
# Definizioni di Base

# Campionamento, Istogramma

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# Psicofisica

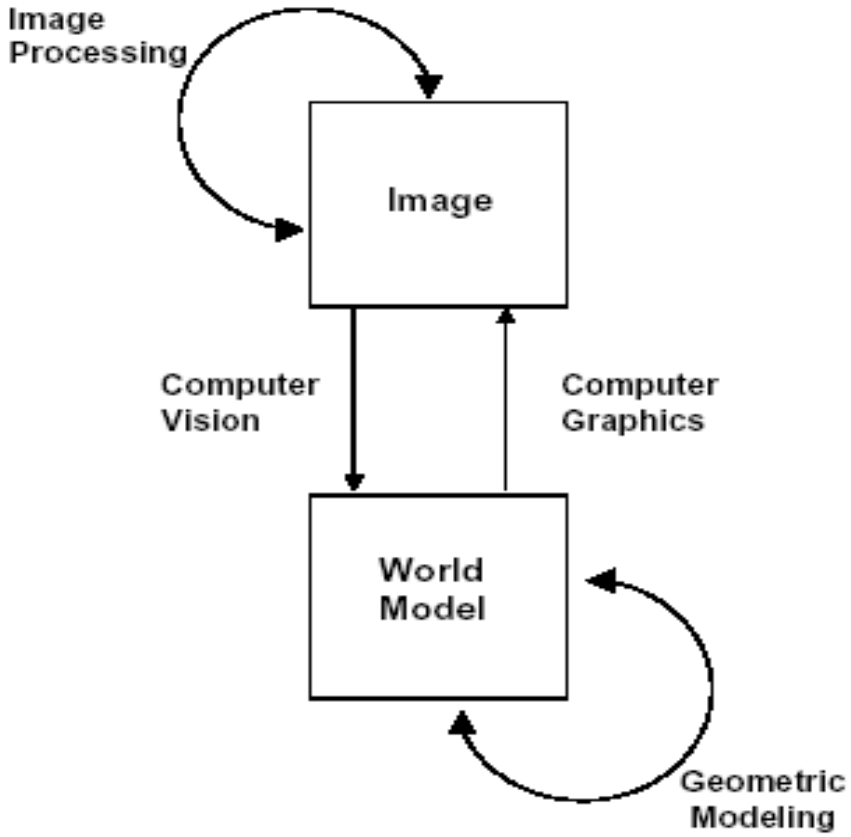
- **Sensazione:** esperienza soggettiva di cambiamenti nel mondo fisico registrati dai nostri organi sensoriali
- **Psicofisica:** La scienza che definisce relazioni QUANTITATIVE tra gli eventi fisici e psicologici (cioè le sensazioni)

# Le Origini della Psicofisica

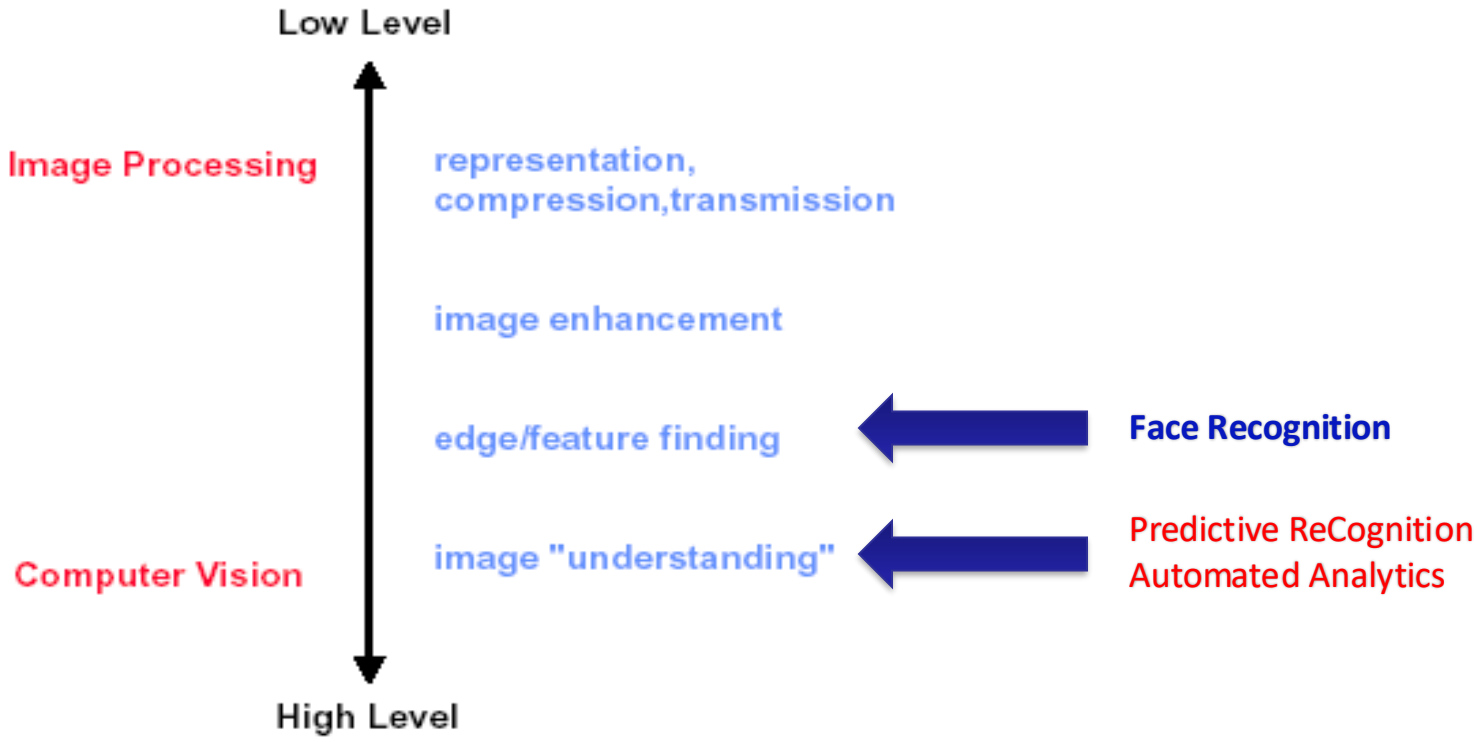
- Ernst Weber (1795–1878) scoprì che il più piccolo cambiamento di uno stimolo (ad esempio il suo peso o l'intensità di luce) che può essere rilevato è una proporzione costante del livello di stimolazione — "Legge di Weber"
- JND (just noticeable difference) la differenza minima richiesta per rilevare un cambiamento nello stimolo, ad esempio per discriminare 2 stimoli con intensità diversa.
- La JND venne chiamata anche soglia differenziale.

# Psicofisica
# (Il Mito della Caverna di Platone e Matrix)

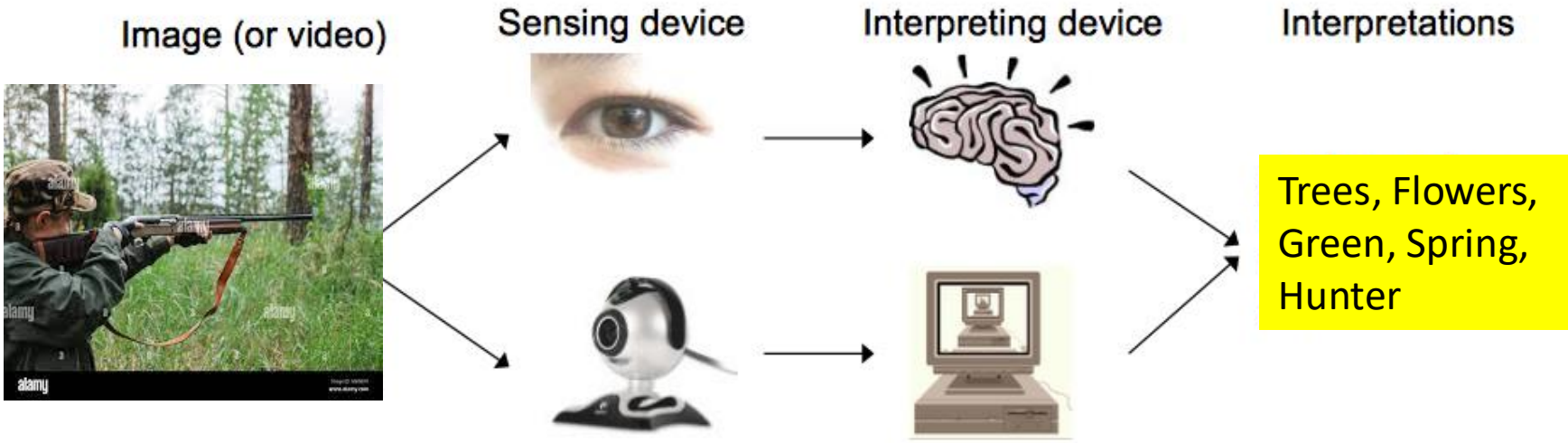
# Visual Sciences



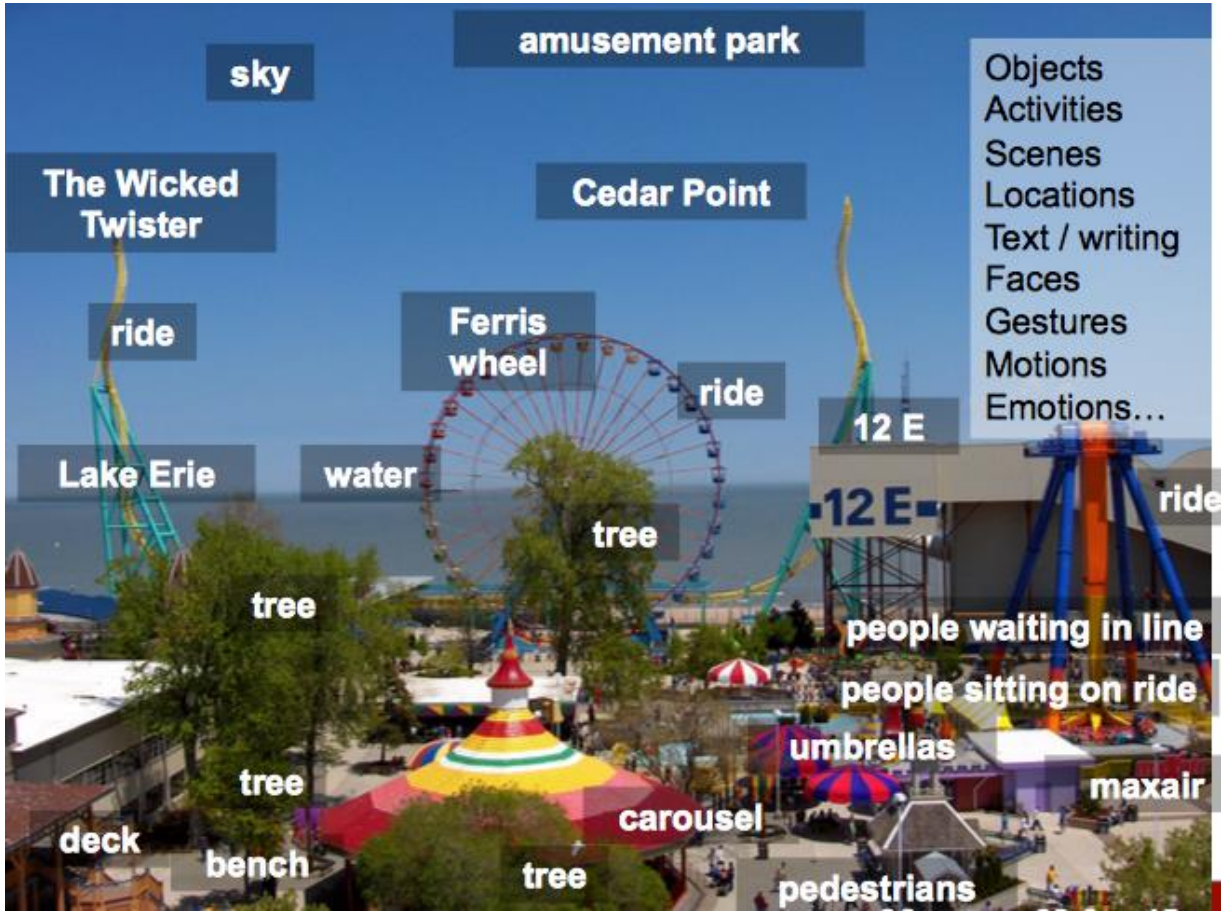
# Image Processing and Computer Vision



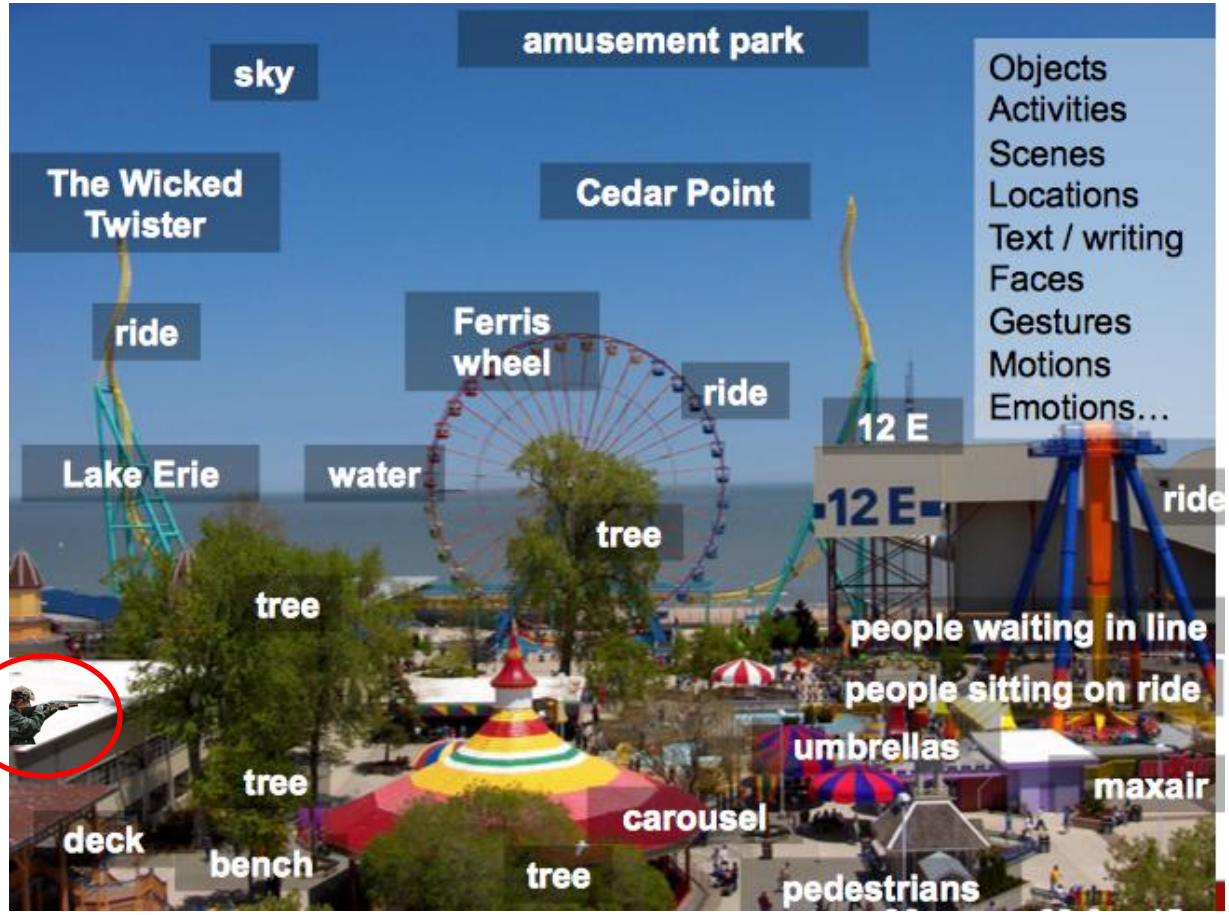
# Image Understanding and Predictive Recognition



# Image Understanding



# Image Understanding (2)




Sniper or Hunter?

# Image Processing and Computer Vision: Applications

- **Robotics**
  - Object Recognition (assembly line)
  - Autonomous Vehicles Obstacle
  - Avoidance
- **Earth Remote Sensing**
  - Pollution Control (River, City)
  - Landsat Image Analysis, Synthesis and Coding
- **Arial Photography**
  - Image Enhancement (espionage)
  - Missile Guidance
  - Geological Mapping
- **Astronomy**
  - Astronomical Image Enhancement
  - Chemical/Spectral Analysis
- **Medicine**
  - Computerized Scanners (MRI,CT,etc)
  - Radiological Organ Segmentation
- **Chemistry**
  - Chemical Composition
  - Molecular Imaging
  - Electron Microscope
- **Graphics**
  - Image Warping
  - Animation
  - Texture/Image Mapping
- **Security and Forensic**
  - Biometric
  - Videosurveillance

# Intensity and Brightness

- **Image Intensity**
  - Light energy emitted from a unit area in the image.
  - Device dependence.
- **Image Brightness**
  - The subjective appearance of a unit area in the image.
  - Context dependence.
  - Subjective

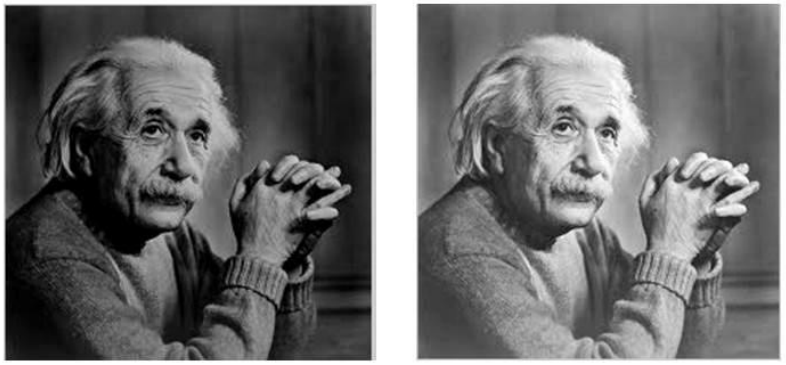
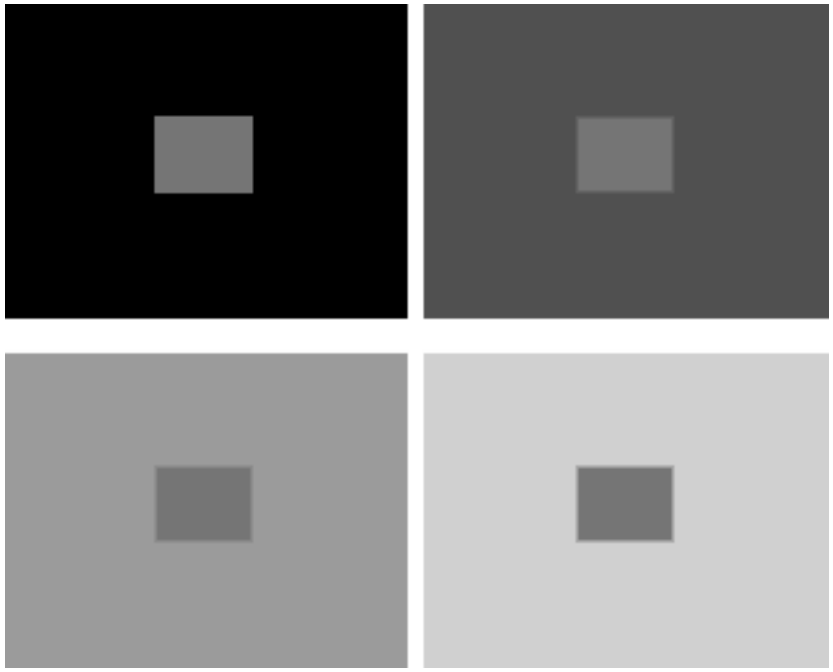


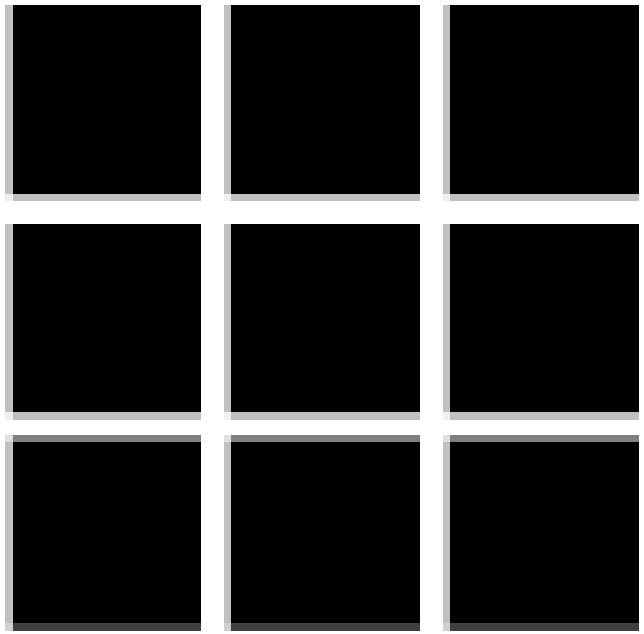
Image on the right is brighter than image on the left.

# Intensity vs Brightness (cont.)

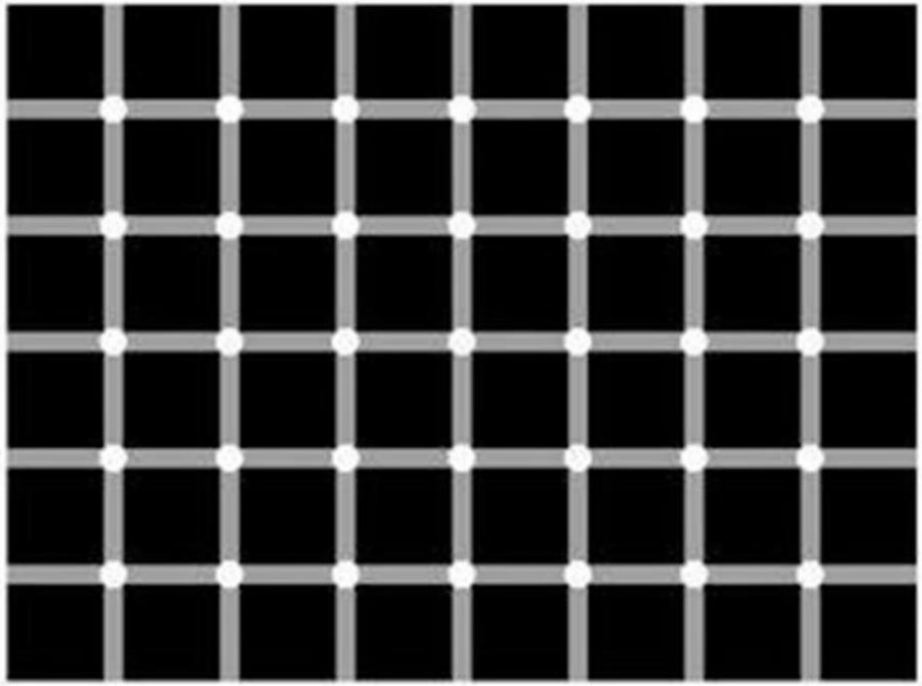
- All the small squares have exactly the same intensity
- But they appear progressively darker as the background becomes lighter



# Quanti Punti Neri (Versione Debole)?

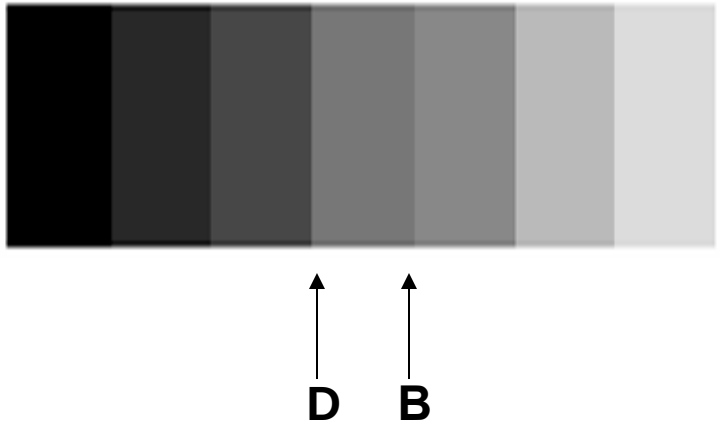


# Quanti Punti Neri (Versione Forte)?

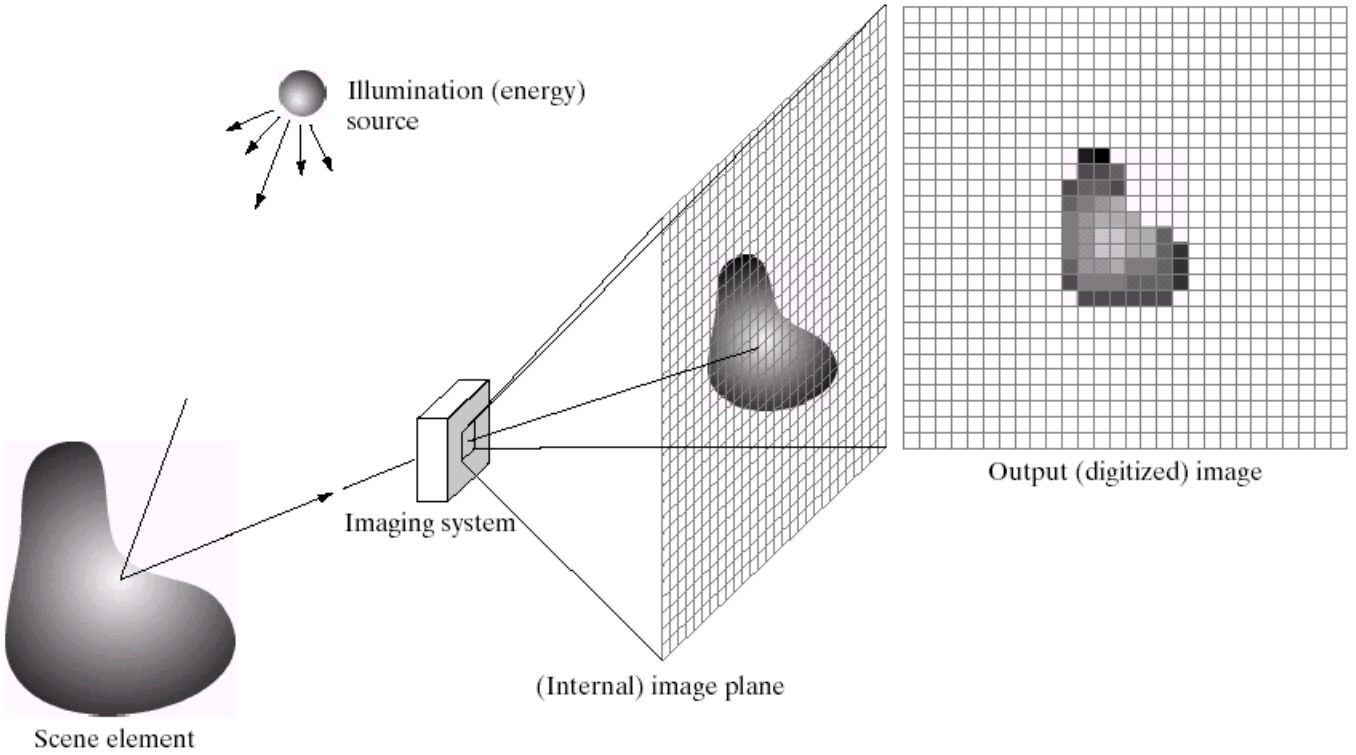


# Intensity vs Brightness (cont.)

- Intesity on the strip is constant
- D is perceived brighter than B



# Image Formation

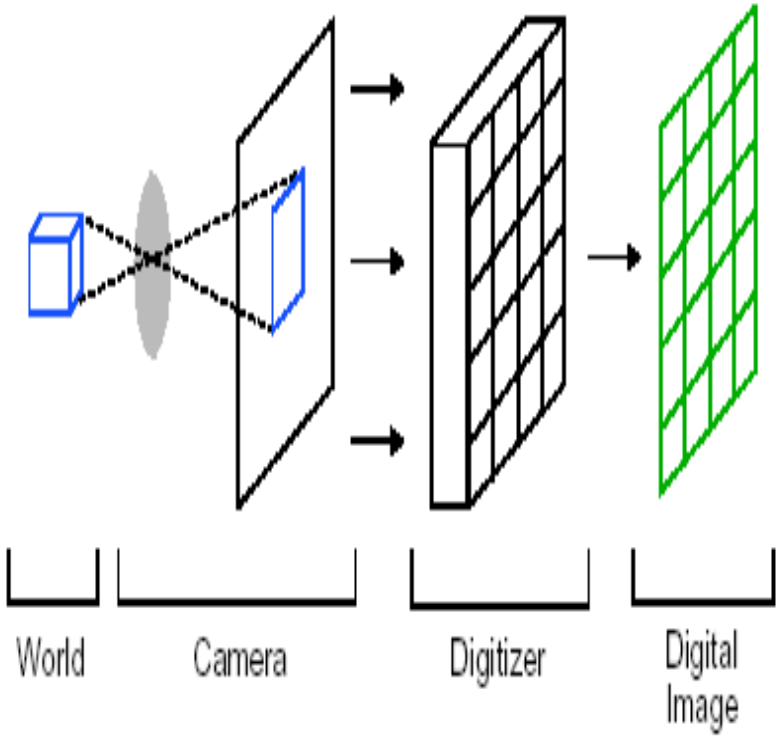



a b c d e

**FIGURE 2.15** An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

***f(x,y) = reflectance(x,y) * illumination(x,y)***
***Reflectance in [0,1], illumination in [0,inf]***

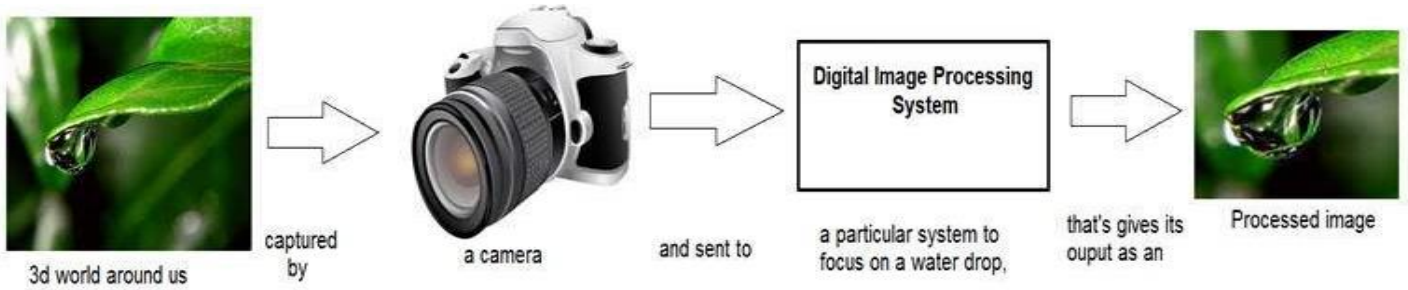
# Image Digitization



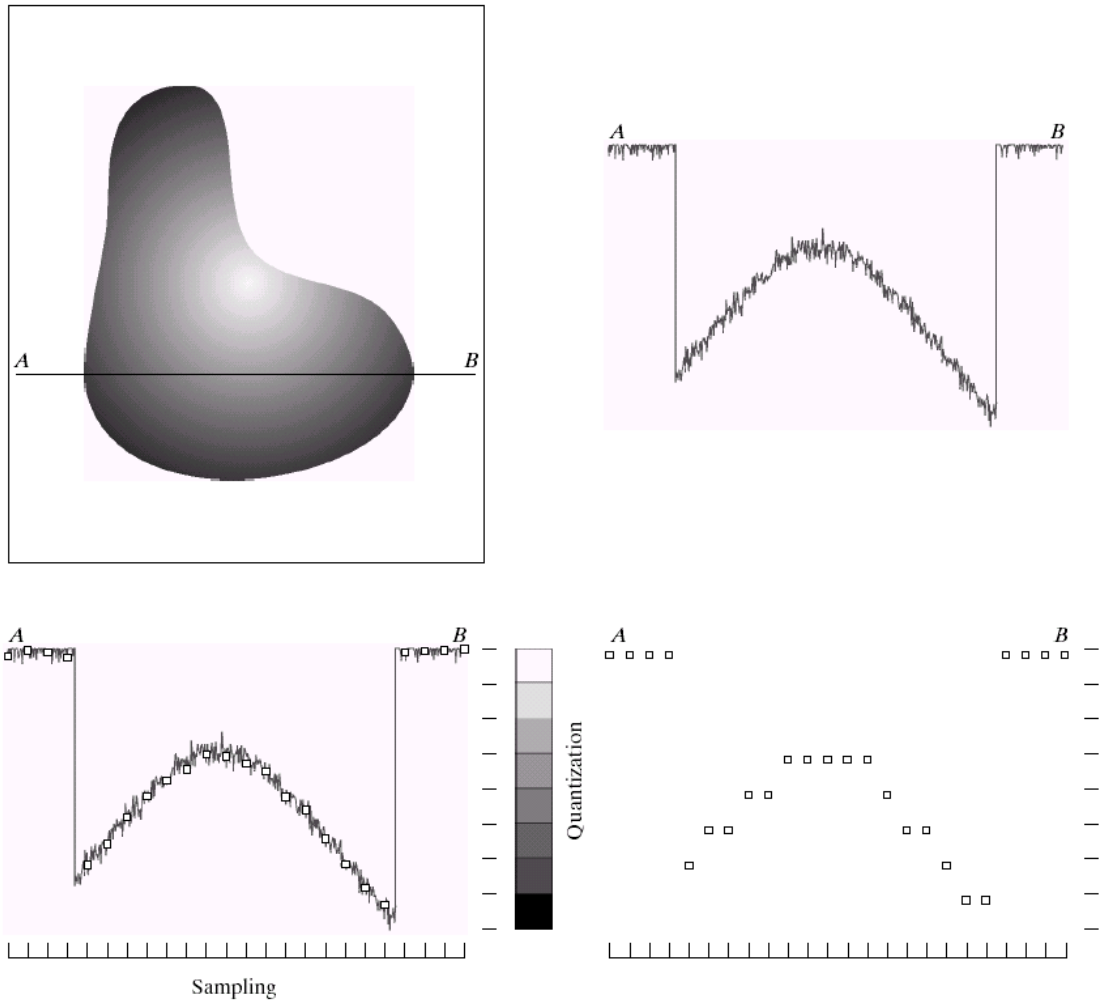

| | | | | | | |
|---|---|---|---|---|---|---|
| 0 | 10 | 10 | 15 | 50 | 70 | 80 |
| 0 | 0 | 100 | 120 | 125 | 130 | 130 |
| 0 | 35 | 100 | 150 | 150 | 80 | 50 |
| 0 | 15 | 70 | 100 | 10 | 20 | 20 |
| 0 | 15 | 70 | 0 | 0 | 0 | 15 |
| 5 | 15 | 50 | 120 | 110 | 130 | 110 |
| 5 | 10 | 20 | 50 | 50 | 20 | 250 |

PIXEL
(picture element)

Typically:
0 = black
255 = white



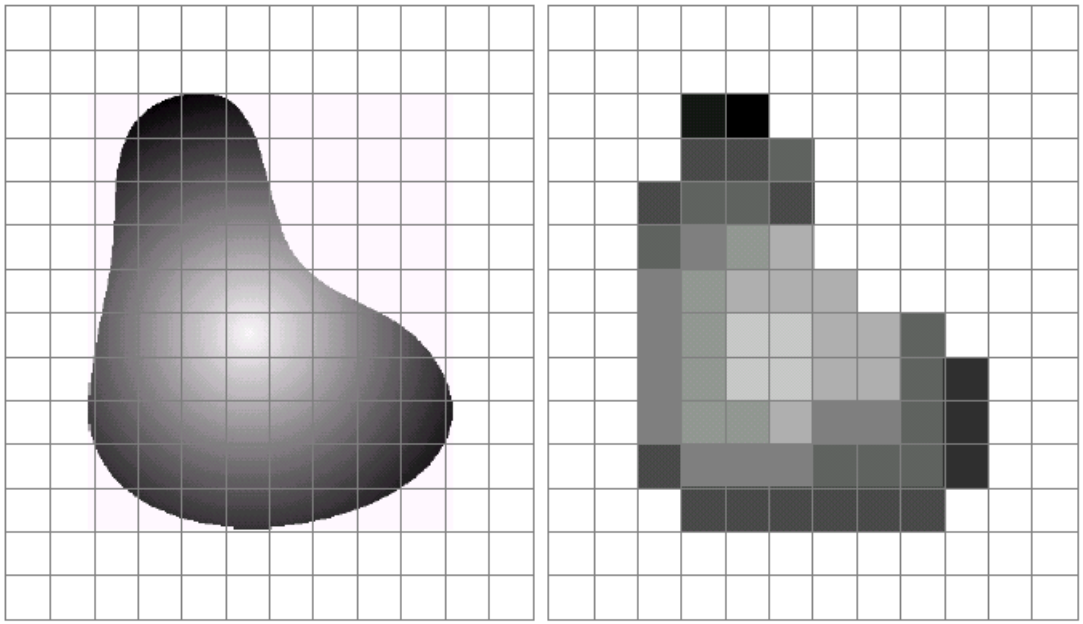
# Sampling and Quantization




a b
c d

**FIGURE 2.16** Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

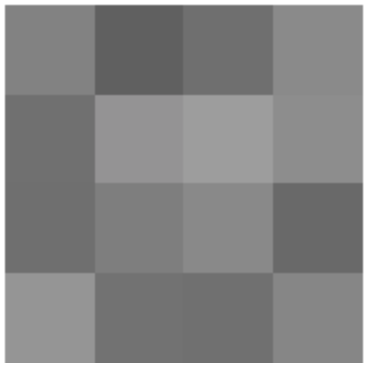
# Sampling and Quantization



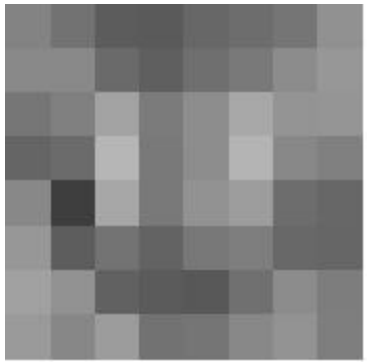
a b

**FIGURE 2.17** (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

# Sampling



**4x4=16**

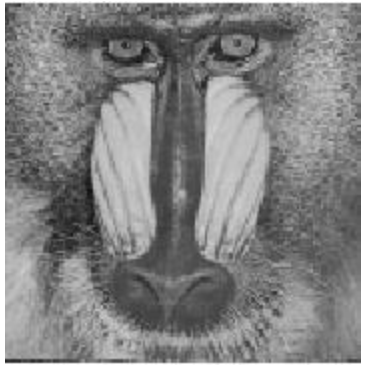


**8x8=64**

**16x16=256**

**32x32=1024**

**64x64=4096**



**128x128=16384**

# Quantization

8bpp

7bpp

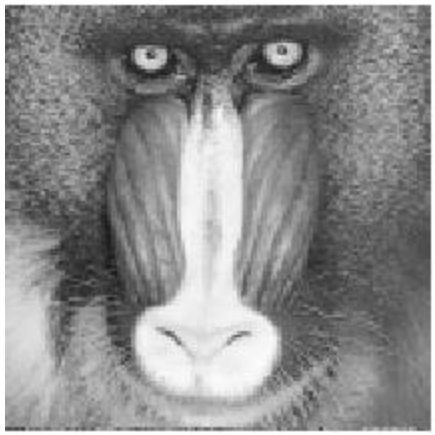
4bpp

2bpp

1bpp

# Image Types

- Binary Images
  - black and white
- Gray Scale Images
  - Black, white and graylevel
- Color Images



# What is an image?

- We can think of an image as a function, f, from R2 to R:
  - $f(x, y)$ gives the **intensity** at position $(x, y)$
  - Realistically, we expect the image only to be defined over a rectangle, with a finite range:
    - $f$: $[a,b]$x$[c,d]$ → $[0,1]$

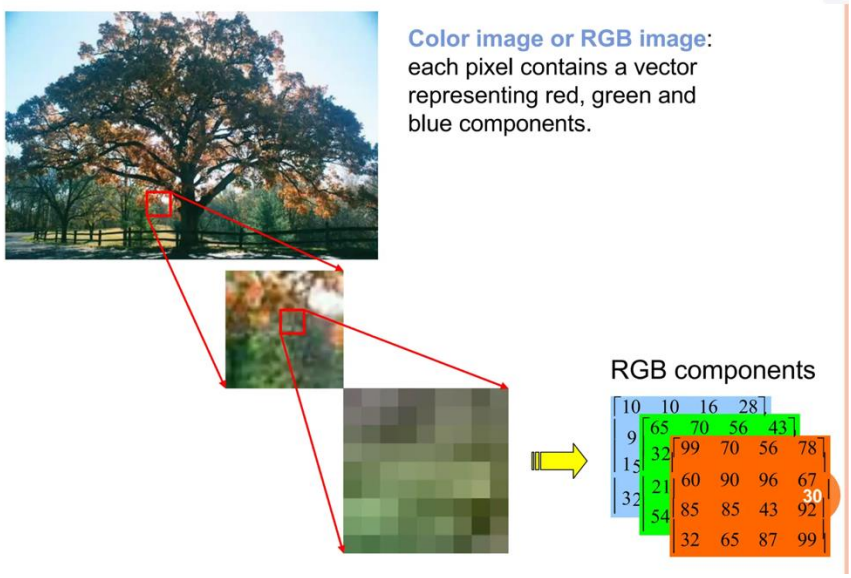
- A color image is just three functions pasted together. We can write this as a "vector-valued" function:

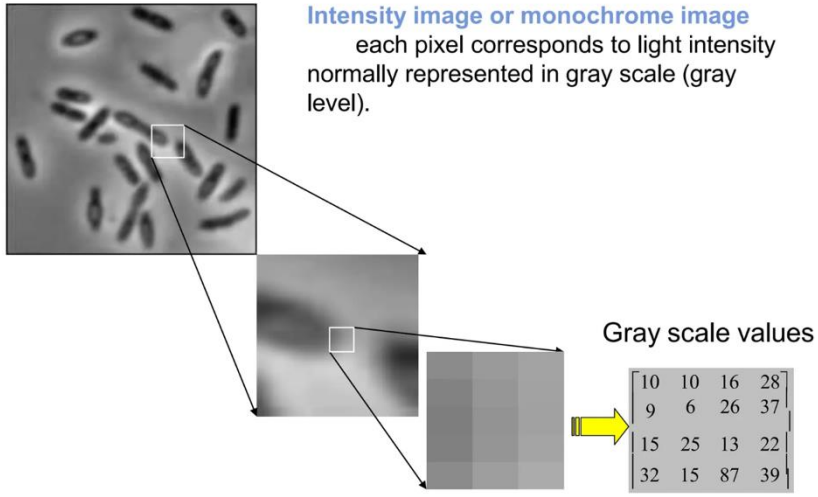
$$f(x, y) = \begin{bmatrix} r(x, y) \\ g(x, y) \\ b(x, y) \end{bmatrix}$$

# What is an image?

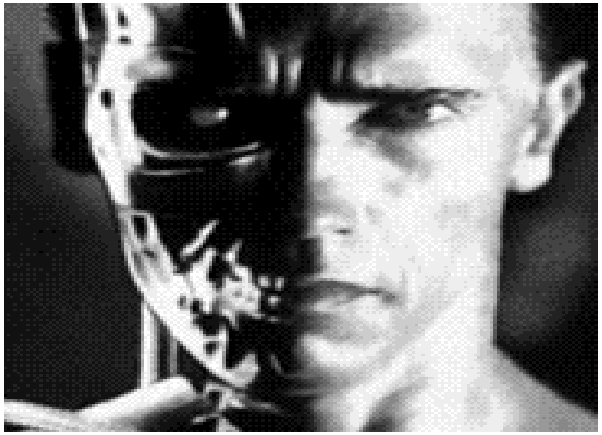

- **An image**: **a multidimensional function of spatial coordinates.**
- **Spatial coordinate**: $(x,y)$ for 2D case such as photograph,
  $(x,y,z)$ for 3D case such as CT scan images
  $(x,y,t)$ for movies
- The function $f$ may represent intensity (for monochrome images) or color (for color images) or other associated values.

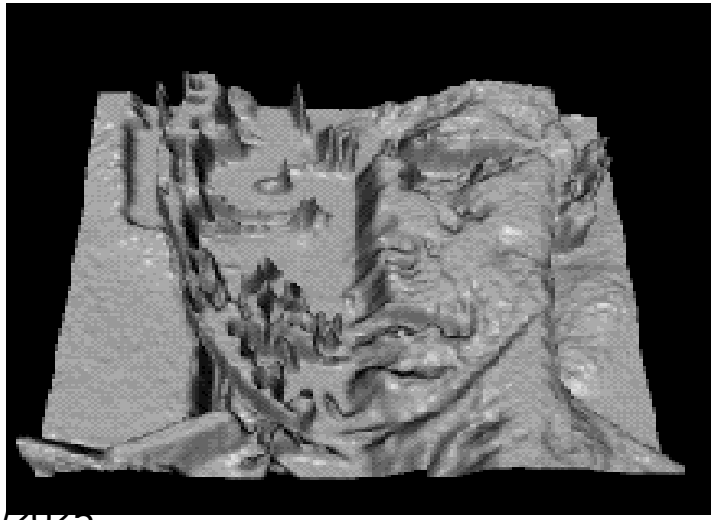
# What is an image?

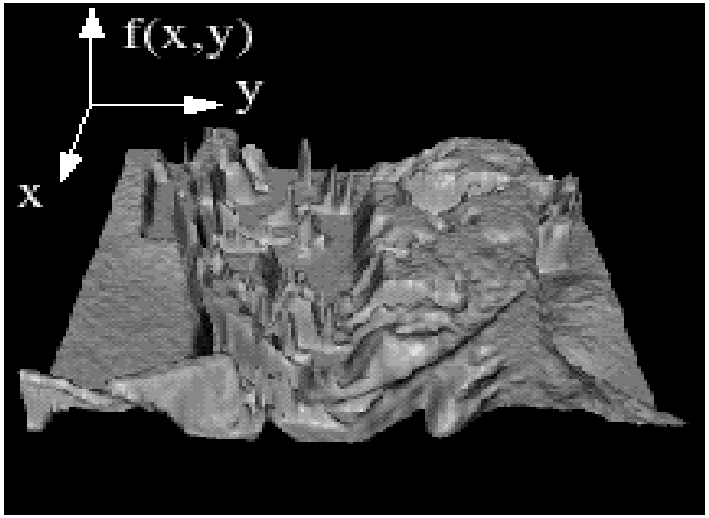


# Images as functions







# What is a digital image?

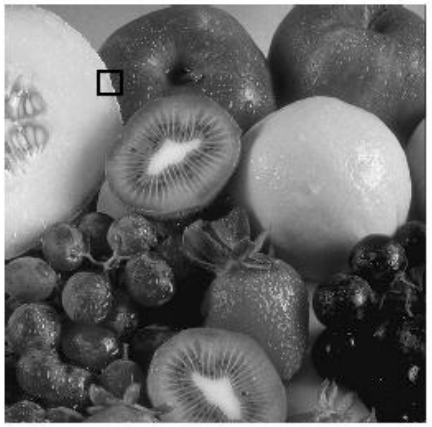
- We usually operate on **digital** (**discrete**) images:
  - **Sample** the 2D space on a regular grid
  - **Quantize** each sample (round to nearest integer)
- If our samples are $\Delta$ apart, we can write this as:
- $f[i, j] = \text{Quantize}\{ f(i\,\Delta, j\,\Delta) \}$
- The image can now be represented as a matrix of integer values

$j \longrightarrow$

$i \downarrow$

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 62 | 79 | 23 | 119 | 120 | 105 | 4 | 0 |
| 10 | 10 | 9 | 62 | 12 | 78 | 34 | 0 |
| 10 | 58 | 197 | 46 | 46 | 0 | 0 | 48 |
| 176 | 135 | 5 | 188 | 191 | 68 | 0 | 49 |
| 2 | 1 | 1 | 29 | 26 | 37 | 0 | 77 |
| 0 | 89 | 144 | 147 | 187 | 102 | 62 | 208 |
| 255 | 252 | 0 | 166 | 123 | 62 | 0 | 31 |
| 166 | 63 | 127 | 17 | 1 | 0 | 99 | 30 |

# Sampling + Quantization



| x = | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| y = | | | | | | | | | | | | | | | |
| 41 | 210 | 209 | 204 | 202 | 197 | 247 | 143 | 71 | 64 | 80 | 84 | 54 | 54 | 57 | 58 |
| 42 | 206 | 196 | 203 | 197 | 195 | 210 | 207 | 56 | 63 | 58 | 53 | 53 | 61 | 62 | 51 |
| 43 | 201 | 207 | 192 | 201 | 198 | 213 | 156 | 69 | 65 | 57 | 55 | 52 | 53 | 60 | 50 |
| 44 | 216 | 206 | 211 | 193 | 202 | 207 | 208 | 57 | 69 | 60 | 55 | 77 | 49 | 62 | 61 |
| 45 | 221 | 206 | 211 | 194 | 196 | 197 | 220 | 56 | 63 | 60 | 55 | 46 | 97 | 58 | 106 |
| 46 | 209 | 214 | 224 | 199 | 194 | 193 | 204 | 173 | 64 | 60 | 59 | 51 | 62 | 56 | 48 |
| 47 | 204 | 212 | 213 | 208 | 191 | 190 | 191 | 214 | 60 | 62 | 66 | 76 | 51 | 49 | 55 |
| 48 | 214 | 215 | 215 | 207 | 208 | 180 | 172 | 188 | 69 | 72 | 55 | 49 | 56 | 52 | 56 |
| 49 | 209 | 205 | 214 | 205 | 204 | 196 | 187 | 196 | 86 | 62 | 66 | 87 | 57 | 60 | 48 |
| 50 | 208 | 209 | 205 | 203 | 202 | 186 | 174 | 185 | 149 | 71 | 63 | 55 | 55 | 45 | 56 |
| 51 | 207 | 210 | 211 | 199 | 217 | 194 | 183 | 177 | 209 | 90 | 62 | 64 | 52 | 93 | 52 |
| 52 | 208 | 205 | 209 | 209 | 197 | 194 | 183 | 187 | 187 | 239 | 58 | 68 | 61 | 51 | 56 |
| 53 | 204 | 206 | 203 | 209 | 195 | 203 | 188 | 185 | 183 | 221 | 75 | 61 | 58 | 60 | 60 |
| 54 | 200 | 203 | 199 | 236 | 188 | 197 | 183 | 190 | 183 | 196 | 122 | 63 | 58 | 64 | 66 |
| 55 | 205 | 210 | 202 | 203 | 199 | 197 | 196 | 181 | 173 | 186 | 105 | 62 | 57 | 64 | 63 |

# Risoluzione

- *Spaziale:*
  - *Definisce il numero di pixel da usare (in alternativa DPI – dot per inch: il numero di pixel al centimetro).*

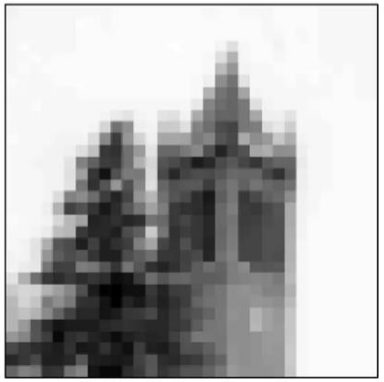
- *Temporale:*
  - *Definisce il numero di immagini al secondo da usare. Per la visione umana si usano* da 15 a 30 immagini al secondo, ma il gaming ha spostato questo limite molto più avanti

# Risoluzione Spaziale: Gli effetti

256x256 pixels

128x128 pixels

64x64 pixels



32x32 pixels

# Risoluzione Spaziale: Gli effetti

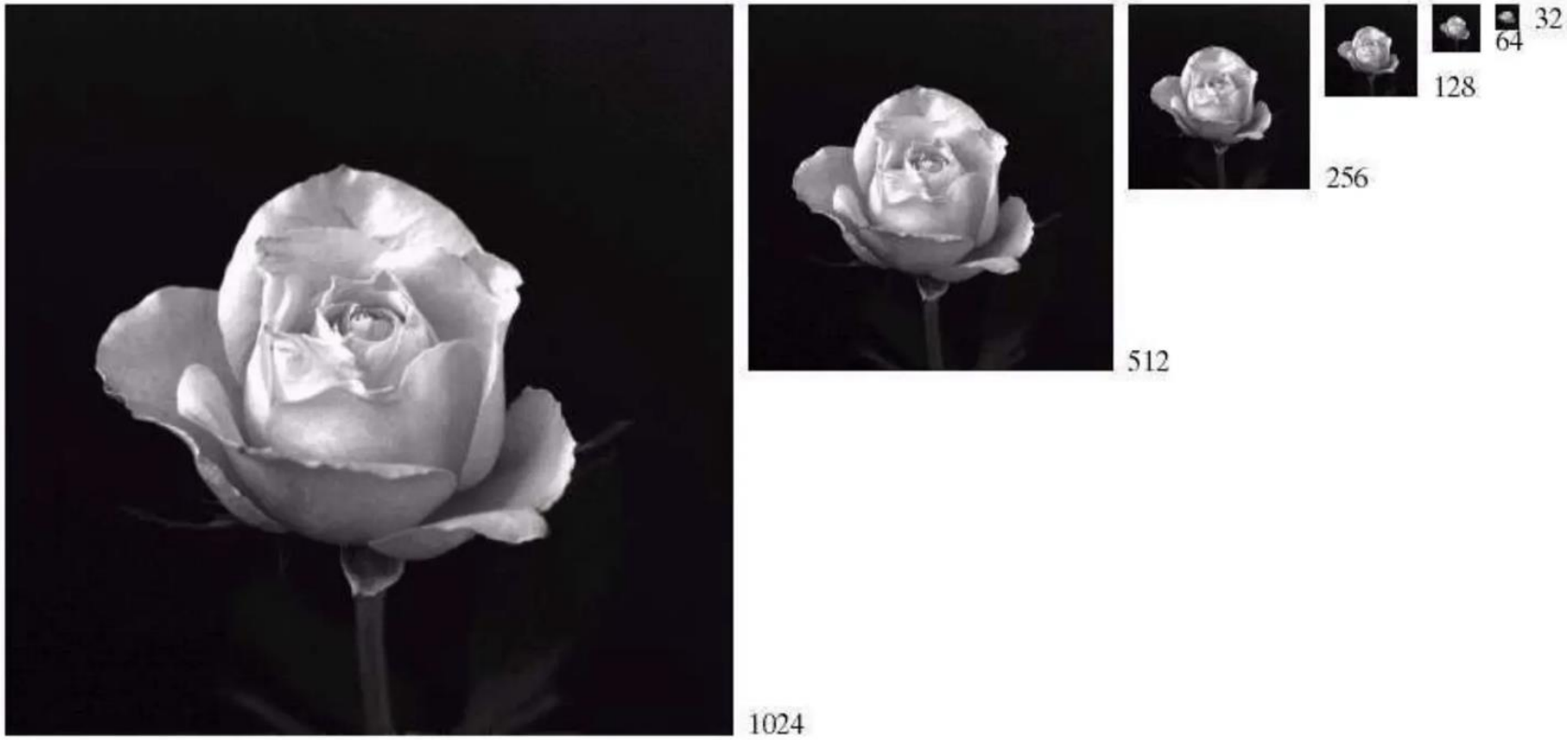


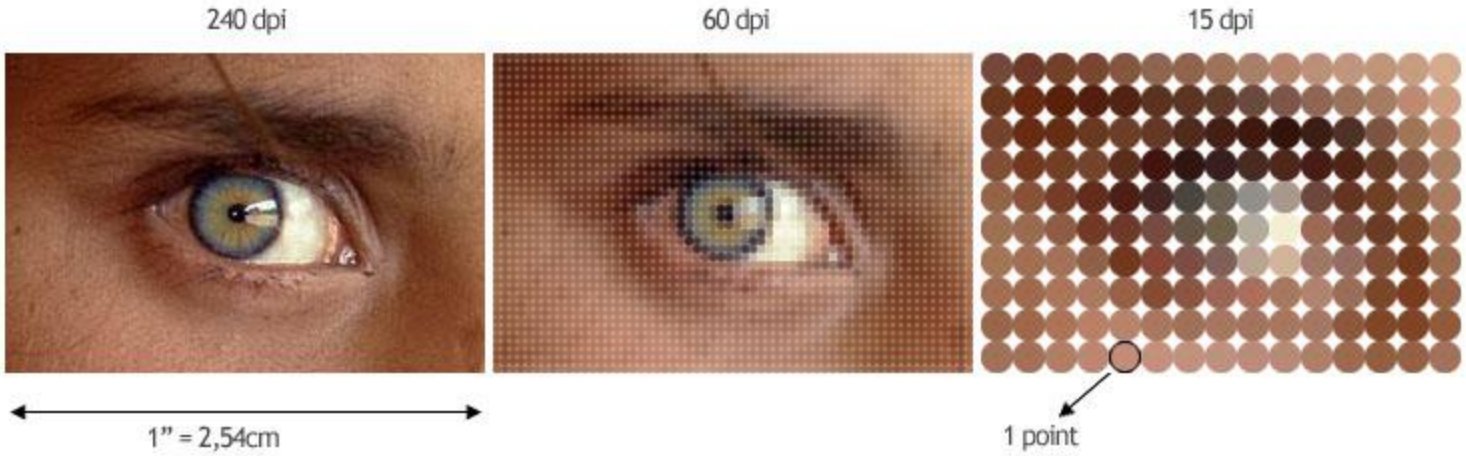

**FIGURE 2.19** A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

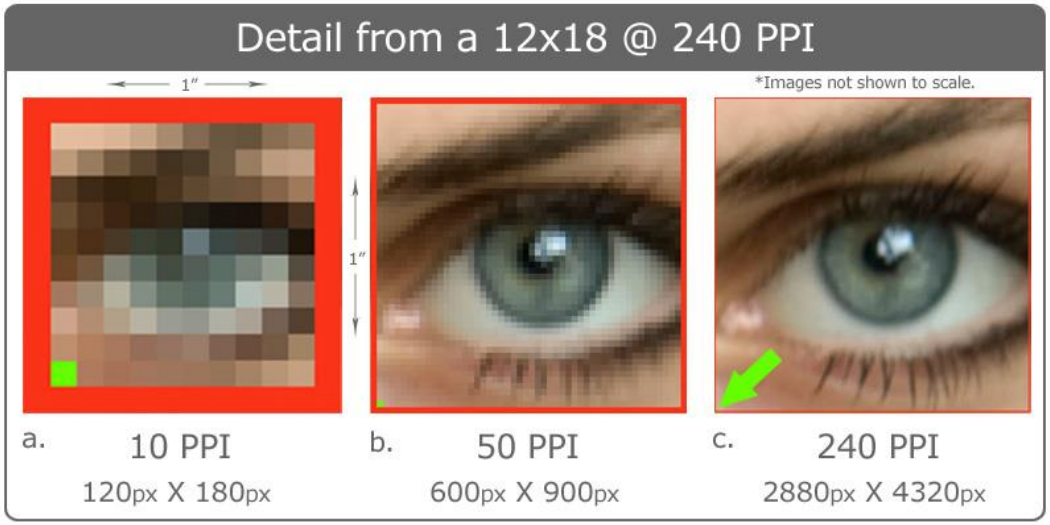
# Risoluzione Spaziale: Gli effetti





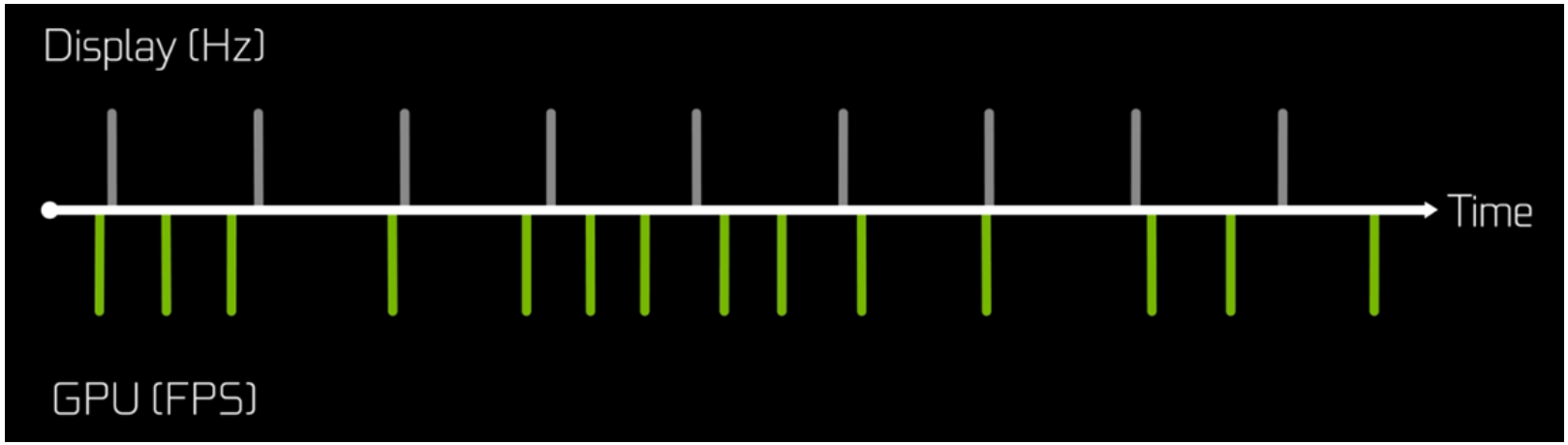

# Risoluzione in Pixel



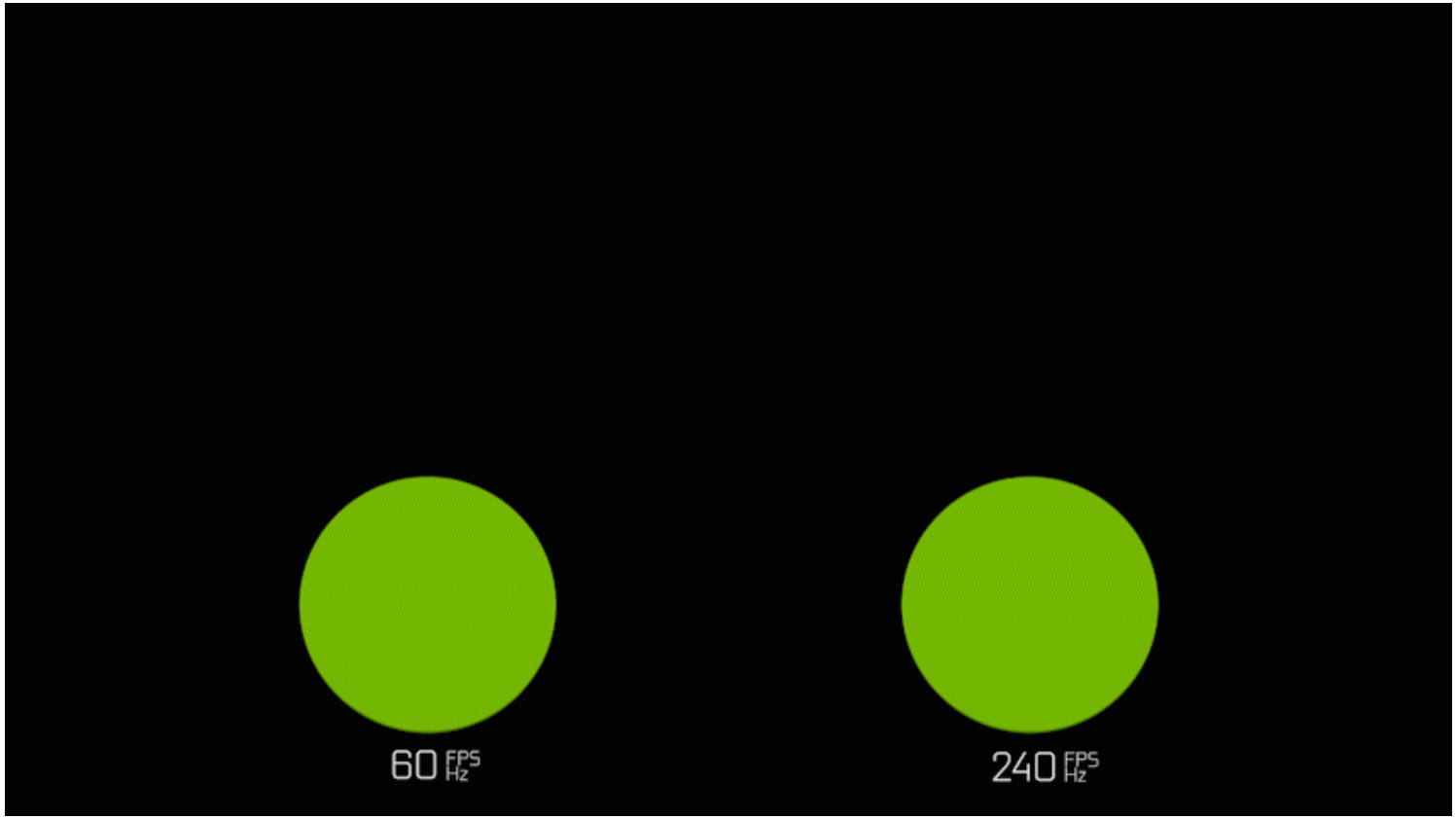



# Risoluzione Temporale: FPS e Hz

- **FPS (Frames per Seconds)**: velocità con cui la GPU completa i frame
- **Herz (HZ):** cicli per secondi, associata al display e misura la velocità a cui il display mostra i frame completati.

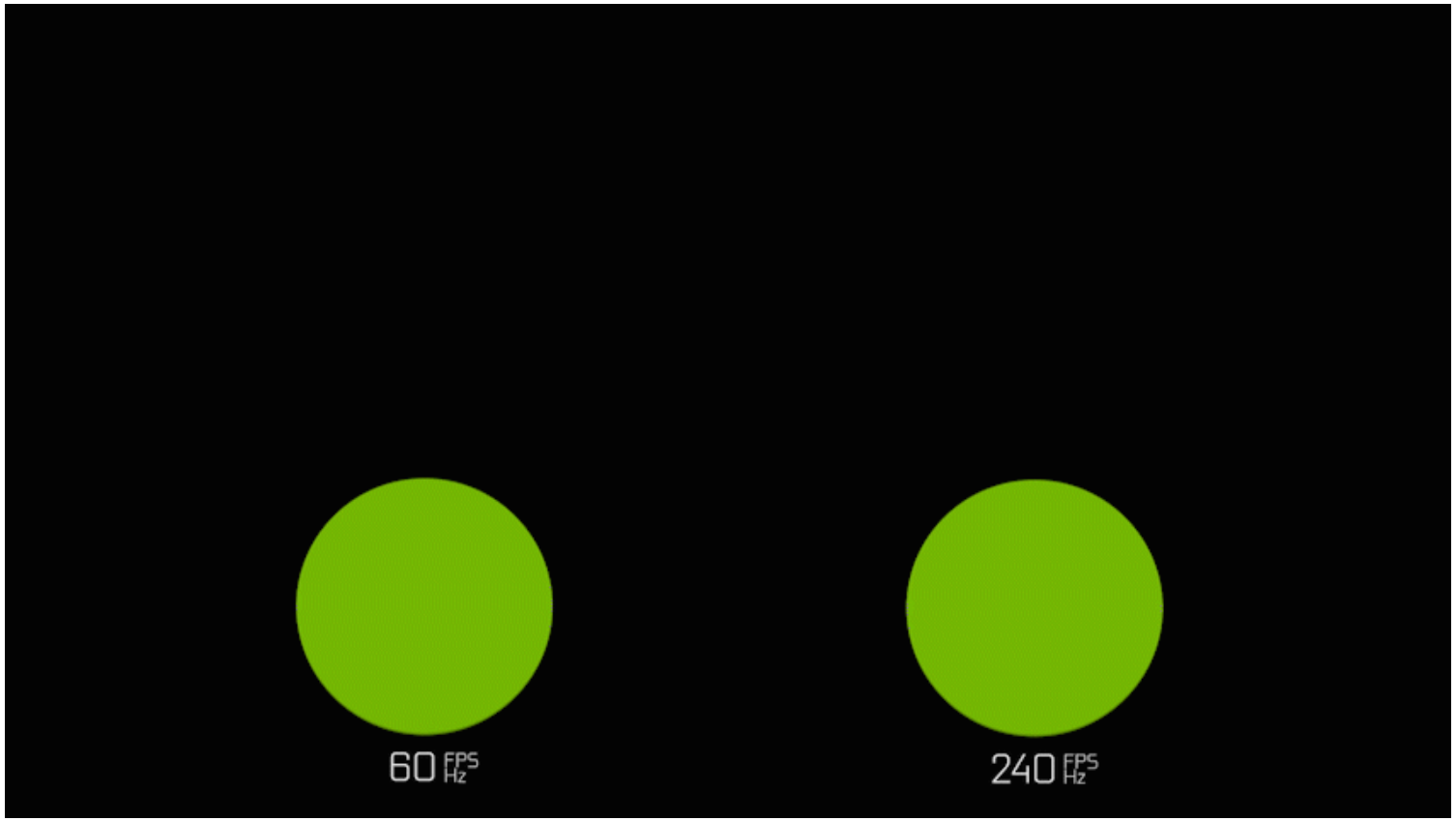


# Fluidità




https://www.nvidia.com/it-it/geforce/news/what-is-fps-and-how-it-helps-you-win-games/

# Ghosting
## (Latenza del Cambio del Colore dei Pixel)






https://www.nvidia.com/it-it/geforce/news/what-is-fps-and-how-it-helps-you-win-games/

# Tearing

(Si verifica quando Display e GPU hanno velocità diverse: FPS ≠ Hz)

https://www.nvidia.com/it-it/geforce/news/what-is-fps-and-how-it-helps-you-win-games/
https://youtu.be/u3xEgIK8omU)

# Image Processing

- An **image processing** operation typically defines a new image $g$ in terms of an existing image $f$.
- We can transform either the range of $f$.

$$g(x,y) = t(f(x,y))$$

- Or the domain of $f$:

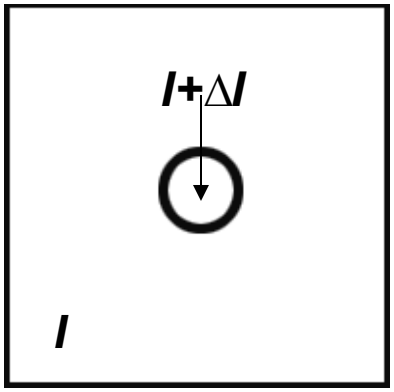
$$g(x,y) = f(t_x(x,y), t_y(x,y))$$

- What kinds of operations can each perform?

# Weber Law's

**Good Brightness Discrimination:**
**$\Delta I / I$ = small value)**

**Poor Brightness Discrimination:**
**$\Delta I / I$ = large value)**



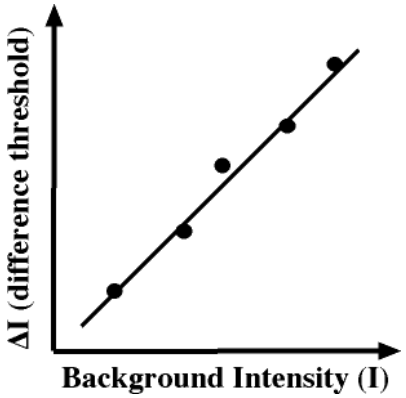

In general, $\Delta I$ needed for just noticeable difference (JND) over background $I$ was found to satisfy:

$$\frac{\Delta I}{I} = \text{constant}$$

($I$ is intensity, $\Delta I$ is change in intensity)

Weber's Law:

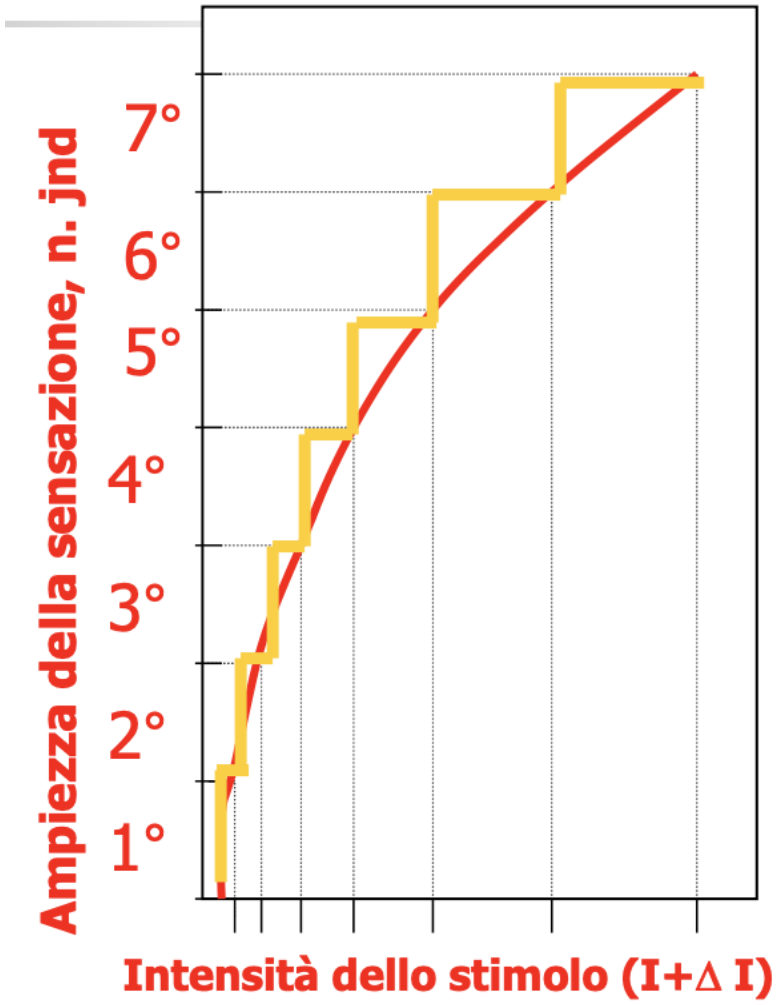
Perceived Brightness = log ($I$)



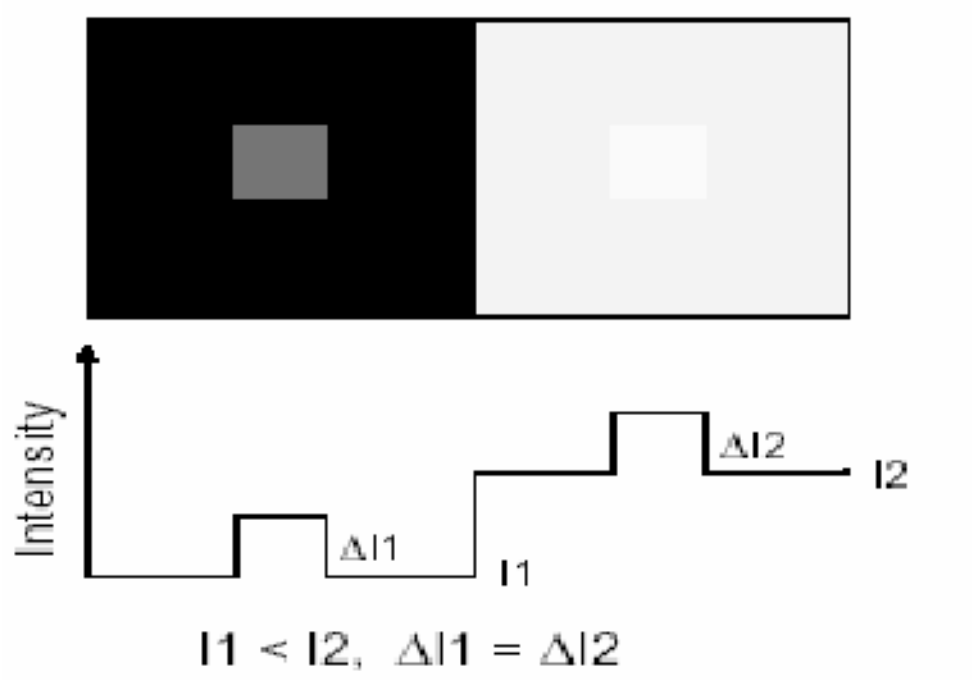
# Fechner Law's

- **Analisi delle Ascisse: se cresce I, cresce sempre più I + ΔI, cioè ΔI deve aumentare al crescere di I.**
- **Analisi delle Ordinate: Le distanze rimangono uguali, quindi la curva sale meno ripidamente.**
- **La relazione tra la Sensazione S e l'Intensità I è logaritmica:**

$$S = c \log I$$



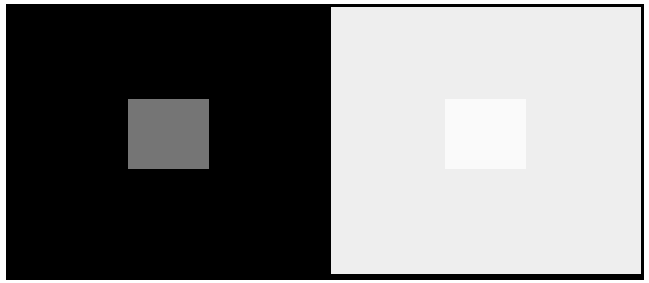
# Image Contrast



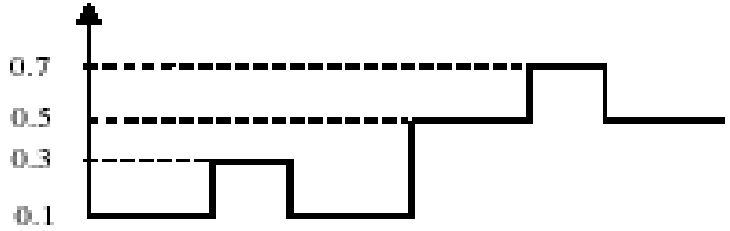
# Image Contrast (cont.)

- The contrast at an image point denotes the (relative) difference between the intensity of the point and the intensity of its neighborhood

$$C = \left| \frac{I_p - I_n}{I_n} \right|$$



$C = \left| \frac{0.3 - 0.1}{0.1} \right| = 2$ $\quad$ $C = \left| \frac{0.7 - 0.5}{0.5} \right| = 0.4$

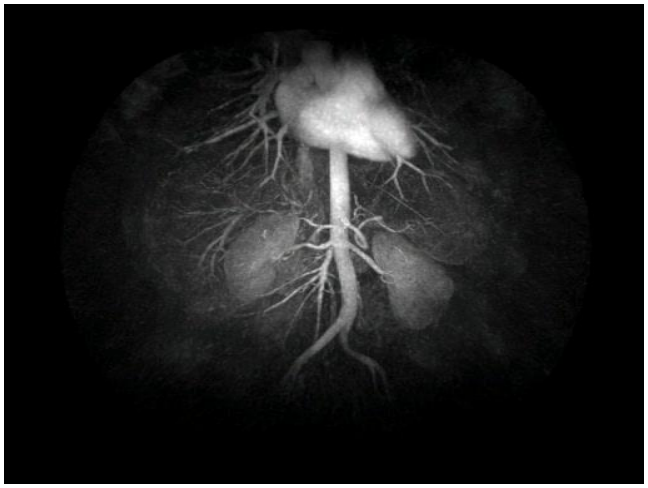


# Image Contrast (cont.)

- The contrast definition of the entire image is ambiguous.
- In general it is said that the image contrast is high if the image gray-levels fill the entire range.

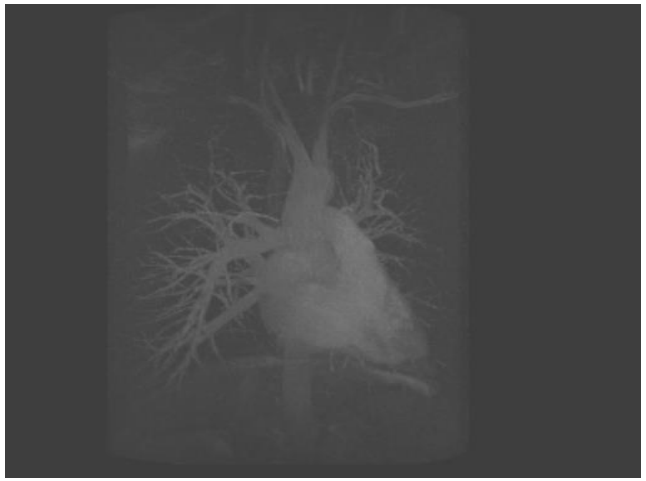
# Image Contrast (cont.)

*Non contrast Abdominal Imaging*



*Contrast-enhanced Abdominal Imaging*

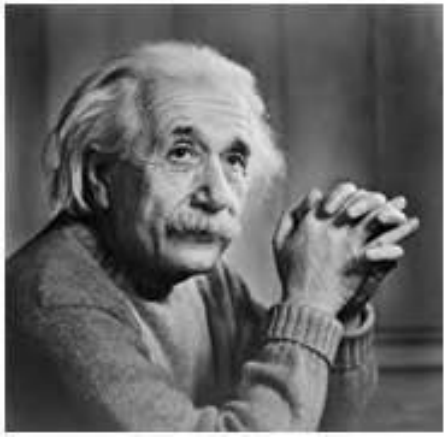
# Image Contrast (cont.)

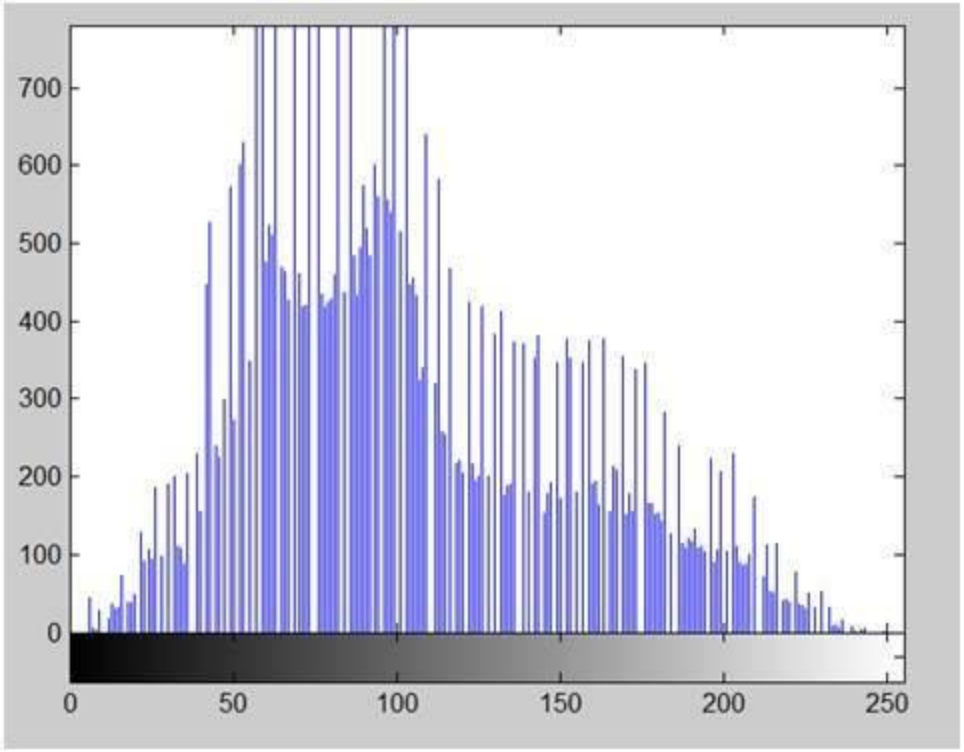


*Non contrast MR Cardiac Imaging*

*Contrast-enhanced MR Cardiac Imaging*

# Image Histogram

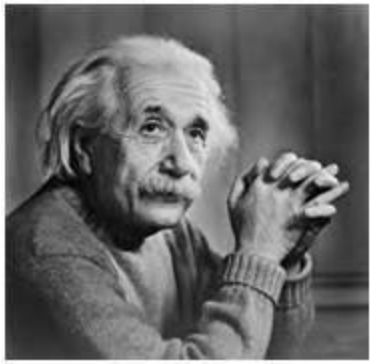


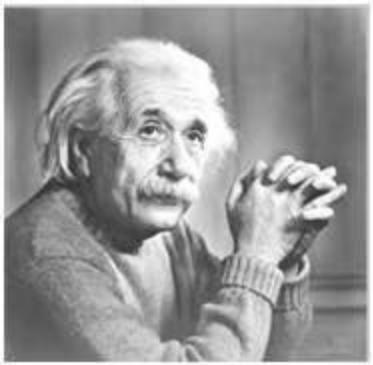


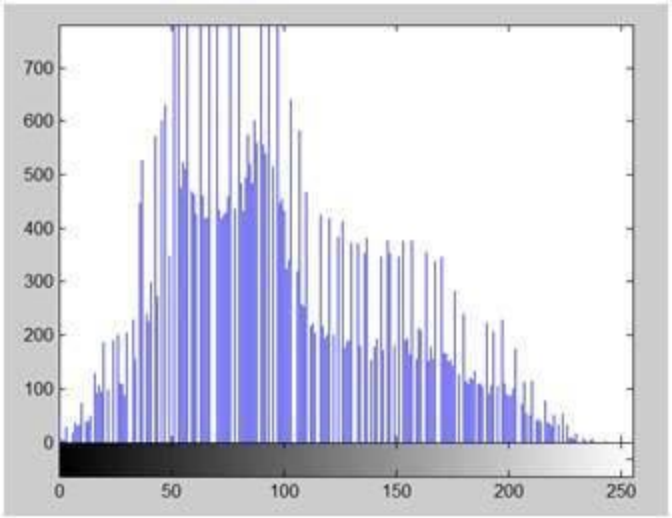

- Image histogram shows frequency of pixel intensity values.
- X axis shows the gray level intensities
- Y axis shows the frequency of intensities
- For 8 bpp image, we have 256 levels of gray shades

# Histogram sliding

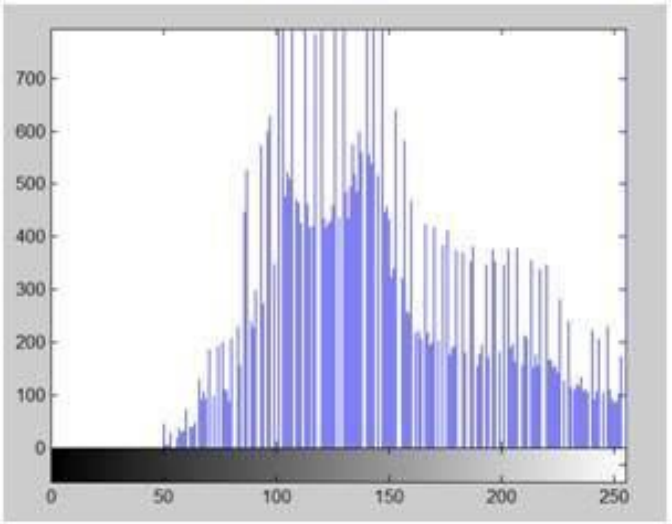
- Brightness is changed by shifting the histogram to left or right.





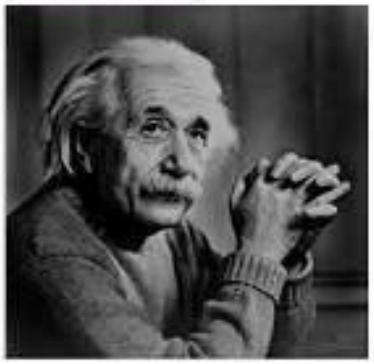



**+50**



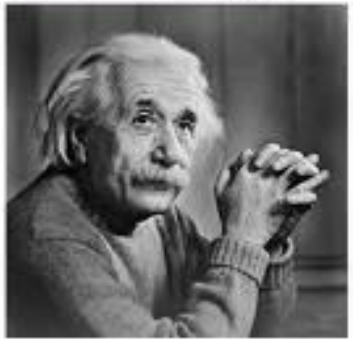
# Histogram sliding

New image.

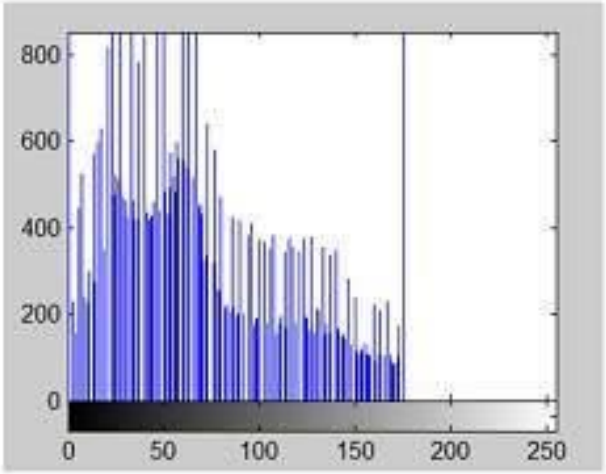


- 30

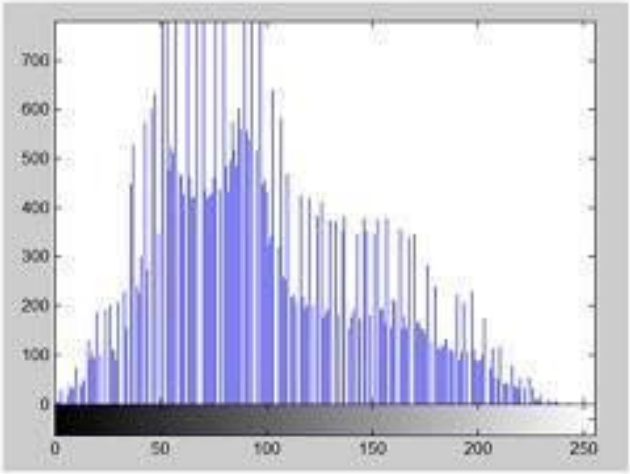
Original image.



New Histogram.

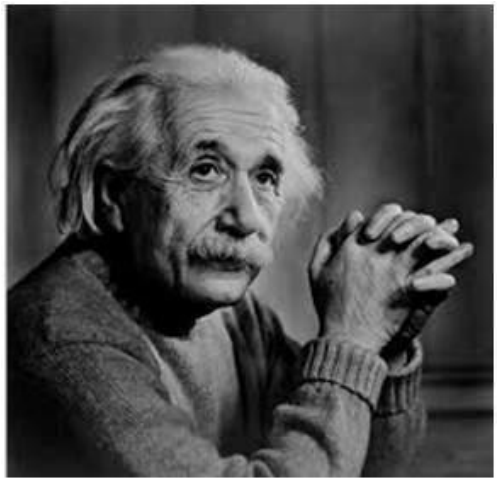


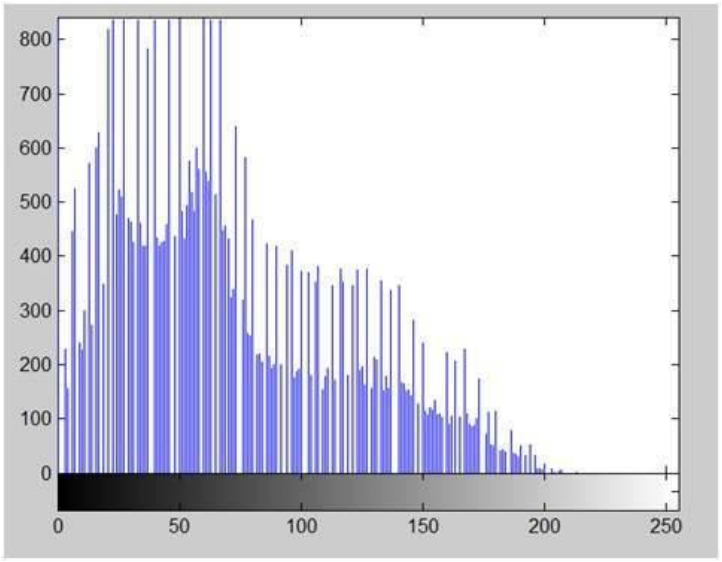

Original Histogram.



# Histogram stretching

- Contrast can be increased using:
  1. Histogram stretching
  2. Histogram equalization





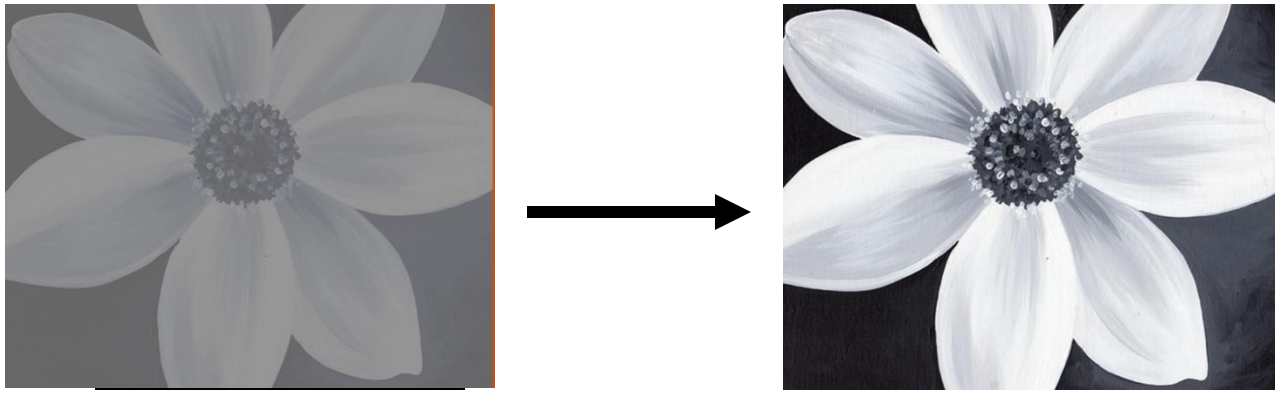

- Contrast is the difference between maximum and minimum pixel intensity. Contrast = 225.

# Increasing the contrast

$$g(x,y) = \frac{f(x,y)-fmin}{fmax-fmin} * 2^{bpp}$$

$$g(x,y) = \frac{f(x,y)-0}{225-0} * 255$$

**f(x,y)** **g(x,y)**



Low contrast image High contrast image

## HIGH CONTRAST

## LOW CONTRAST

# Histogram Equalization

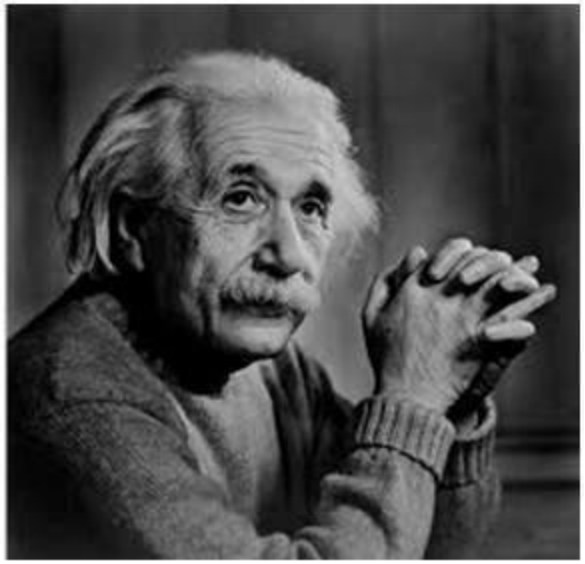
- Better visual discrimination
- Improve Contrast

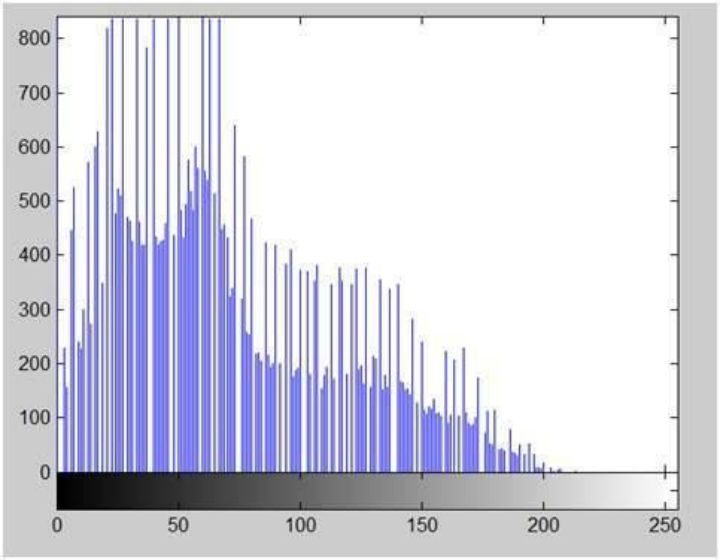
- Define a gray-level transformation such that:

$$\hat{G}=T(G)$$

- The histogram according to is as flat as possible.
- The order of Gray-levels is maintained.
- The histogram bars are not fragmented.

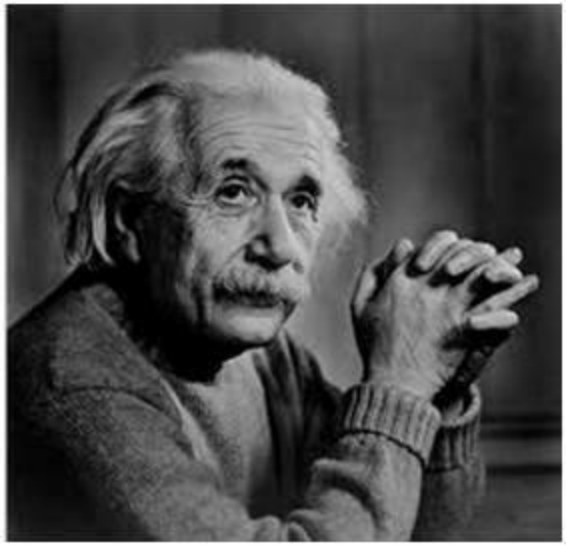
# Contrast stretching

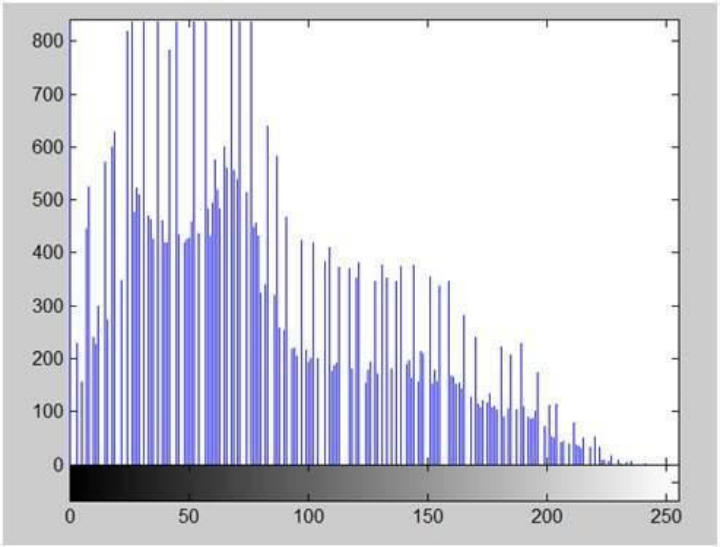





**Before**

**Contrast = 225**

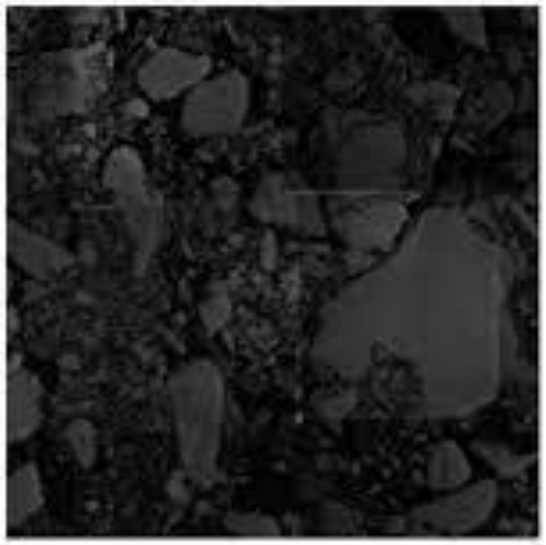


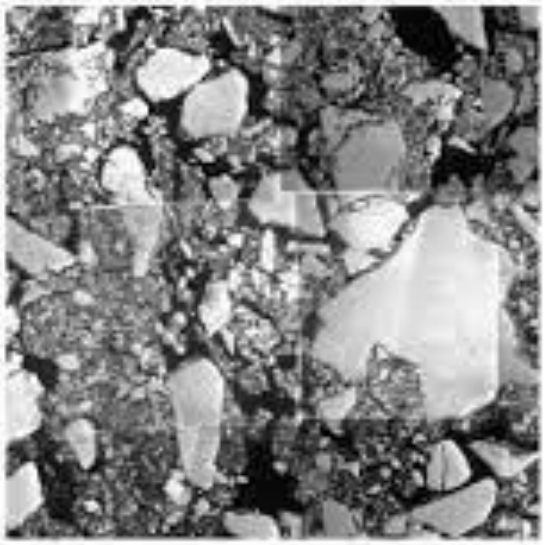


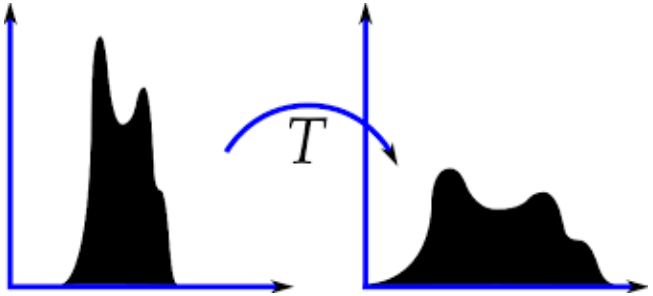

**After**

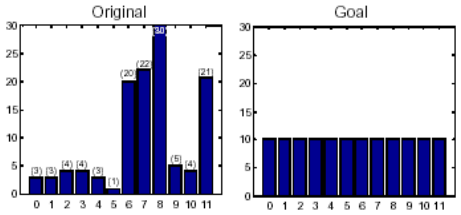
**Contrast = 240**

# Histogram Equalization



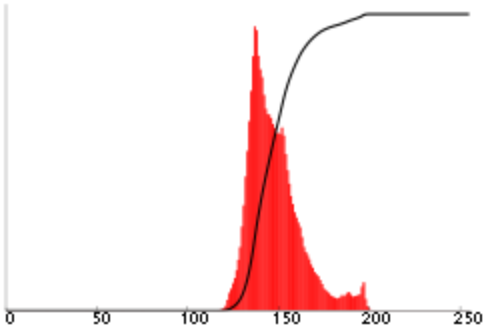




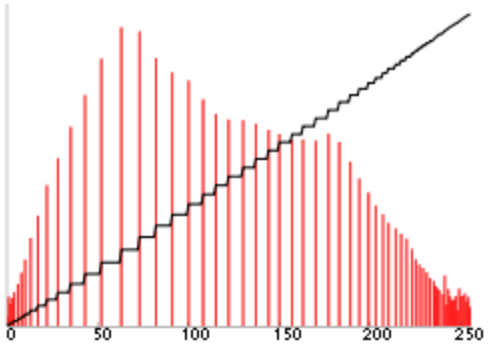
# Histogram equalization

An unequalized image




Corresponding histogram (red) and cumulative histogram (black)

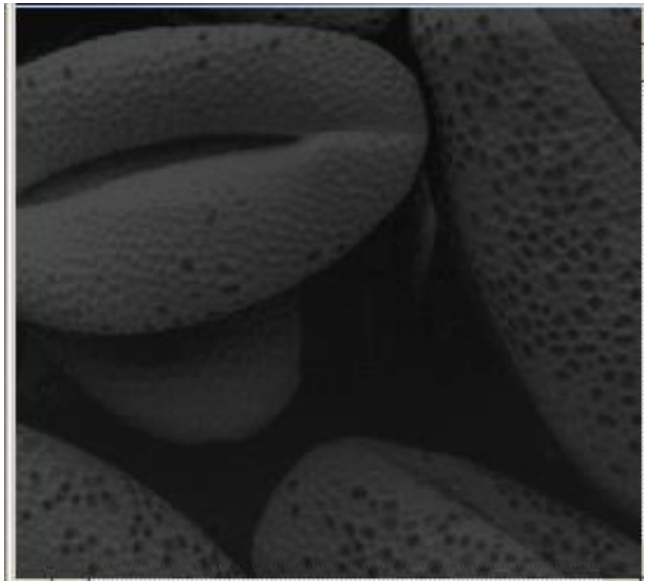
The same image after histogram equalization

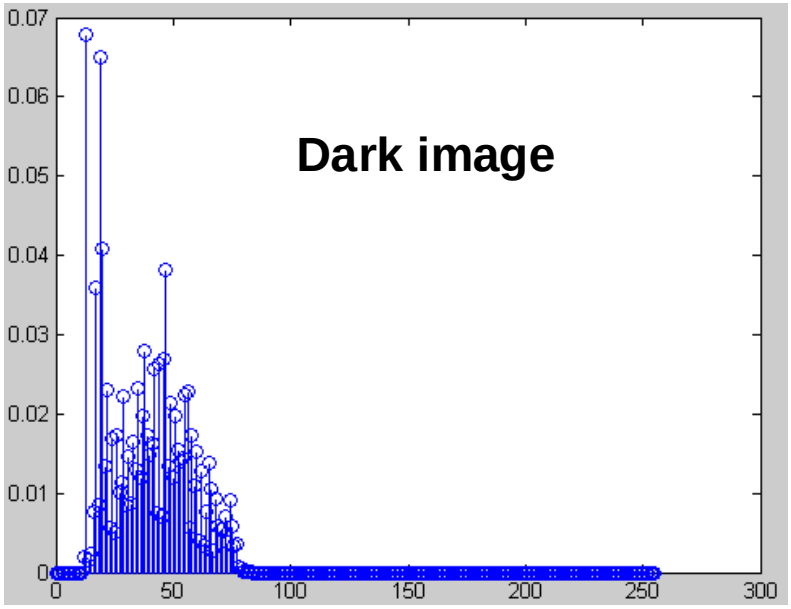


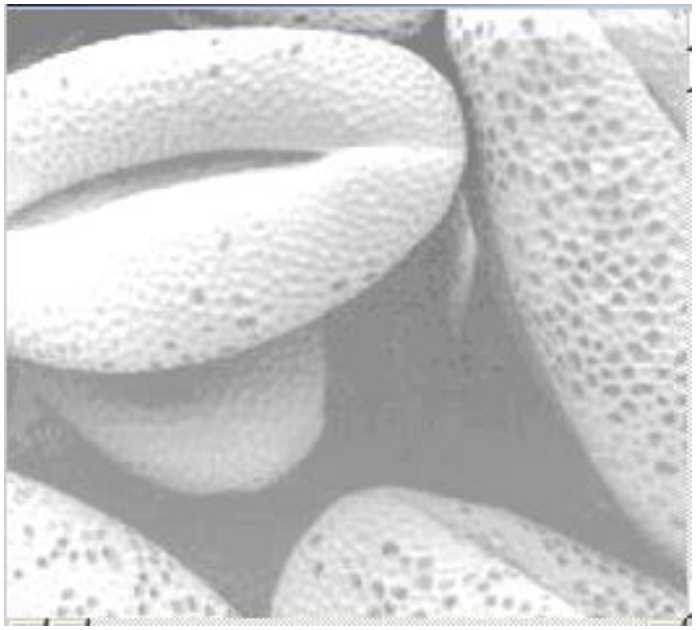

Corresponding histogram (red) and cumulative histogram (black)

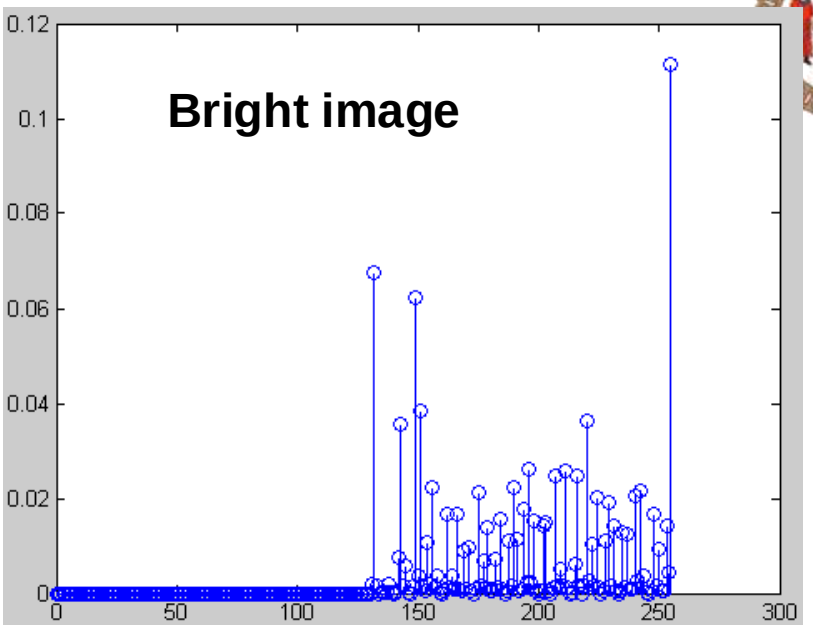
# Some Typical Histograms

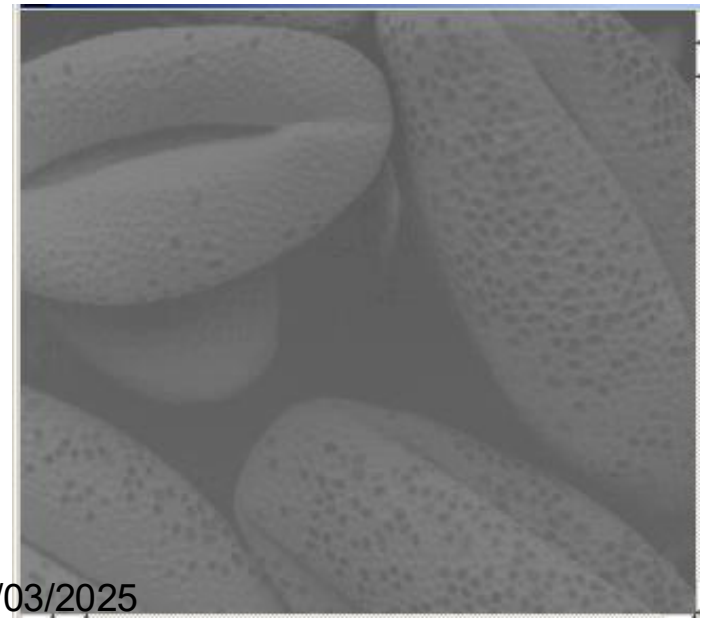
- **The shape of a histogram provides useful information for contrast enhancement.**

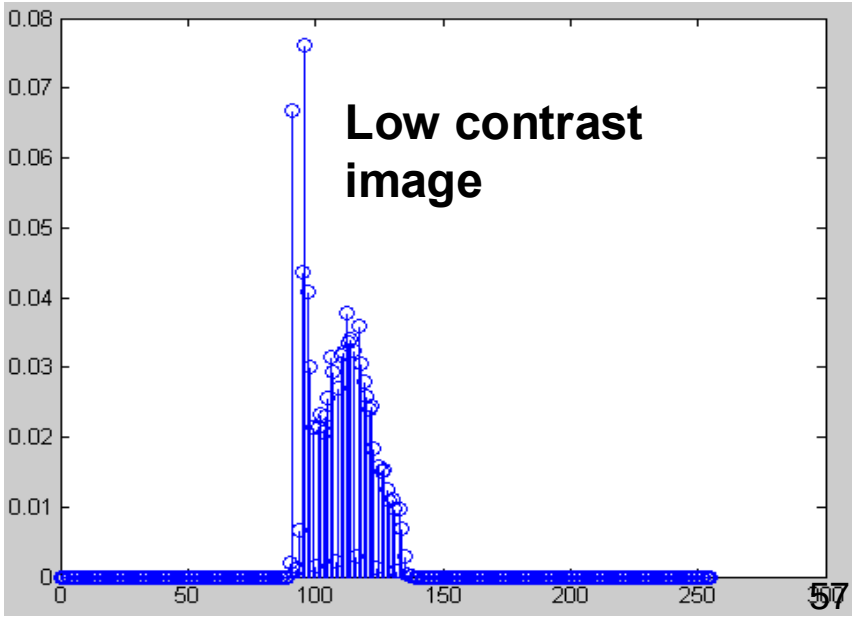


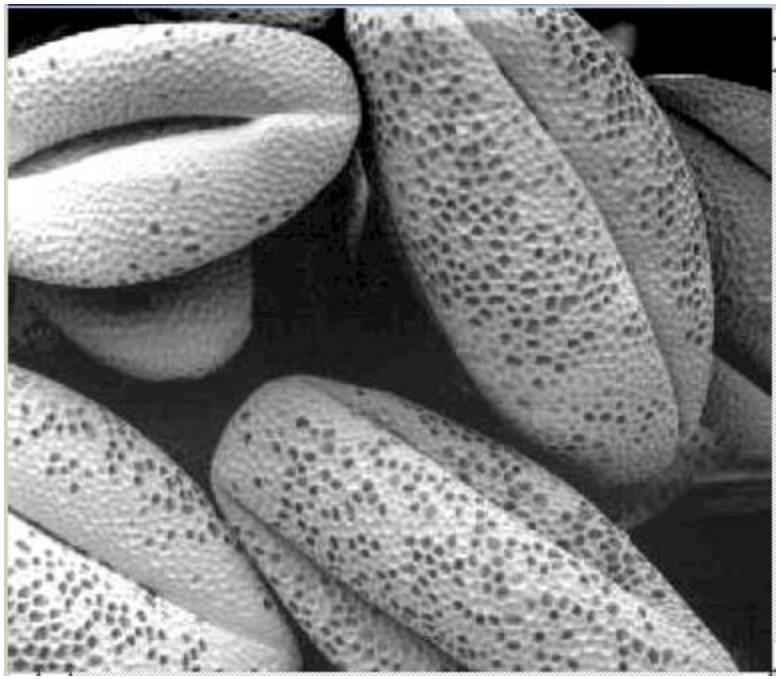


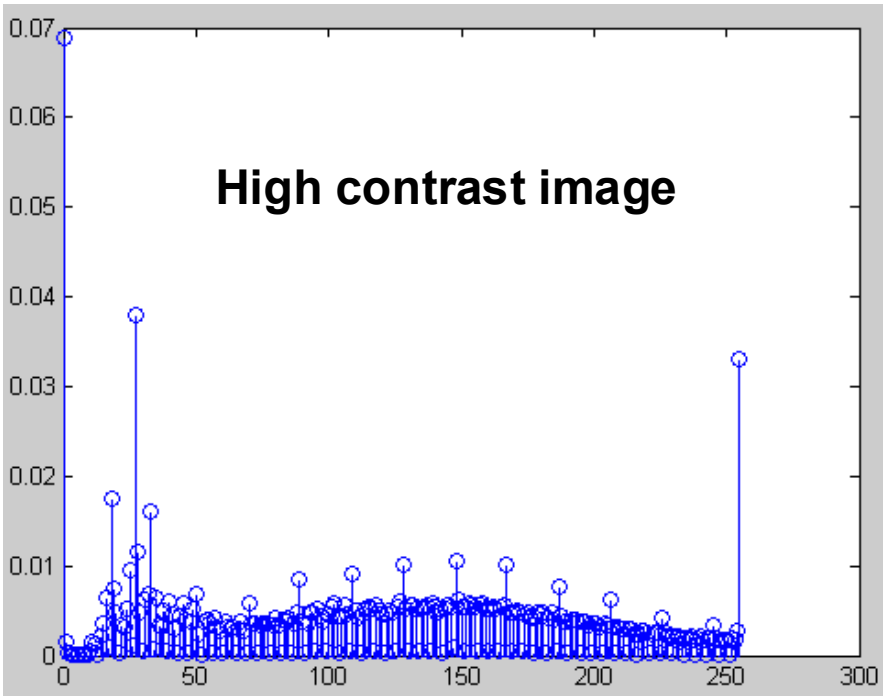



Bright image
0.12
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
200
250
300



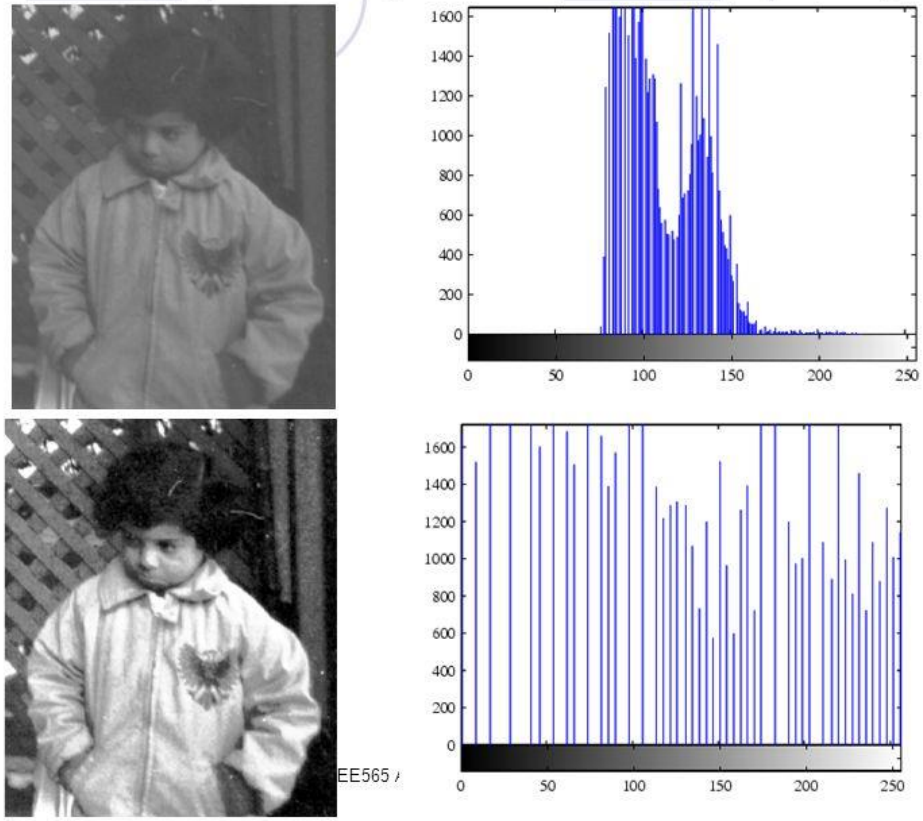

Low contrast image
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
50
100
150
200
250



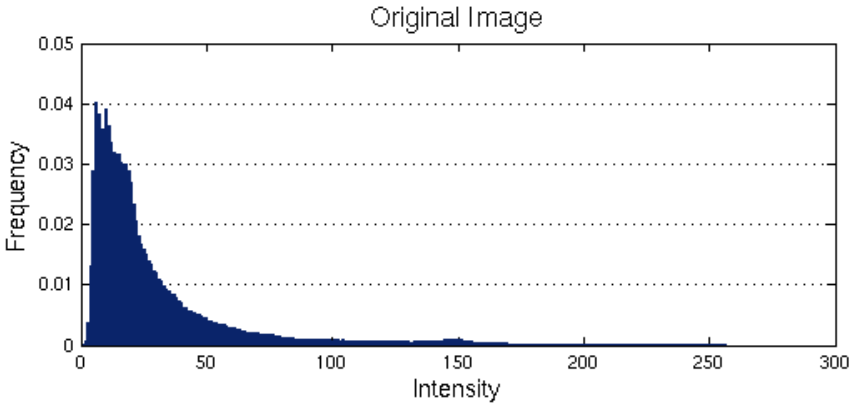

High contrast image
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
50
100
150
200
250
300

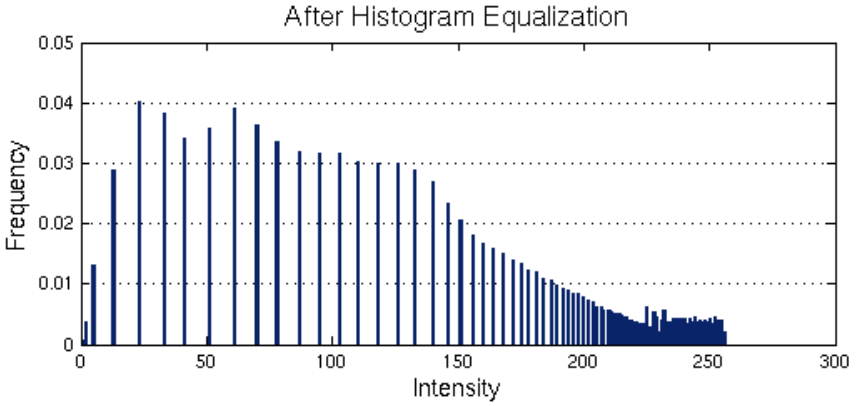
# Some Typical Histograms

## Histogram Equalization Example



# Some Typical Histograms



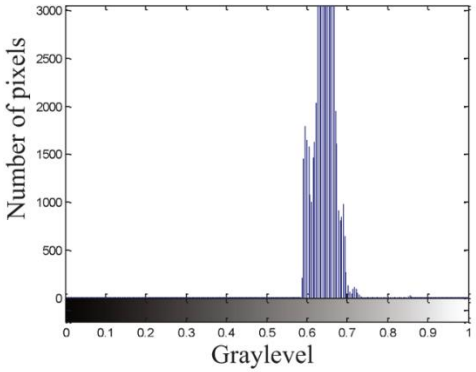



# Some Typical Histograms

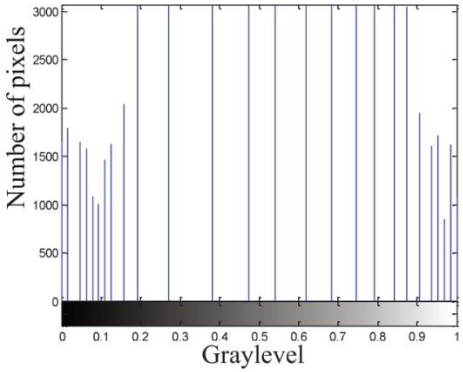
(a)

(b)

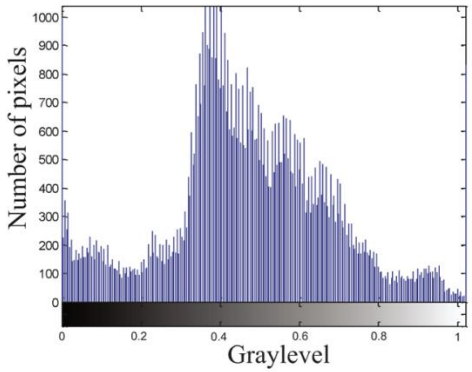
(c)




(d)




(e)



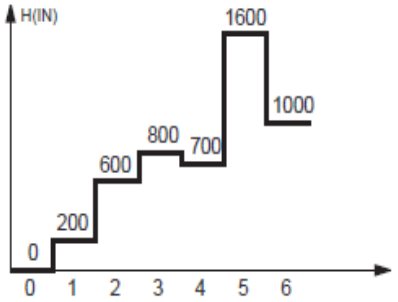

(f)

# Histogram Equalization

- Si tratta di rendere l'istogramma il più piatto possibile. Questo potrebbe rendere l'immagine più leggibile, anche se la cosa è opinabile (in alcuni casi).
- Supponiamo che l'immagine di partenza sia di dimensioni 512x*512, ovvero che sia composta da* $2^{18}$ *punti.*
- *Questo* significa che, detto H(i) l'istogramma, deve valere che :

$$\sum_{i=0}^{255} H(i) = 2^{18}$$

| IN | OUT |
|---|---|
| 0 | 0 |
| 1 | 0 |
| 2 | 0 |
| 3 | 1 |
| 4 | 1 |
| 5 | 3 |
| ... | ... |



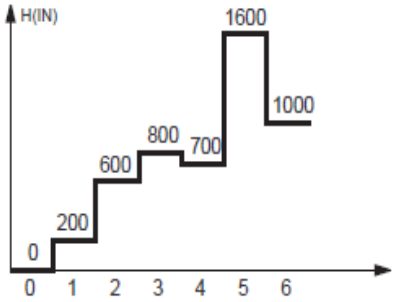

- Se vogliamo rendere l'istogramma piatto significa che vogliamo che

$$H(i) = 2^{18}/256 = 2^{10} = 1024, \forall i.$$

# Histogram Equalization

- Naturalmente non potremo ottenere proprio l'uguaglianza, visto i limiti dell'elaborazione, ma vogliamo avvicinarci il più possibile.
- Nel primo livello di uscita vorremmo ottenere 1024: se sommiamo i primi tre livelli (0, 1 e 2) dell'ingresso otteniamo 800, se sommiamo i primi quattro 1600.
- Poiché 800 è più vicino a 1024 di 1600 scegliamo di sommare i primi tre.

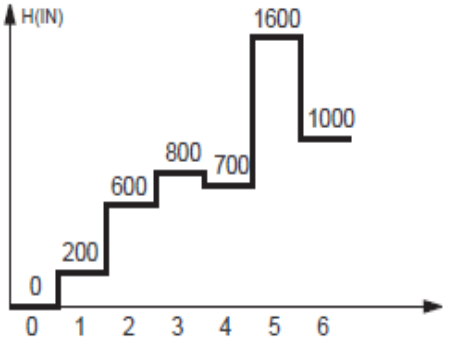
| IN | OUT |
|---|---|
| 0 | 0 |
| 1 | 0 |
| 2 | 0 |
| 3 | 1 |
| 4 | 1 |
| 5 | 3 |
| ... | ... |



# Histogram Equalization

- Passiamo al secondo livello dell'uscita: anche lui dovrebbe essere riempito con 1024 livelli ma, per evitare accumuli dell'errore, bisogna considerare che nei primi due livelli voglio 1024 + 1024 = 2048 punti. Poiché nel primo ne ho già inseriti 800 dovrò cercare di approssimare, per il secondo, il valore di 1248.

| IN | OUT |
|---|---|
| 0 | 0 |
| 1 | 0 |
| 2 | 0 |
| 3 | 1 |
| 4 | 1 |
| 5 | 3 |
| ... | ... |




- Quindi scelgo di inserire i livelli 3 e 4 dell'ingresso, visto che 800 + 700 = 1500 è più vicino a 1248 di 800.

# Histogram Equalization

- Nel terzo livello di uscita ci va ancora 1024 e la somma dei primi tre deve essere 3072. Ne ho già sistemato 800 + 1500 = 2300 e quindi ne restano 772. Poiché il primo livello da sistemare dell'ingresso (il 5) vale 1600 e 1600−772 = 828 lascio vuoto il terzo livello dell'uscita.
- Nel quarto livello di uscita devo approssimare 4096 − 2300 =1996, se inserisco il livello di ingresso 5 ne mancano 396, se inserisco 5+6 ne avanzano 2600 − 1996 = 604 quindi scelgo 5.

| IN | OUT |
|---|---|
| 0 | 0 |
| 1 | 0 |
| 2 | 0 |
| 3 | 1 |
| 4 | 1 |
| 5 | 3 |
| ... | ... |