Digital Image Processing

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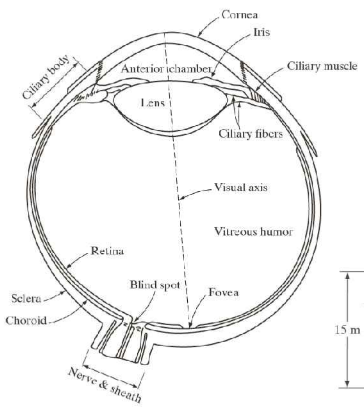
II. Digital Image Fundamentals

1. Elements of the human visual perception
2. Light and electromagnetic spectrum
3. Image sensing and acquisition
4. Image sampling and quantization
   - Basic concepts
   - Representing digital images
   - Spatial and intensity resolution
   - Image interpolation
5. Some basic relationships between pixels
   - Neighbors of a pixel
   - Adjacency, connectivity, regions, and boundaries
   - Distance measure

Elements of the human visual perception



Retina
- Cone : 6~7 M, bright light (photopic), color
  central area (1.5 x 1.5 mm^2) = ~300 k
- Rod : 75~150 M, dim light (scotopic), no color

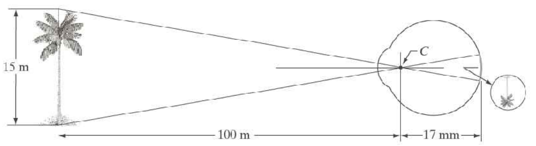
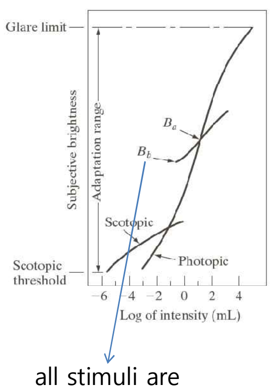


FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point *C* is the optical center of the lens.

Brightness Adaptation and Discrimination

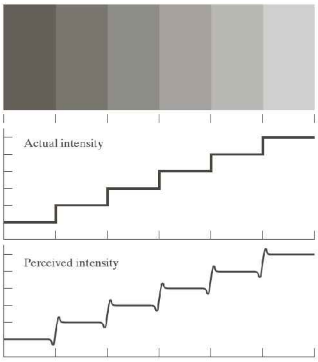
- The eye is able to adapt to a huge range of light intensity levels (on the order of 10^{10}).
- Subjective brightness is a logarithmic function of the light intensity incident on the eye.
- The total range that can be perceived simultaneously is much smaller.
  – The eye adapts itself to a narrower range (B_a, B_b in figure)
  → *Brightness adaptation*



all stimuli are perceived as indistinguishable blacks below B_b.

Mach Band Effect

- Although the intensity of the stripes is constant, we actually perceive a brightness pattern that is strongly scalloped, especially near the boundaries.
- These seemingly scalloped bands are called Mach bands after Ernst Mach, who first described the phenomenon in 1865.
- In neurobiology, **lateral inhibition** is the capacity of an excited neuron to reduce the activity of its neighbors.

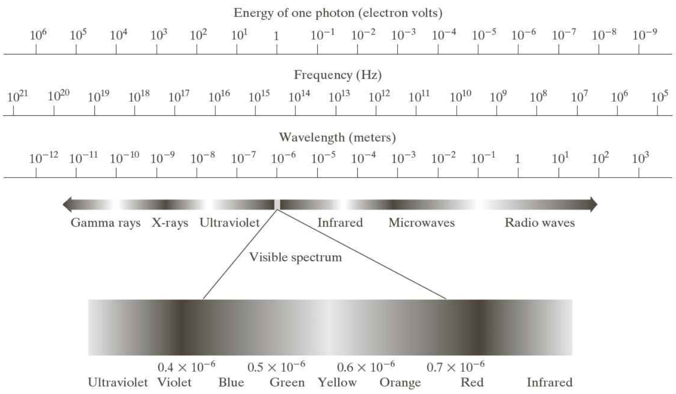


Human Visual Perception

- Nonlinear
- Small range of discrimination
- Very subjective

→ Enhancement

Light and the Electromagnetic Spectrum



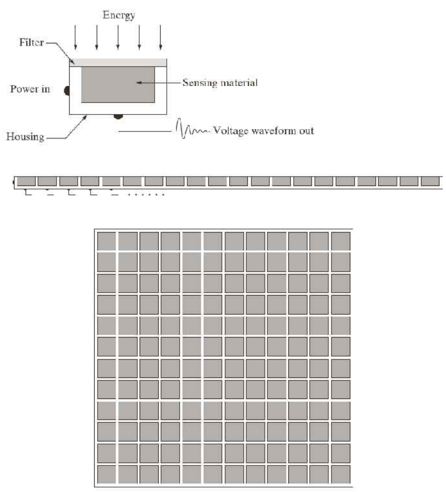
The EM spectrum.
Note that the visible spectrum is a rather narrow portion of the EM spectrum

Image Sensing and Acquisition

- Sensor: Incoming energy → a voltage by combination of input electrical power and sensor material
  (photon → electron → voltage)

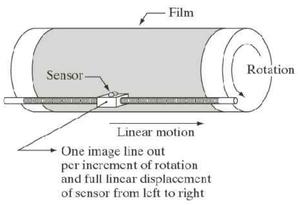
- Types of sensor:
  - Single sensor
  - Line sensor
  - Array sensor

} Mechanical scan



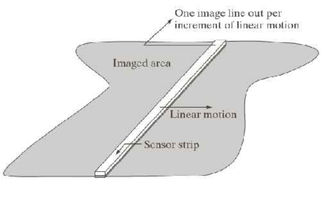
Single sensor

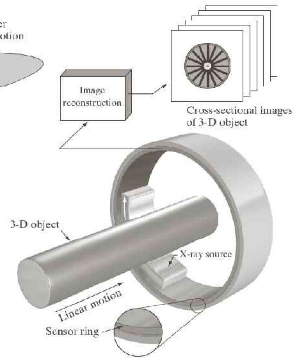
- Mechanical scan and/or moving mirrors
- High precision but slow
- Very large FOV



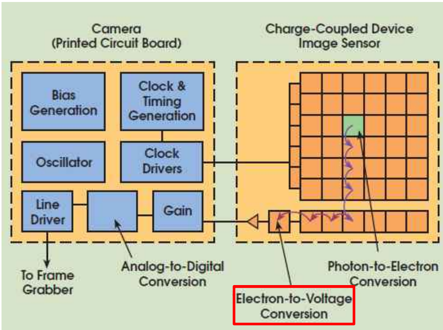
Line sensor

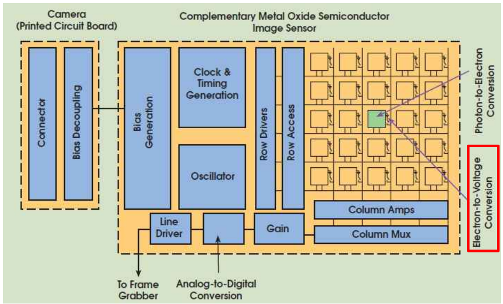
- Mechanical scan
- Large FOV
  - Flat bed scanner
  - Inspection
  - CT





CCD vs. CMOS



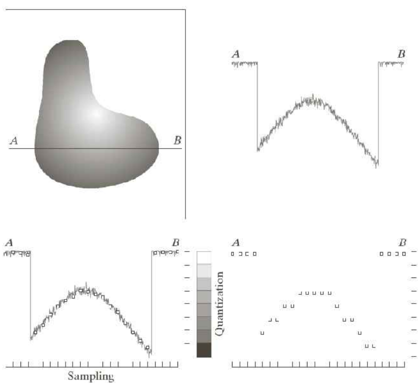


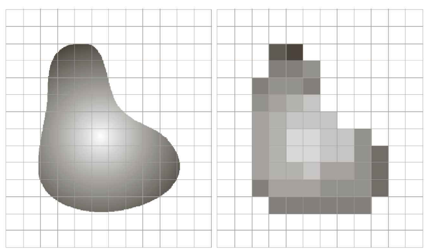
- Fill factor (100% : 75%) → SNR
- Uniformity
- Cost
- Size, extra circuits

Image Sampling and Quantization

- Convert a continuous image f(x,y) in digital format
  - digitizing the coordinate values → Sampling → the number of samples
  - digitizing the amplitude values → Quantization → discrete gray levels (bit depth)

→ Image Quality



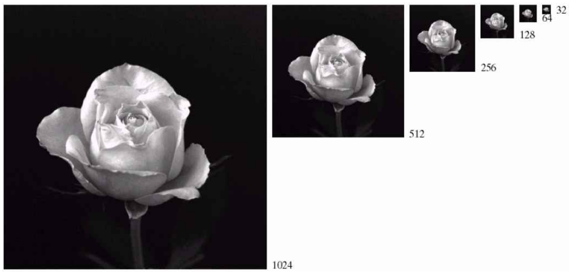


a b

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

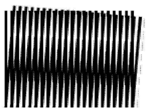
Spatial Resolution

- A measure of the smallest discernible detail in a image
- Line pairs per unit distance, dots (pixels) per unit per distance (ex. lpi, dpi)

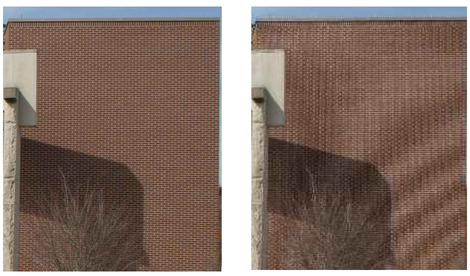


Coarse sampling → Poor resolution
Aliasing ex) Moiré Pattern

Moiré Pattern

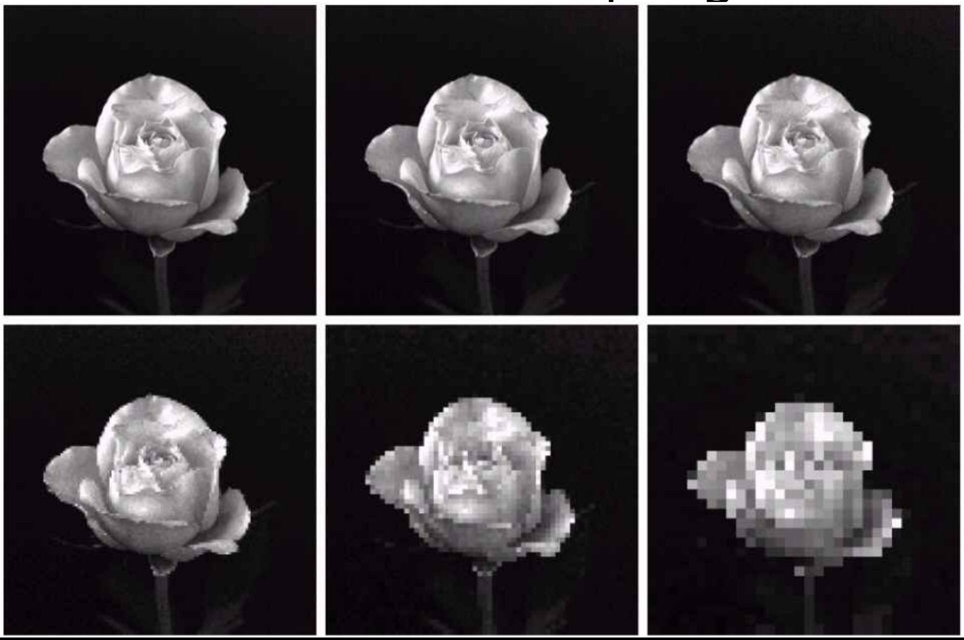


A moiré pattern, formed by two sets of parallel lines, one set inclined at an angle of 5° to the other

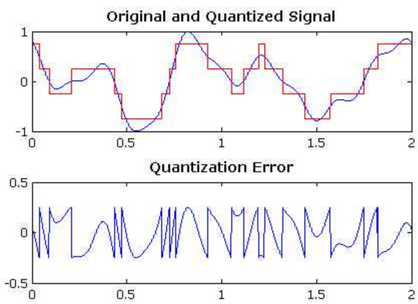


A moiré pattern formed by incorrectly downsampling the left image

Effects of Sampling



Quantization Error (Noise)



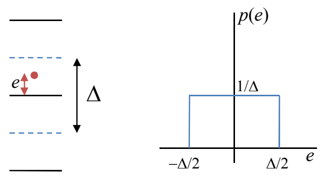
Quantization Noise

- Probability density function

  $p(e)=1/\Delta \quad (-\Delta/2 \le e \le \Delta/2),$

  $\quad\quad 0 \quad (\text{otherwise})$

  step size $\Delta=D/2^N$ (N: bit depth)



- Mean of e = 0
- Variance of e (noise power)

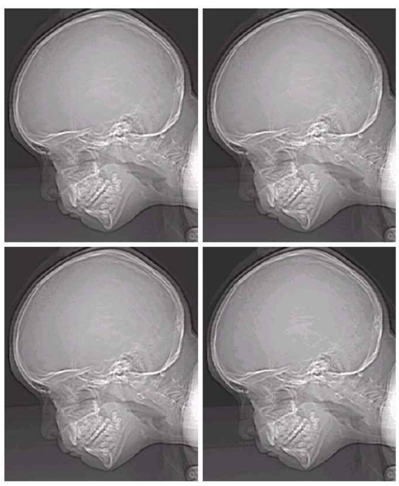
$$\sigma_e^2 = \int_{-\infty}^{\infty} e^2 p(e)de = \int_{-\Delta/2}^{\Delta/2} e^2 \cdot \frac{1}{\Delta} de = \frac{\Delta^2}{12} \qquad (\sigma_e = \frac{\Delta}{\sqrt{12}})$$

ex) D=10[v], N=8

$\Delta=10/2^8=10/256$ [v]

quantization noise $\sigma_e=\Delta/12^{1/2}=0.0113$[v]

Intensity Resolution



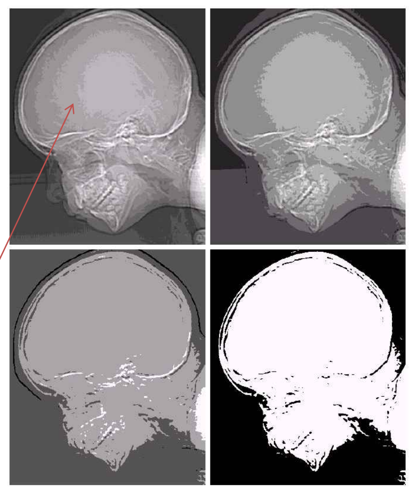
a b
c d

FIGURE 2.21 (a) 452 × 374, 256-level image. (b)–(d) Image displayed in 128, 64, and 32 gray levels, while keeping the spatial resolution constant.

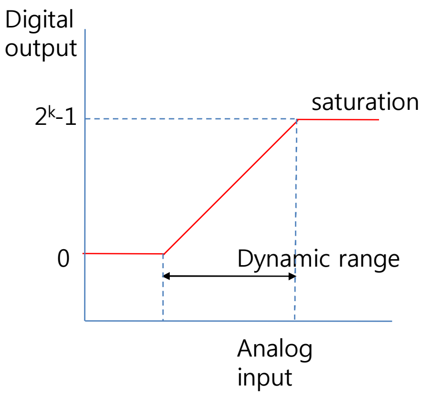
e f
g h

FIGURE 2.21 *(Continued)* (e)–(h) Image displayed in 16, 8, 4, and 2 gray levels. (Original courtesy of Dr. David R. Pickens, Department of Radiology & Radiological Sciences, Vanderbilt University Medical Center.)

Quantization Errors
→
False contouring
↓
Posterization



Dynamic Range of Intensity
and
Intensity Resolution

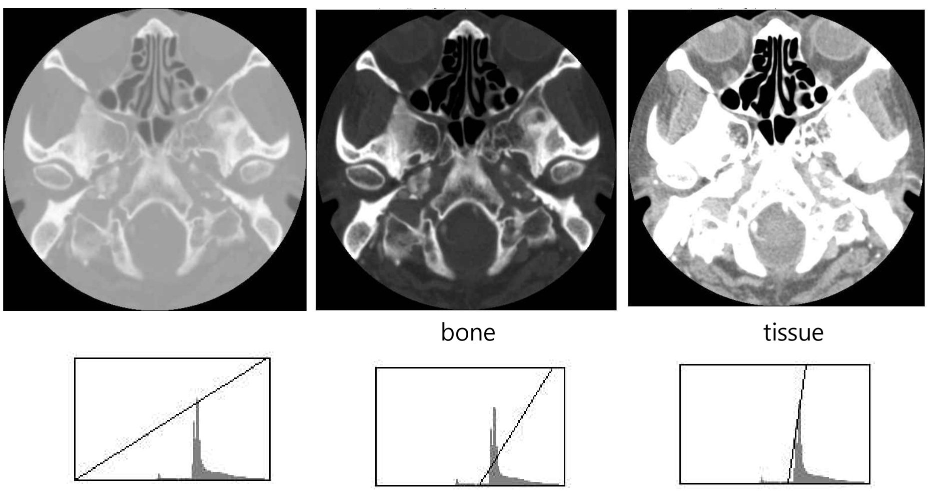


The larger the dynamic range is,
the poorer the intensity resolution is.

→ Bit depth ↑

Some of medical images require large bit depth. ex) X-ray, CT, MRI, …

Why a large bit depth is required for CT images.



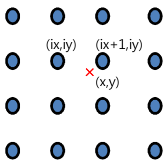
Trade-off

- Spatial Resolution
- Intensity Resolution/Dynamic Range

- SNR
- Acquisition time (timing resolution)
- Amount of data
- Cost

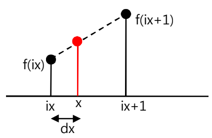
Image Interpolation

- A basic tool used extensively in lots of tasks
  - Zooming, shrinking, rotating, geometric correction
  - Reconstruction
- Resampling



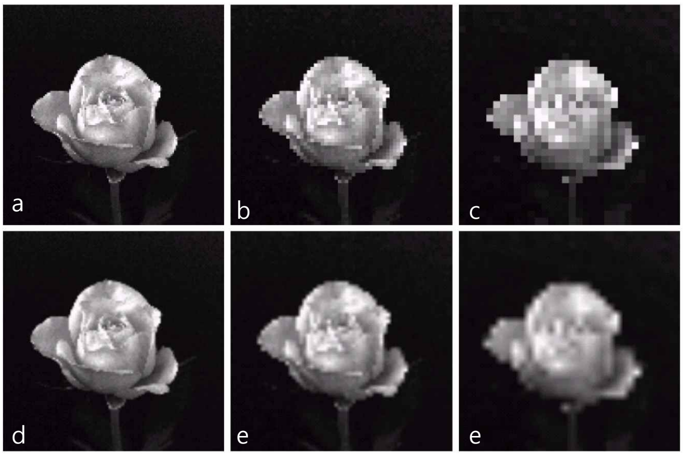
- Nearest neighbor interpolation (0^{th} order)
  : pixel duplication
- Linear interpolation (1^{st} order)

  f(x)=f(ix)*(1-dx)+f(ix+1)*dx



- Bicubic interpolation (higher order)

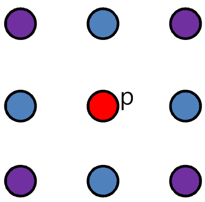
Example : Zooming Digital Images



Images zoomed from 128x128, 64x64 32x32 pixels to 1024x1024 pixels.
Top row : nearest neighbor interpolation
Bottom row : bilinear interpolation

Some Basic Relationships between Pixels - Neighbors

- 8 neighbor pixels of p : $N_8(p)$
  - 4 horizontal and vertical neighbors : $N_4(p)$
  - 4 diagonal neighbors : $N_D(p)$



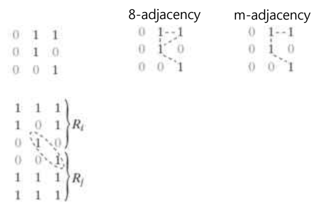
* if p is on the border of the image…?

- 3D : 26 neighbors

Some Basic Relationships between Pixels – Adjacency, Connectivity

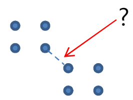
- 4-adjacent

- 8-adjacent



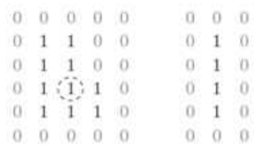
- m-adjacent
  - 4-adjacent or 8-adjacent
  - 4-adjacency has a priority

- Connected



Some Basic Relationships between Pixels – Boundary, Edge

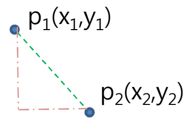
- Boundary (border, contour)
  - the set of pixels that have at least 1 background neighbor.
- Specify the connectivity to define adjacency
- Inner or outer border
  - → border following algorithm

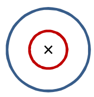


- Boundary : closed paths
  Edge : intensity discontinuities

Some Basic Relationships between Pixels - Distance Measure

- Euclidean distance : $D_e(p_1,p_2)=[(x_1-x_2)^2+(y_1-y_2)^2]^{1/2}$





- D_4 (city-block) distance : $D_4(p_1,p_2)=|(x_1-x_2|+|y_1-y_2|$

2

2 1 2

2 1 0 1 2

2 1 2

2

- D_8 (chessboard) distance : $D_8(p_1,p_2)=\max(|(x_1-x_2|,\ |y_1-y_2|)$

2 2 2 2 2

2 1 1 1 2

2 1 0 1 2

2 1 1 1 2

2 2 2 2 2

An introduction to the mathematical tools used in DIP

- Matrix operations
- Linear and nonlinear operations

  $H[af_1(x,y)+bf_2(x,y)]=aH[f_1(x,y)]+bH[f_2(x,y)]$

  additivity, homogeneity

- ....

Additive Noise

- $g(x, y) = f(x, y) + n(x, y)$

  $f(x, y)$: noiseless image

  $n(x, y)$: uncorrelated noise

  with zero average value

- Averaging $\bar{g}(x, y) = \dfrac{1}{K}\sum_{i=1}^{K} g_i(x, y)$

  $$E\{\bar{g}(x, y)\} = f(x, y)$$

  $$\sigma^2_{\bar{g}(x,y)} = \frac{1}{K}\sigma^2_{n(x,y)} \qquad \left(\sigma_{\bar{g}(x,y)} = \frac{1}{\sqrt{K}}\sigma_{n(x,y)}\right)$$

  → Improve SNR

  ex) MRI

Geometric Spatial Transformation

- Modify the spatial relationship between pixels
  i) Spatial transformation of coordinates

     $(x, y) = T\{(v, w)\}$

  ii) Intensity interpolation

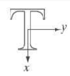
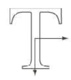
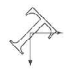
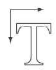
  ex) Affine transform

  $$[x \quad y \quad 1] = [v \quad w \quad 1]\mathbf{T} = [v \quad w \quad 1]\begin{bmatrix} t_{11} & t_{12} & 0 \\ t_{21} & t_{22} & 0 \\ t_{31} & t_{32} & 1 \end{bmatrix}$$

  $\mathbf{T}$: scale, rotate, translate, shear

Affine Transform

TABLE 2.2
Affine transformations based on Eq. (2.6.–23).

Transformation Name	Affine Matrix, T	Coordinate Equations	Example
Identity	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v$ $y = w$	
Scaling	$\begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = c_x v$ $y = c_y w$	
Rotation	$\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v\cos\theta - w\sin\theta$ $y = v\cos\theta + w\sin\theta$	
Translation	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ t_x & t_y & 1 \end{bmatrix}$	$x = v + t_x$ $y = w + t_y$	
Shear (vertical)	$\begin{bmatrix} 1 & 0 & 0 \\ s_v & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v + s_v w$ $y = w$	
Shear (horizontal)	$\begin{bmatrix} 1 & s_h & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v$ $y = s_h v + w$