Chapter 2: Digital Image Fundamentals

2.1.1
Structure of the Human Eye

- The cross section of human eye.

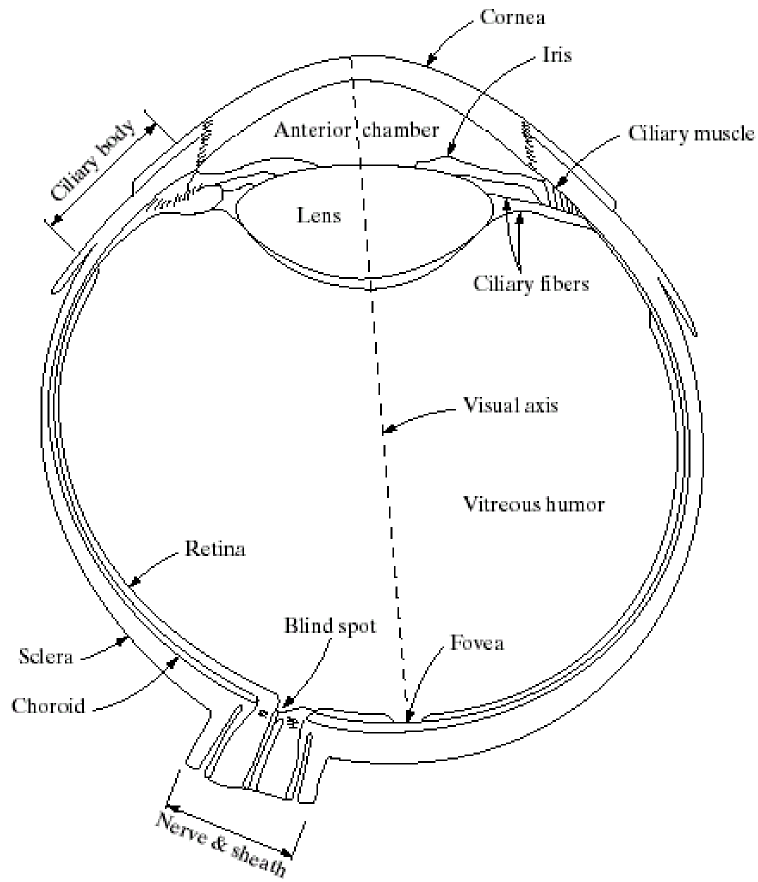


FIGURE 2.1 Simplified diagram of a cross section of the human eye.

2.1.1 Structure of the Human Eye

- Receptors:
  - Cones (圓錐體):
    - 6~7 million
    - Located in the central position of retina, called ***fovea***
    - Highly sensitive to color
    - Cone vision is called ***photopic*** (適光的) or ***bright-light vision***
  - Rods (柱狀體):
    - 75~150 million
    - Distributed on the retina surface
    - Rods serve to give a general, overall picture of the field of view.
    - Rod vision is called ***scotopic*** (適應暗光的) or ***dim-light vision***

2.1.1
Structure of the Human Eye

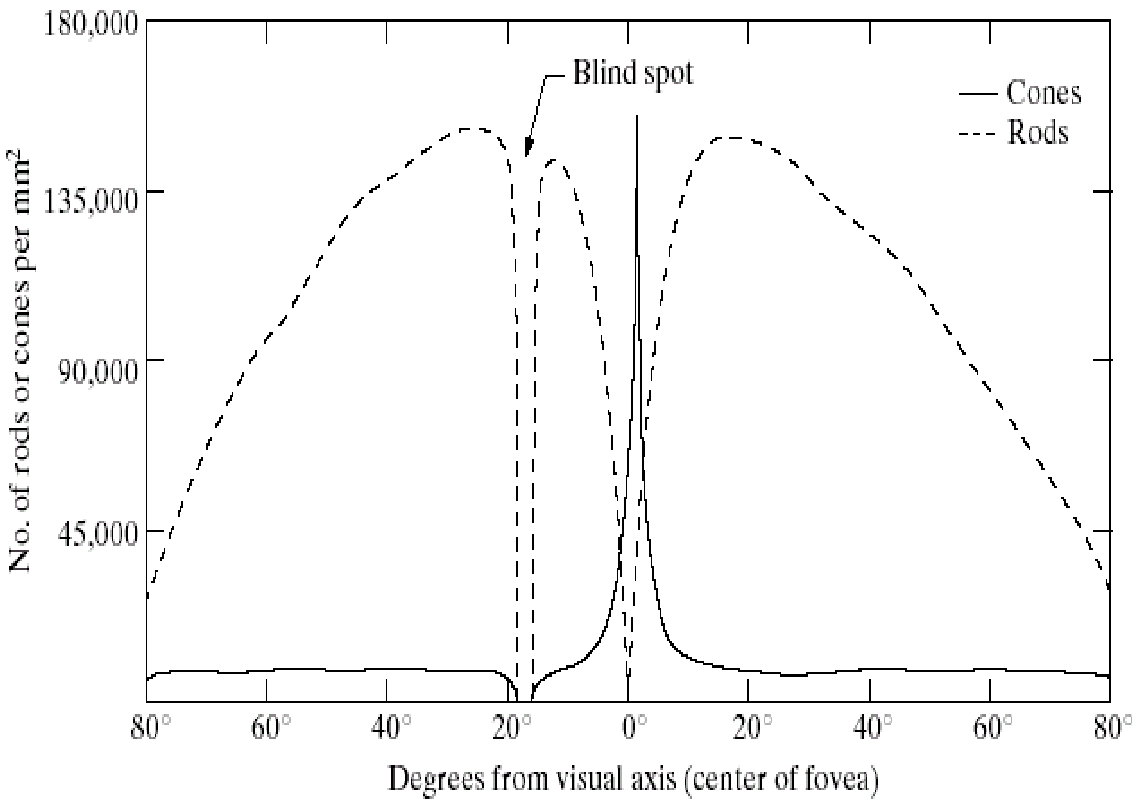
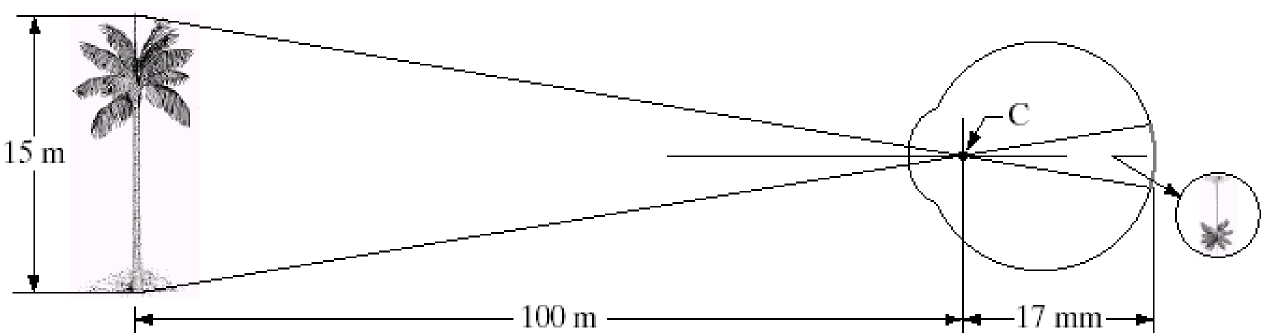


FIGURE 2.2 Distribution of rods and cones in the retina.

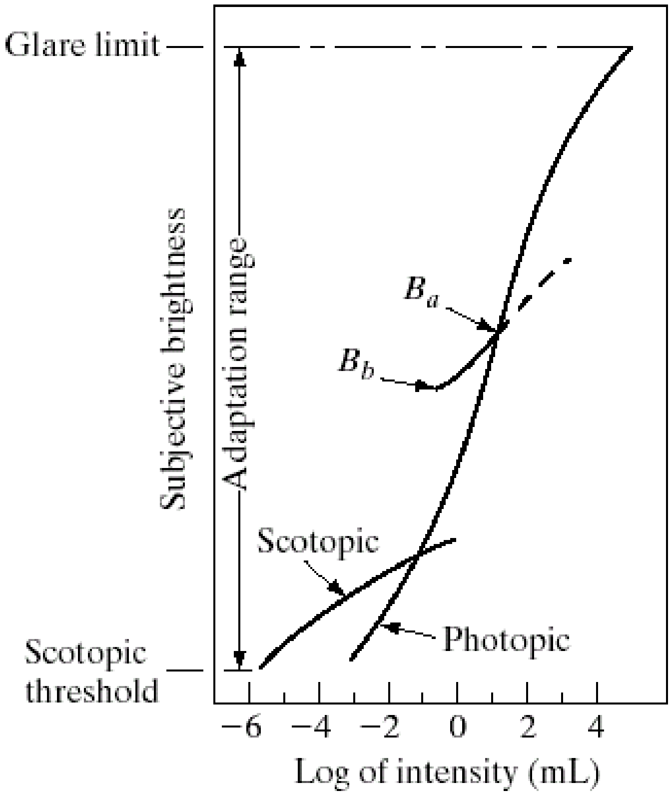
2.1.2 Image Formation in the Eye

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



2.1.3 Brightness Adaptation and Discrimination

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



2.1.3 Brightness Adaptation and Discrimination

- Subjective brightness (intensity as *perceived* by the human visual system) is a logarithmic function of the light intensity incident on the eye.
- For any given set of conditions, the current sensitivity level of the visual system is called ***brightness adaptation level*** (B_a).
- The short intersecting curve represents the range of subjective brightness that eye can perceive when adapted to this level.
- The range is rather restricted, having a level (B_b) at and below which all stimuli are perceived as indistinguishable blacks.

2.1.3 Brightness Adaptation and Discrimination

- The ability of the eye to discriminate between changes in light intensity at any specific adaptation level is also of considerable interest
- Weber ratio: $\dfrac{\Delta I_c}{I}$
- ΔI_c: the increment of illumination discriminable 50% of the time with background illumination I.

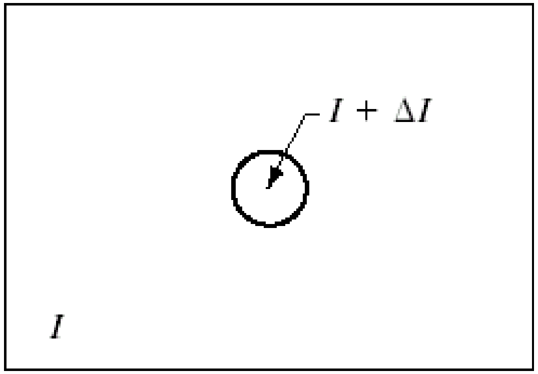
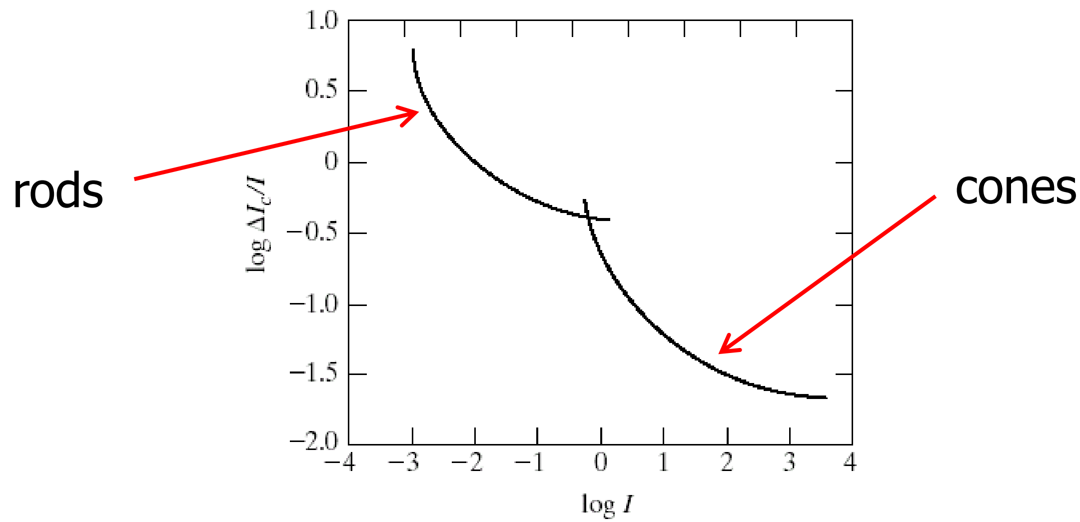


FIGURE 2.5 Basic experimental setup used to characterize brightness discrimination.

2.1.3 Brightness Adaptation and Discrimination

- Small value of Weber ratio: a small percentage change in intensity us discriminable
- ➢ "good" brightness discrimination
- The Weber function ratio as a function of intensity:

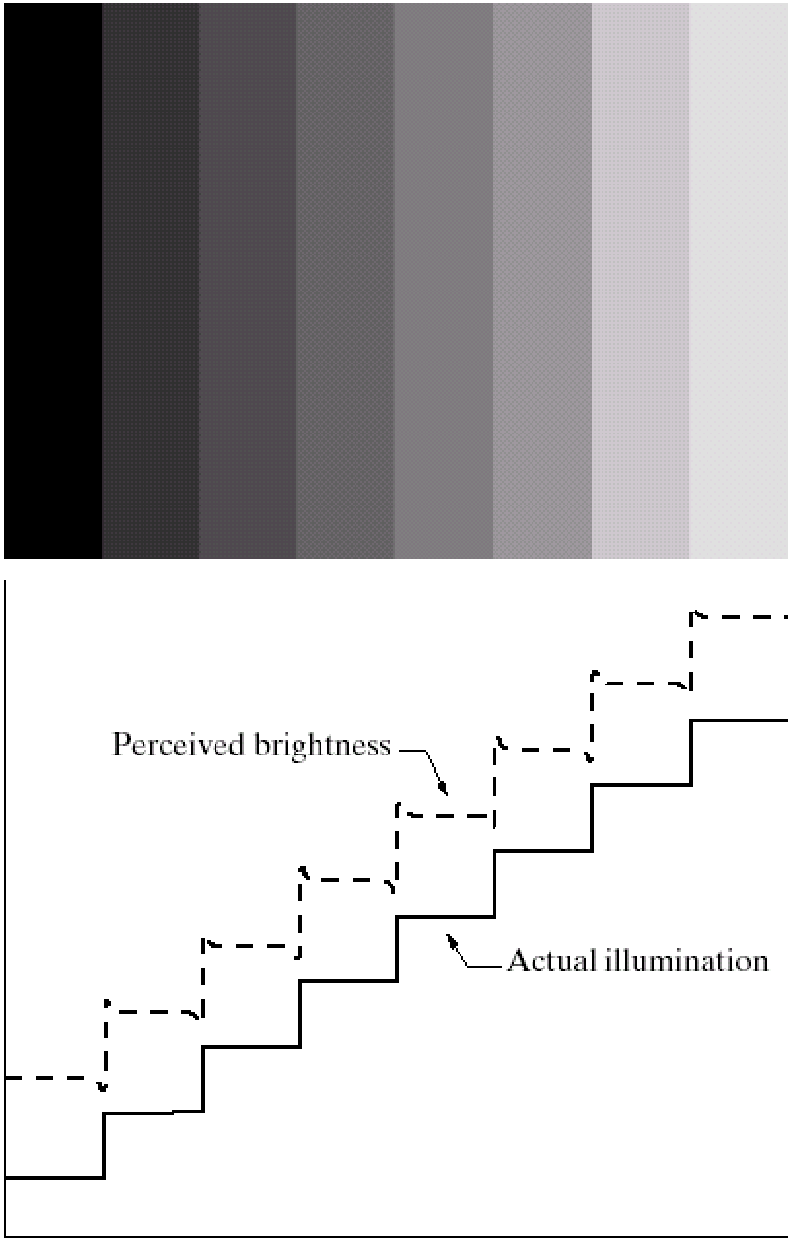
FIGURE 2.6 Typical Weber ratio as a function of intensity.



2.1.3 Brightness Adaptation and Discrimination

- Perceived brightness is not a simple function of intensity:
- Perceptibility is affected by two phenomena:

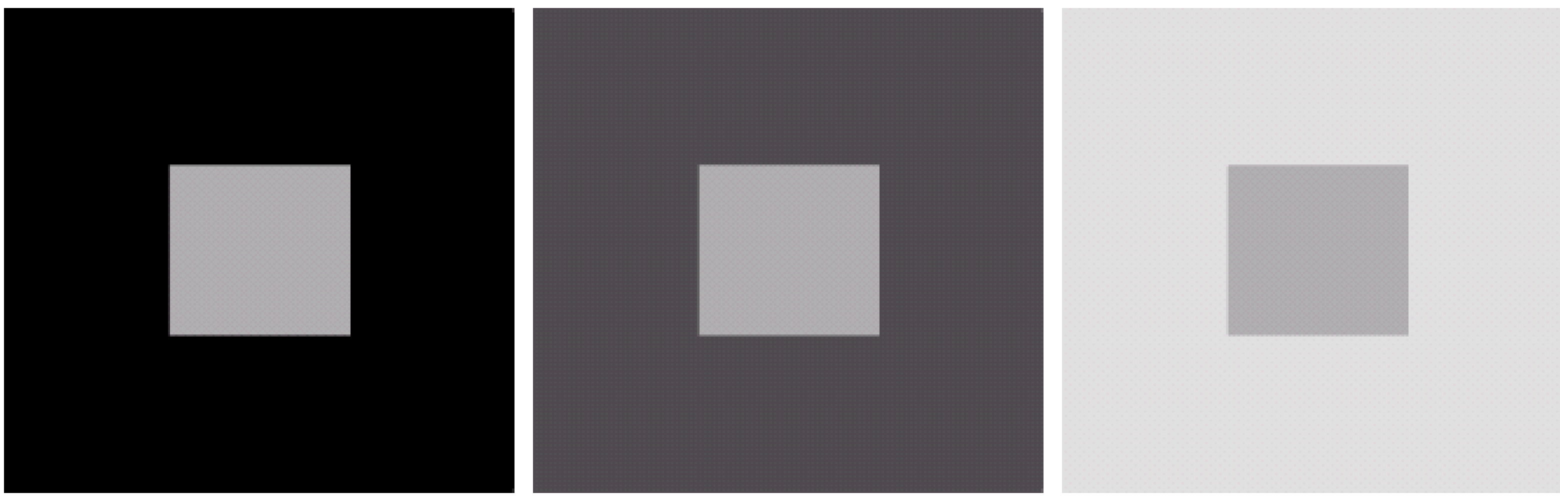
1. **Mach bands** (Fig. 2.7)- the visual system tends to undershoot or overshoot around the boundary of regions of different intensities
2. **Simultaneous contrast** (Fig. 2.8)- a region's perceived brightness does not depend simply on its intensity



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.

2.1.3 Brightness Adaptation and Discrimination

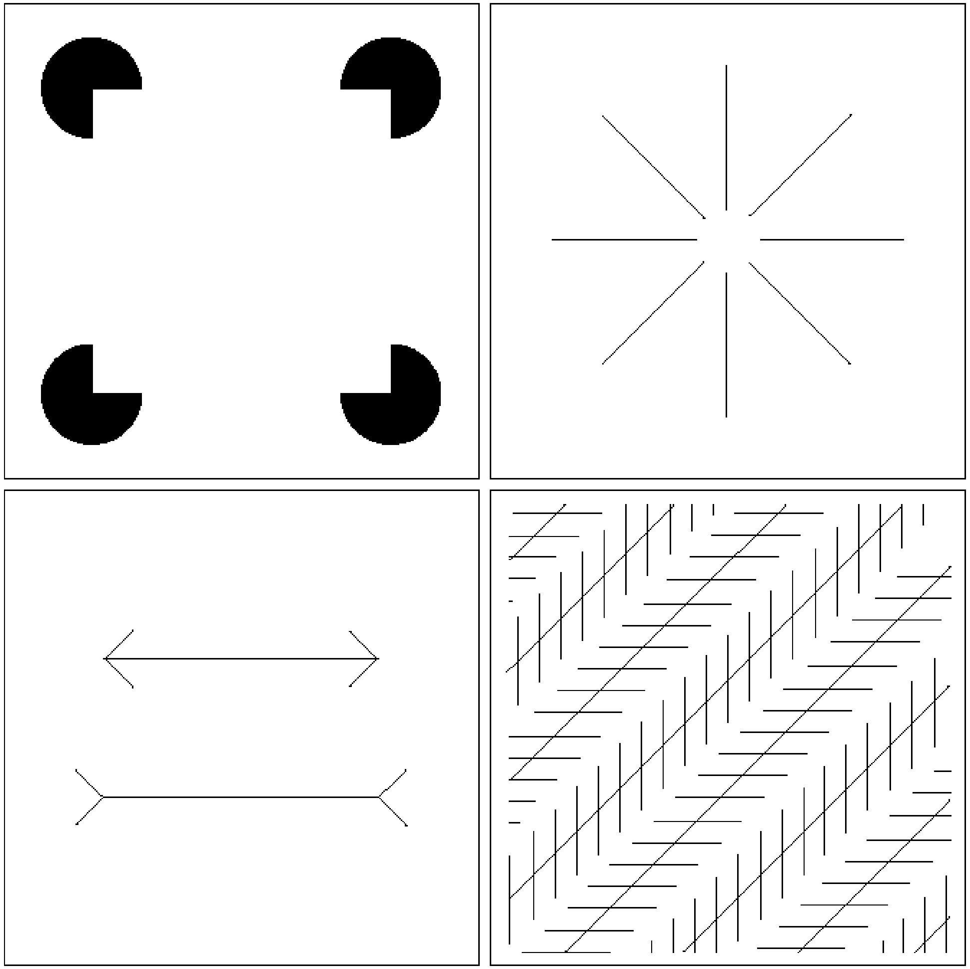


a b c

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.

2.1.3 Brightness Adaptation and Discrimination

- **Optical Illusions-** The eyes fills in non-existing information or wrongly perceiving geometrical properties of objects



2.2 Light and the Electromagnetic Spectrum

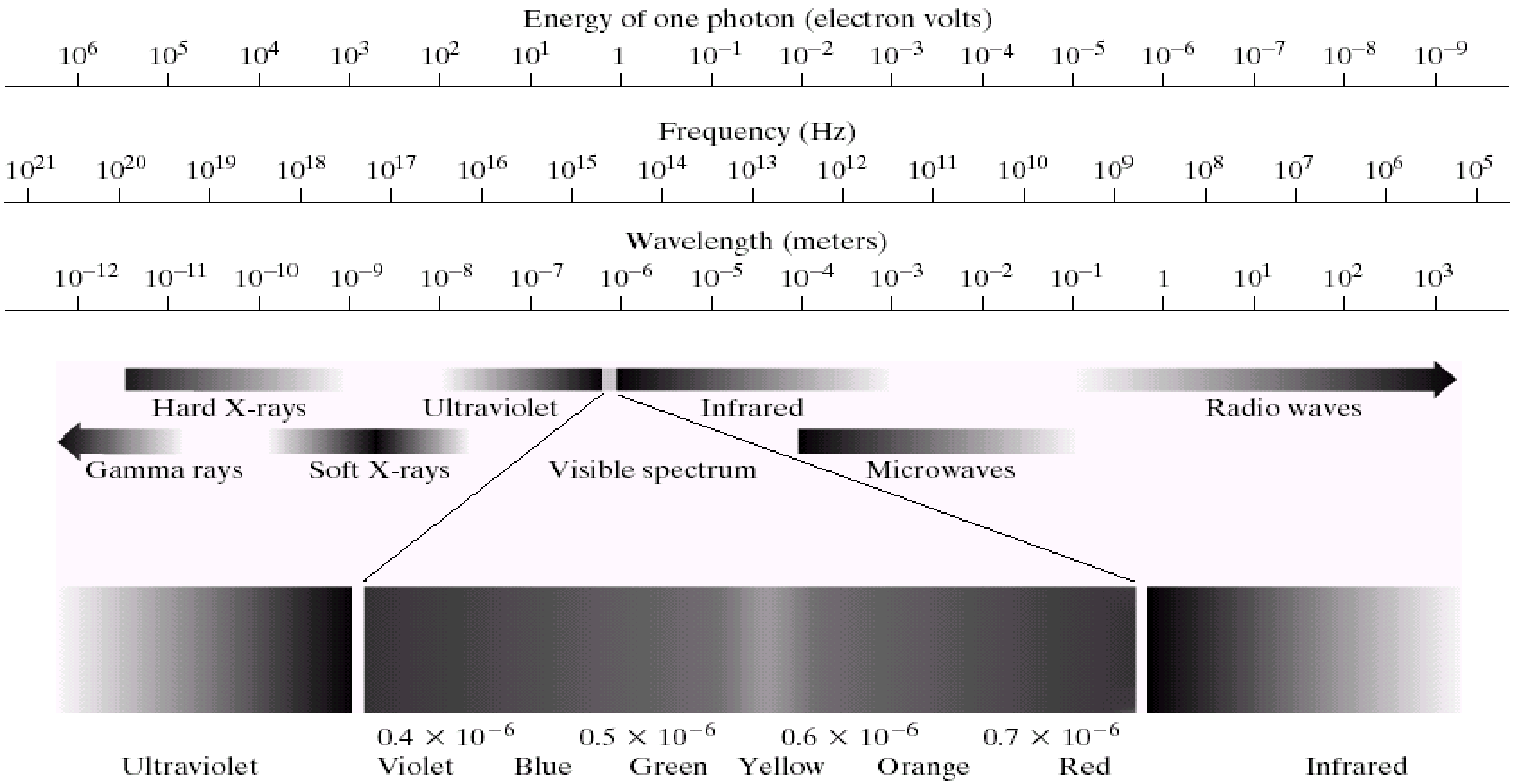
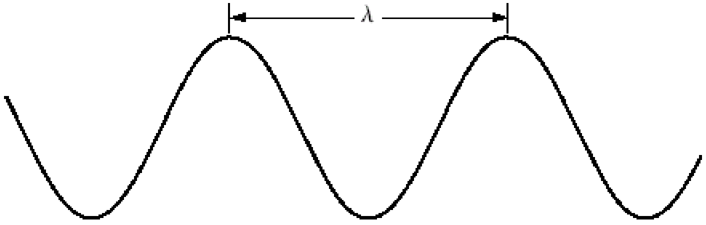


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

2.2 Light and the Electromagnetic Spectrum

- Wavelength:

FIGURE 2.11
Graphical representation of one wavelength.



- $\lambda = \frac{c}{v}$

  c: the speed of light (2.998×108 m/s)
  v: frequency

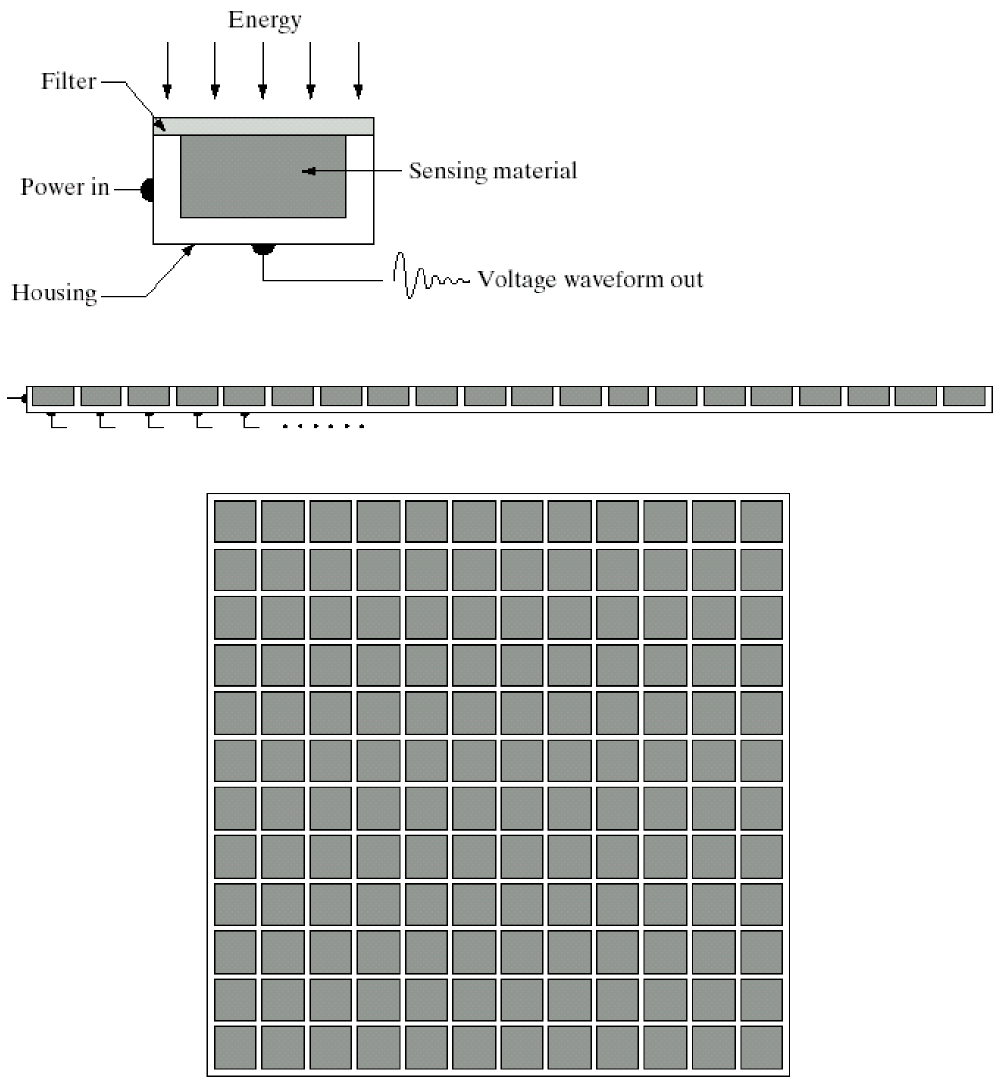
- $E = hv$

  h: Planck's constant

2.3 Image sensing and acquisition

a
b
c

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



2.3 Image sensing and acquisition

- Image acquisition using a single sensor

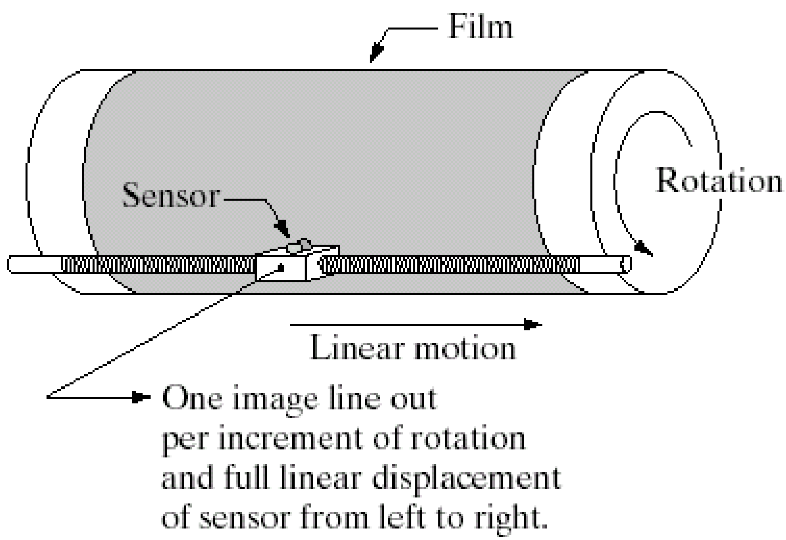


FIGURE 2.13 Combining a single sensor with motion to generate a 2-D image.

2.3 Image sensing and acquisition

- Image acquisition using sensor strips

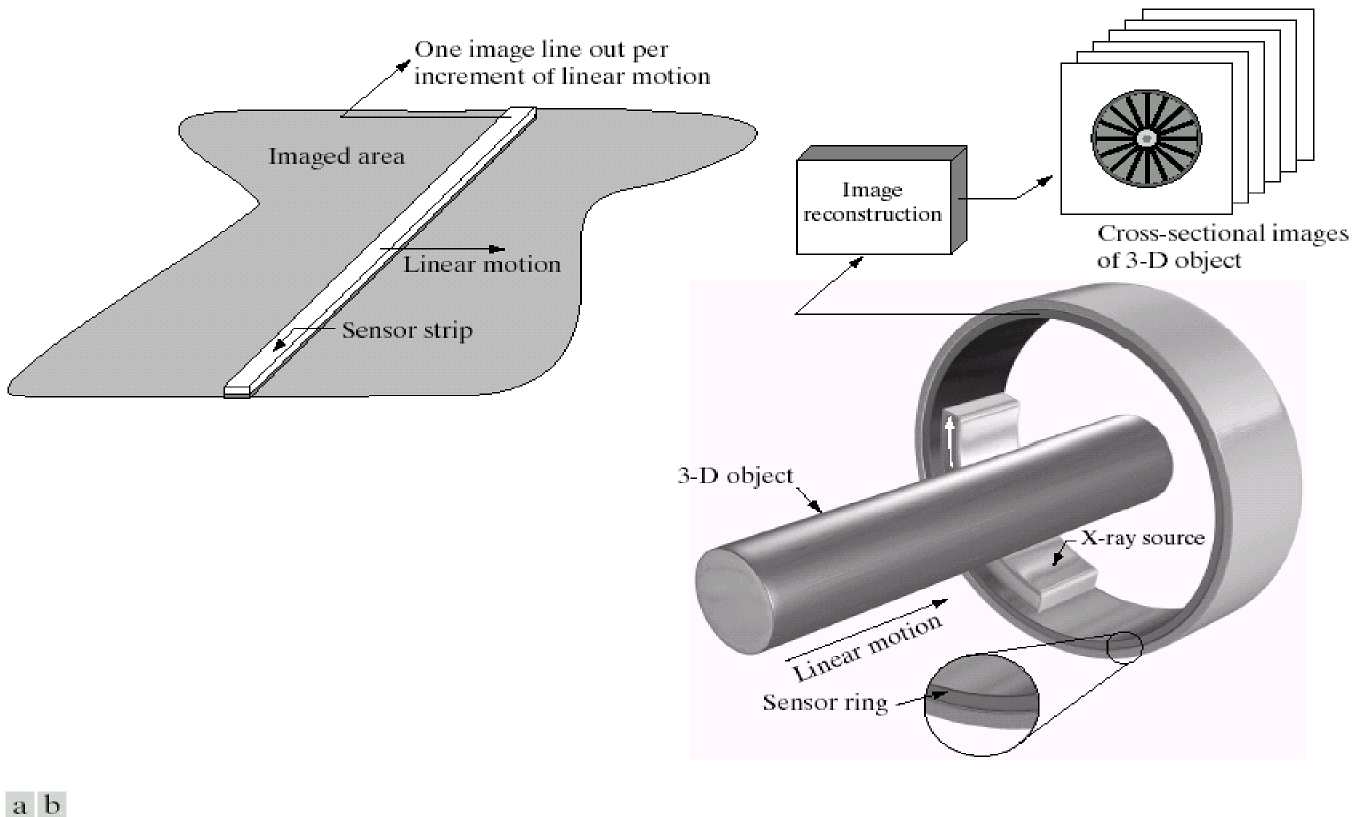


FIGURE 2.14 (a) Image acquisition using a linear sensor strip. (b) Image acquisition using a circular sensor strip.

2.3 Image sensing and acquisition

- Image acquisition using sensor arrays

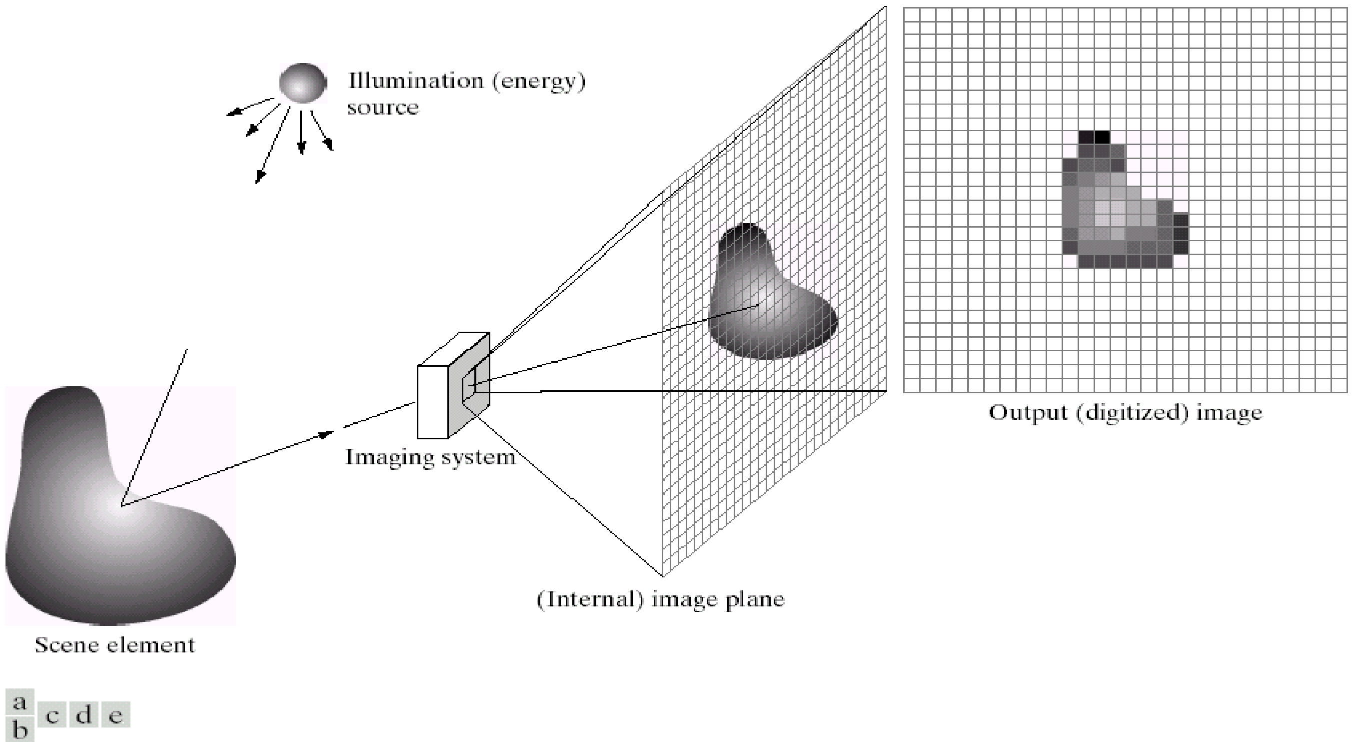


FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

2.3.4 Image Formation Model

- An image can be denoted by two-dimensional functions of the form $f(x, y)$
- $f(x, y) = i(x, y)\, r(x, y)$
  - $i(x, y)$- **illumination** component (the amount of source illumination incident on the scene being perceived), $0 < i(x, y) < \infty$
  - $r(x, y)$- **reflectance** component (the amount of illumination reflected by the objects in the scene) $0 < r(x, y) < 1$ (0: total absorption, 1: total reflectance)

2.3.4 Image Formation Model

- The intensity of a monochrome image at any coordinates (x_0, y_0) is called the gray level (l) of the image at that point

  $$l = f(x_0, y_0)$$

- $L_{min} < l < L_{max}$
- The interval $[L_{min}, L_{max}]$ is called the gray scale
- The gray scale can be shifted to the interval $[0, L-1]$
  $l = 0$: black
  $l = L-1$: white

2.4 Image Sampling & Quantization

- Sampling
- Quantization

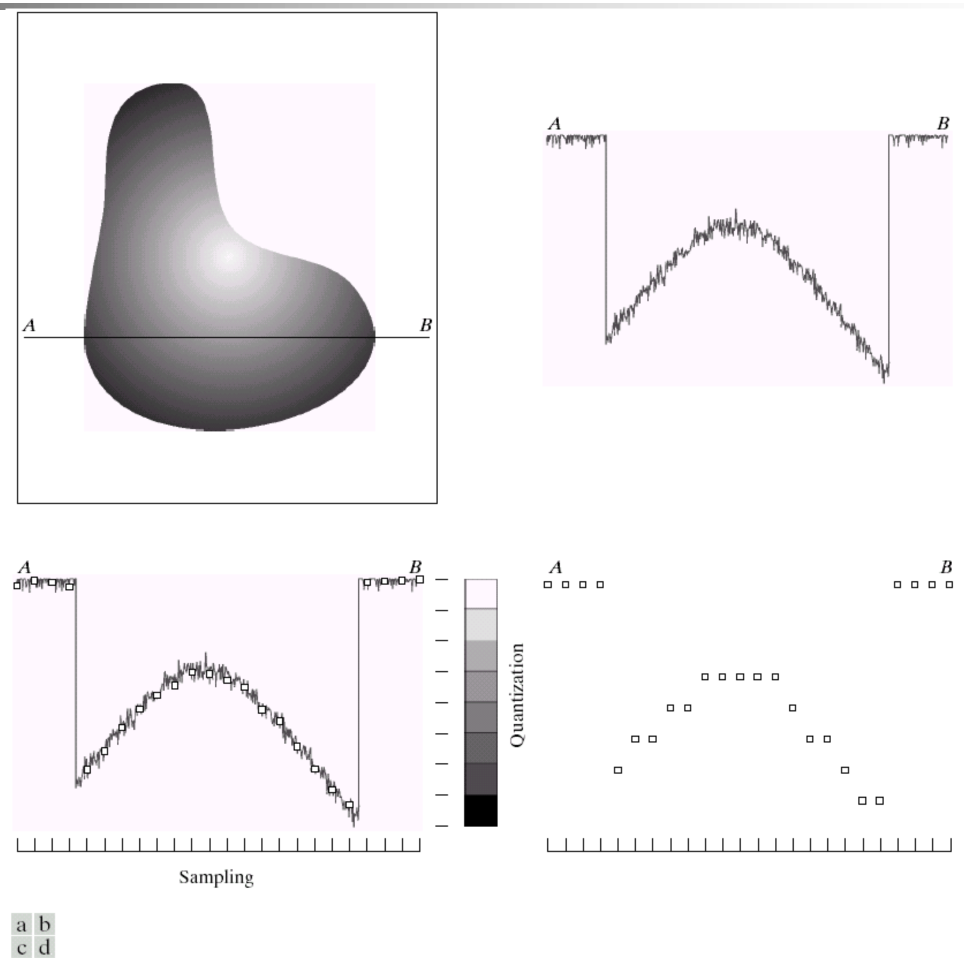


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

2.4 Image Sampling & Quantization

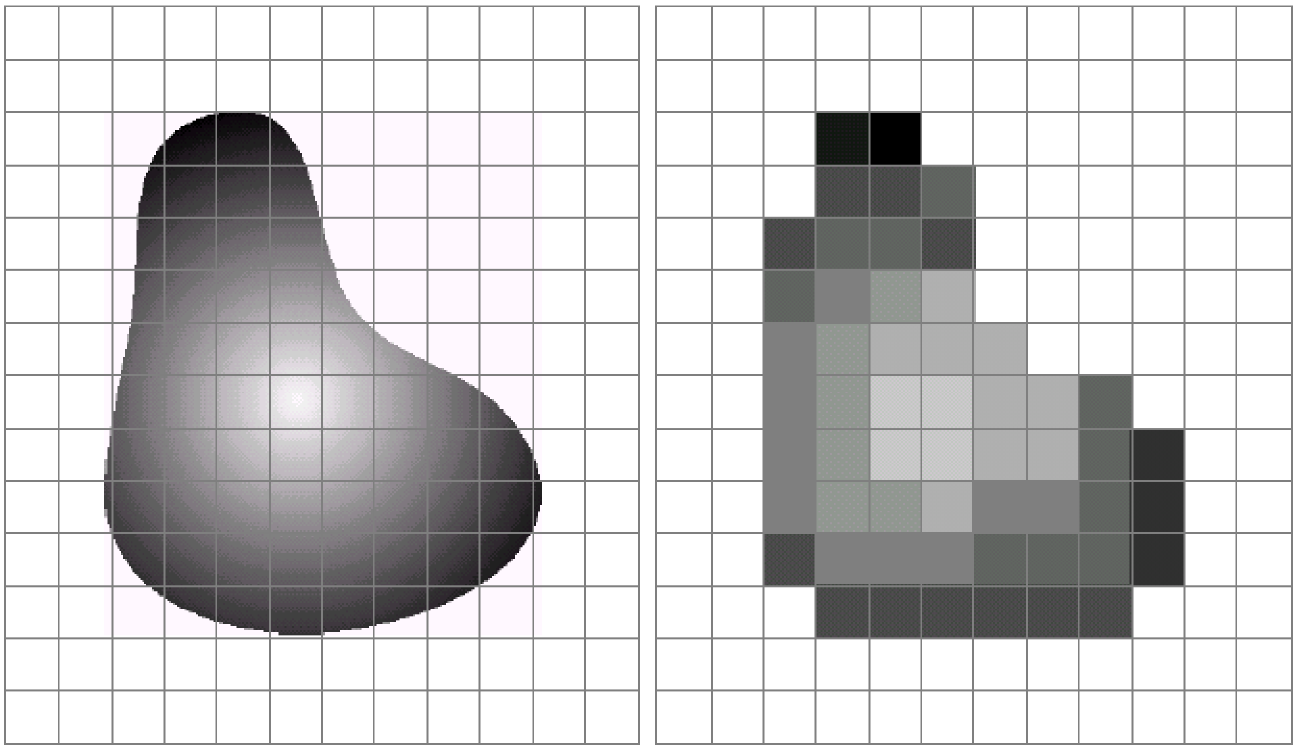


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

2.4.2 Representing Digital Image

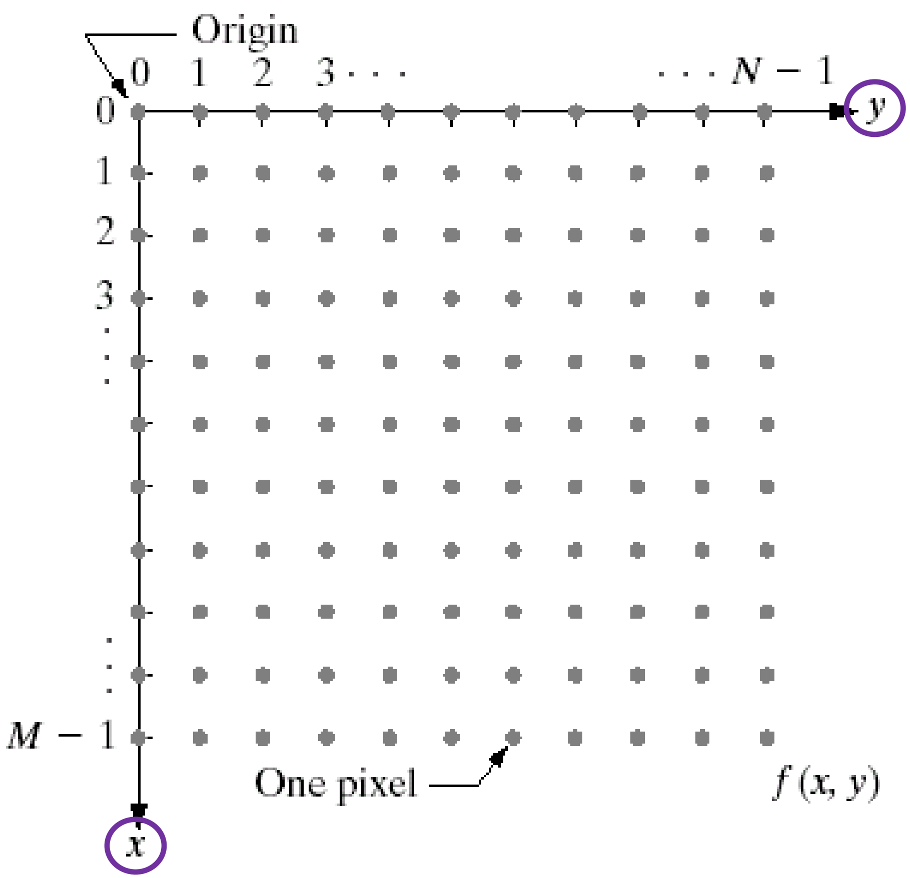


FIGURE 2.18 Coordinate convention used in this book to represent digital images.

2.4.2 Representing Digital Image

- The M×N image can be represented by a matrix:

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

- Each element of the matrix array is called an image element, picture element, pixel, or pel

2.4.2 Representing Digital Image

- The digitization process requires decisions about values for M, N (sampling) and the number L (quantization) of discrete gray levels allowed for each pixel
  - Typically, the number of gray levels is an integer power of 2:

$$L = 2^k$$

  - The range of values spanned by the gray scale is called the **dynamic range** of an image
    - High dynamic range image- images whose gray levels span a significant portion of the gray scale → high contrast
    - Low dynamic range image → dull, washed out gray look

2.4.2 Representing Digital Image

2.4.2 Representing Digital Image

(a) Exposure: T

(b) Exposure: 4T

(c) Exposure: 16T

(d) Exposure: 64T

2.4.2 Representing Digital Image

- The number of bits, b, required to store a digitized image:

  $b = M \times N \times k = N^2 k$ (if $M = N$)

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

2.4.3 Spatial and Gray-Level Resolution

- Spatial resolution

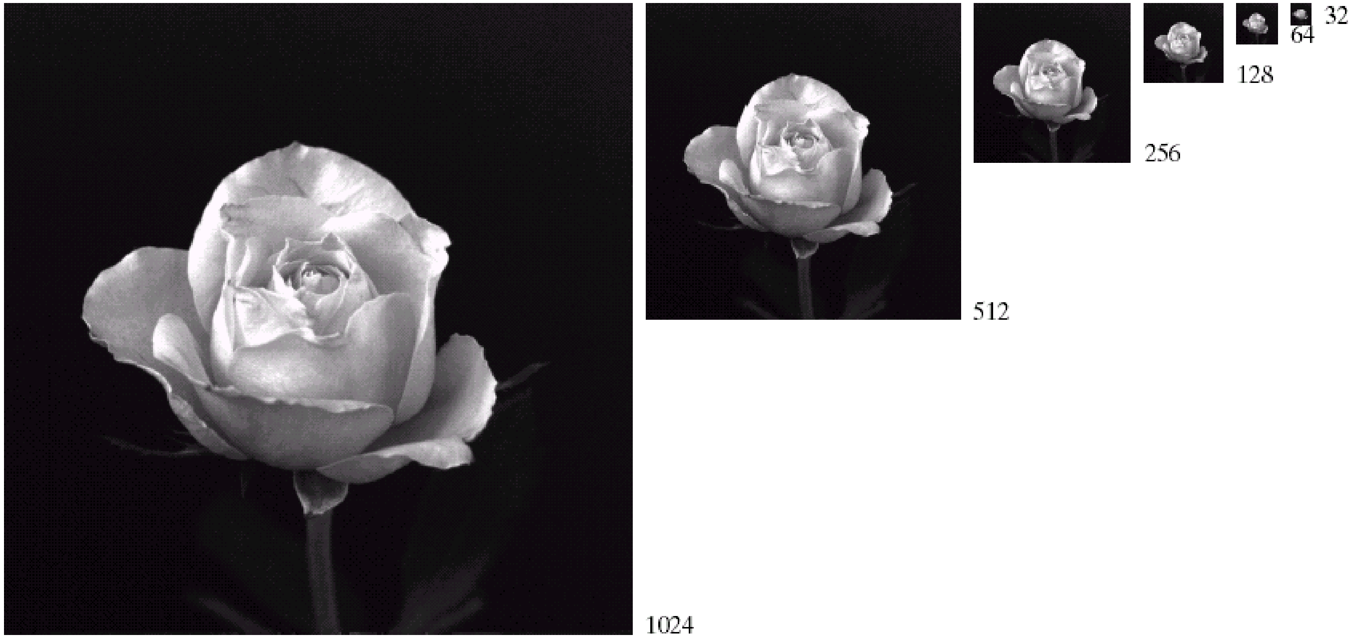
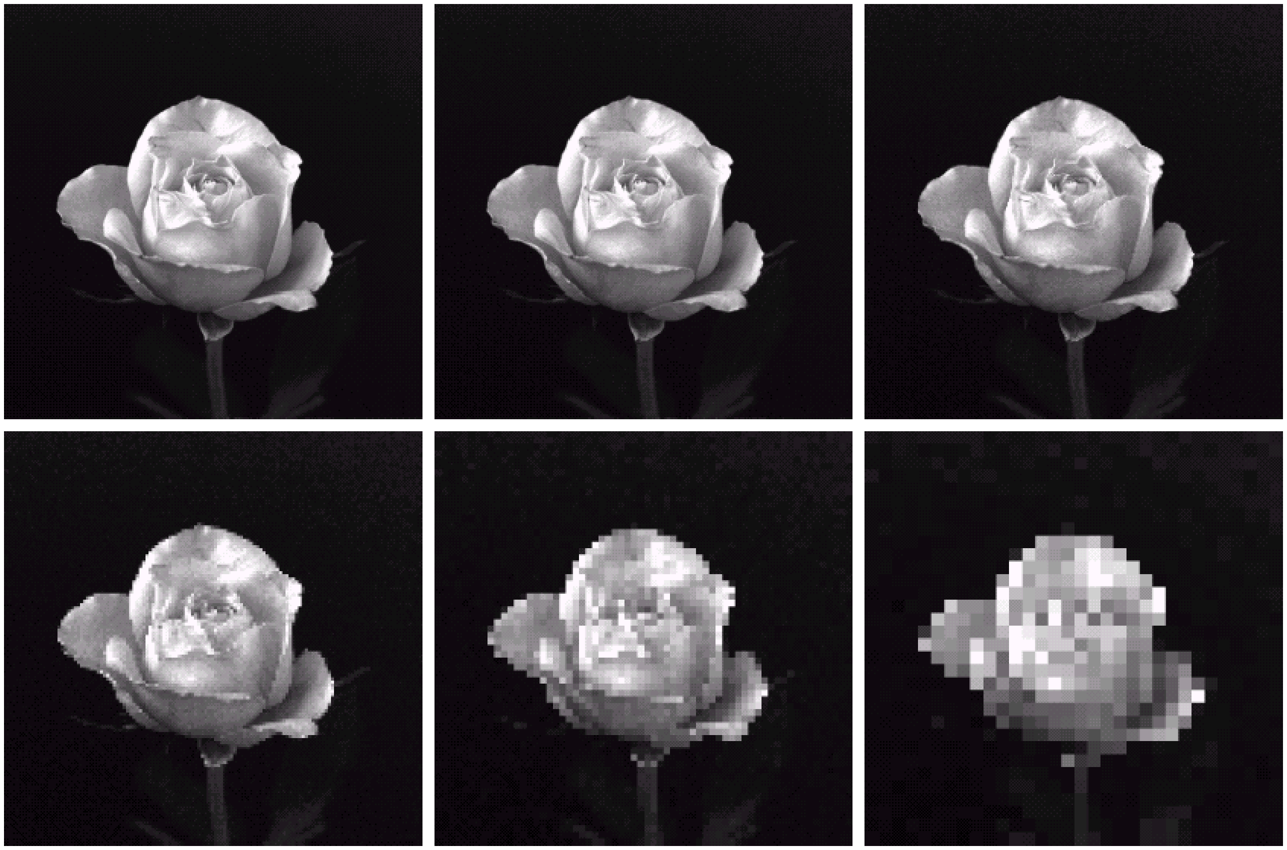


FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

2.4.3 Spatial and Gray-Level Resolution

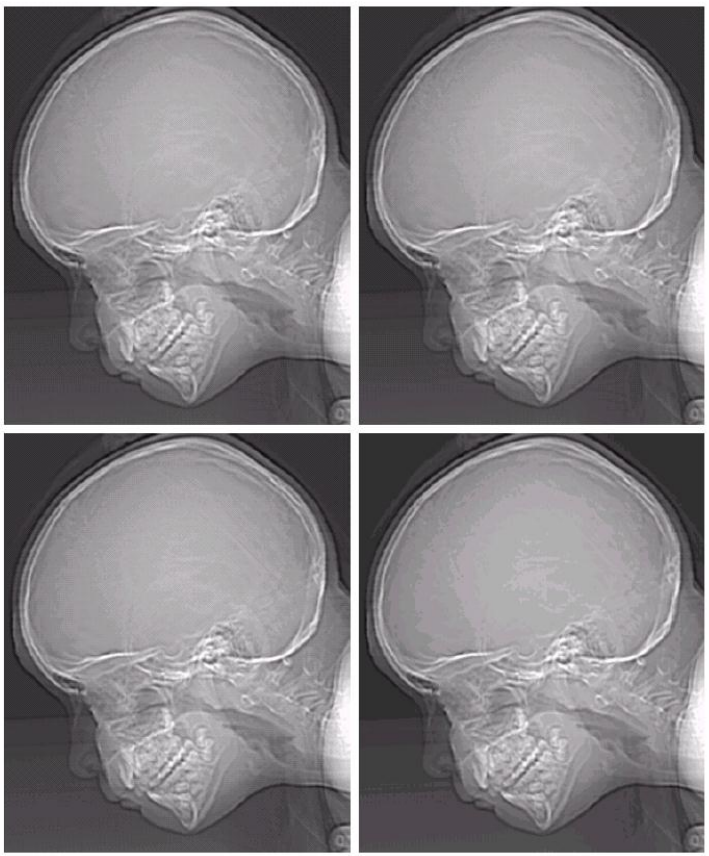


a b c
d e f

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.

2.4.3 Spatial and Gray-Level Resolution

- Gray-level resolution

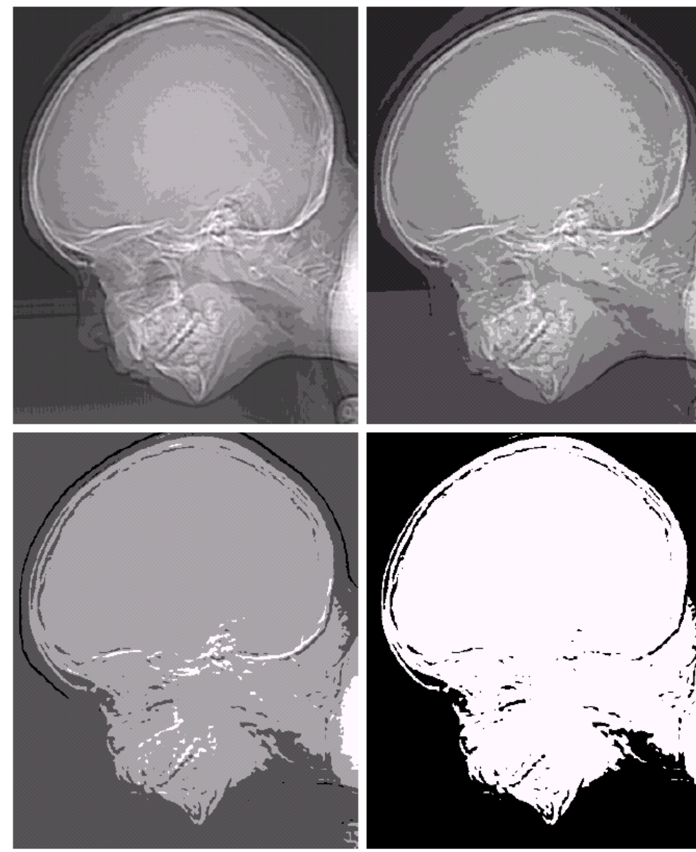


a b
c d

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.

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.)



2.4.3 Spatial and Gray-Level Resolution

- **Isopreference curves** in the *NK*-plane – points lying on this curve correspond to images of equal subjective quality

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.)

2.4.3 Spatial and Gray-Level Resolution

- Isopreference curves

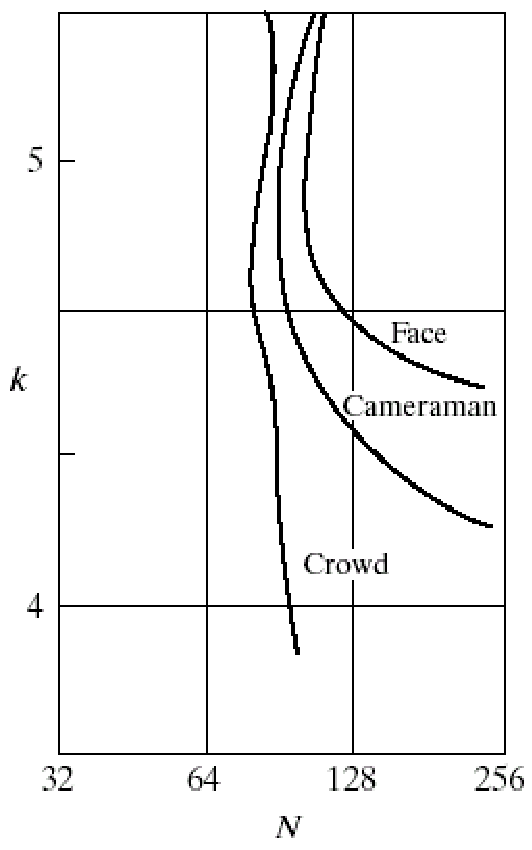


FIGURE 2.23 Representative isopreference curves for the three types of images in Fig. 2.22.

2.4.4 Aliasing and Moire Patterns

- Aliasing: introduced by under-sampling, additional frequency components may be introduced into the sampled function
- Moire effect:

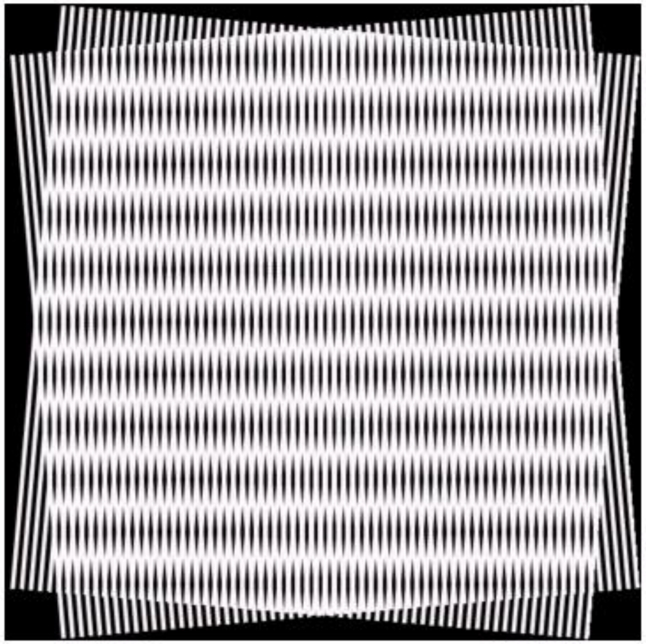
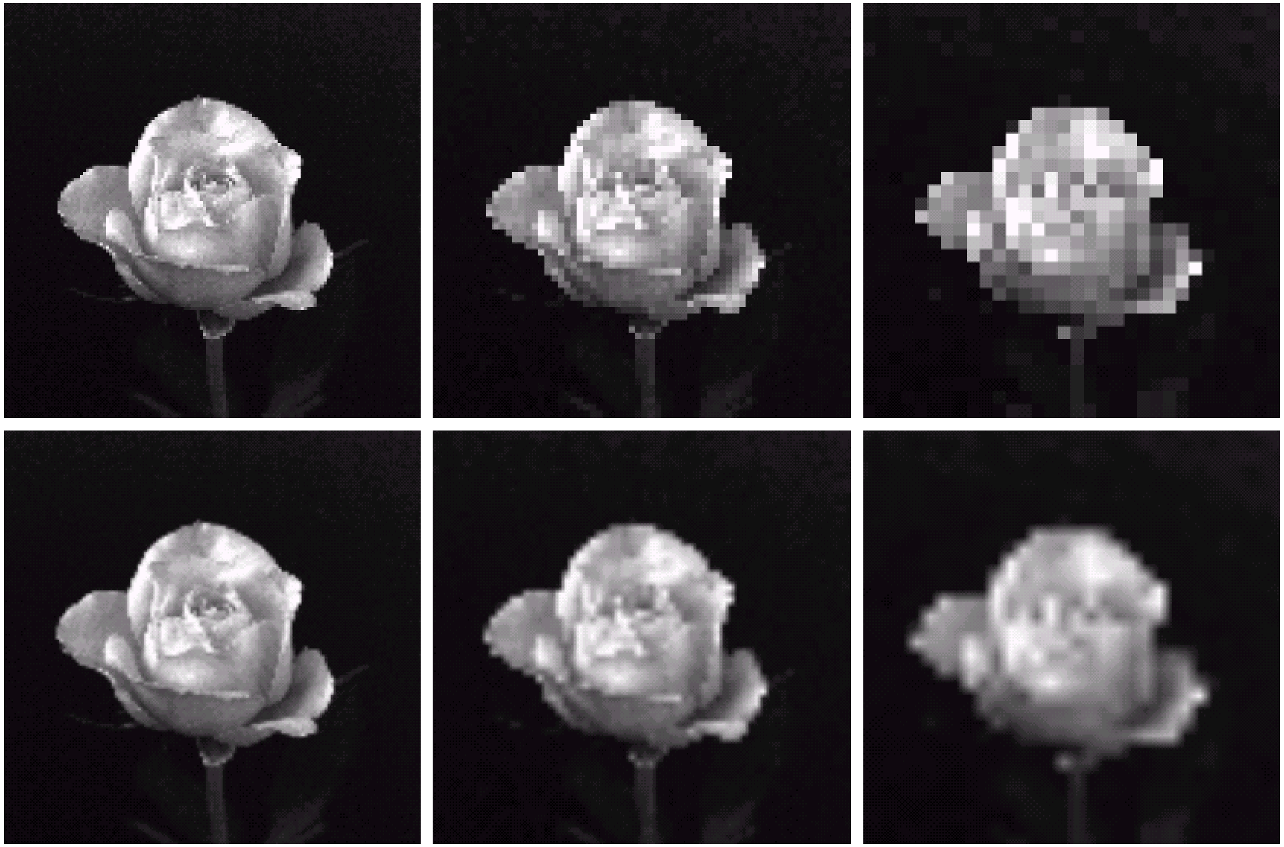


FIGURE 2.24 Illustration of the Moiré pattern effect.

2.4.5 Zooming and Shrinking Digital Images



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 Basic Relationships Between Pixels

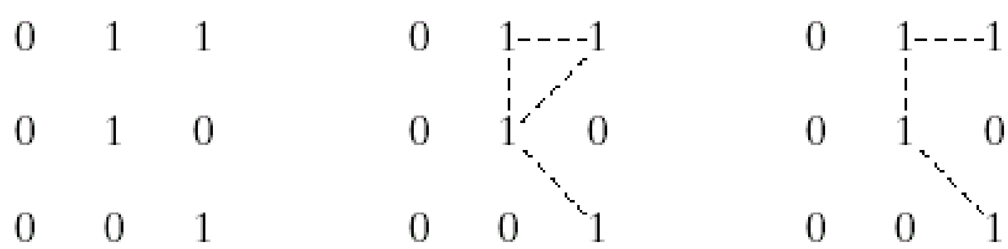
- $N_4(p)$: horizontal and vertical 4-neighbors of pixel p
- $N_D(p)$: diagonal 4-neighbors of pixel p
- N_8(p): 8-neighbors of pixel p, $N_8(p) = N_4(p) \cup N_D(p)$

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

2.5.2 Adjacency, Connectivity, Regions, and Boundaries

- Adjacency:
  - 4-adjacency: Two pixels p and q with the values from V are 4-adjacency if q is in the set $N_4(p)$.
  - 8-adjacency: Two pixels p and q with the values from V are 8-adjacency if q is in the set N_8(p).
  - *m*-adjacency (*mixed* adjacency): two pixels p and q with the values from V are *m*-adjacency if
    1. q is in the set $N_4(p)$ or
    2. q is in $N_8(p)$ and the set $N_4(p) \cap N_4(q)$ has no pixels whose values are from V

2.5.2 Adjacency, Connectivity, Regions, and Boundaries



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.

2.5.2 Adjacency, Connectivity, Regions, and Boundaries

- Path (Curve) from pixel p with coordinates (x, y) to pixel q with coordinates (s, t) is a sequence of distinct pixels with coordinates:

  $(x_0, y_0), (x_1, y_1), \ldots, \text{and } (x_n, y_n)$

  where $(x_0, y_0) = (x, y)$, $(x_n, y_n) = (s, t)$ and pixels (x_i, y_i) and (x_{i-1}, y_{i-1}) are adjacent for $1 \le i \le n$.
  - n is the *length* of the path
  - If $(x_0, y_0) = (x_n, y_n)$, the path is a *closed* path

2.5.2 Adjacency, Connectivity, Regions, and Boundaries

- *S*: a subset of pixels in an image
- Connected: Two pixels are said to be connected in *S* if there exists a *path* between them.
- For any pixel *p* in *S*, the *set* of pixels that are connect to it in *S* is called a *connected component* of *S*.
- The set *S* is called a *connected set* if it only has <u>one connected component</u>

2.5.2 Adjacency, Connectivity, Regions, and Boundaries

- *R*: a subset of pixels in an image
- *R* is a region of the image if *R* is a connected set
- The boundary (border, contour) of region *R* is the set of pixels in *R* that has one or more neighbors that are not in *R*.

2.5.3 Distance Measures

- For pixels p, q, and z, with coordinates (x, y), (s, t), and (v, w). D is a distance function or metric if
  a) $D(p, q) \geq 0$ ($D(p, q) = 0$ iff $p = q$),
  b) $D(p, q) = D(q, p)$, and
  c) $D(p, z) \leq D(p, q) + D(q, z)$

2.5.3 Distance Measures

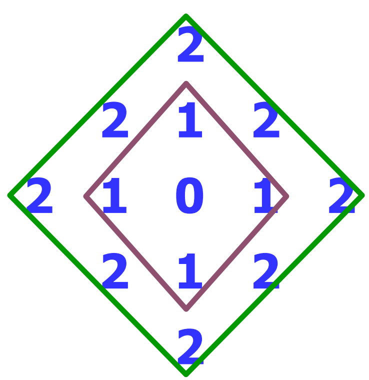
- Euclidean distance

$$D_e(p,q) = \left[(x-s)^2 + (y-t)^2\right]^{\frac{1}{2}}$$

- D_4 distance (city-block distance)

$$D_4(p,q) = |x-s| + |y-t|$$

  - An example: $D_4 \leq 2$ (diamond shape)



2.5.3 Distance Measures

- D_8 distance (chessboard distance)

$$D_8(p,q) = \max(|x-s|, |y-t|)$$

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

2.5.3 Distance Measures

- D_m distance: the shortest m-path between two pixels
- An example (p, p_2, p_4: 1, p_1, p_3: 1 or 0)

	p_3	p_4
p_1	p_2	
p		

  - If p_1 and p_3 are 0: $D_m(p, p_4) = 2$
  - If p_1 is 1 (p and p_2 will no longer be m-adjacent): $D_m(p, p_4) = 3$ ($p\ p_1\ p_2\ p_4$)
  - If p_3 is 1 and p_1 is 0 : $D_m(p, p_4) = 3$ ($p\ p_2\ p_3\ p_4$)
  - If p_1 and p_3 are 1 : $D_m(p, p_4) = 4$ ($p\ p_1\ p_2\ p_3\ p_4$)