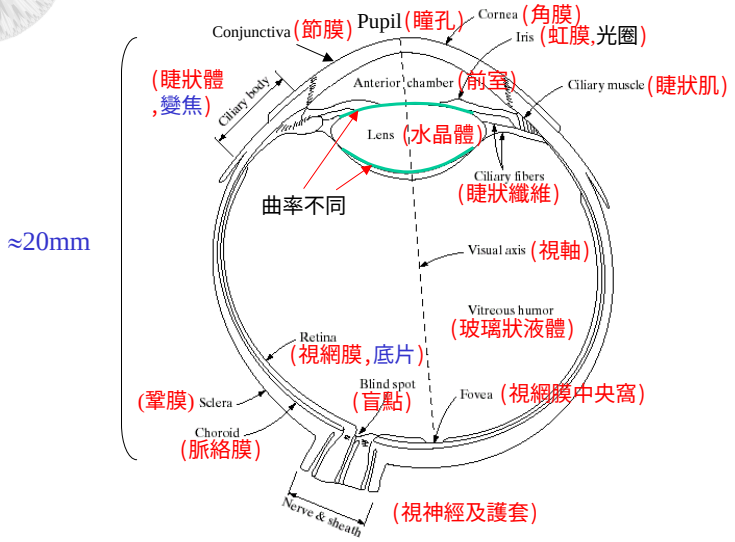
Chapter 2 Digital Image fundamentals

2.1 Elements of visual perception

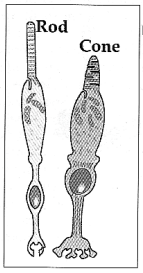
2.1.1 Structure of the Human Eye

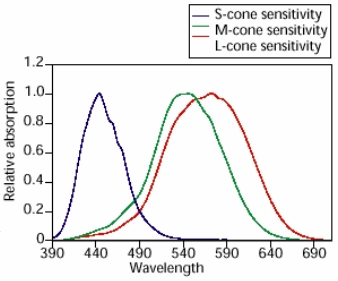


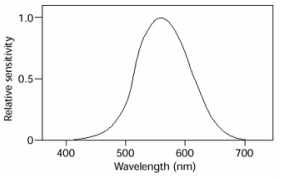
2.1 Elements of visual perception

2.1.1 Structure of the Human Eye

- ***Light Reception***
  - Cones (椎狀細胞)
    - 6-7millions
    - sensitive to Color
    - Photopic or Bright-light vision
  - Rods (桿狀細胞)
    - 75-150millions
    - Scotopic or Dim-light vision







眼睛由不同波長所造成的對亮度的相對感應。

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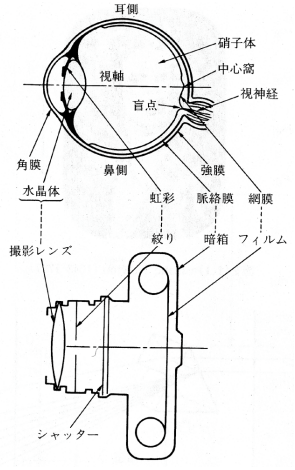
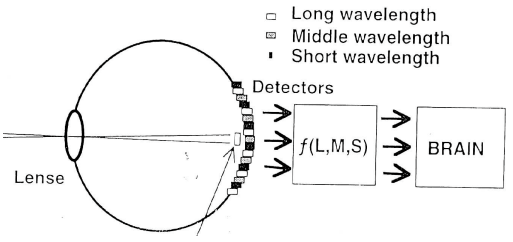
2.1 Elements of visual perception

2.1.1 Structure of the Human Eye





2.1 Elements of visual perception

2.1.1 Structure of the Human Eye

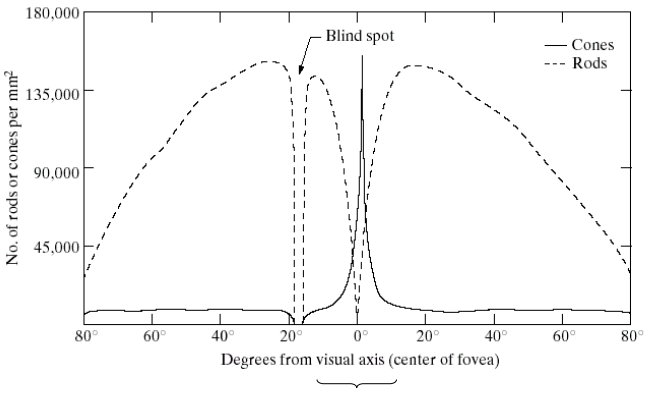


FIGURE 2.2 Distribution of rods and cones in the retina.

≈1.5 mm
≈337000 cones

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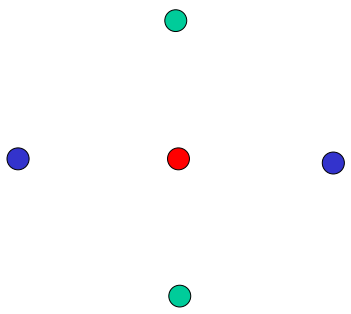
2.1 Elements of visual perception

2.1.1 Structure of the Human Eye

盲點實驗



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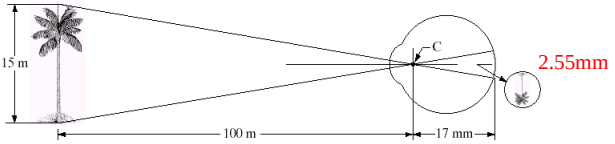
2.1 Elements of visual perception

2.1.2 Image formation in the Eye

- 睫狀體調整Len半徑
- 影像距焦至Fovea附近
- 光感細胞感受各自位置強度
- 腦部成像及識別

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



14mm ~ 17mm

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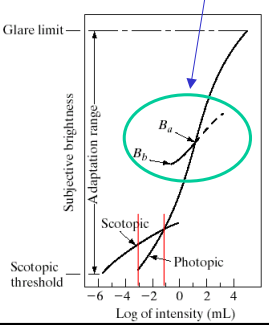
2.1 Elements of visual perception

2.1.3 Brightness adaptation and discrimination

- Subjective Brightness is a logarithm function
  - on the order of 10^{10}
- The total range of distinct intensity levels it can discriminate simultaneously is rather small

FIGURE 2.4 Range of subjective brightness sensations showing a particular adaptation level.

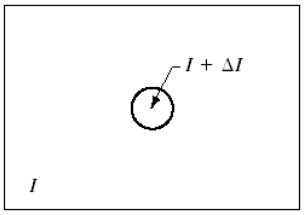


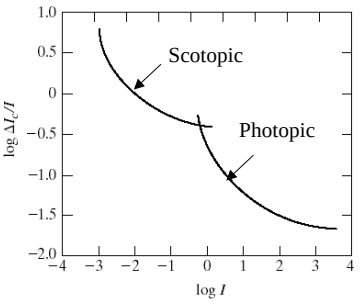
milliLambert:亮度單位

2.1 Elements of visual perception

A classic experiment for brightness discrimination

- Weber Ratio : $\Delta I_c / I$
  - a small value means Good brightness discrimination
  - a large value means Poor brightness discrimination
- the typical observer can discern 1~2 dozen different intensity changes





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2.1 Elements of visual perception

Two examples

- to demonstrate the perceived brightness is not a simple function of intensity
- Mach Bands - 1865, Ernst Mach

a
b

FIGURE 2.7
(a) An example showing that perceived brightness is not a simple function of intensity. The relative vertical positions between the two profiles in (b) have no special significance; they were chosen for clarity.

2.1 Elements of visual perception

- Simultaneous contrast

a b c

FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

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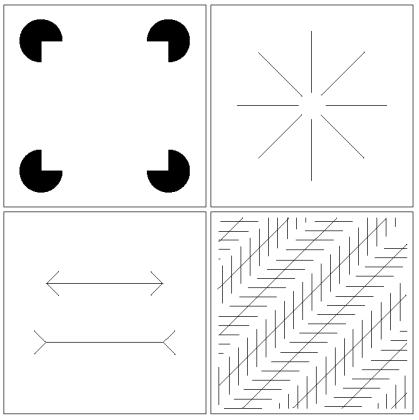
2.1 Elements of visual perception

- **Optical Illusion(視覺錯覺)**
  - is not fully understood

a b
c d

FIGURE 2.9 Some well-known optical illusions.



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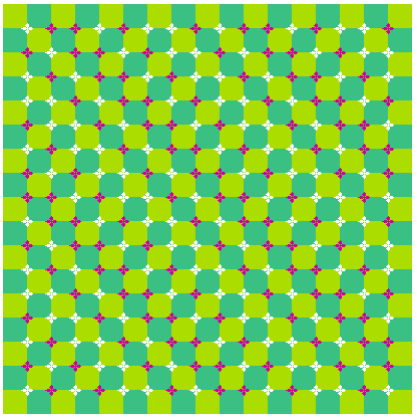

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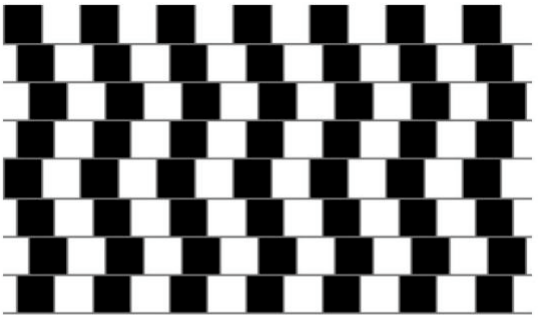
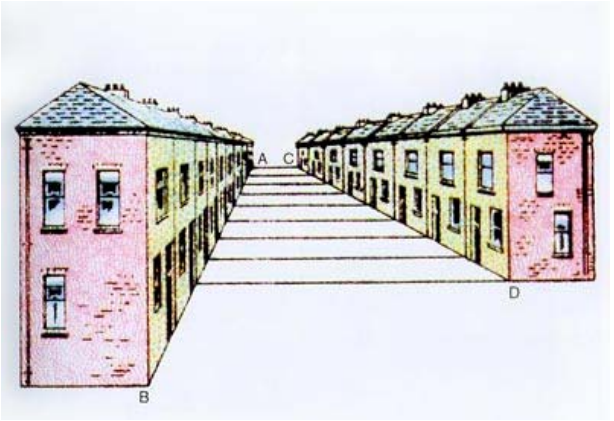
2.1 Elements of visual perception



Are the horizontal lines parallel or do they slope?

2.1 Elements of visual perception



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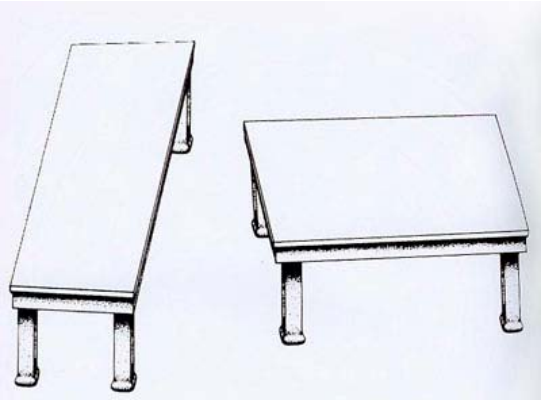
2.1 Elements of visual perception



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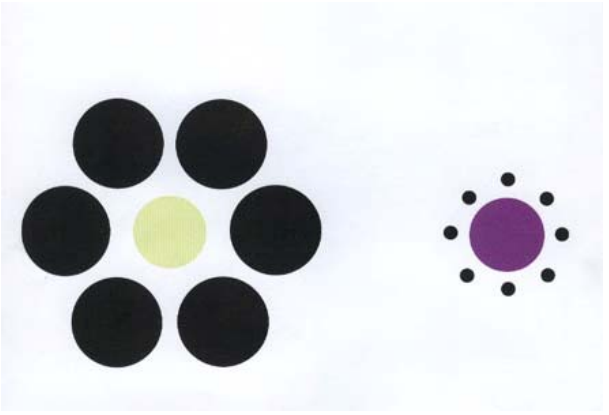
2.1 Elements of visual perception



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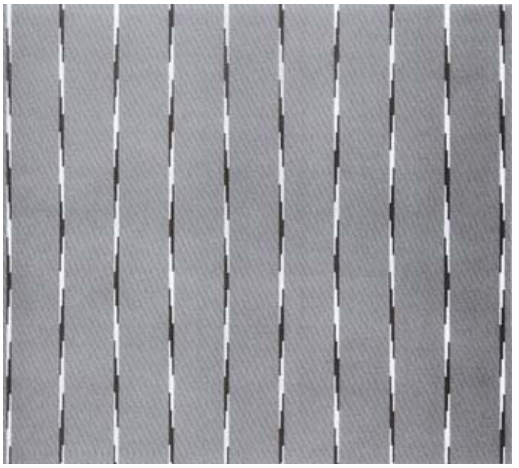
2.1 Elements of visual perception



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2.1 Elements of visual perception

Keep staring at the black dot. After a while the gray haze around it will appear to shrink.

2.2 Light and the Electromagnetic Spectrum

Electromagnetic Spectrum(電磁頻譜)

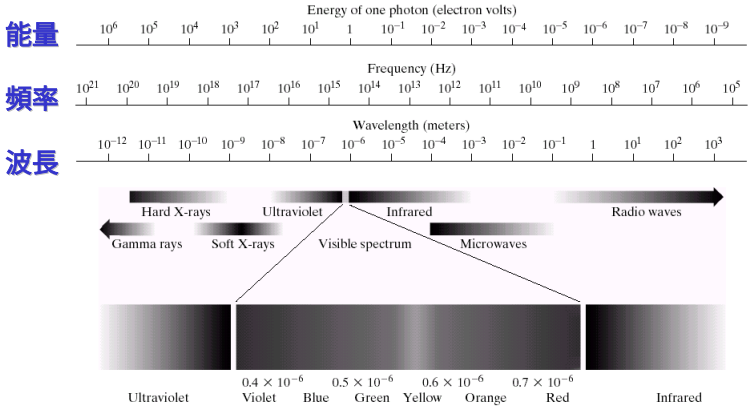
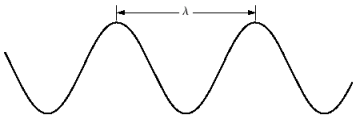


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

2.2 Light and the Electromagnetic Spectrum

- Wavelength λ



- 波長與頻率關係式
  - $\lambda = \frac{c}{\nu}$ (2.2-1)

    $c = 2.998 \times 10^8$ m/s
- 能量與頻率關係式
  - $E = h\nu$ (2.2-2)

    $h = 6.626068 \times 10^{-34}\ Js$ $1eV = 1.6 \times 10^{-19}\ J$

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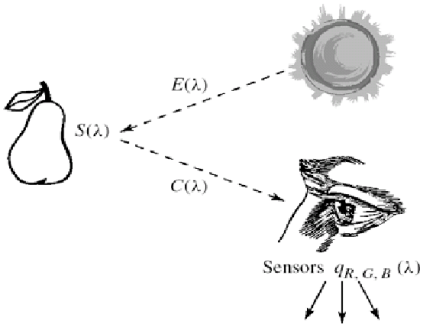
2.2 Light and the Electromagnetic Spectrum

- Visible Band
  - ■430um~790nm
  - ■Illuminant (光源)
  - ■reflected light from objects (物體反射光)
  - ■Achromatic or Monochromatic (Gray Level)
  - ■Chromatic - Color
  - ■Light Source
    - Radiance (光度) - measured in Watts
    - Luminance (明度) - measured in lumens
    - Brightness (亮度) - subjective descriptor

2.3 Image Sensing and Acquisition

Image Sensing

- Scene (場景)
  - Molecules
  - Human Brain
  - ...
- Illumination(照明)
  - Radar
  - Infrared
  - X-ray
  - Sun
  - ...
- Reflection(反射)



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2.3 Image Sensing and Acquisition

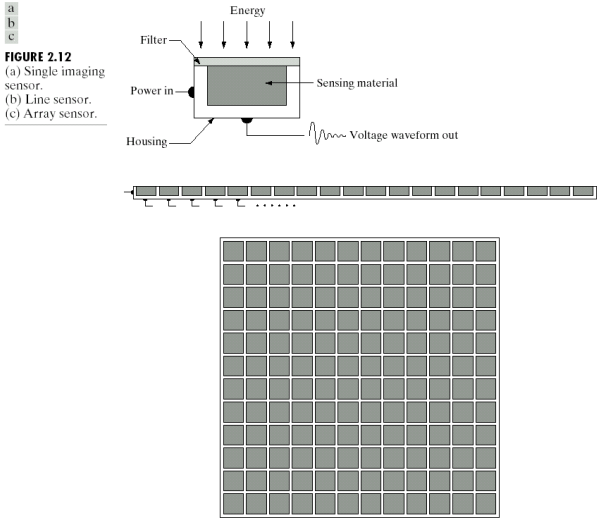

FIGURE 2.12
(a) Single imaging sensor.
(b) Line sensor.
(c) Array sensor.

2.3 Image Sensing and Acquisition

2.3.1 Image acquisition using a single sensor

- Photodiode(光二極體)

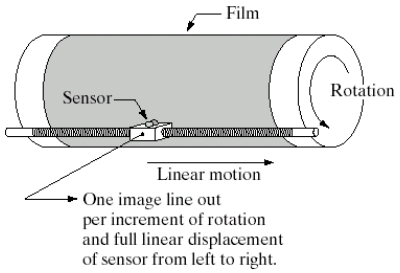

FIGURE 2.13 Combining a single sensor with motion to generate a 2-D image.

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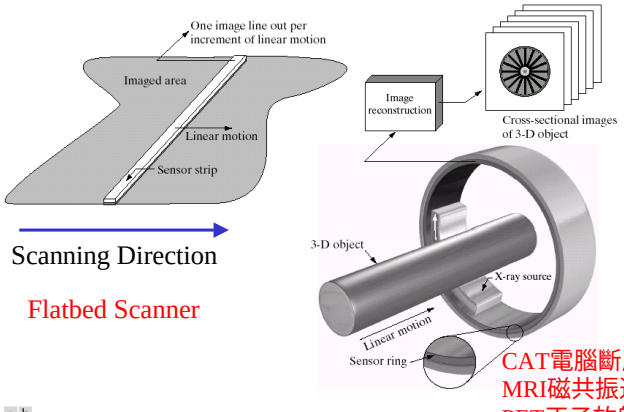
2.3 Image Sensing and Acquisition

2.3.2 Image acquisition using sensor strips



CAT電腦斷層掃描
MRI磁共振造影
PET正子放射斷層掃描

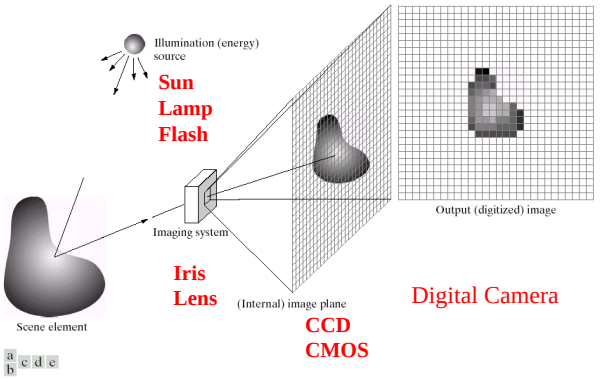
a b

FIGURE 2.14 (a) Image acquisition using a linear sensor strip. (b) Image acquisition using a circular sensor strip.

2.3 Image Sensing and Acquisition

2.3.3 Image acquisition using sensor arrays

- Charged Couple Diode (CCD)



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.

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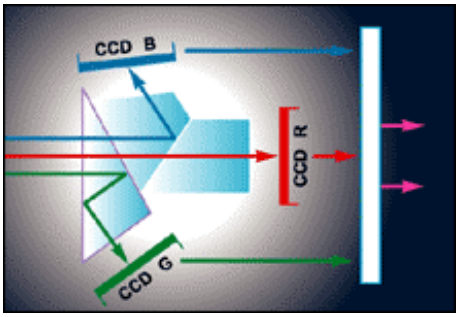
2.3 Image Sensing and Acquisition



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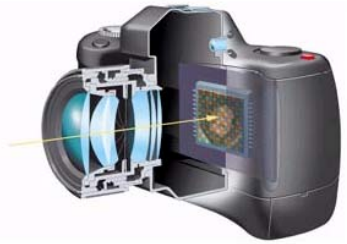
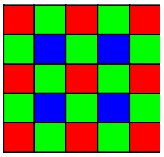
2.3 Image Sensing and Acquisition

Color Filter Array (CFA)





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2.3 Image Sensing and Acquisition

2.3.4 A simple image formation model

- Image
  - 2D Intensity function

$$0 < f(x,y) < \infty \qquad (2.3\text{-}1)$$

$$f(x,y) = i(x,y) \cdot r(x,y) \qquad (2.3\text{-}2)$$

  - Illumination

$$0 < i(x,y) < \infty \qquad (2.3\text{-}3)$$

  - Reflectance

$$0 < r(x,y) < 1 \qquad (2.3\text{-}4)$$

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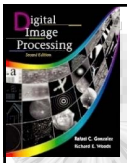

2.3 Image Sensing and Acquisition

- Typical values of $i(x,y)$
  - ■晴天的太陽 $i = 90000$ lm/m^2
  - ■陰天的太陽 $i = 10000$ lm/m^2
  - ■晴天的滿月 $i = 0.1$ lm/m^2
  - ■辦公室照明 $i = 1000$ lm/m^2
- Typical values of $r(x,y)$
  - ■黑天鵝絨 $r = 0.01$
  - ■不銹鋼 $r = 0.65$
  - ■上漆白牆 $r = 0.8$
  - ■銀盤 $r = 0.9$
  - ■雪 $r = 0.93$

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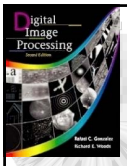

2.3 Image Sensing and Acquisition

- Intensity at (x_0, y_0)

$$l = f(x_0, y_0) \qquad (2.3\text{-}5)$$

$$L_{\min} \le l \le L_{\max} \qquad (2.3\text{-}6)$$

$$L_{\min} = i_{\min} r_{\min}$$

$$L_{\max} = i_{\max} r_{\max}$$

- $[L_{min}, L_{max}]$ is called gray scale
- Shift this interval to $[0, L - 1]$
  - ■ $l = 0$ is black
  - ■ $l = L - 1$ is white
  - ■All intermediate values are shades of gray

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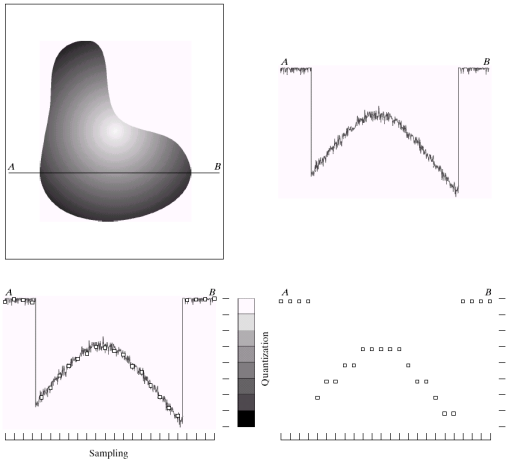
2.4 Image sampling and quantization

2.4.1 Basic concepts in sampling and quantization



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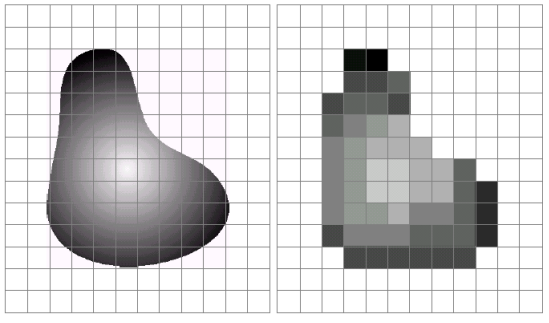
2.4 Image sampling and quantization

Sampling (取様)　Quantization (量化)

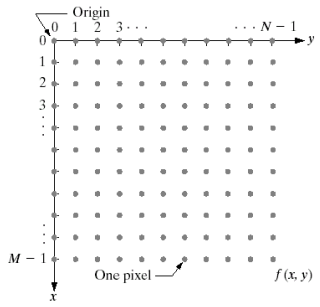


a b

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

2.4 Image sampling and quantization

2.4.2 Representing digital images



Compact Matrix Form(2.4-1)

$$f(x,y)=\begin{bmatrix} f(0,0) & f(0,1) & \cdots & f(0,N-1) \\ f(1,0) & f(1,1) & \cdots & f(1,N-1) \\ \vdots & & & \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1) \end{bmatrix}$$

Traditional Matrix Form(2.4-2)

$$\mathbf{A}=\begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & & & \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}$$

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2.4 Image sampling and quantization

Storage space for digital images

- For Gray-Level $L=2^k$, k bits required for a pixel
- For an $M \times N$ image, $b= M \times N \times k$ bits required for an image
- For an $N \times N$ image, $b= N^2 k$ bits required for an image

TABLE 2.1
Number of storage bits for various values of N and k.

N/k	1 (L = 2)	2 (L = 4)	3 (L = 8)	4 (L = 16)	5 (L = 32)	6 (L = 64)	7 (L = 128)	8 (L = 256)
32	1,024	2,048	3,072	4,096	5,120	6,144	7,168	8,192
64	4,096	8,192	12,288	16,384	20,480	24,576	28,672	32,768
128	16,384	32,768	49,152	65,536	81,920	98,304	114,688	131,072
256	65,536	131,072	196,608	262,144	327,680	393,216	458,752	524,288
512	262,144	524,288	786,432	1,048,576	1,310,720	1,572,864	1,835,008	2,097,152
1024	1,048,576	2,097,152	3,145,728	4,194,304	5,242,880	6,291,456	7,340,032	8,388,608
2048	4,194,304	8,388,608	12,582,912	16,777,216	20,971,520	25,165,824	29,369,128	33,554,432
4096	16,777,216	33,554,432	50,331,648	67,108,864	83,886,080	100,663,296	117,440,512	134,217,728
8192	67,108,864	134,217,728	201,326,592	268,435,456	335,544,320	402,653,184	469,762,048	536,870,912

2.4 Image sampling and quantization

2.4.3 Spatial and Gray-Level Resolution

Spatial Resolution

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.

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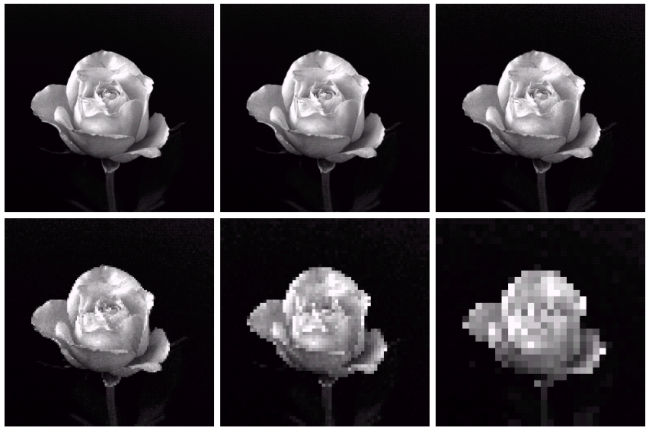
2.4 Image sampling and quantization

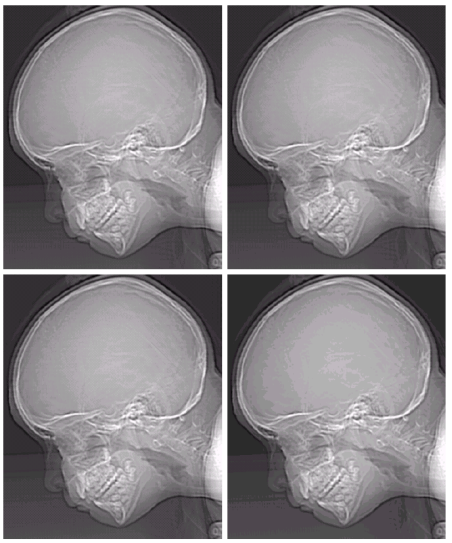


a b c
d e f

FIGURE 2.20 (a) 1024 × 1024, 8-bit image. (b) 512 × 512 image resampled into 1024 × 1024 pixels by row and column duplication. (c) through (f) 256 × 256, 128 × 128, 64 × 64, and 32 × 32 images resampled into 1024 × 1024 pixels.

2.4 Image sampling and quantization

Gray-Level 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.

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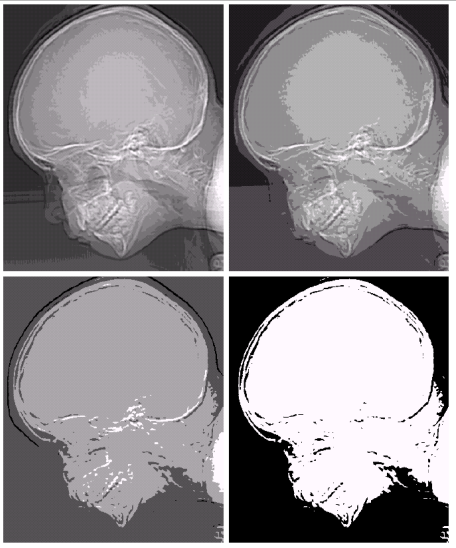
2.4 Image sampling and quantization

Gray-Level Resolution



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.)

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2.4 Image sampling and quantization

Spatial and Gray-Level Resolution

a b c

FIGURE 2.22 (a) Image with a low level of detail. (b) Image with a medium level of detail. (c) Image with a relatively large amount of detail. (Image (b) courtesy of the Massachusetts Institute of Technology.)

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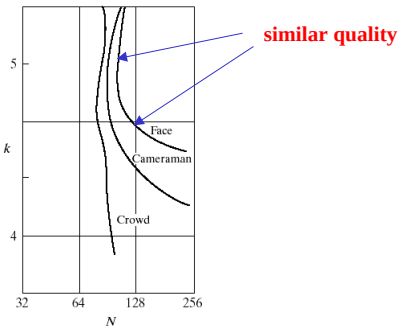
2.4 Image sampling and quantization

Spatial and Gray-Level Resolution

FIGURE 2.23 Representative isopreference curves for the three types of images in Fig. 2.22.



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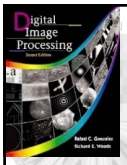

2.4 Image sampling and quantization

2.4.4 Aliasing and Moire Pattern

- **Band-Limited functions**
  - The highest frequency of a function is finite and the function is of unlimited duration
- **Shannon sampling theorem**
  - If a band-limited function is sampled at a rate equal to or greater than twice its highest frequency, it is possible to recover completely the original function from its samples

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2.4 Image sampling and quantization

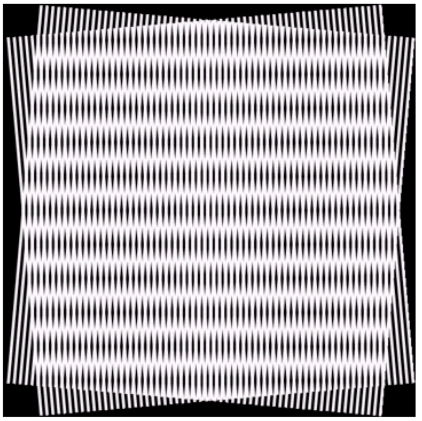

FIGURE 2.24 Illustration of the Moiré pattern effect.

2.4 Image sampling and quantization

- An example



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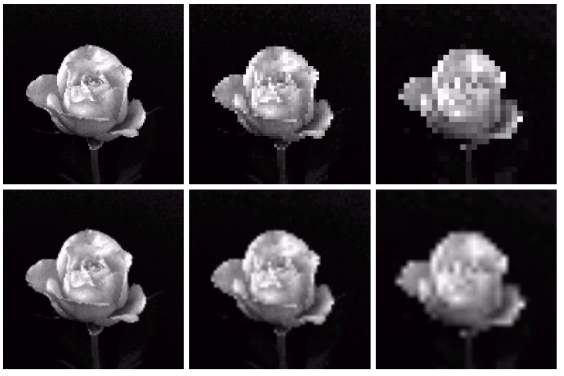
2.4 Image sampling and quantization

2.4.5 Zooming and shrinking digital images

Nearest Neighbor Interpolation

Bilinear Interpolation

$v(x',y') = ax'+by'+cx'y'+d$



a b c
d e f

FIGURE 2.25 Top row: images zoomed from 128 × 128, 64 × 64, and 32 × 32 pixels to 1024 × 1024 pixels, using nearest neighbor gray-level interpolation. Bottom row: same sequence, but using bilinear interpolation.

2.5 Some Basic Relationships Between Pixels

2.5.1 Neighbors of a pixel

A pixel p at coordinates (x, y) has four *horizontal* and *vertical* neighbors whose coordinates are given by

$$(x + 1, y), (x - 1, y), (x, y + 1), (x, y - 1)$$

This set of pixels, called the 4-*neighbors* of p, is denoted by $N_4(p)$. Each pixel is a unit distance from (x, y), and some of the neighbors of p lie outside the digital image if (x, y) is on the border of the image.

The four *diagonal* neighbors of p have coordinates

$$(x + 1, y + 1), (x + 1, y - 1), (x - 1, y + 1), (x - 1, y - 1)$$

and are denoted by $N_D(p)$. These points, together with the 4-neighbors, are called the 8-*neighbors* of p, denoted by $N_8(p)$. As before, some of the points in $N_D(p)$ and $N_8(p)$ fall outside the image if (x, y) is on the border of the image.

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2.5 Some Basic Relationships Between Pixels

2.5.2 Adjacency, Connectivity, Regions, and Boundries

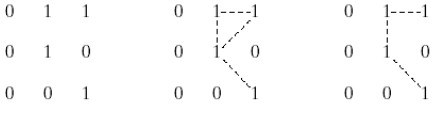
(a) 4-*adjacency*. Two pixels p and q with values from V are 4-adjacent if q is in the set $N_4(p)$.

(b) 8-*adjacency*. Two pixels p and q with values from V are 8-adjacent if q is in the set $N_8(p)$.

(c) *m-adjacency* (mixed adjacency). Two pixels p and q with values from V are m-adjacent if

(i) q is in $N_4(p)$, *or*

(ii) q is in $N_D(p)$ *and* the set $N_4(p) \cap N_4(q)$ has no pixels whose values are from V.



a b c

FIGURE 2.26 (a) Arrangement of pixels; (b) pixels that are 8-adjacent (shown dashed) to the center pixel; (c) m-adjacency.

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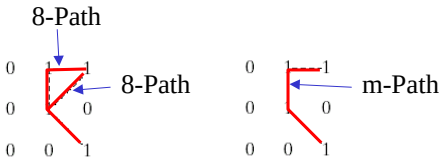
2.5 Some Basic Relationships Between Pixels

- Path
  - **4**-Path
  - **8**-Path
  - **m**-Path



- Length

$(x_0, y_0), (x_1, y_1), \ldots, (x_n, y_n)$

  - Length=***n***,
  - if $(1 \le i \le n)$ and pixels (x_{i-1}, y_{i-1}) and (x_i, y_i) are adjacent
  - if $(x_0, y_0) = (x_n, y_n)$, the path is a ***closed*** path

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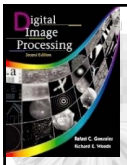
2.5 Some Basic Relationships Between Pixels

- Connected
  - Let ***S*** represent a subset of pixels in an image
  - Pixels ***p*** and ***q*** in ***S***
  - If there exists a path between two pixels ***p*** and ***q***
- Connected components
  - For any pixel ***p*** in ***S***, the set of pixels that are connected to ***p*** in ***S*** is called a ***connected component***
- connected sets
  - If there is only one connected component in ***S***, ***S*** is called a ***connected set***



2.5 Some Basic Relationships Between Pixels

- Regions
  - Let ***R*** be a subset of pixels in an image.We call ***R*** a ***region*** of the image if ***R*** is ***a connected set***.
- Boundaries
  - The ***boundary*** (also called ***border*** or ***contour***) of a region ***R*** is the set of pixels in the region that have ***one or more neighbors*** that are not in ***R***.

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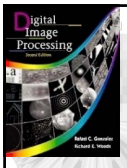

2.5 Some Basic Relationships Between Pixels

2.5.3 Distance Measures

For pixels p, q, and z, with coordinates (x, y), (s, t), and (v, w), respectively, D is a *distance function* or *metric* if

(a) $D(p, q) \geq 0 \quad (D(p, q) = 0 \quad \text{iff} \quad p = q)$,
(b) $D(p, q) = D(q, p)$, and
(c) $D(p, z) \leq D(p, q) + D(q, z)$.

The *Euclidean distance* between p and q is defined as

$$D_e(p, q) = [(x - s)^2 + (y - t)^2]^{\frac{1}{2}}. \qquad (2.5\text{-}1)$$

For this distance measure, the pixels having a distance less than or equal to some value r from (x, y) are the points contained in a disk of radius r centered at (x, y).

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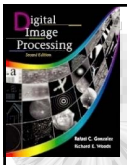

2.5 Some Basic Relationships Between Pixels

D_4 distance

The D_4 *distance* (also called *city-block distance*) between p and q is defined as

$$D_4(p, q) = |x - s| + |y - t|. \quad (2.5\text{-}2)$$

In this case, the pixels having a D_4 distance from (x, y) less than or equal to some value r form a diamond centered at (x, y). For example, the pixels with D_4 distance ≤ 2 from (x, y) (the center point) form the following contours of constant distance:

$$\begin{array}{ccccc} & & 2 & & \\ & 2 & 1 & 2 & \\ 2 & 1 & 0 & 1 & 2 \\ & 2 & 1 & 2 & \\ & & 2 & & \end{array}$$

The pixels with $D_4 = 1$ are the 4-neighbors of (x, y).

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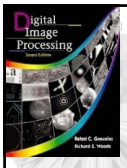


2.5 Some Basic Relationships Between Pixels

D_8 distance

The D_8 *distance* (also called *chessboard distance*) between p and q is defined as

$$D_8(p, q) = \max(|x - s|, |y - t|). \quad (2.5\text{-}3)$$

In this case, the pixels with D_8 distance from (x, y) less than or equal to some value r form a square centered at (x, y). For example, the pixels with D_8 distance ≤ 2 from (x, y) (the center point) form the following contours of constant distance:

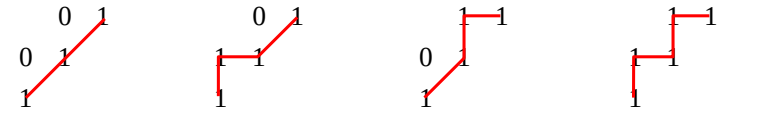
$$\begin{array}{ccccc} 2 & 2 & 2 & 2 & 2 \\ 2 & 1 & 1 & 1 & 2 \\ 2 & 1 & 0 & 1 & 2 \\ 2 & 1 & 1 & 1 & 2 \\ 2 & 2 & 2 & 2 & 2 \end{array}$$

The pixels with $D_8 = 1$ are the 8-neighbors of (x, y).

2.5 Some Basic Relationships Between Pixels

- D_m distance
  - is defined as the shortest m-path between the points
  - depends on the values of pixels

p_3 p_4
p_1 p_2
p



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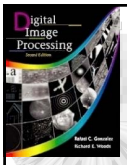
2.5 Some Basic Relationships Between Pixels

2.5.4 Image operations on a pixel basis

- Arithmatic
  - +, -, *, /
- Logic operation
  - not, and, or, xor
- Operation is carried out between corresponding pixels in the two images



2.6 Linear and non-linear operations

- ***Let H be an operator whose input and output are images. H is said to be a linear operator if, for any two images f and g and any two scalars a and b.***

$$H(af + bg) = aH(f) + bH(g) \quad (2.6\text{-}1)$$