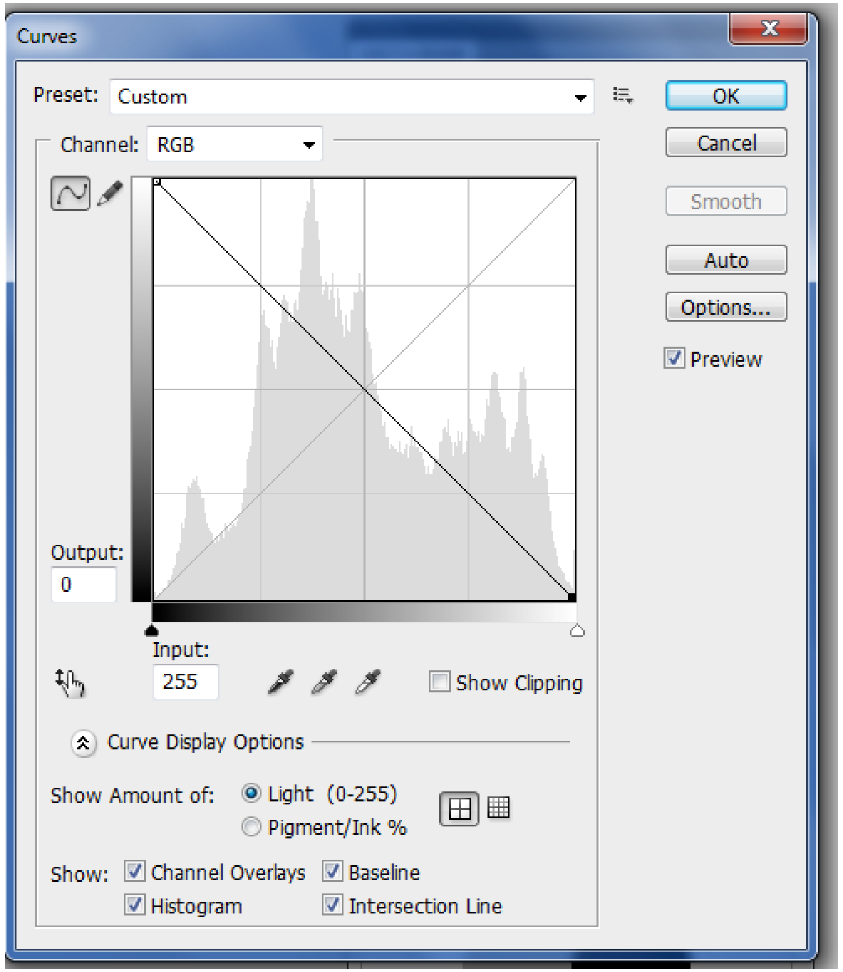


Negative

- It is the simplest point operation.
- It consists of associating the **f(x,y)** value of the pixel with the value **255 - f(x,y)**

Negative - How does the curve change?





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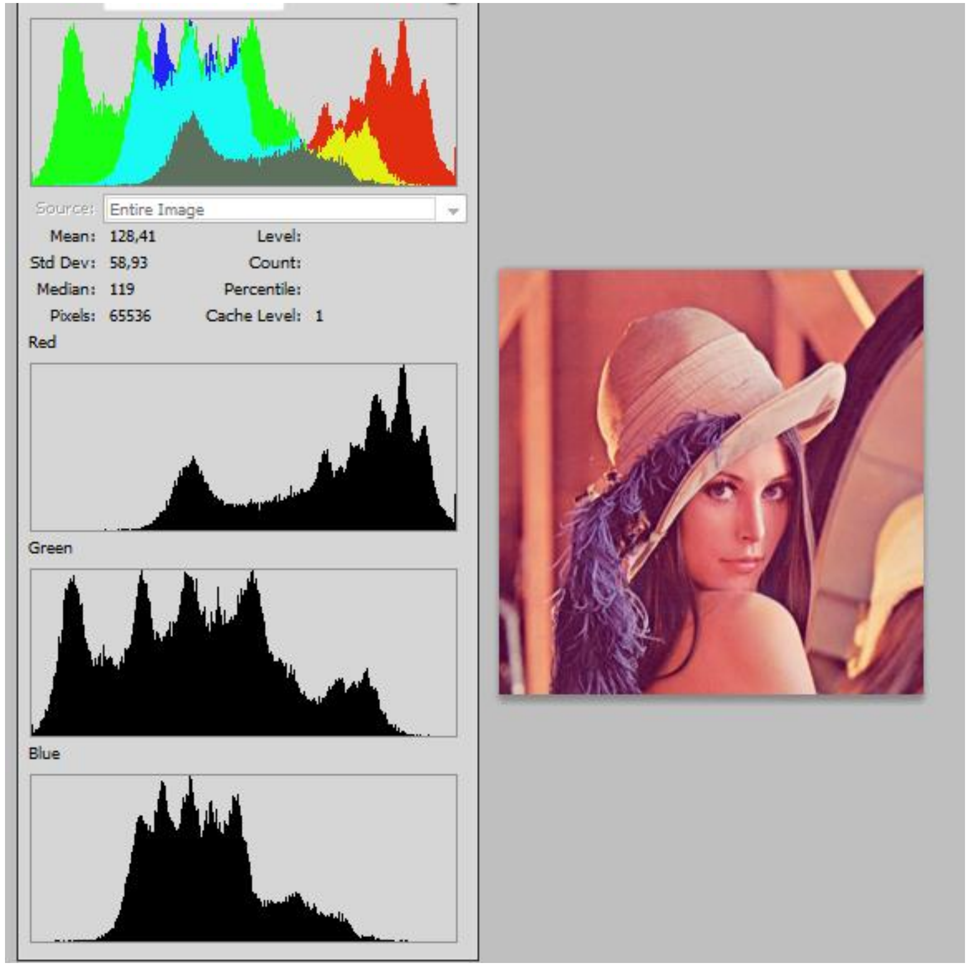
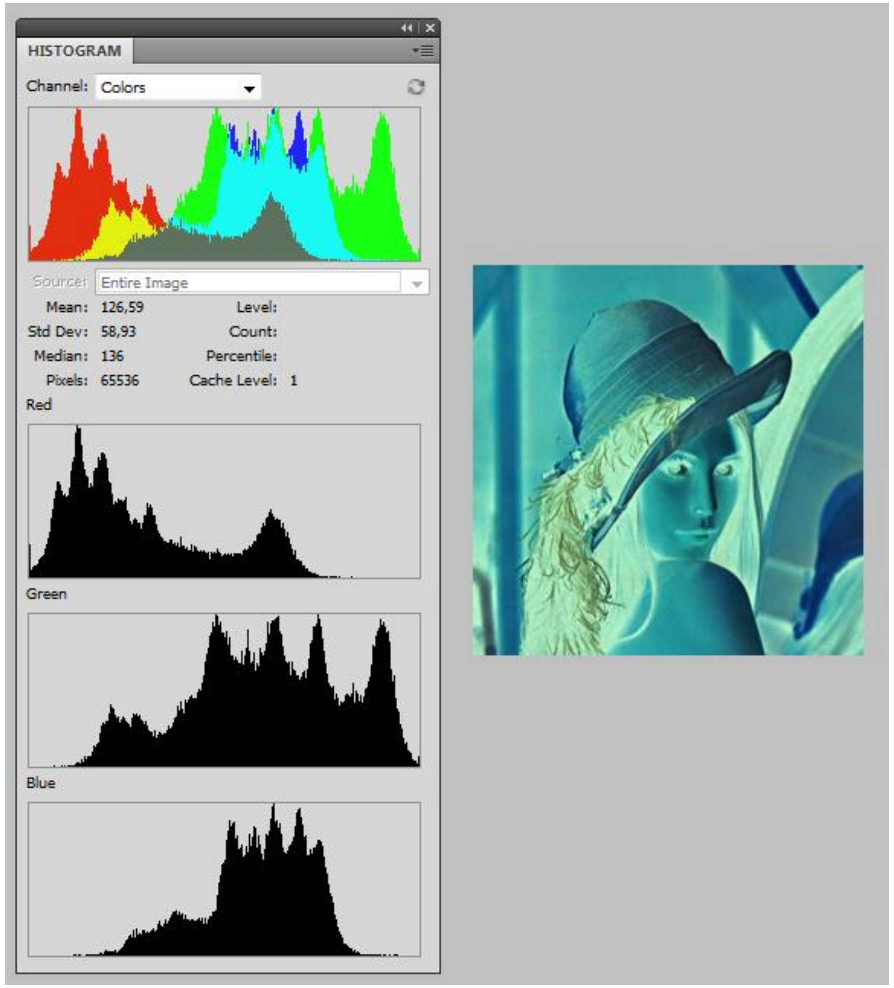
Negative - How does the curve change?





Negative


Curve
Regola le curve di colore
0_1-_1_.png-2 ([0_1-_1_] (importata))
Preimpostazioni:
Canale: Valore
Reimposta canale
Ingresso: 255
Uscita: 255
Tipo:
Tipo di curva: Smussata
Opzioni di fusione
Anteprima
Dividi vista
Aiuto
Reimposta
OK
Annulla

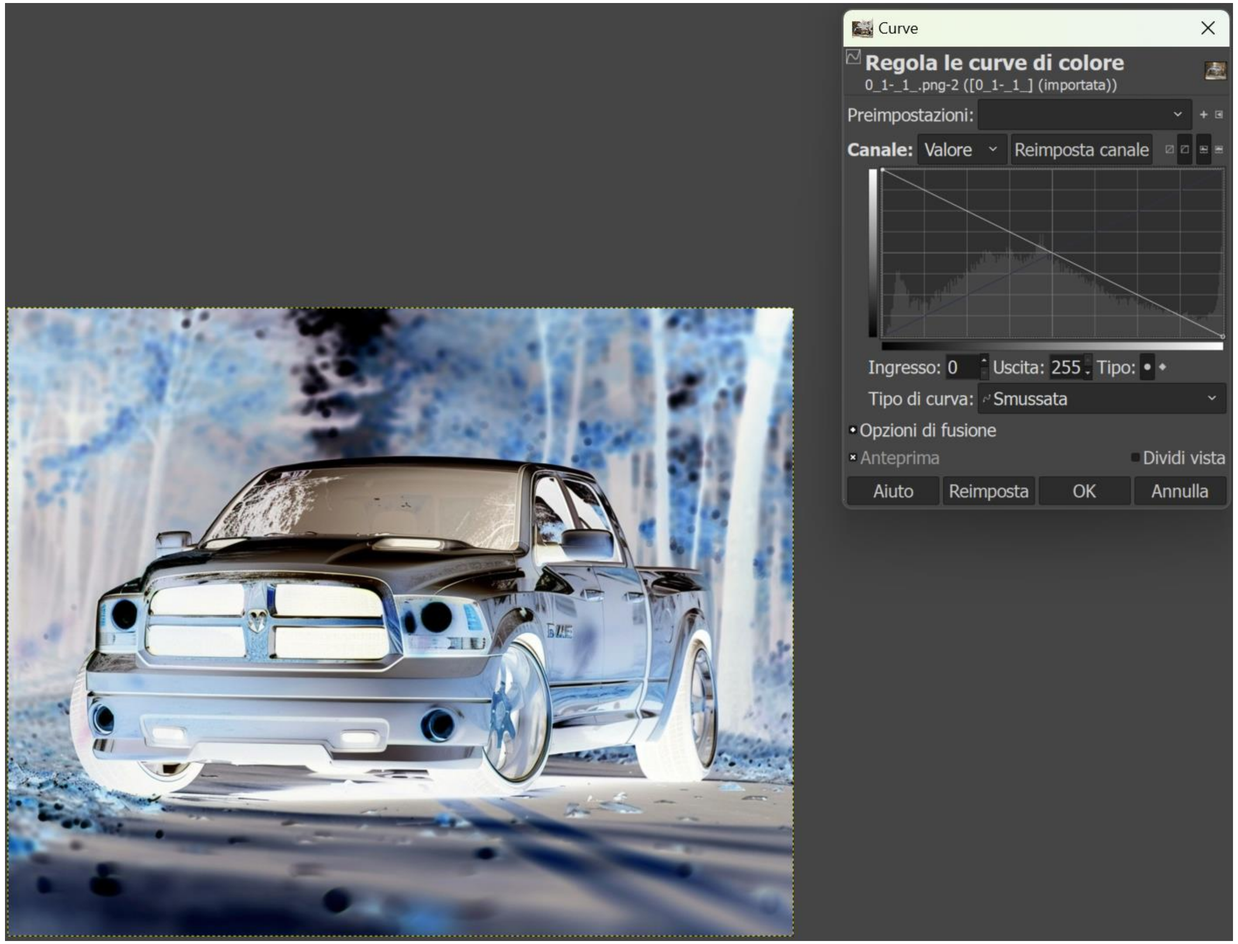

Curve
Regola le curve di colore
0_1-_1_.png-2 ([0_1-_1_] (importata))
Preimpostazioni:
Canale: Valore
Reimposta canale
Ingresso: 0
Uscita: 255
Tipo:
Tipo di curva: Smussata
Opzioni di fusione
Anteprima
Dividi vista
Aiuto
Reimposta
OK
Annulla

Image darkening

- How should I modify my curve?

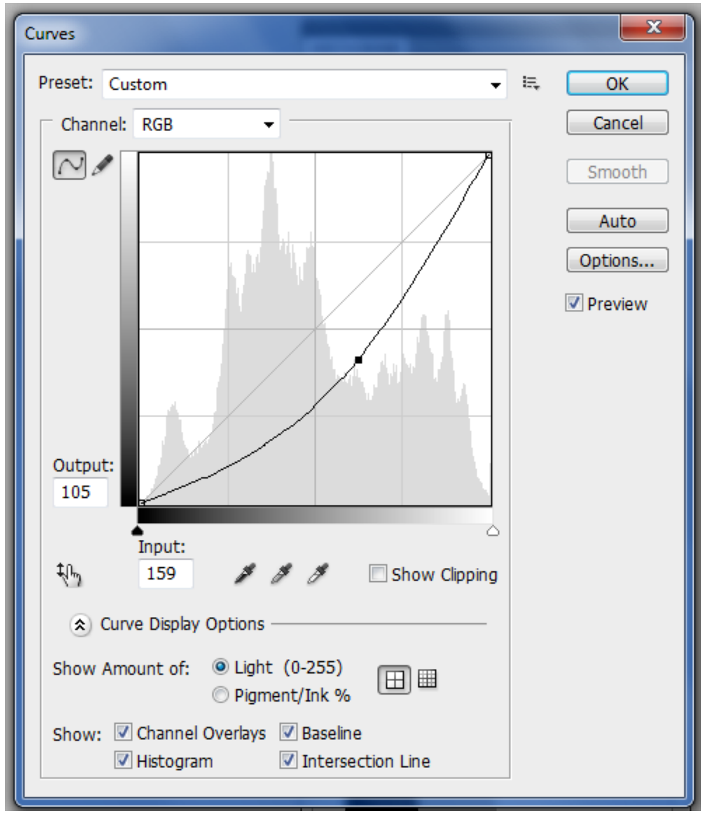
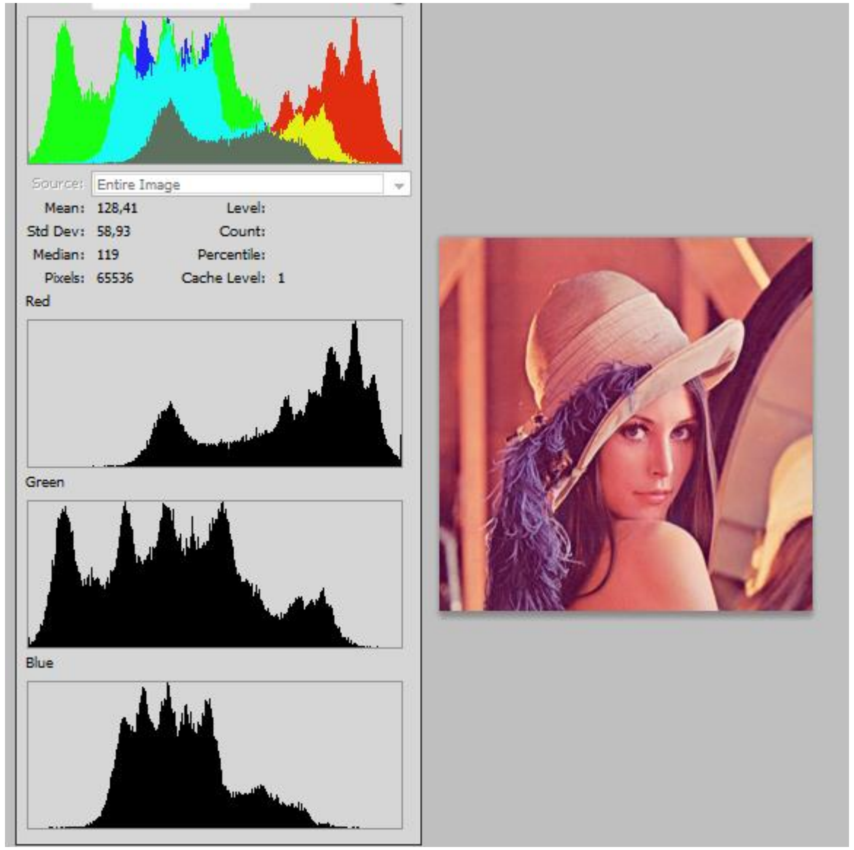


Image darkening



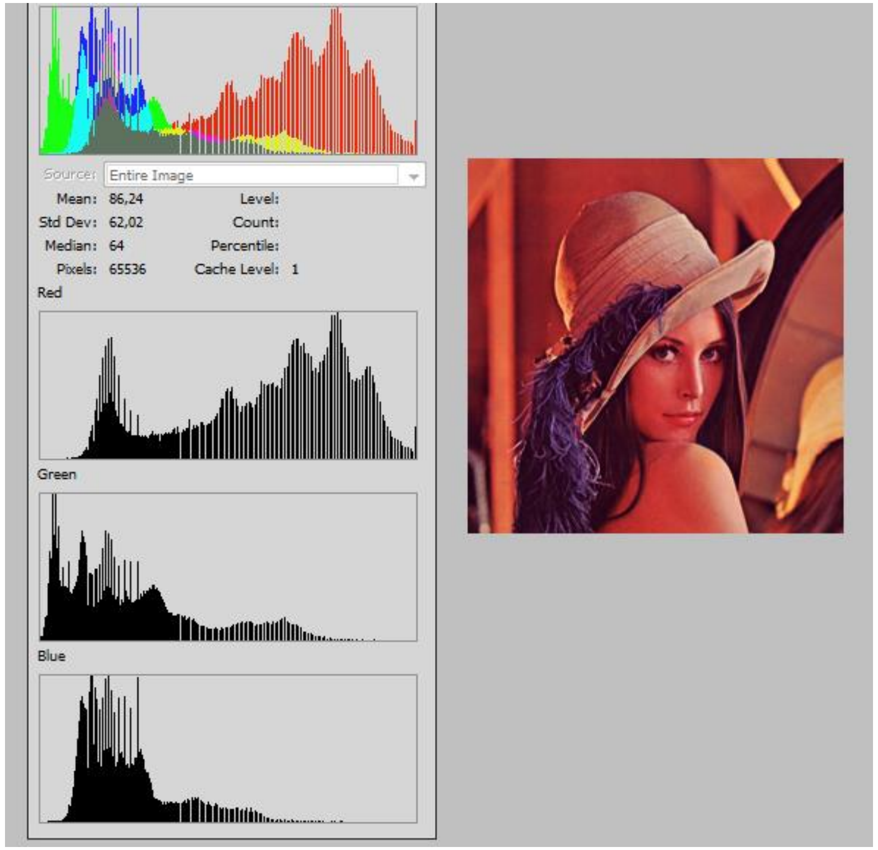
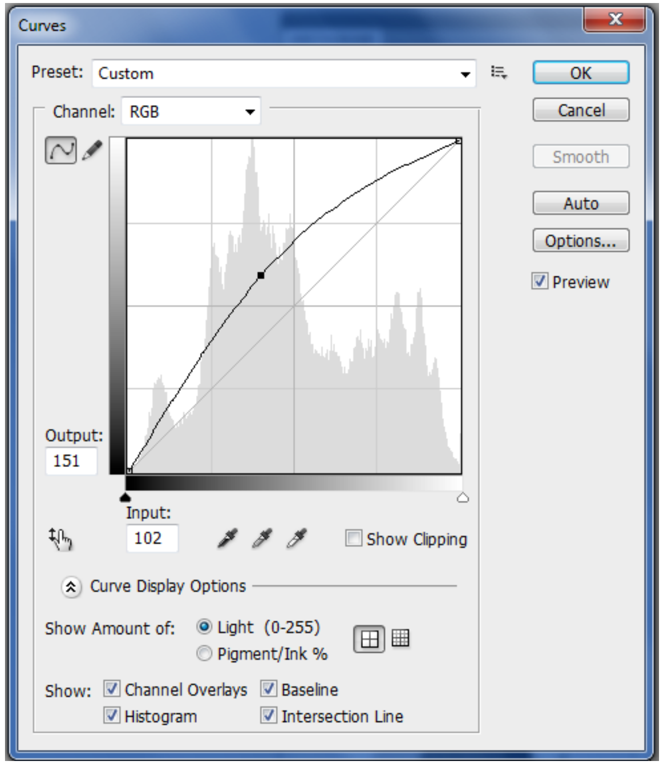
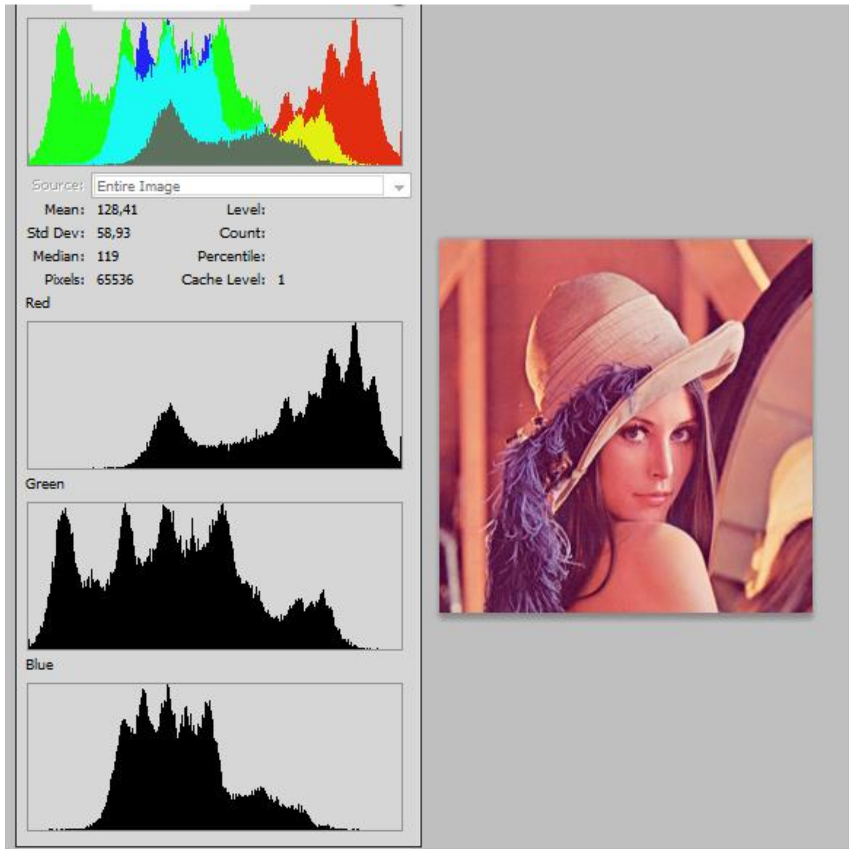


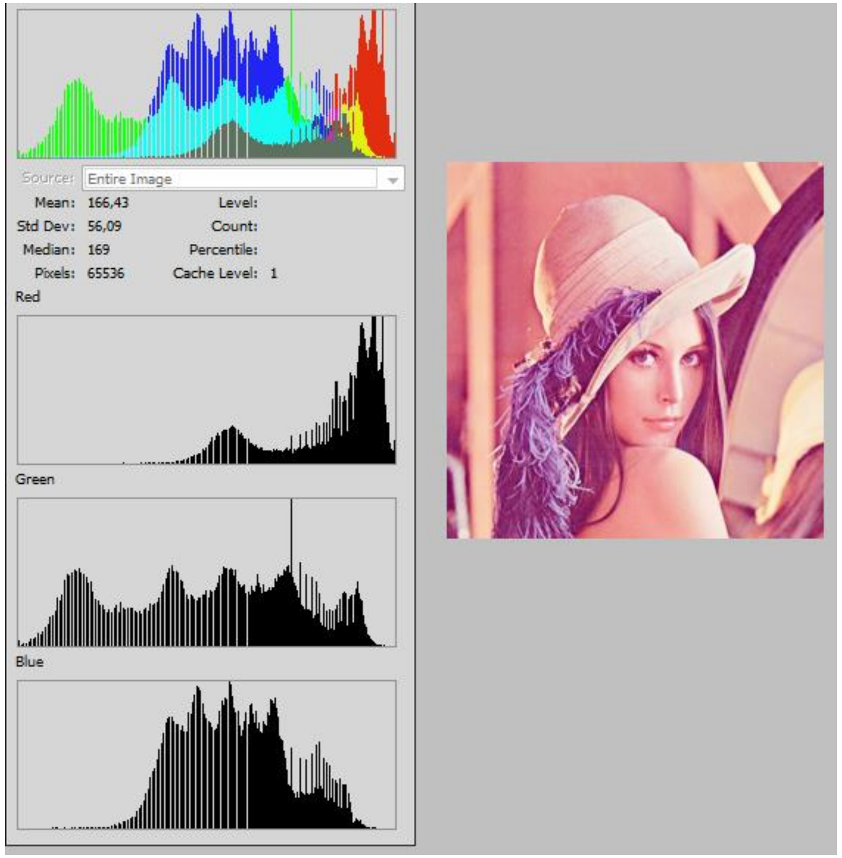
Image Clarification

- How should I modify the curve?



Clarification





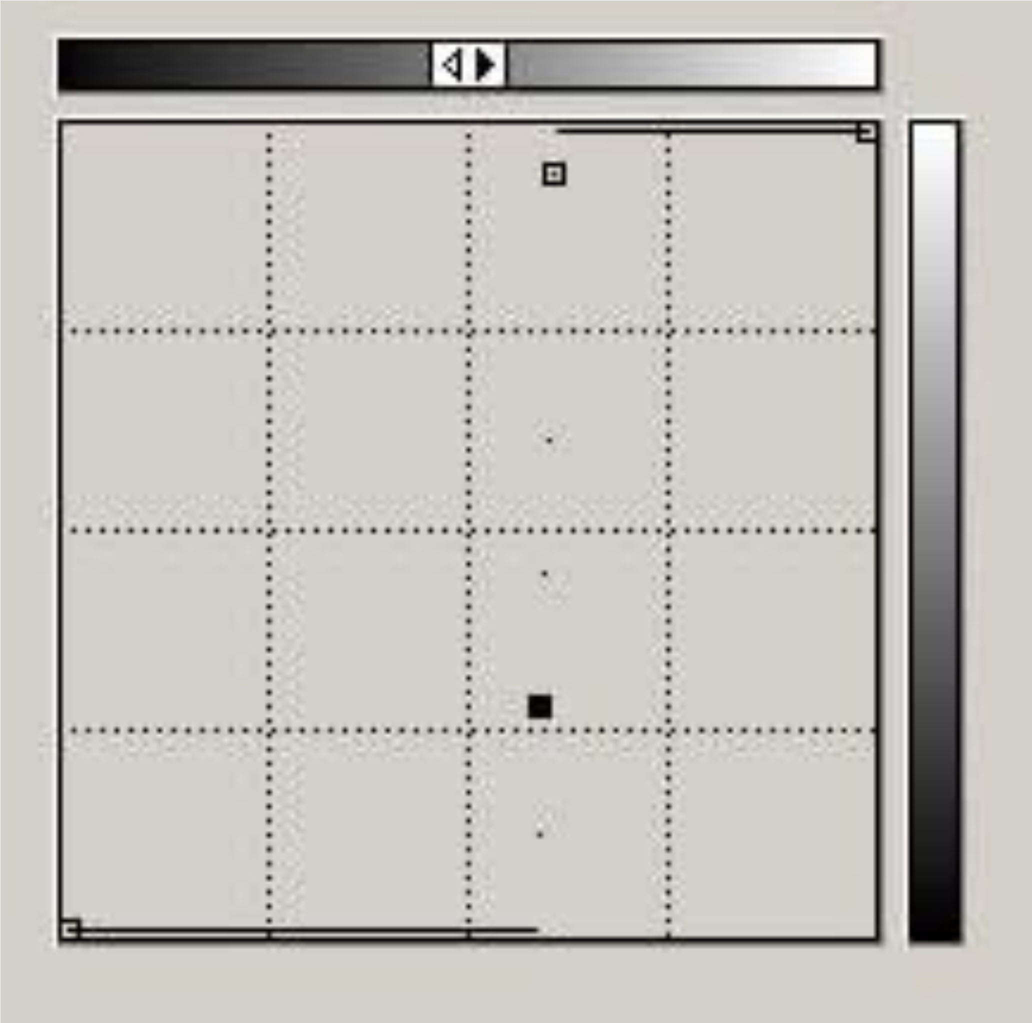
Binarization

- It produces an image that has only two levels: black and white.

- It is obtained by choosing a threshold T and putting all pixels whose value is less than T to black and all others to white.

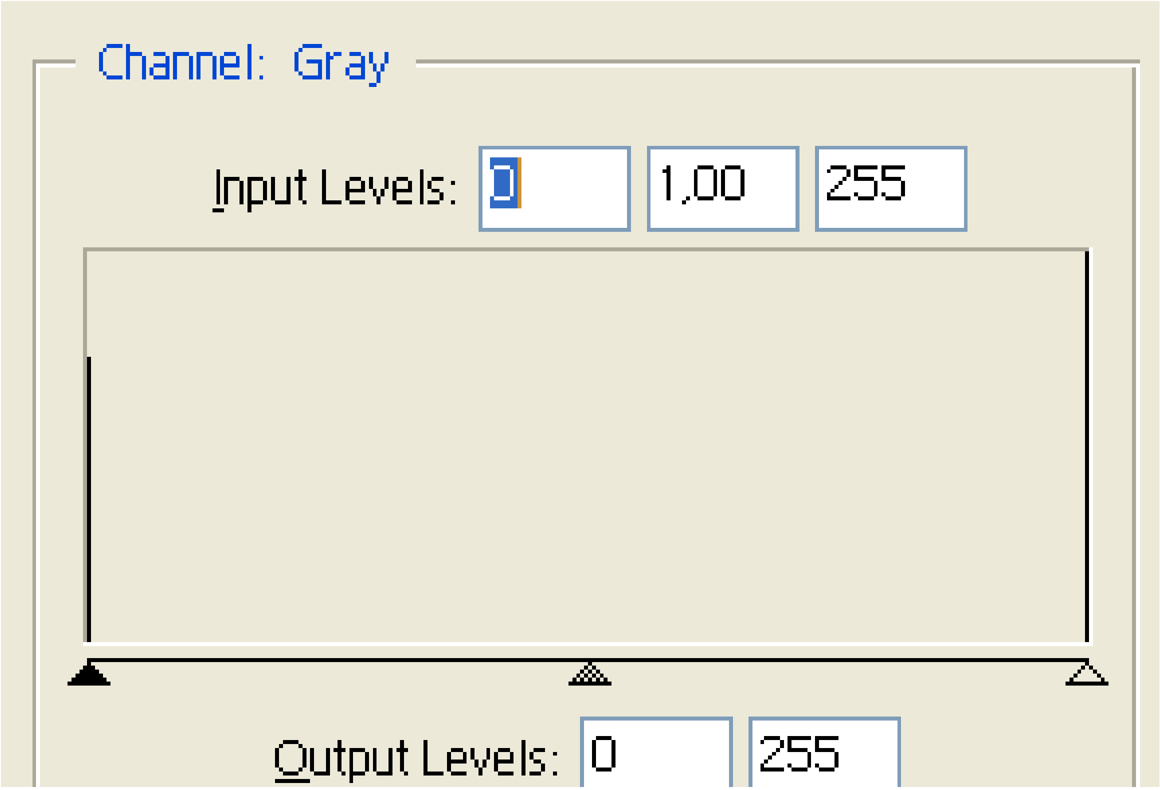
Binarization

- How do you act on the curve?



Binarization

- How does the histogram change?



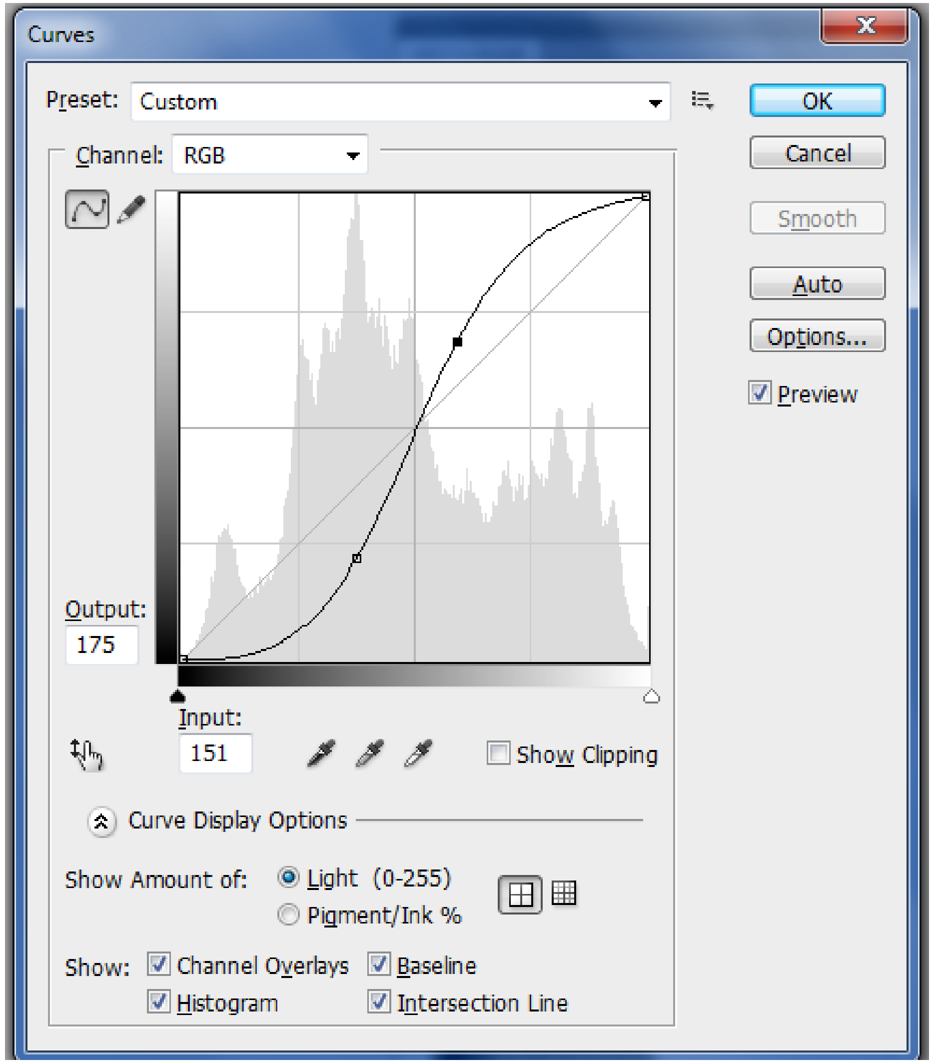
Variations in contrast

- Increasing the contrast, means making color differences more evident.
- This is achieved by going to change the value of one pixel to another that is darker or lighter.

Increased contrast

Increased contrast

- How should the curve be changed?



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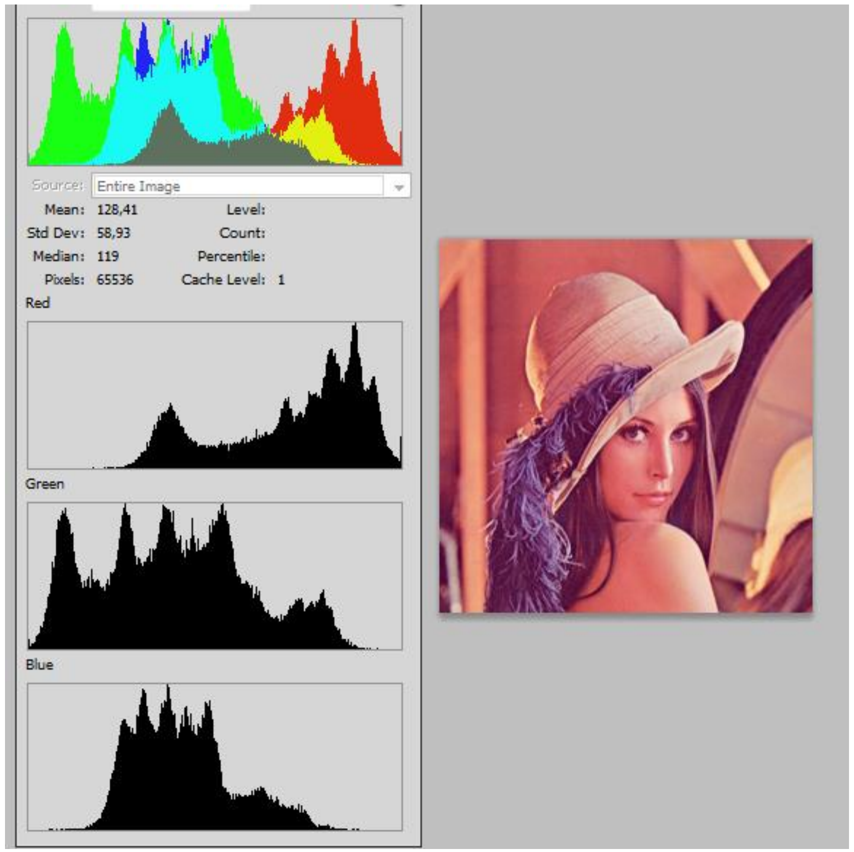
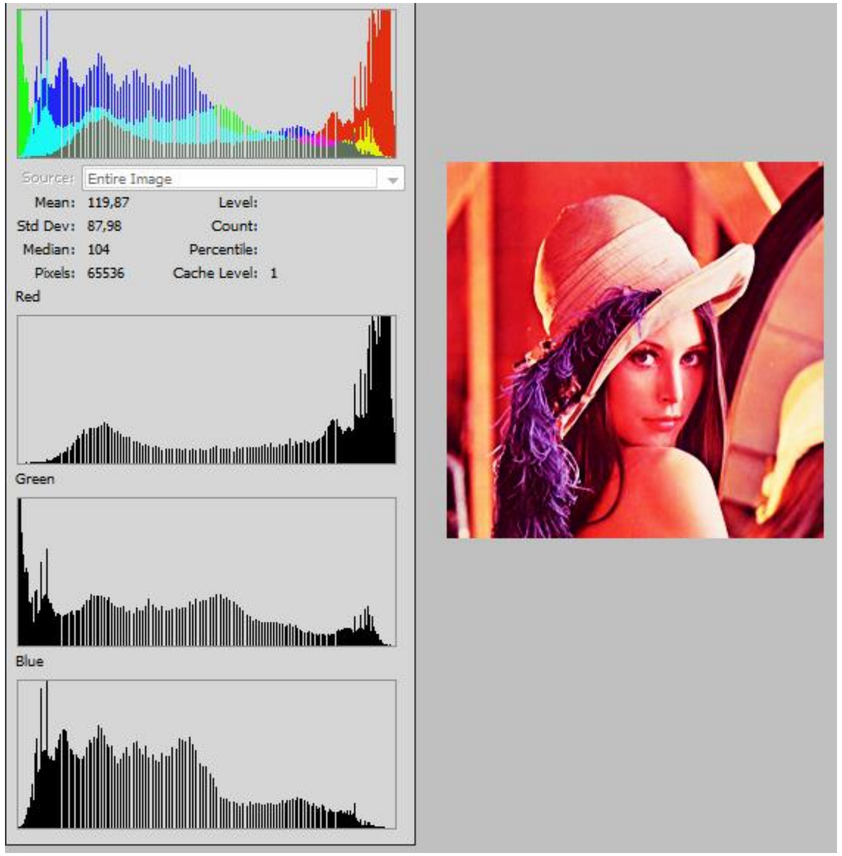
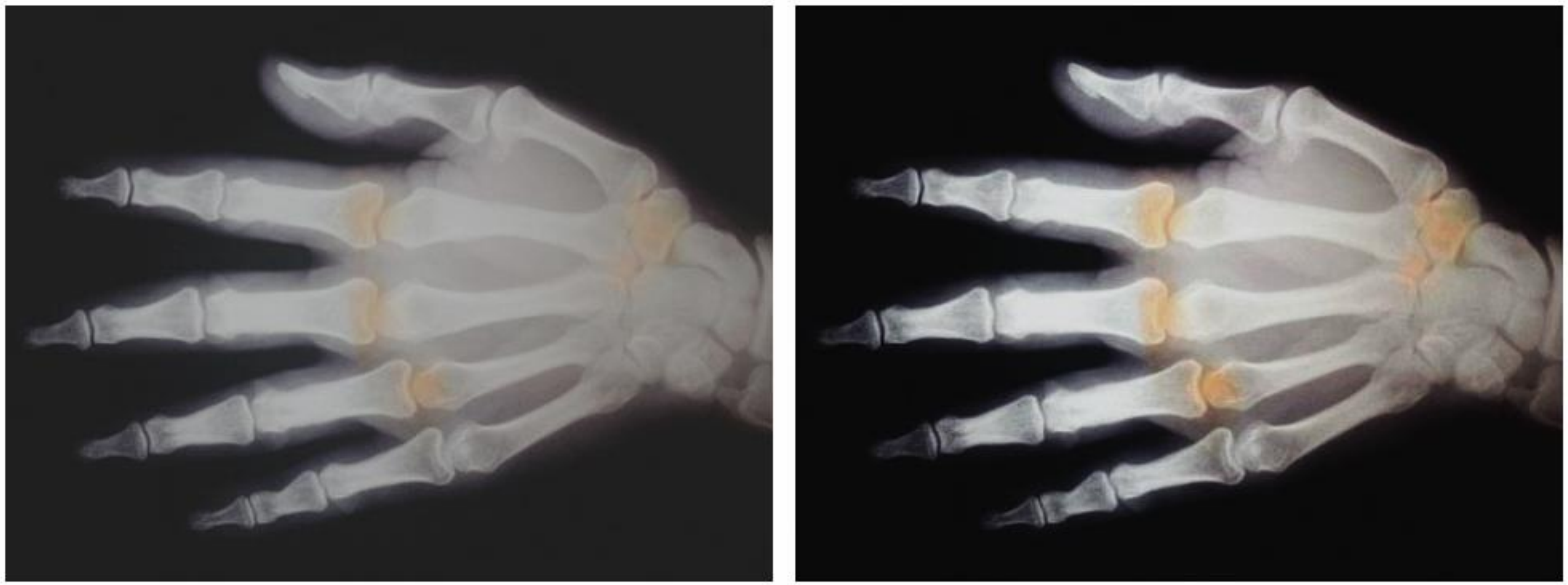
Increased contrast





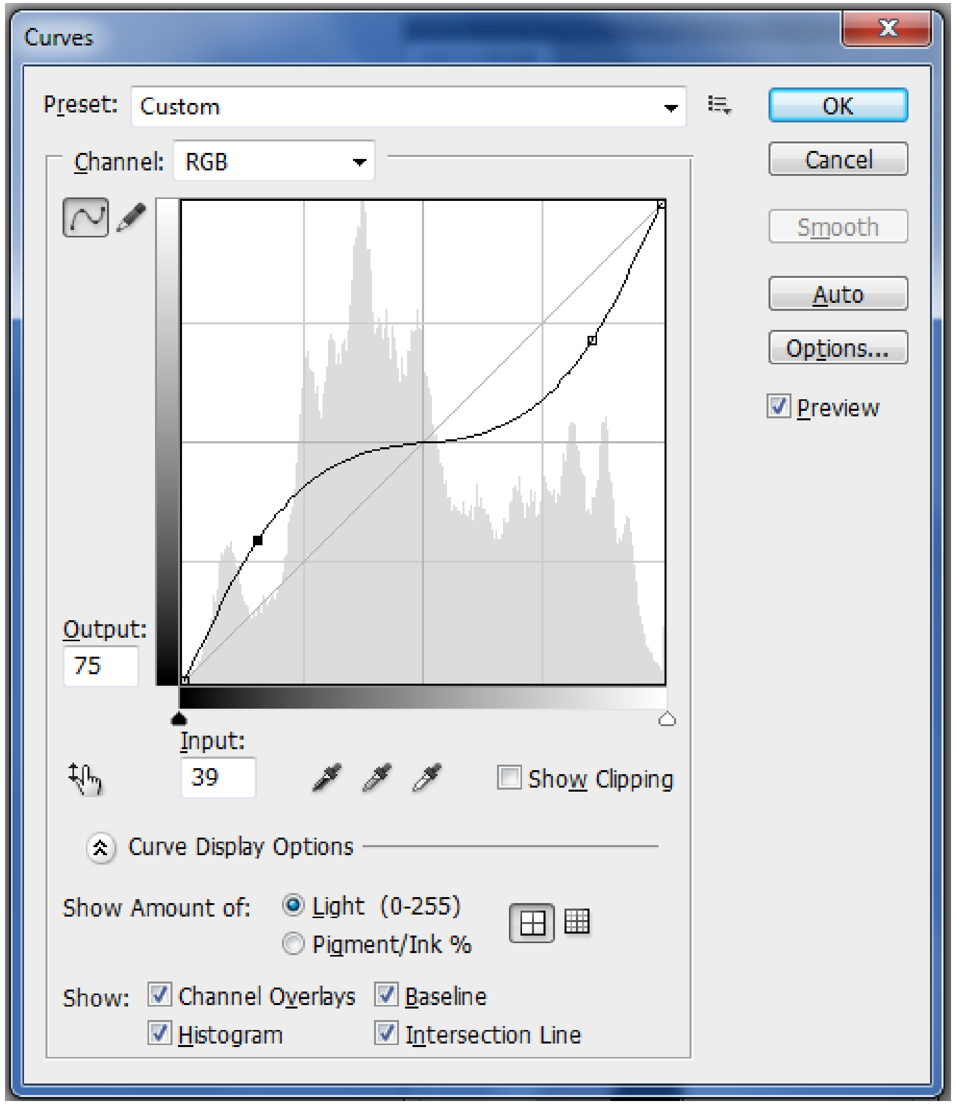
Increased contrast - Other example



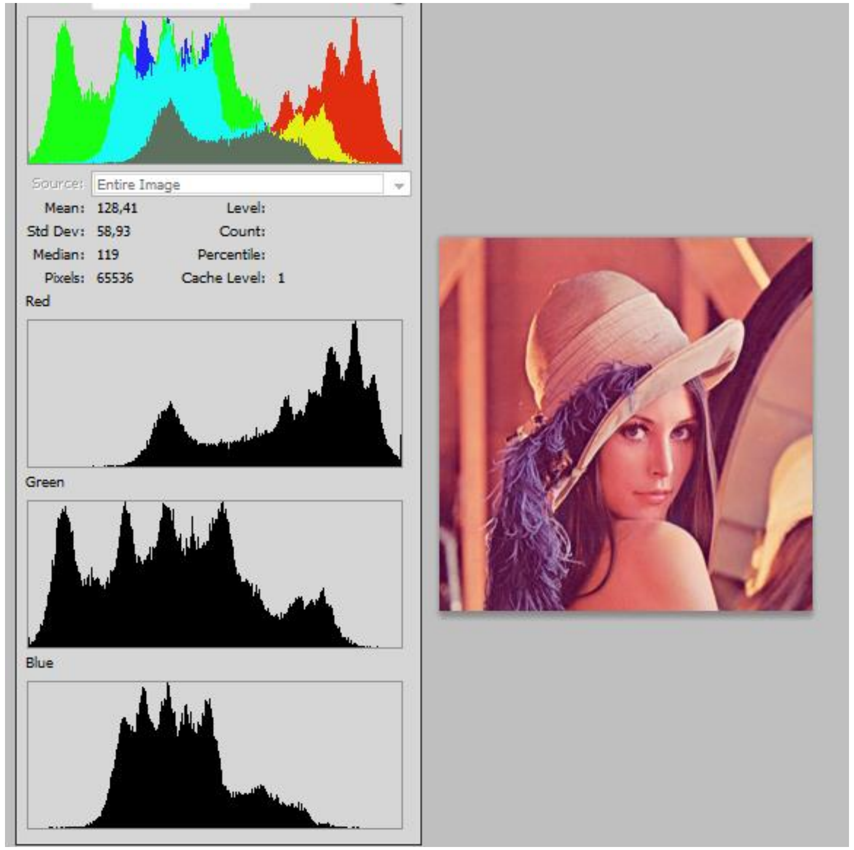
Decrease in contrast

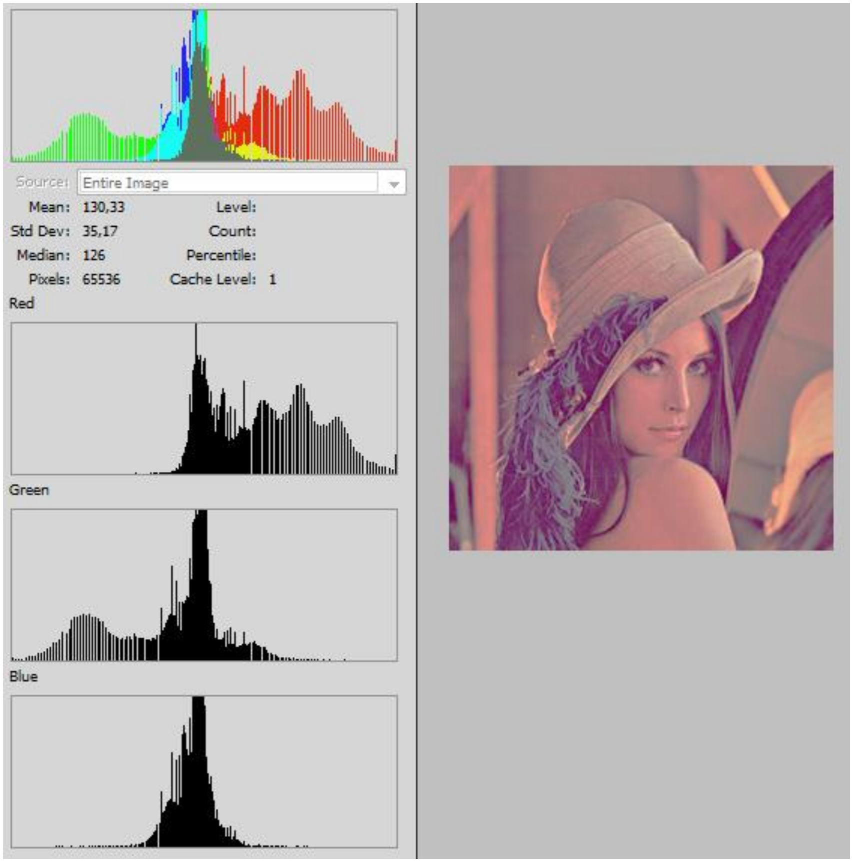
Decrease in contrast

- How do I change the curve?



Decrease in contrast





Types of operations

The size of the neighborhood of (x,y) defines the character of the processing:

- **punctual (the neighborhood coincides with the pixel itself);**
- local (for example, a small square region centered on the pixel);
- global (the neighborhood coincides with the entire f).

Histogram

Luca Guarnera, Ph.D.

Research Fellow

luca.guarnera@unict.it

University of Catania

Dipartimento di Economia e Impresa