

Introduction & Fundamentals

Introduction

► What is Digital Image Processing?

$$f(x, y)$$

Digital Image

— a two-dimensional function

x and y are spatial coordinates

The amplitude of f is called intensity or gray level at the point (x, y)

Digital Image Processing

— process digital images by means of computer, it covers low-, mid-, and high-level processes

low-level: inputs and outputs are images

mid-level: outputs are attributes extracted from input images

high-level: an ensemble of recognition of individual objects

Pixel

— the elements of a digital image

Origins of Digital Image Processing



FIGURE 1.1 A digital picture produced in 1921 from a coded tape by a telegraph printer with special type faces. (McFarlane.[†])

Sent by submarine cable between London and New York, the transportation time was reduced to less than three hours from more than a week

Origins of Digital Image Processing



FIGURE 1.4 The first picture of the moon by a U.S. spacecraft. *Ranger 7* took this image on July 31, 1964 at 9 : 09 A.M. EDT, about 17 minutes before impacting the lunar surface. (Courtesy of NASA.)

Sources for Images

- ▶ Electromagnetic (EM) energy spectrum
- ▶ Acoustic
- ▶ Ultrasonic
- ▶ Electronic
- ▶ Synthetic images produced by computer

Electromagnetic (EM) energy spectrum

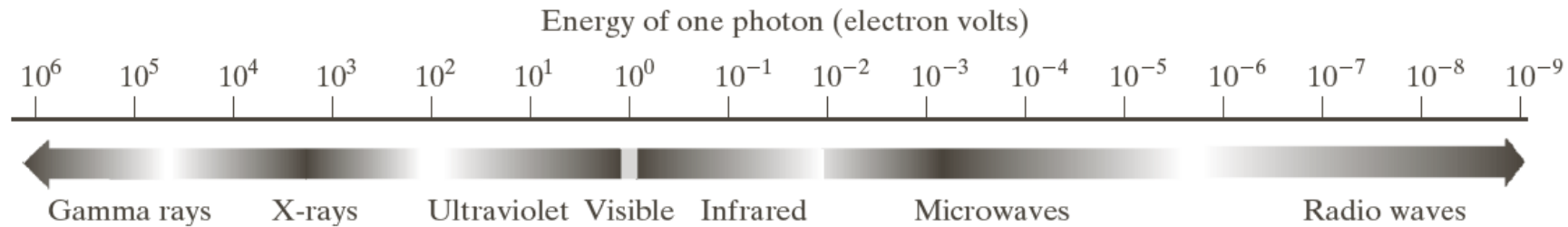


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

Major uses

Gamma-ray imaging: nuclear medicine and astronomical observations

X-rays: medical diagnostics, industry, and astronomy, etc.

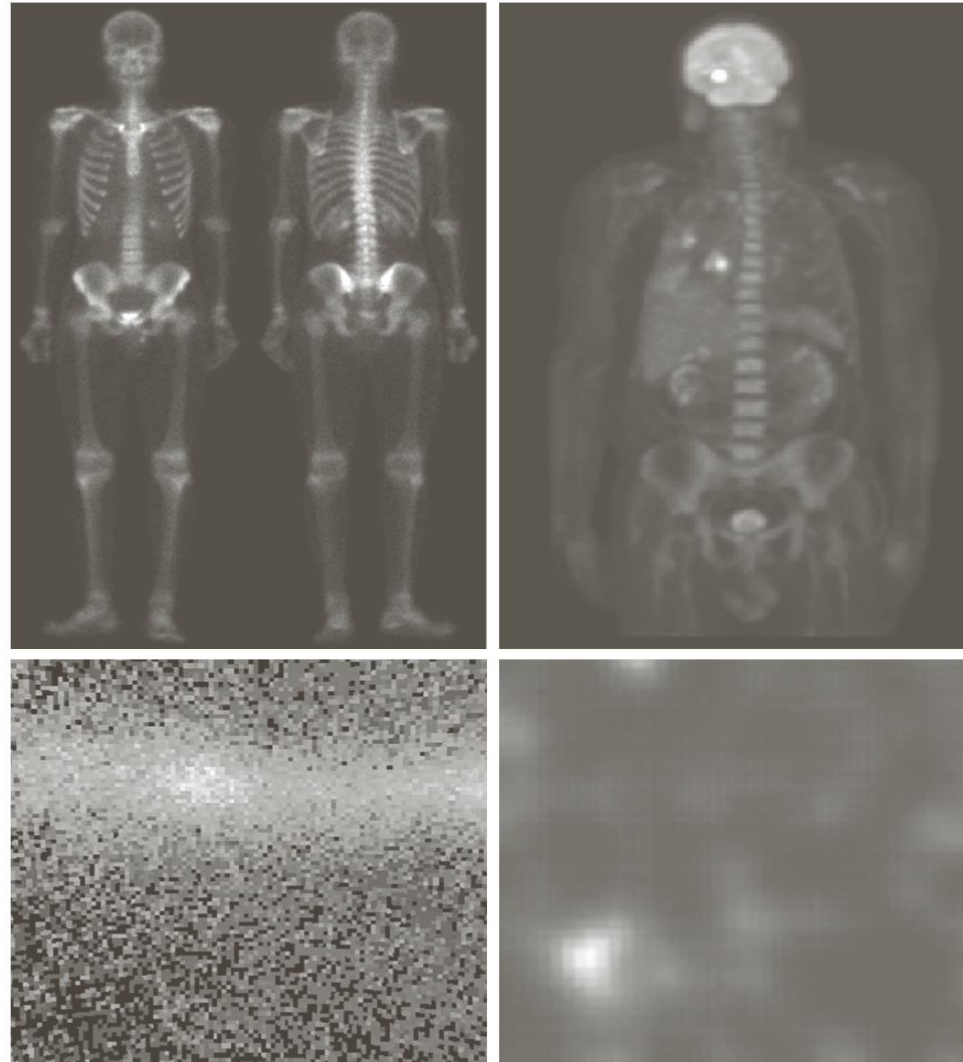
Ultraviolet: lithography, industrial inspection, microscopy, lasers, biological imaging, and astronomical observations

Visible and infrared bands: light microscopy, astronomy, remote sensing, industry, and law enforcement

Microwave band: radar

Radio band: medicine (such as MRI) and astronomy

Examples: Gama-Ray Imaging



a	b
c	d

FIGURE 1.6

Examples of gamma-ray imaging. (a) Bone scan. (b) PET image. (c) Cygnus Loop. (d) Gamma radiation (bright spot) from a reactor valve.

(Images courtesy of (a) G.E.

Medical Systems,

(b) Dr. Michael E. Casey, CTI

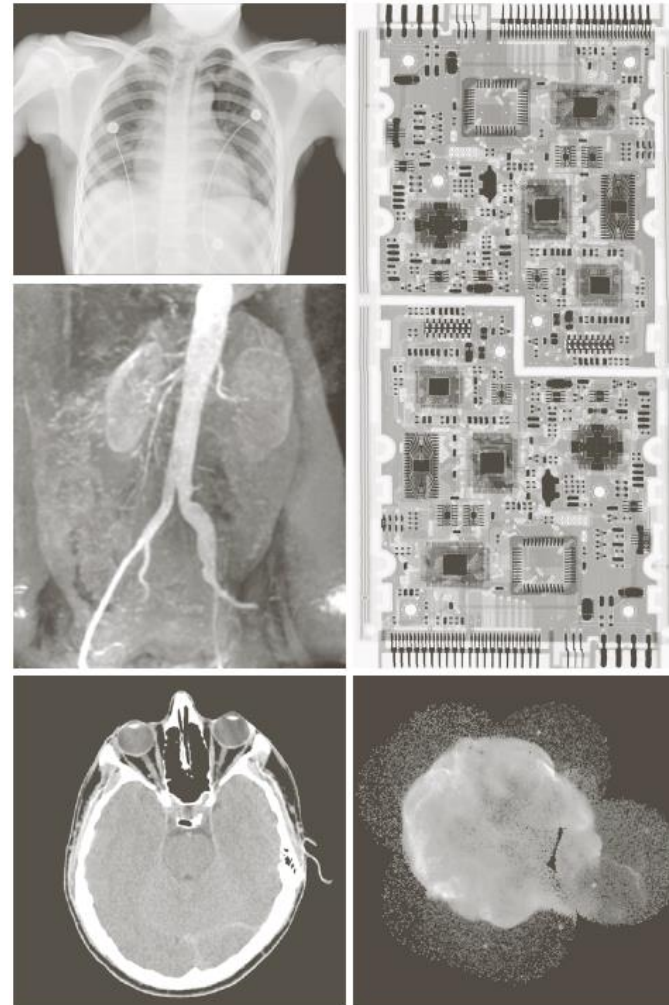
PET Systems,

(c) NASA,

(d) Professors Zhong He and David K. Wehe,

University of Michigan.)

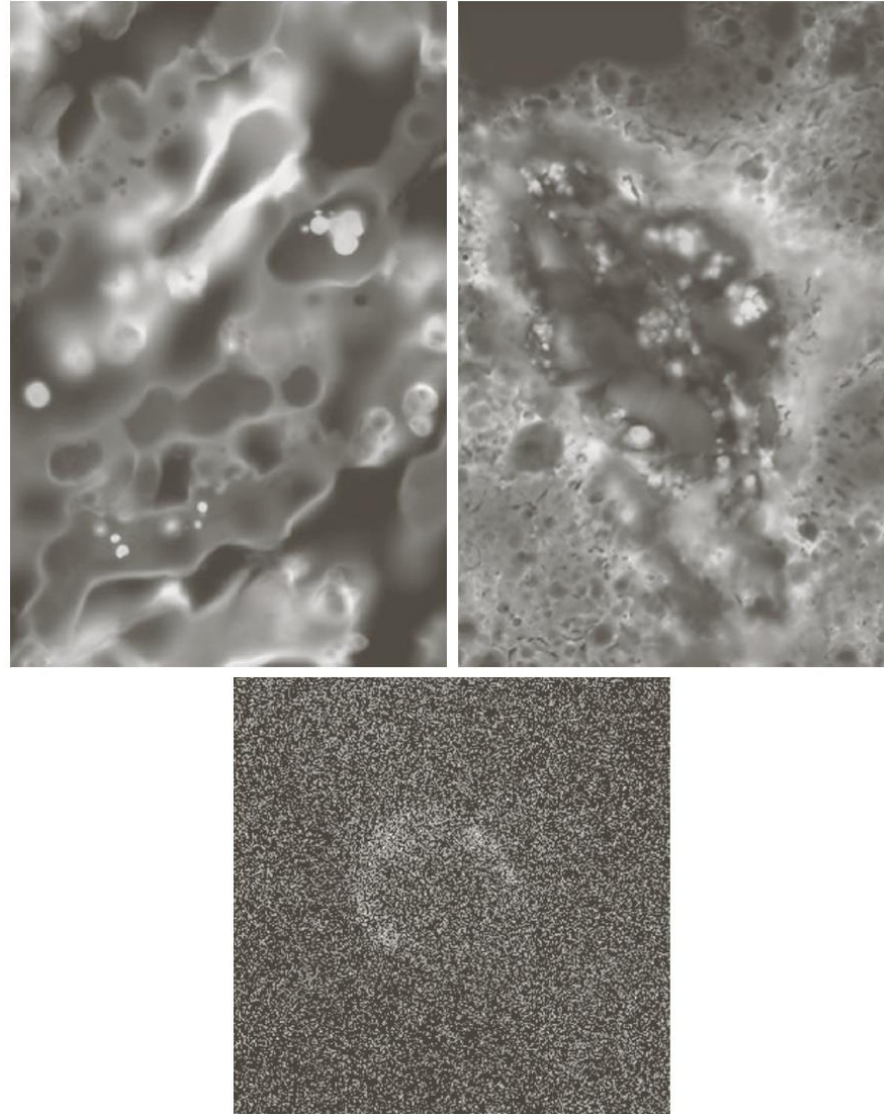
Examples: X-Ray Imaging



a	d
b	d
c	e

FIGURE 1.7 Examples of X-ray imaging. (a) Chest X-ray. (b) Aortic angiogram. (c) Head CT. (d) Circuit boards. (e) Cygnus Loop. (Images courtesy of (a) and (c) Dr. David R. Pickens, Dept. of Radiology & Radiological Sciences, Vanderbilt University Medical Center; (b) Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School; (d) Mr. Joseph E. Pascente, Lixi, Inc.; and (e) NASA.)

Examples: Ultraviolet Imaging



a b
c

FIGURE 1.8

Examples of ultraviolet imaging.

- (a) Normal corn.
- (b) Smut corn.
- (c) Cygnus Loop. (Images courtesy of (a) and (b) Dr. Michael W. Davidson, Florida State University, (c) NASA.)

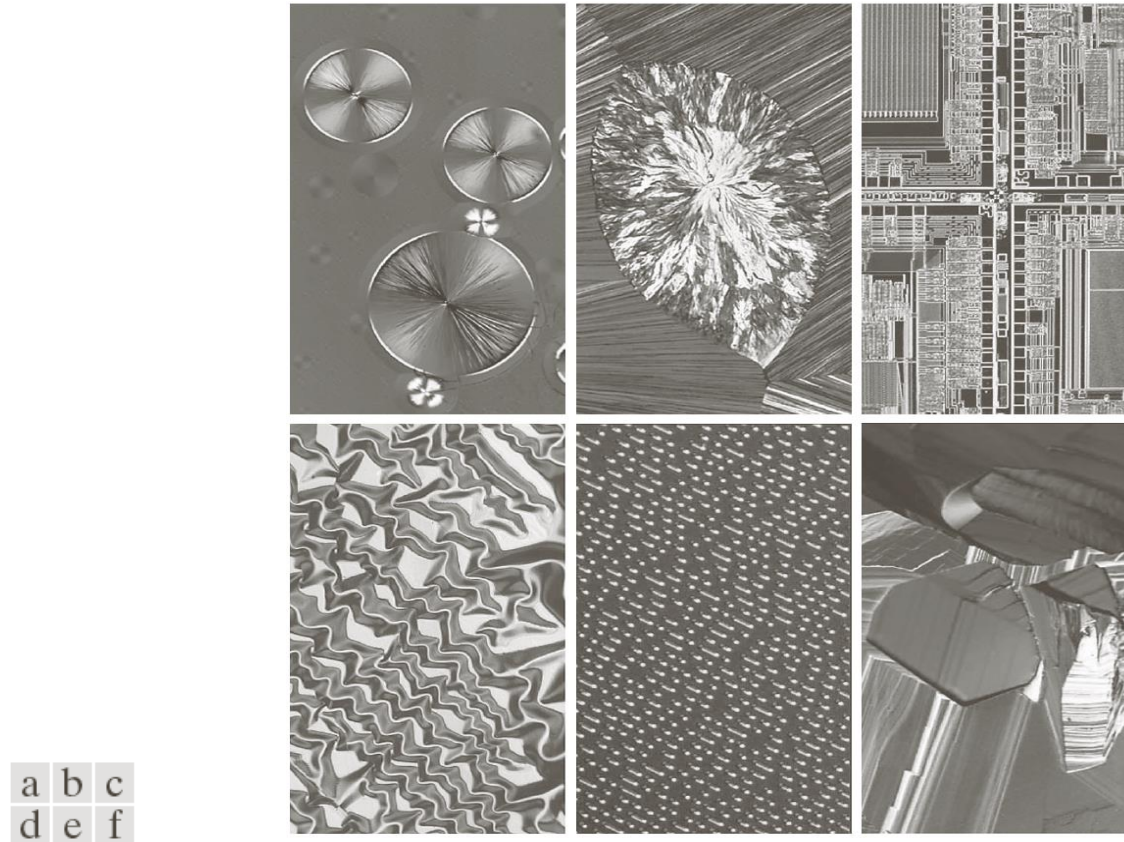


FIGURE 1.9 Examples of light microscopy images. (a) Taxol (anticancer agent), magnified 250 \times . (b) Cholesterol—40 \times . (c) Microprocessor—60 \times . (d) Nickel oxide thin film—600 \times . (e) Surface of audio CD—1750 \times . (f) Organic superconductor—450 \times . (Images courtesy of Dr. Michael W. Davidson, Florida State University.)

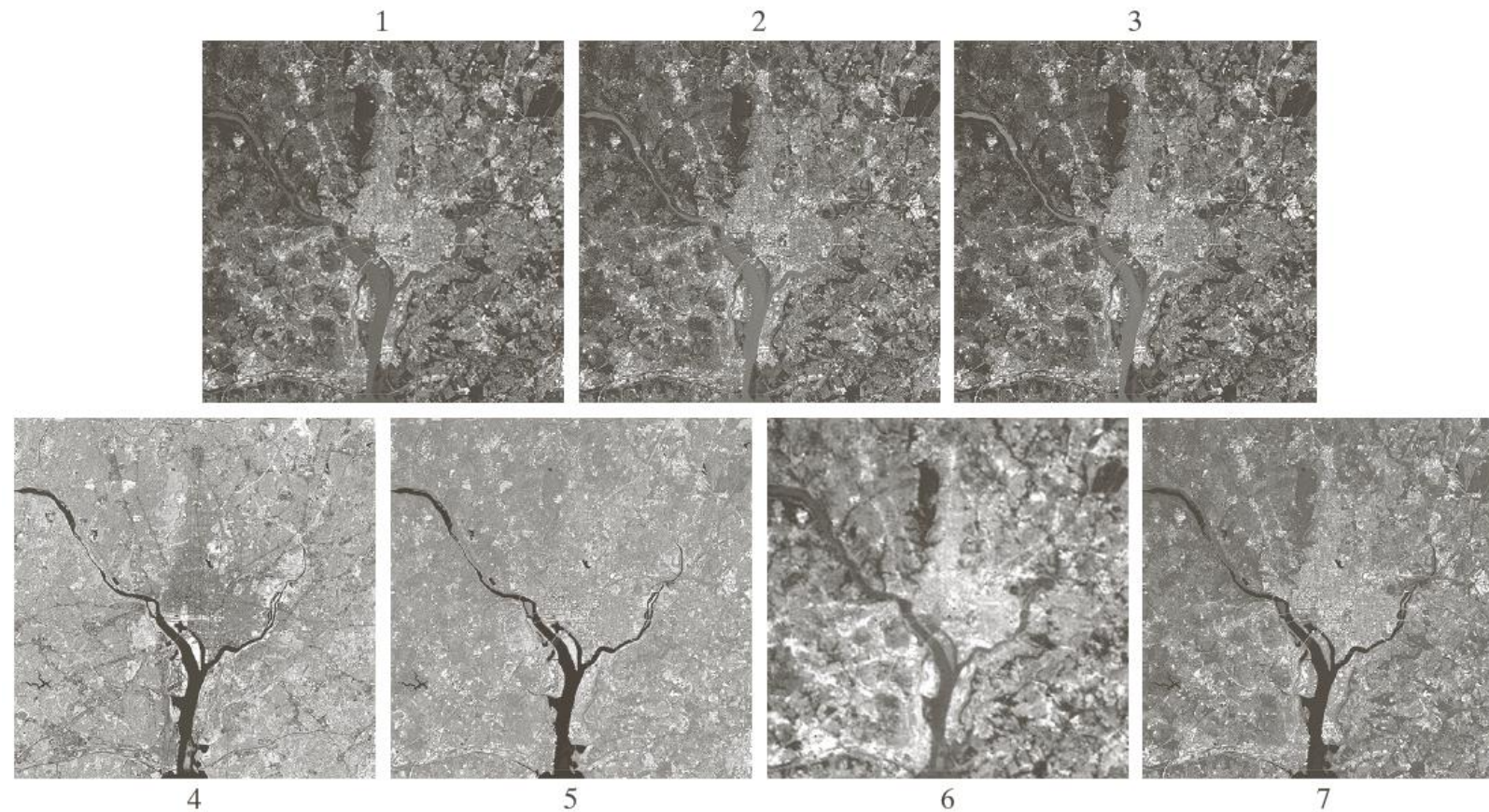


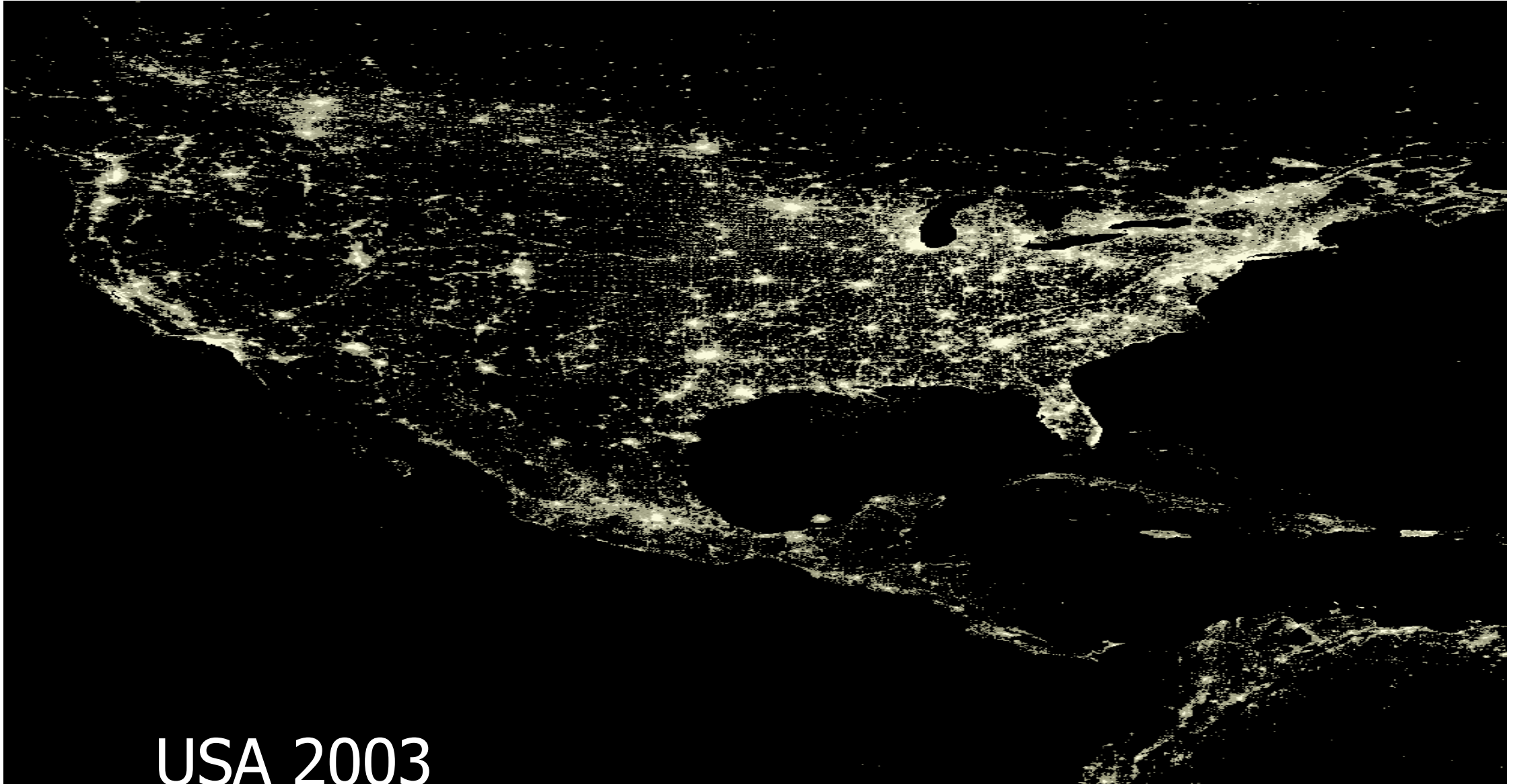
FIGURE 1.10 LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

TABLE 1.1

Thematic bands
in NASA's
LANDSAT
satellite.

Band No.	Name	Wavelength (μm)	Characteristics and Uses
1	Visible blue	0.45–0.52	Maximum water penetration
2	Visible green	0.52–0.60	Good for measuring plant vigor
3	Visible red	0.63–0.69	Vegetation discrimination
4	Near infrared	0.76–0.90	Biomass and shoreline mapping
5	Middle infrared	1.55–1.75	Moisture content of soil and vegetation
6	Thermal infrared	10.4–12.5	Soil moisture; thermal mapping
7	Middle infrared	2.08–2.35	Mineral mapping

Examples: Infrared Satellite Imaging

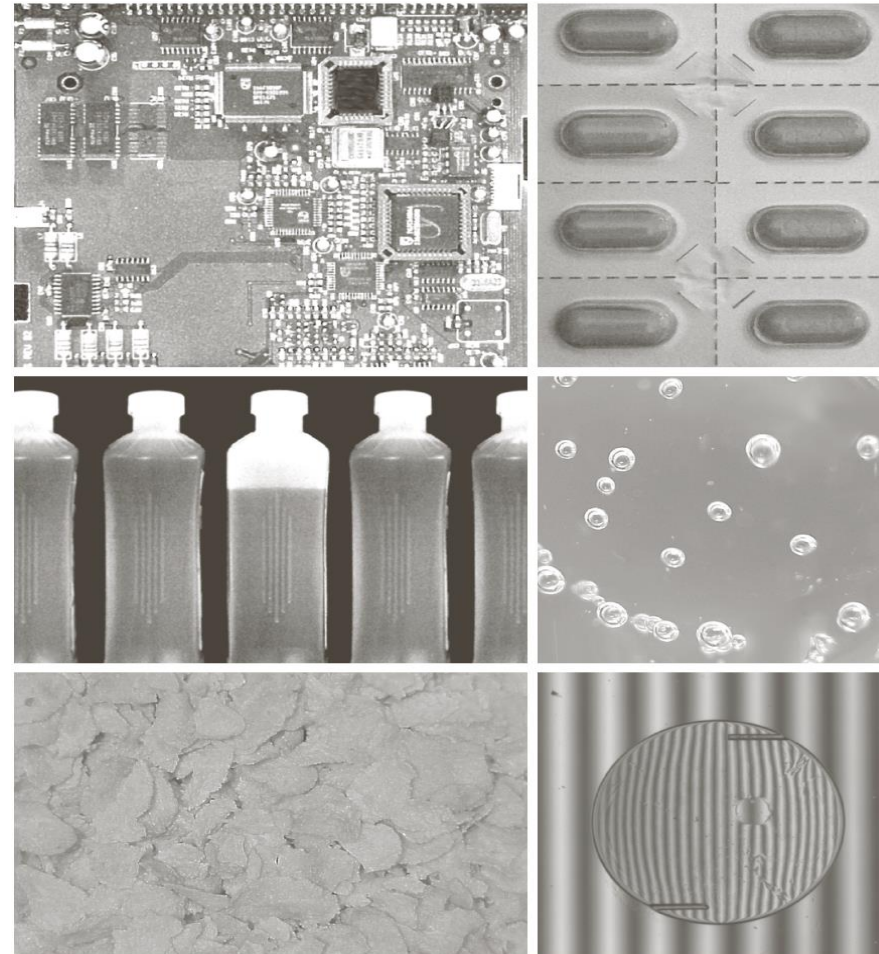


USA 2003

Examples: Infrared Satellite Imaging



Examples: Automated Visual Inspection



a	b
c	d
e	f

FIGURE 1.14

Some examples of manufactured goods often checked using digital image processing.

- (a) A circuit board controller.
 - (b) Packaged pills.
 - (c) Bottles.
 - (d) Air bubbles in a clear-plastic product.
 - (e) Cereal.
 - (f) Image of intraocular implant.
- (Fig. (f) courtesy of Mr. Pete Sites, Perceptics Corporation.)

Examples: Automated Visual Inspection



a b
c
d

FIGURE 1.15 Some additional examples of imaging in the visual spectrum. (a) Thumb print. (b) Paper currency. (c) and (d) Automated license plate reading. (Figure (a) courtesy of the National Institute of Standards and Technology. Figures (c) and (d) courtesy of Dr. Juan Herrera, Perceptics Corporation.)

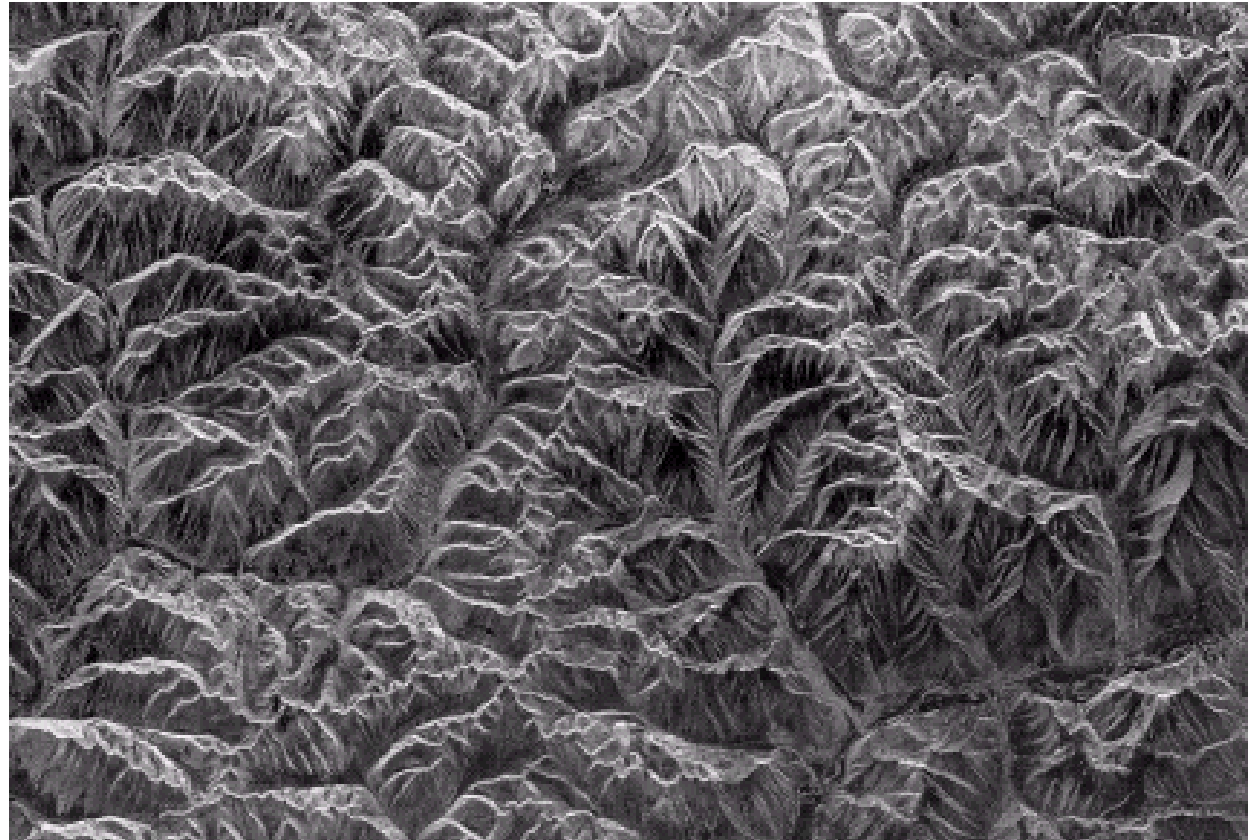
Results of automated reading of the plate content by the system

The area in which the imaging system detected the plate

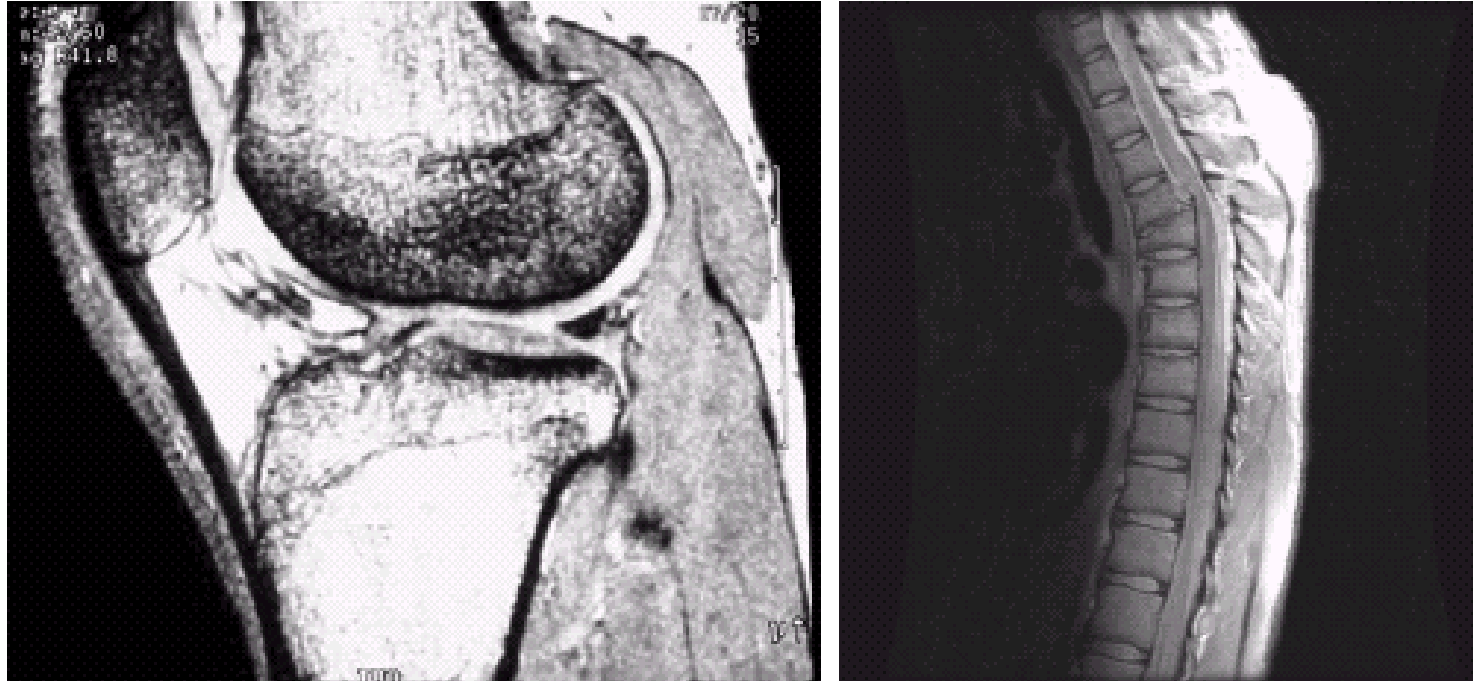


Example of Radar Image

FIGURE 1.16
Spaceborne radar
image of
mountains in
southeast Tibet.
(Courtesy of
NASA.)



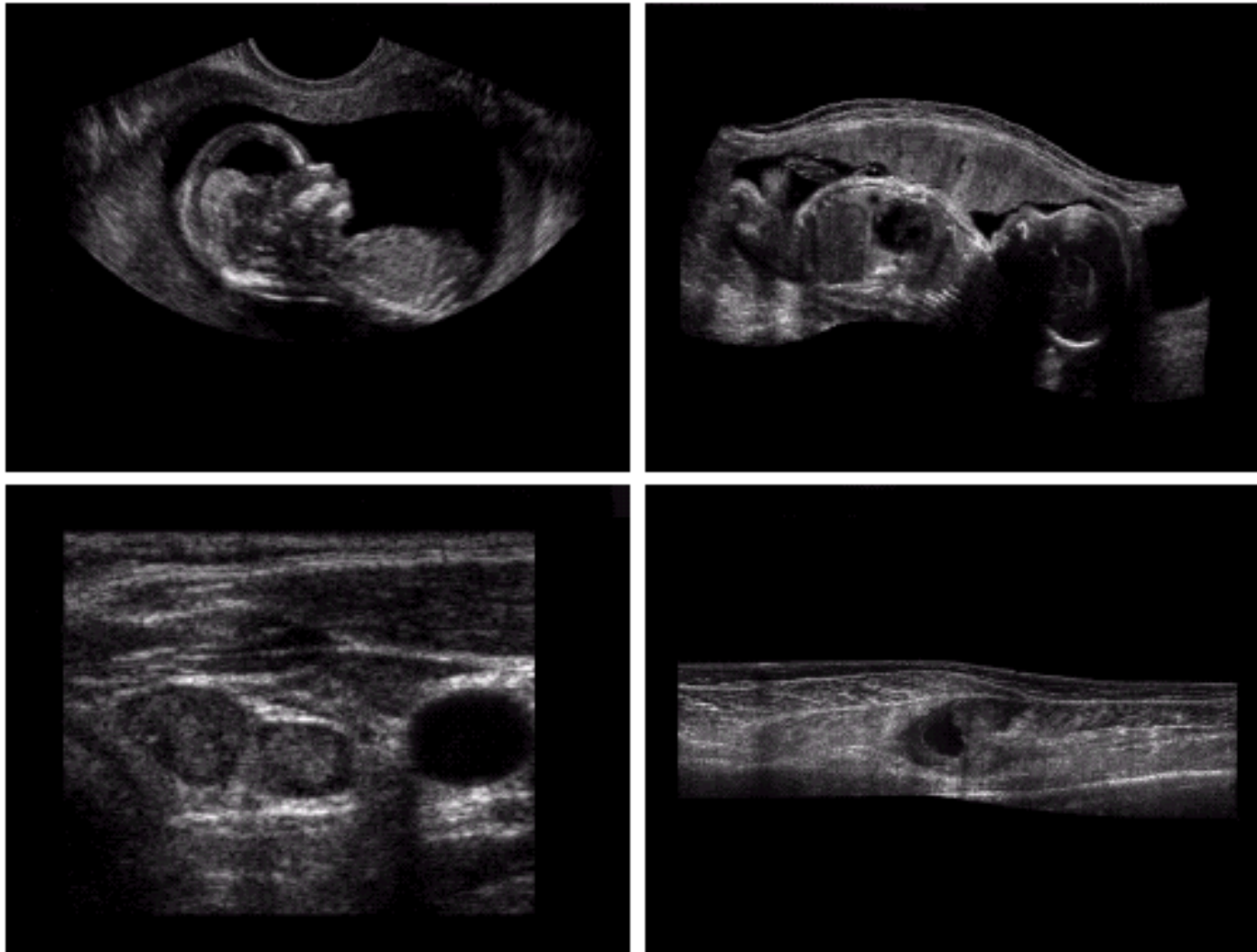
Examples: MRI (Radio Band)



a b

FIGURE 1.17 MRI images of a human (a) knee, and (b) spine. (Image (a) courtesy of Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School, and (b) Dr. David R. Pickens, Department of Radiology and Radiological Sciences, Vanderbilt University Medical Center.)

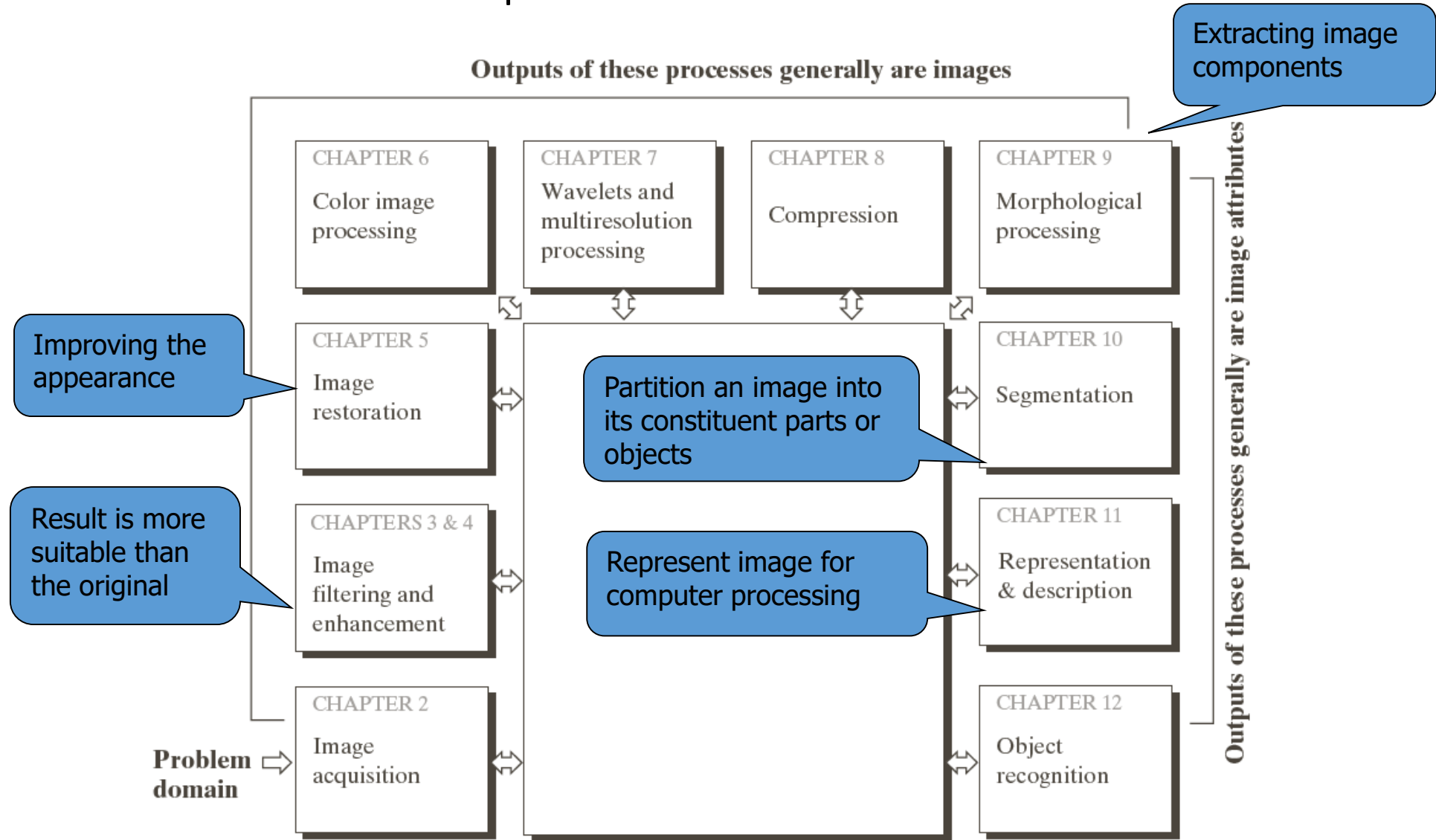
Examples: Ultrasound Imaging



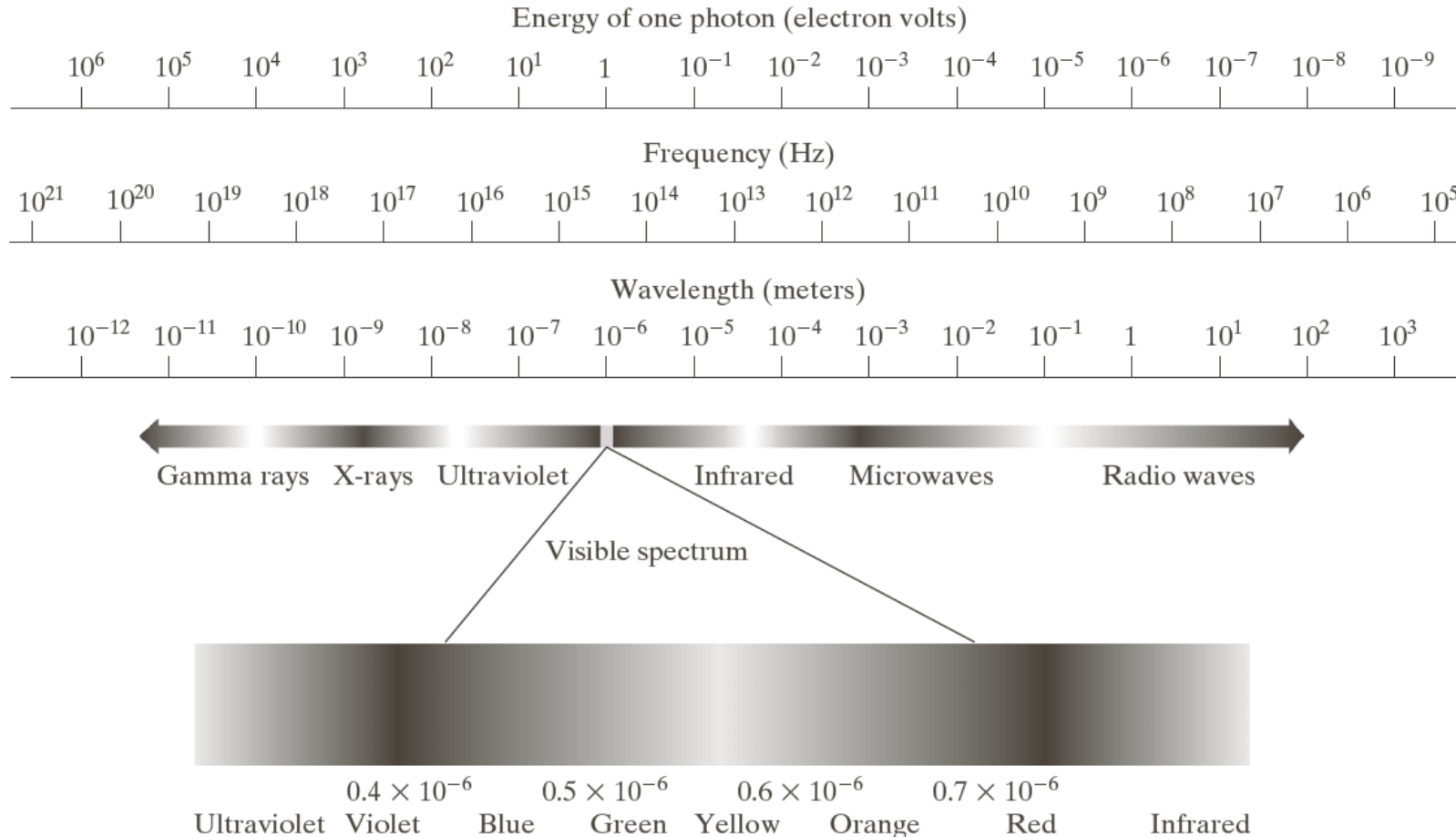
a	b
c	d

FIGURE 1.20
Examples of
ultrasound
imaging. (a) Baby.
(2) Another view
of baby.
(c) Thyroids.
(d) Muscle layers
showing lesion.
(Courtesy of
Siemens Medical
Systems, Inc.,
Ultrasound
Group.)

Fundamental Steps in DIP



Light and EM Spectrum



$$c = \lambda \nu$$

$$E = h\nu, \quad h: \text{Planck's constant.}$$

Light and EM Spectrum

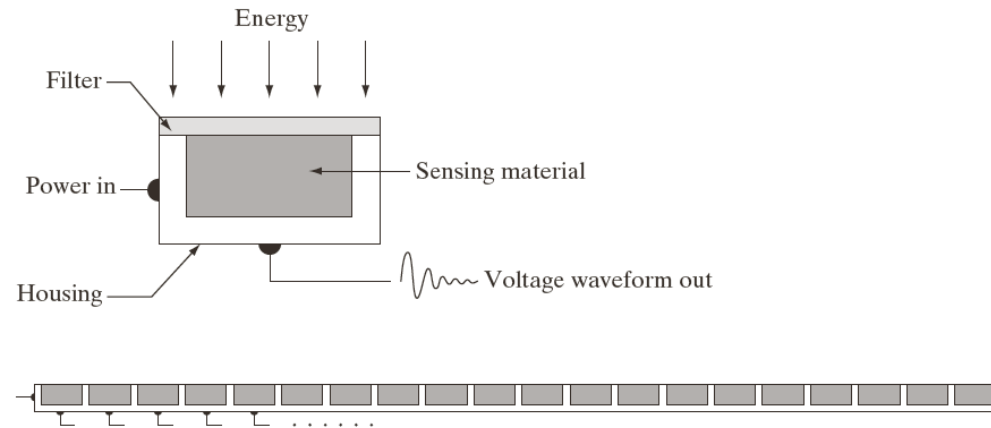
- ▶ The colors that humans perceive in an object are determined by the nature of the light reflected from the object.

e.g. green objects reflect light with wavelengths primarily in the 500 to 570 nm range while absorbing most of the energy at other wavelength

Light and EM Spectrum

- ▶ **Monochromatic light: void of color**
Intensity is the only attribute, from black to white
Monochromatic images are referred to as **gray-scale** images
- ▶ **Chromatic light bands: 0.43 to 0.79 μm**
The quality of a chromatic light source:
 - Radiance:** total amount of energy
 - Luminance (l_m):** the amount of energy an observer perceives from a light source
 - Brightness:** a subjective descriptor of light perception that is impossible to measure. It embodies the achromatic notion of intensity and one of the key factors in describing color sensation.

Image Acquisition



a
b
c

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

Transform illumination energy into digital images

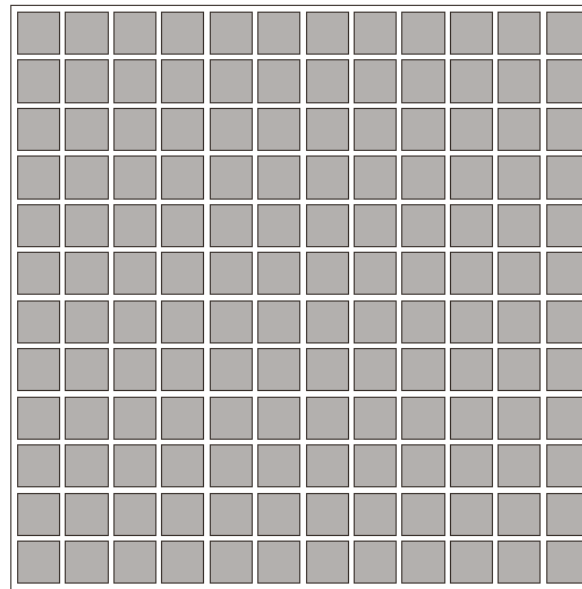
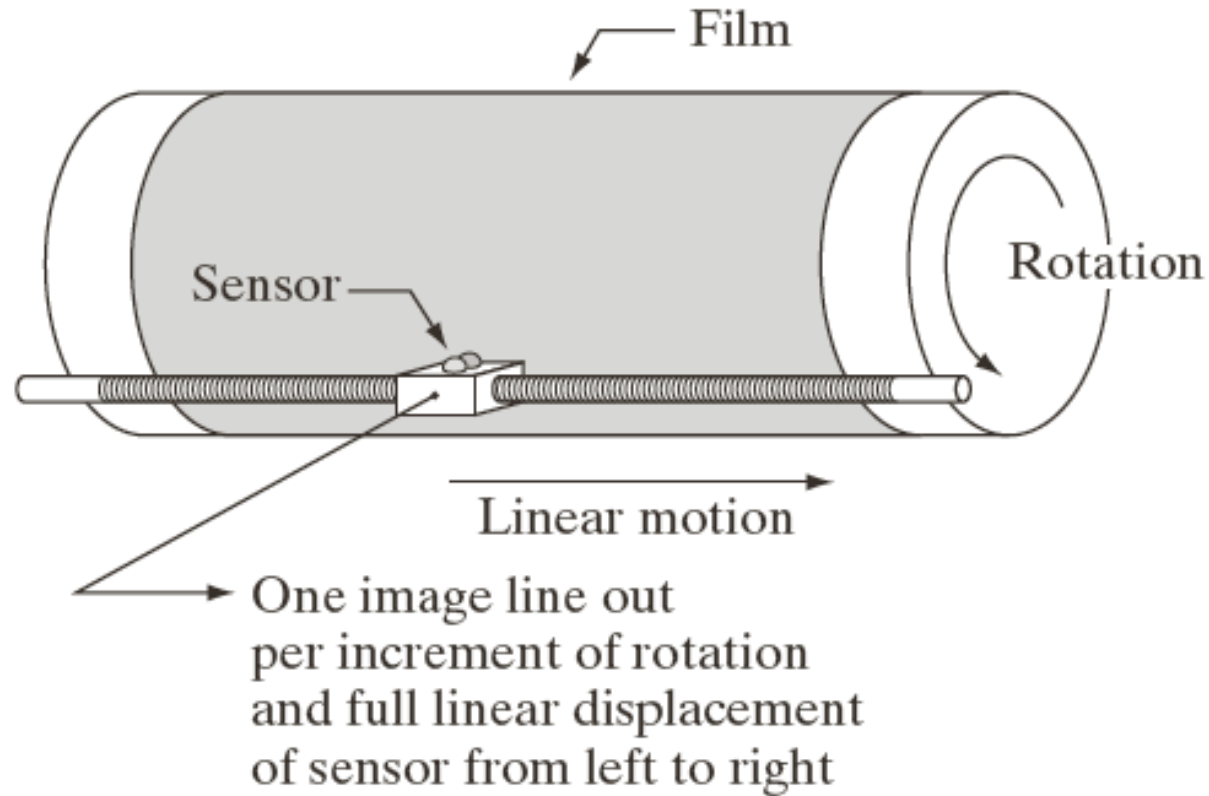
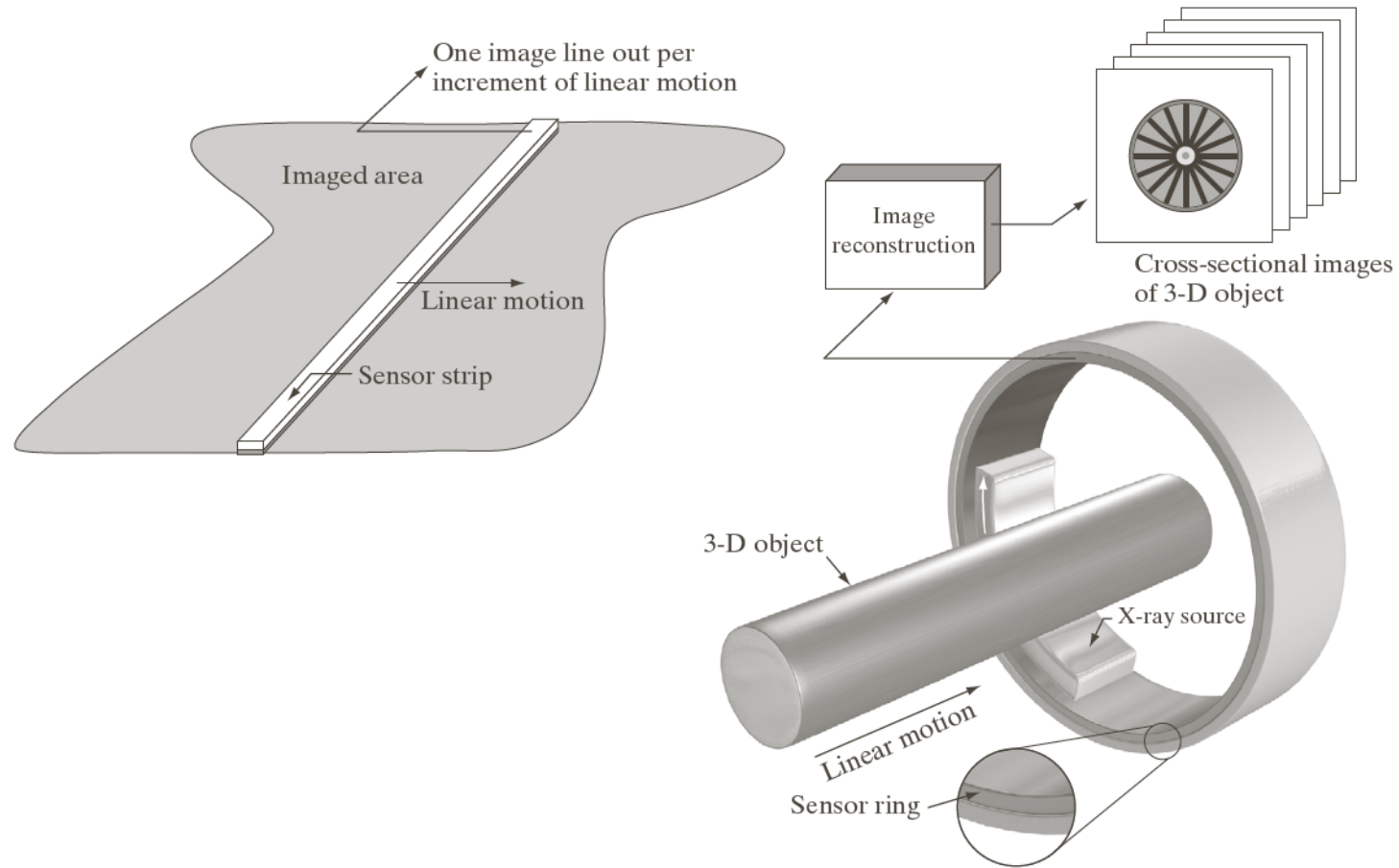


FIGURE 2.13
Combining a single sensor with motion to generate a 2-D image.

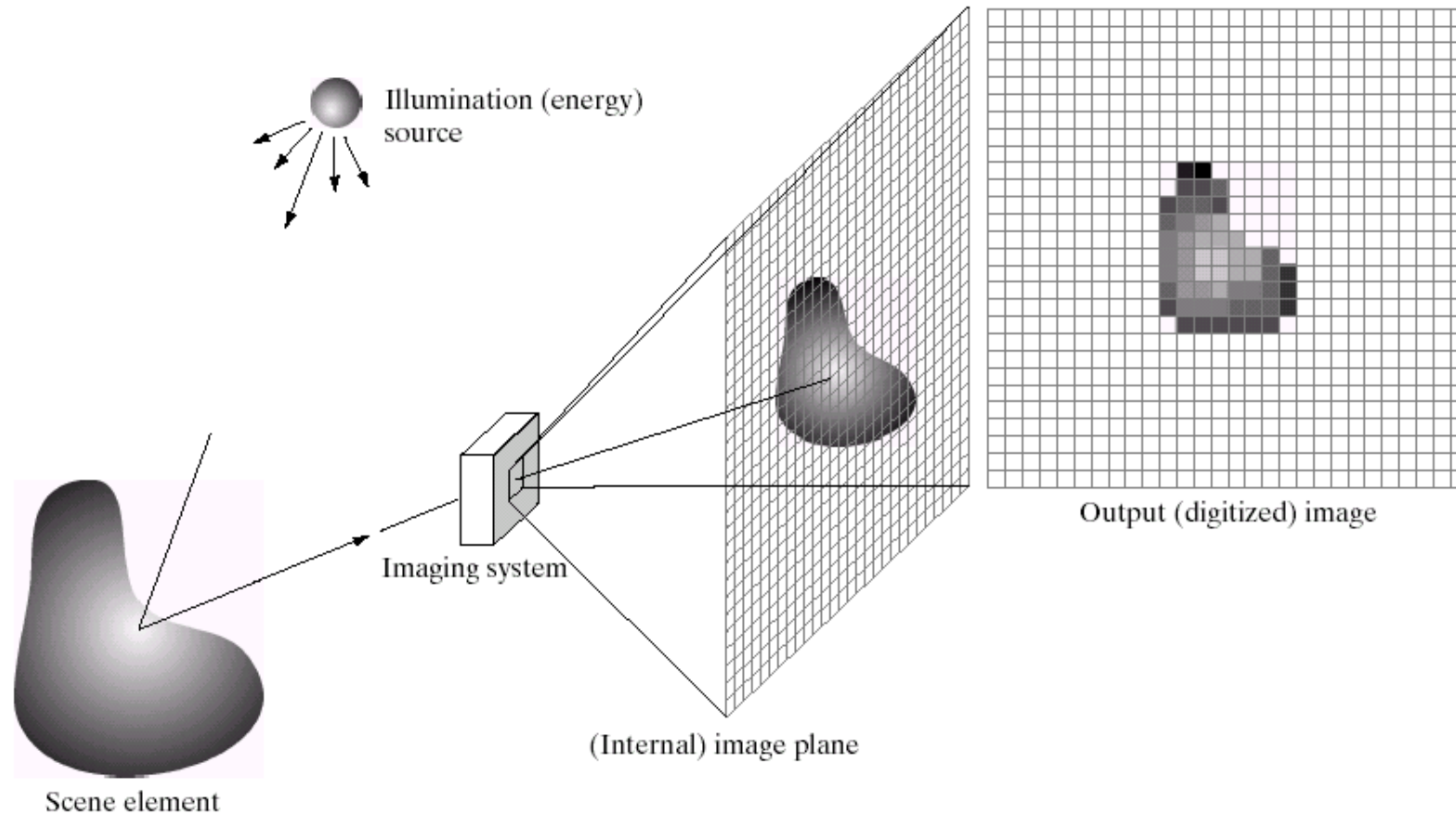




a b

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

Image Acquisition Process



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.

A Simple Image Formation Model

$$f(x, y) = i(x, y)r(x, y)$$

$f(x, y)$: intensity at the point (x, y)

$i(x, y)$: illumination at the point (x, y)

(the amount of source illumination incident on the scene)

$r(x, y)$: reflectance/transmissivity at the point (x, y)

(the amount of illumination reflected/transmitted by the object)

where $0 < i(x, y) < \infty$ and $0 < r(x, y) < 1$

Some Typical Ranges of illumination

► Illumination

Lumen — A unit of light flow or luminous flux

Lumen per square meter (lm/m^2) — The metric unit of measure for illuminance of a surface

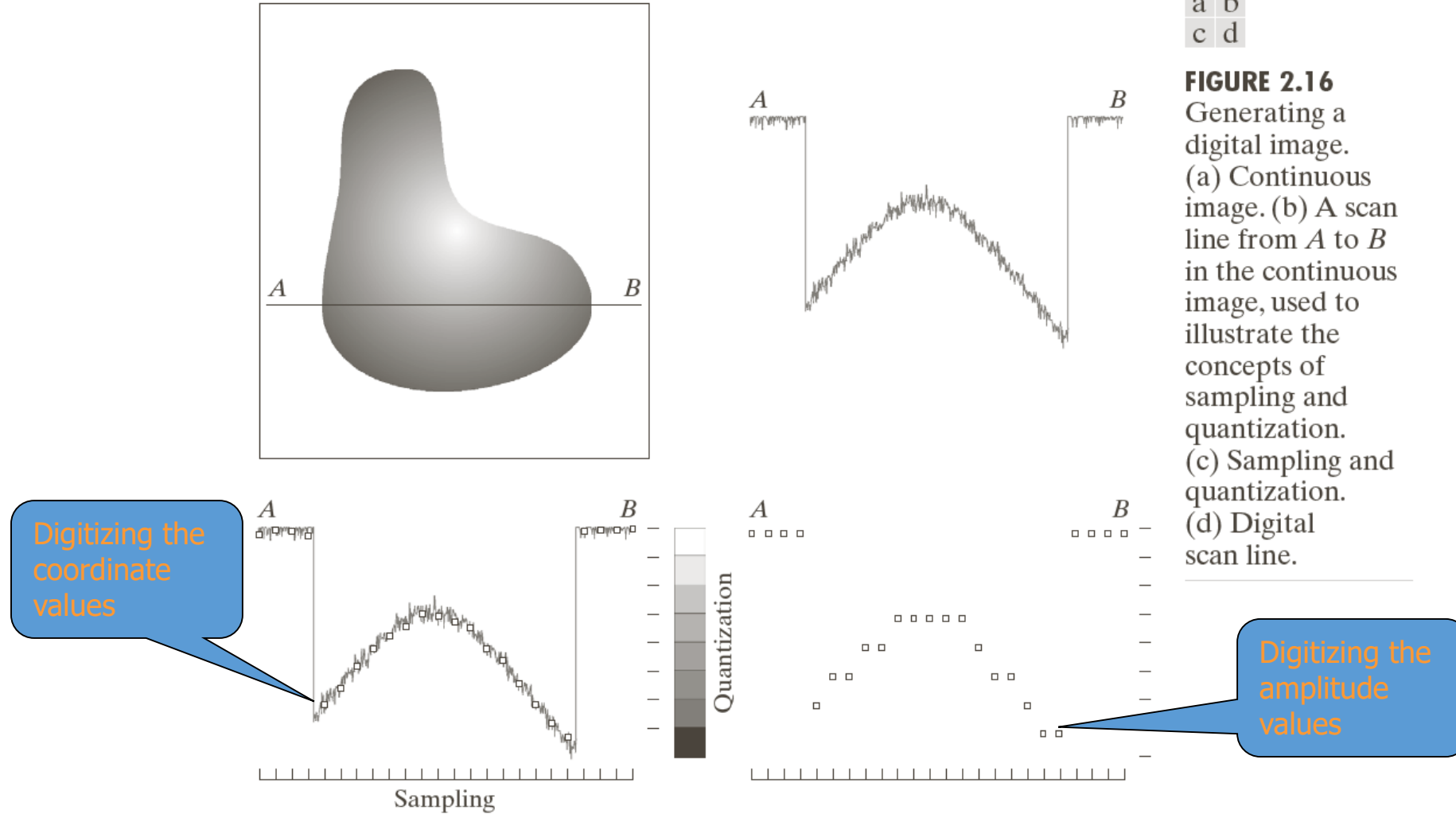
- On a clear day, the sun may produce in excess of $90,000 \text{ lm}/\text{m}^2$ of illumination on the surface of the Earth
- On a cloudy day, the sun may produce less than $10,000 \text{ lm}/\text{m}^2$ of illumination on the surface of the Earth
- On a clear evening, the moon yields about $0.1 \text{ lm}/\text{m}^2$ of illumination
- The typical illumination level in a commercial office is about $1000 \text{ lm}/\text{m}^2$

Some Typical Ranges of Reflectance

► Reflectance

- 0.01 for black velvet
- 0.65 for stainless steel
- 0.80 for flat-white wall paint
- 0.90 for silver-plated metal
- 0.93 for snow

Image Sampling and Quantization



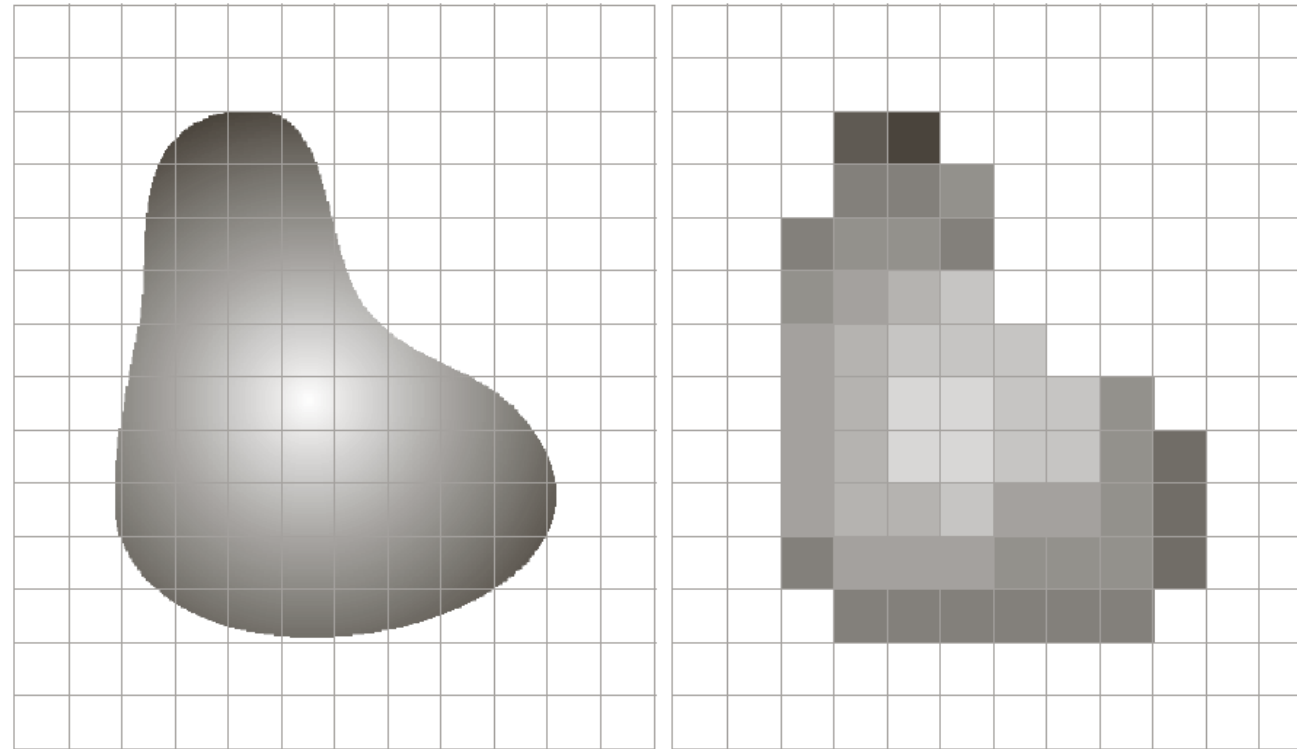
a	b
c	d

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.

Digitizing the
coordinate
values

Digitizing the
amplitude
values

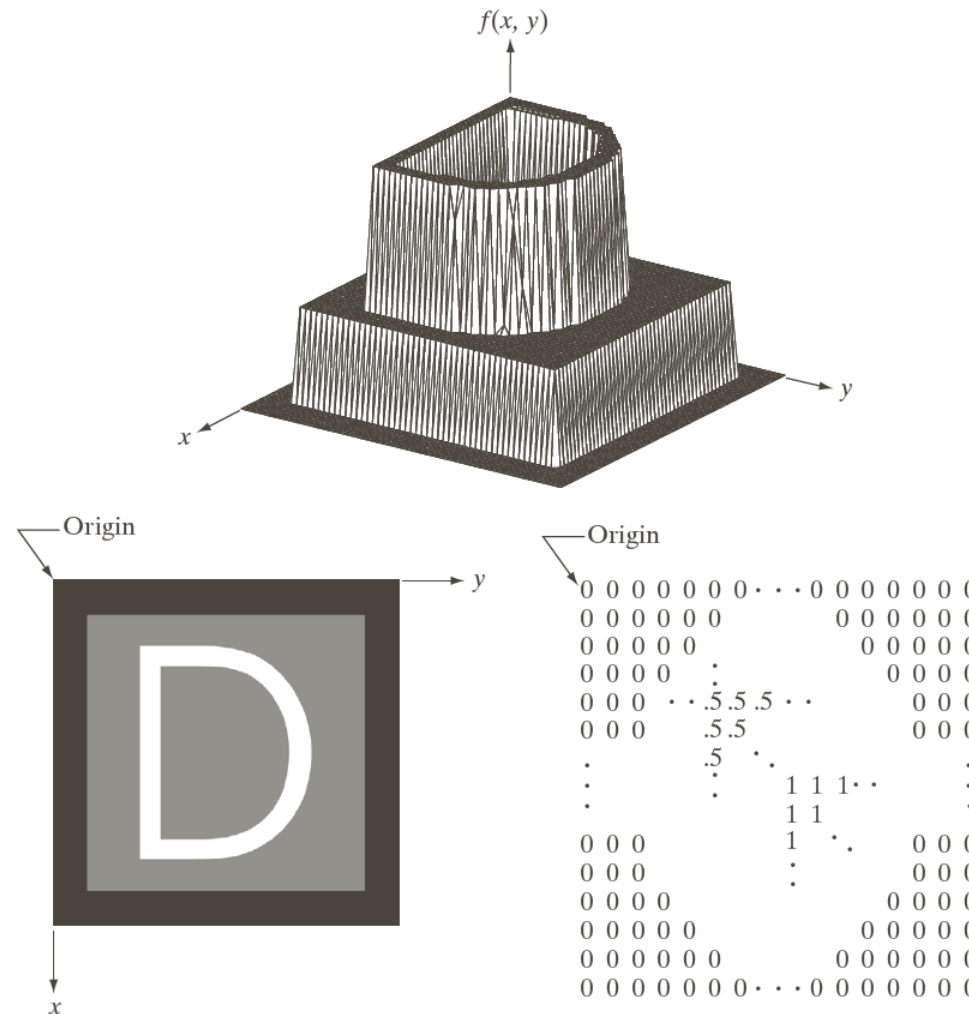
Image Sampling and Quantization



a b

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

Representing Digital Images



a
b c

FIGURE 2.18

(a) Image plotted as a surface.

(b) Image displayed as a visual intensity array.

(c) Image shown as a 2-D numerical array (0, .5, and 1 represent black, gray, and white, respectively).

Representing Digital Images

► The representation of an $M \times N$ numerical array as

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

Representing Digital Images

► The representation of an $M \times N$ numerical array as

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

Representing Digital Images

- ▶ The representation of an $M \times N$ numerical array in MATLAB

$$f(x, y) = \begin{bmatrix} f(1,1) & f(1,2) & \dots & f(1,N) \\ f(2,1) & f(2,2) & \dots & f(2,N) \\ \dots & \dots & \dots & \dots \\ f(M,1) & f(M,2) & \dots & f(M,N) \end{bmatrix}$$

Representing Digital Images

- ▶ Discrete intensity interval $[0, L-1]$, $L=2^k$
- ▶ The number b of bits required to store a $M \times N$ digitized image

$$b = M \times N \times k$$

Representing Digital Images

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

Spatial and Intensity Resolution

- Spatial resolution
 - A measure of the smallest discernible detail in an image
 - stated with *line pairs per unit distance*, *dots (pixels) per unit distance*, *dots per inch (dpi)*
- Intensity resolution
 - The smallest discernible change in intensity level
 - stated with *8 bits*, *12 bits*, *16 bits*, *etc.*

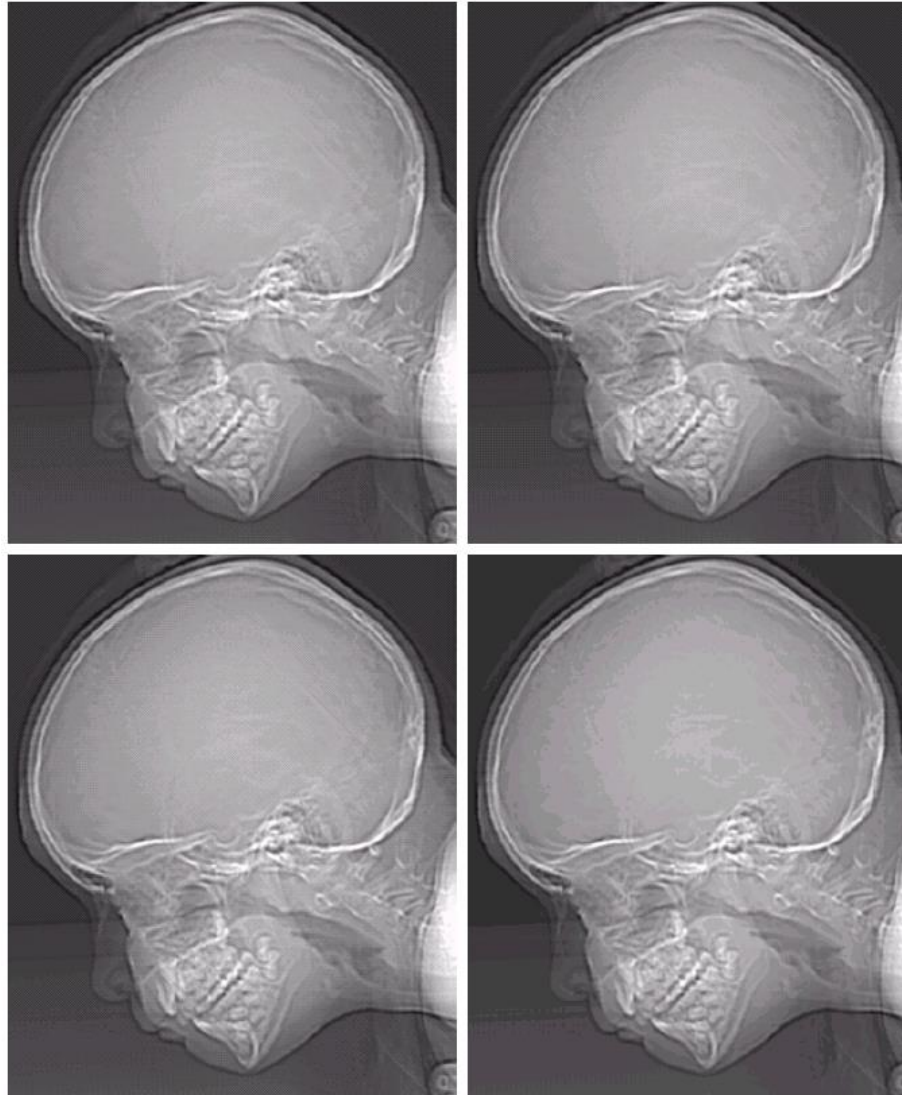
Spatial and Intensity Resolution



a b
c d

FIGURE 2.20 Typical effects of reducing spatial resolution. Images shown at: (a) 1250 dpi, (b) 300 dpi, (c) 150 dpi, and (d) 72 dpi. The thin black borders were added for clarity. They are not part of the data.

Spatial and Intensity Resolution



a b
c d

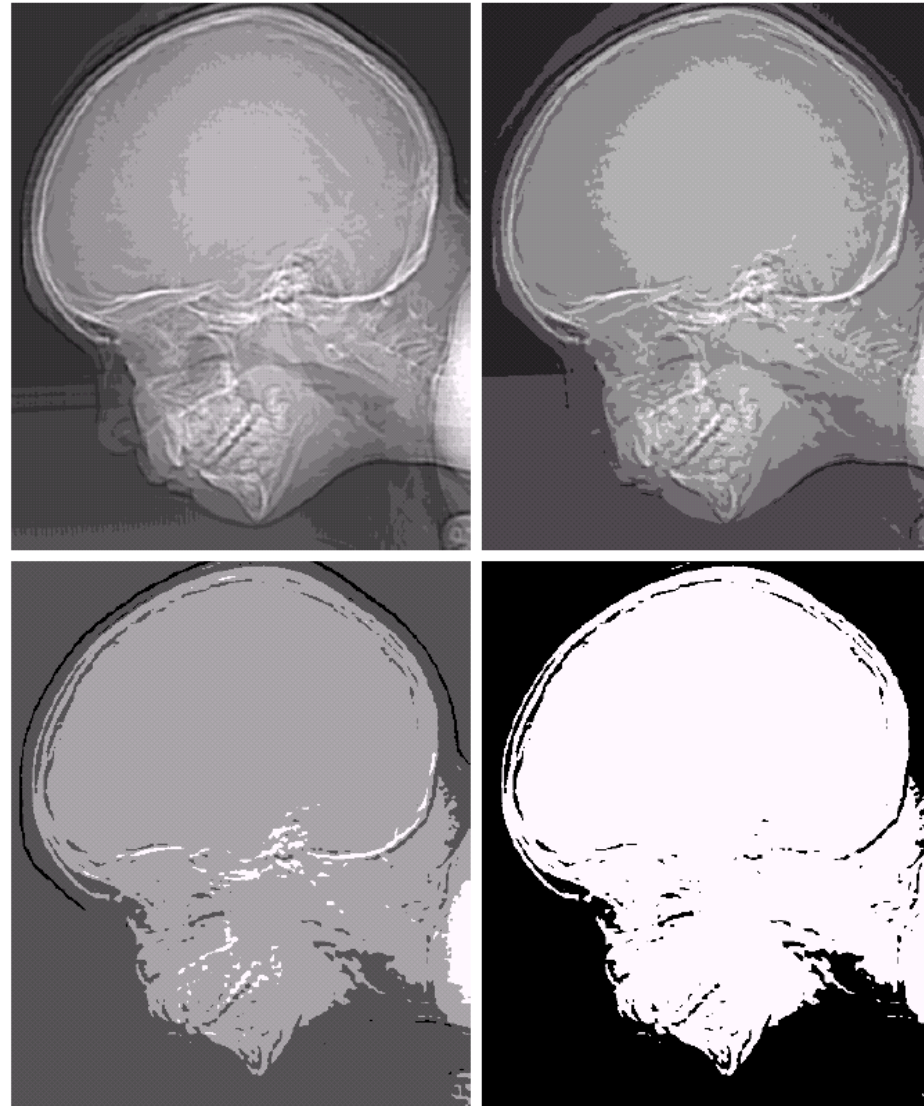
FIGURE 2.21

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

Spatial and Intensity 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.)



▶ **Interpolation** — Process of using known data to estimate unknown values

e.g., zooming, shrinking, rotating, and geometric correction

▶ **Interpolation** (sometimes called *resampling*) — an imaging method to increase (or decrease) the number of pixels in a digital image.

Some digital cameras use interpolation to produce a larger image than the sensor captured or to create digital zoom

<http://www.dpreview.com/learn/?/key=interpolation>

Image Interpolation:

Nearest Neighbor Interpolation

$$f_1(x_2, y_2) = f(\text{round}(x_2), \text{round}(y_2)) = f(x_1, y_1)$$

$$f(x_1, y_1)$$

$$f_1(x_3, y_3) = f(\text{round}(x_3), \text{round}(y_3)) = f(x_1, y_1)$$

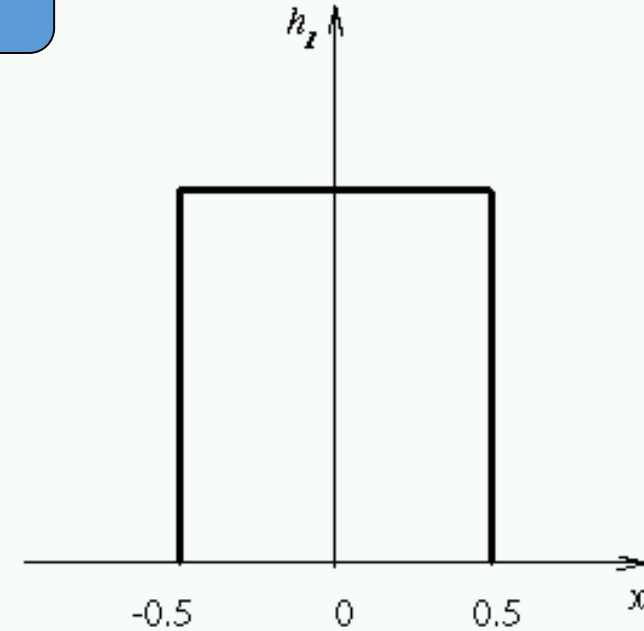
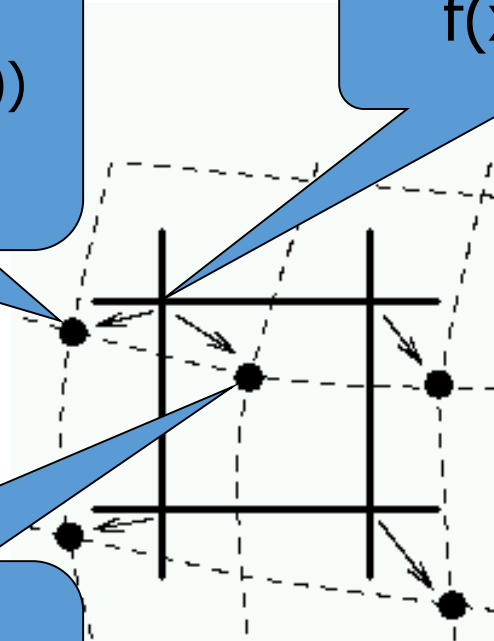
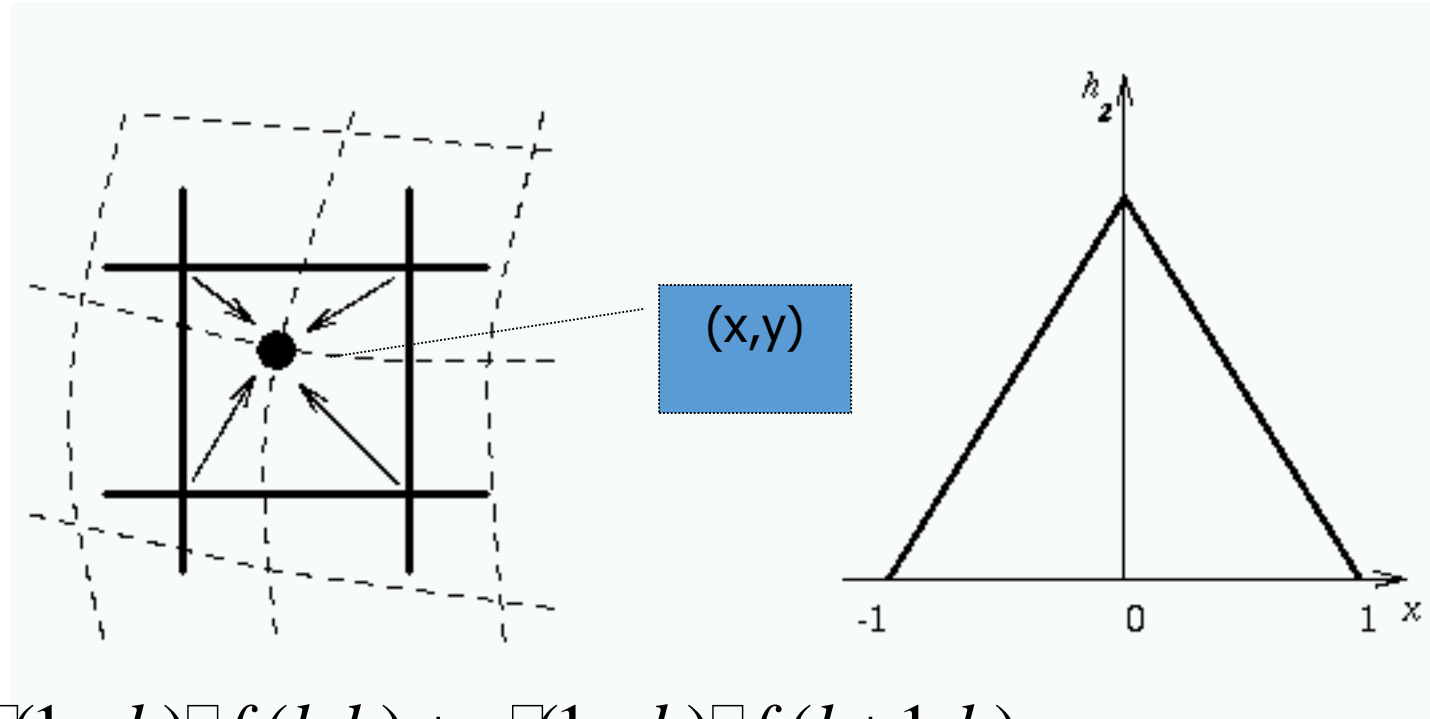


Image Interpolation: Bilinear Interpolation



$$f_2(x, y)$$

$$= (1-a)(1-b)f(l, k) + a(1-b)f(l+1, k)$$

$$+ (1-a)b f(l, k+1) + a b f(l+1, k+1)$$

$$l = \text{floor}(x), k = \text{floor}(y), a = x - l, b = y - k.$$

Image Interpolation: Bicubic Interpolation

- The intensity value assigned to point (x,y) is obtained by the following equation

$$f_3(x, y) = \sum_{i=0}^3 \sum_{j=0}^3 a_{ij} x^i y^j$$

- The sixteen coefficients are determined by using the sixteen nearest neighbors.

http://en.wikipedia.org/wiki/Bicubic_interpolation

Examples: Interpolation

Original Image



Examples: Interpolation

Nearest Neighbor Interpolation



Examples: Interpolation

Bilinear Interpolation



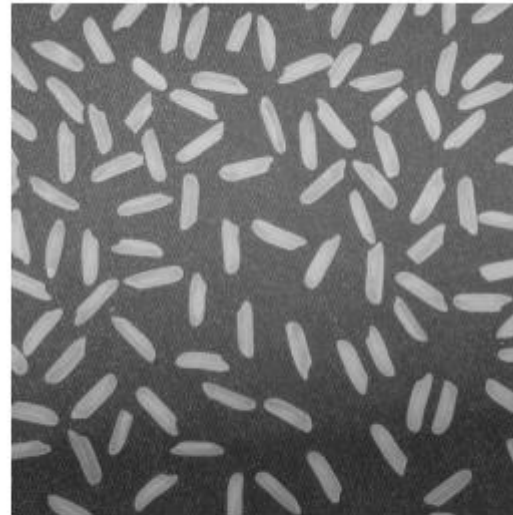
Examples: Interpolation

Bicubic Interpolation



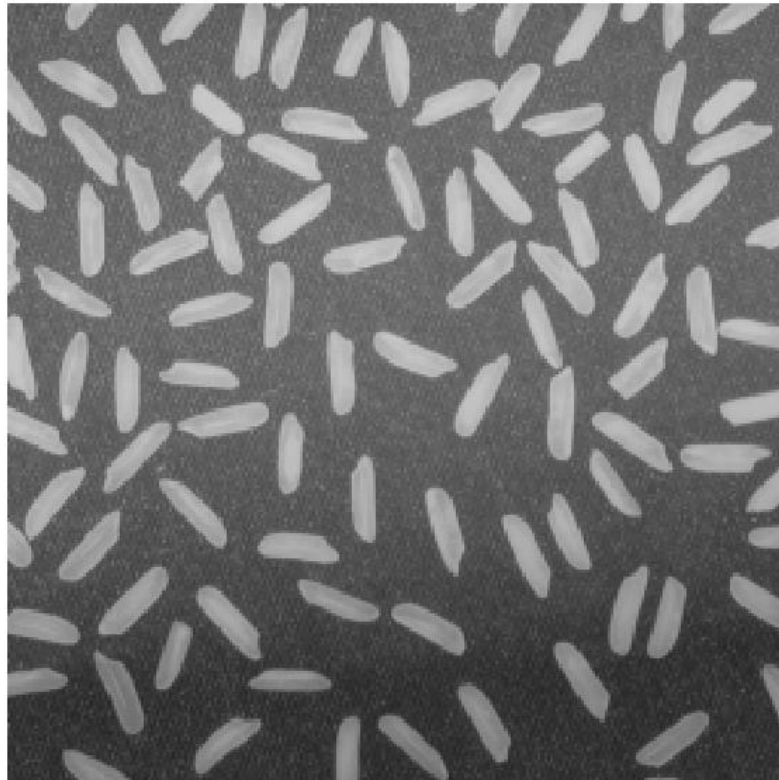
Examples: Interpolation

original image



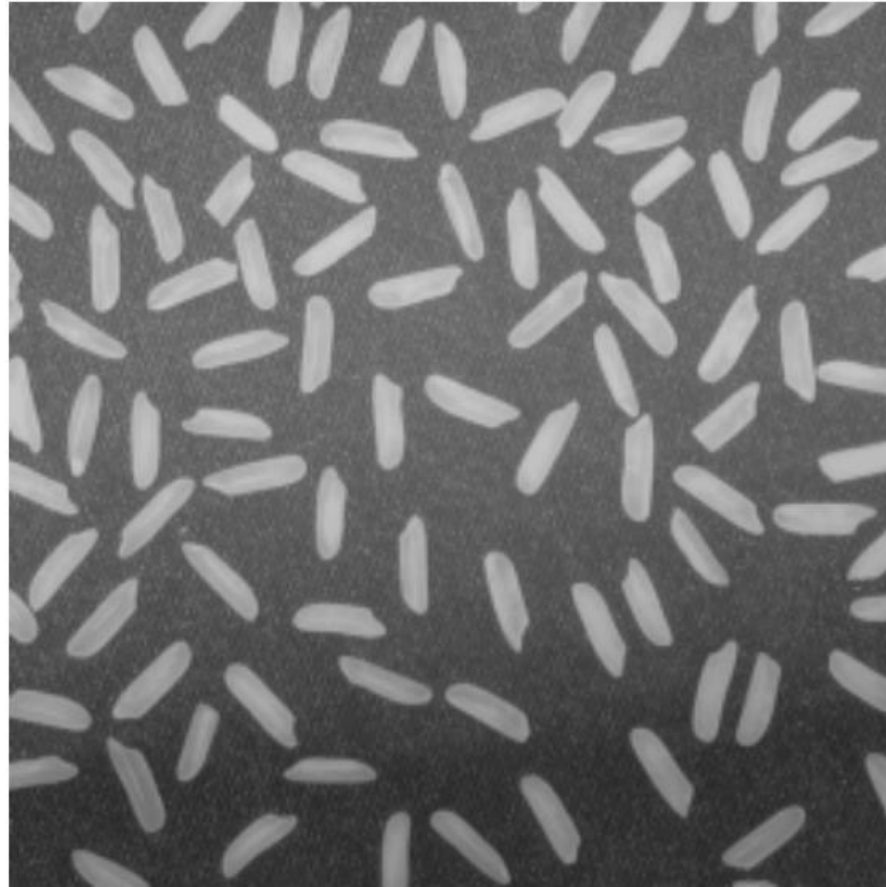
Examples: Interpolation

nearest



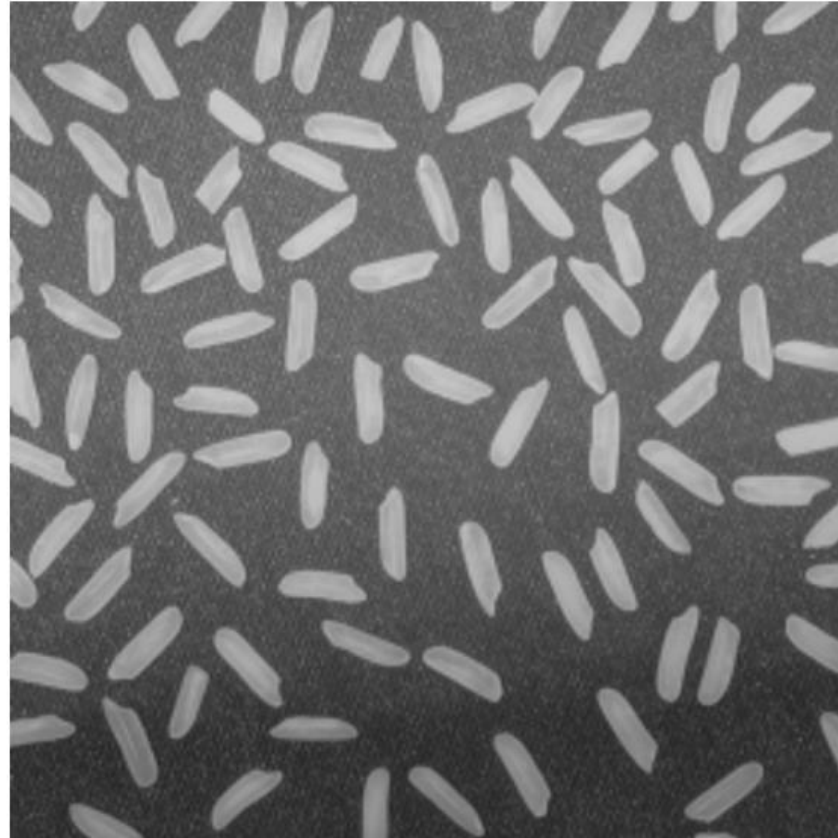
Examples: Interpolation

bilinear



Examples: Interpolation

bicubic



Basic Relationships Between Pixels

- Neighborhood
- Adjacency
- Connectivity
- Paths
- Regions and boundaries

Basic Relationships Between Pixels

- **Neighbors** of a pixel p at coordinates (x,y)
 - **4-neighbors of p** , denoted by $N_4(p)$:
 $(x-1, y)$, $(x+1, y)$, $(x, y-1)$, and $(x, y+1)$.
 - **4 diagonal neighbors of p** , denoted by $N_D(p)$:
 $(x-1, y-1)$, $(x+1, y+1)$, $(x+1, y-1)$, and $(x-1, y+1)$.
 - **8 neighbors of p** , denoted $N_8(p)$
$$N_8(p) = N_4(p) \cup N_D(p)$$

Basic Relationships Between Pixels

- **Adjacency**

Let V be the set of intensity values

- **4-adjacency**: Two pixels p and q with values from V are 4-adjacent if q is in the set $N_4(p)$.
- **8-adjacency**: Two pixels p and q with values from V are 8-adjacent if q is in the set $N_8(p)$.

Basic Relationships Between Pixels

- **Adjacency**

Let V be the set of intensity values

➤ **m-adjacency**: Two pixels p and q with values from V are m-adjacent if

(i) q is in the set $N_4(p)$, or

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

Basic Relationships Between Pixels

- **Path**

- A (digital) path (or curve) from pixel p with coordinates (x_0, y_0) to pixel q with coordinates (x_n, y_n) is a sequence of distinct pixels with coordinates

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

Where (x_i, y_i) and (x_{i-1}, y_{i-1}) are adjacent for $1 \leq i \leq n$.

- Here n is the *length* of the path.
- If $(x_0, y_0) = (x_n, y_n)$, the path is **closed** path.
- We can define 4-, 8-, and m-paths based on the type of adjacency used.

Examples: Adjacency and Path

$$\mathbf{V} = \{\mathbf{1}, \mathbf{2}\}$$

$$0 \ 1 \ 1$$
$$0 \ 1 \ 1$$
$$0 \ 1 \ 1$$
$$0 \ 2 \ 0$$
$$0 \ 2 \ 0$$
$$0 \ 2 \ 0$$
$$0 \ 0 \ 1$$
$$0 \ 0 \ 1$$
$$0 \ 0 \ 1$$

Examples: Adjacency and Path

$$\mathbf{V} = \{1, 2\}$$

0	1	1
0	2	0
0	0	1

0	1	1
0	2	0
0	0	1

0	1	1
0	2	0
0	0	1

8-adjacent

Examples: Adjacency and Path

$$\mathbf{V} = \{1, 2\}$$

0	1	1
0	2	0
0	0	1

0	1	1
0	2	0
0	0	1

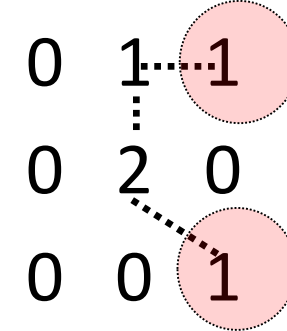
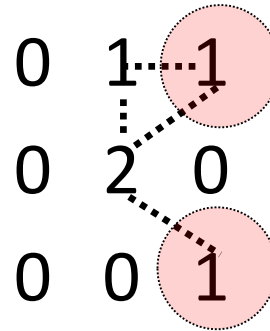
0	1	1
0	2	0
0	0	1

8-adjacent**m-adjacent**

Examples: Adjacency and Path

$$\mathbf{V} = \{1, 2\}$$

$$\begin{matrix} 0_{1,1} & 1_{1,2} & 1_{1,3} \\ 0_{2,1} & 2_{2,2} & 0_{2,3} \\ 0_{3,1} & 0_{3,2} & 1_{3,3} \end{matrix}$$



8-adjacent

m-adjacent

The 8-path from (1,3) to (3,3):

- (i) (1,3), (1,2), (2,2), (3,3)
- (ii) (1,3), (2,2), (3,3)

The m-path from (1,3) to (3,3):

- (1,3), (1,2), (2,2), (3,3)

Basic Relationships Between Pixels

- **Connected in S**

Let S represent a subset of pixels in an image. Two pixels p with coordinates (x_0, y_0) and q with coordinates (x_n, y_n) are said to be **connected in S** if there exists a path

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

Where $\forall i, 0 \leq i \leq n, (x_i, y_i) \in S$

Basic Relationships Between Pixels

Let S represent a subset of pixels in an image

- For every pixel p in S , the set of pixels in S that are connected to p is called a ***connected component*** of S .
- If S has only one connected component, then S is called ***Connected Set***.
- We call R a **region** of the image if R is a connected set
- Two regions, R_i and R_j are said to be ***adjacent*** if their union forms a connected set.
- Regions that are not to be adjacent are said to be ***disjoint***.

Basic Relationships Between Pixels

- **Boundary (or border)**

- The **boundary** of the region R is the set of pixels in the region that have one or more neighbors that are not in R .
- If R happens to be an entire image, then its boundary is defined as the set of pixels in the first and last rows and columns of the image.

- **Foreground and background**

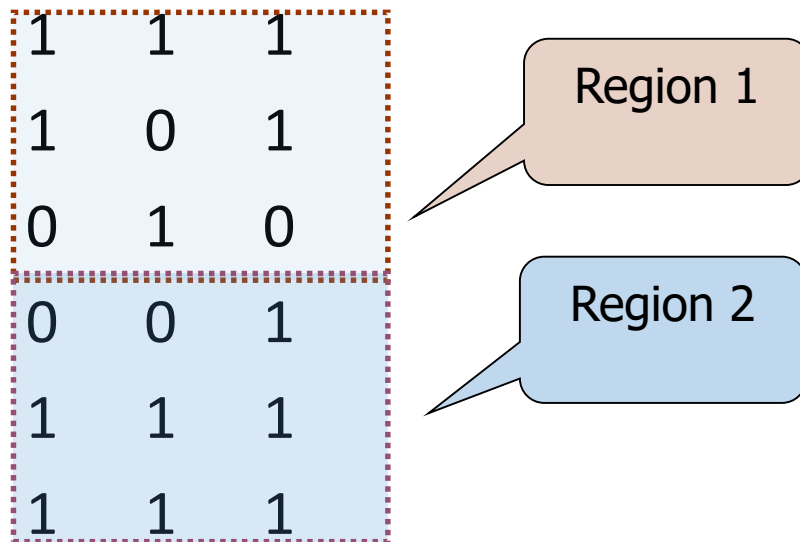
- An image contains K disjoint regions, R_k , $k = 1, 2, \dots, K$. Let R_u denote the union of all the K regions, and let $(R_u)^c$ denote its complement.

All the points in R_u is called **foreground**;

All the points in $(R_u)^c$ is called **background**.

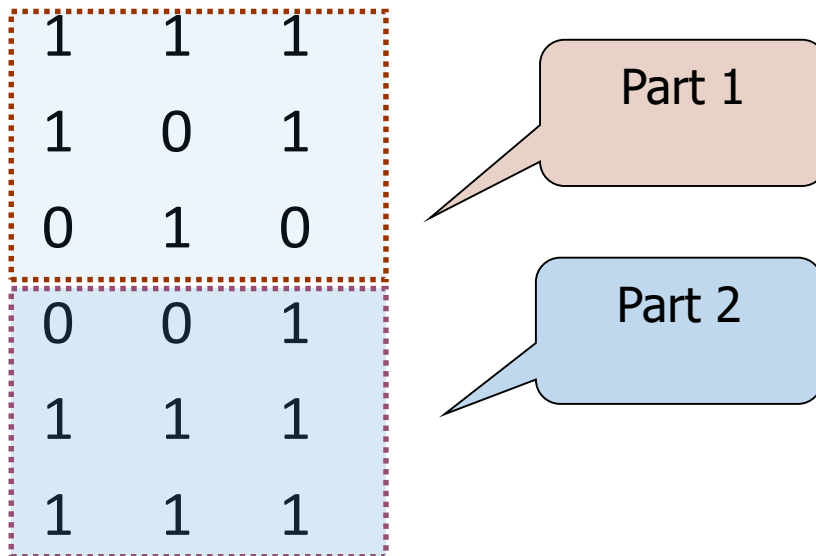
Question 1

- In the following arrangement of pixels, are the two regions (of 1s) adjacent? (if 8-adjacency is used)

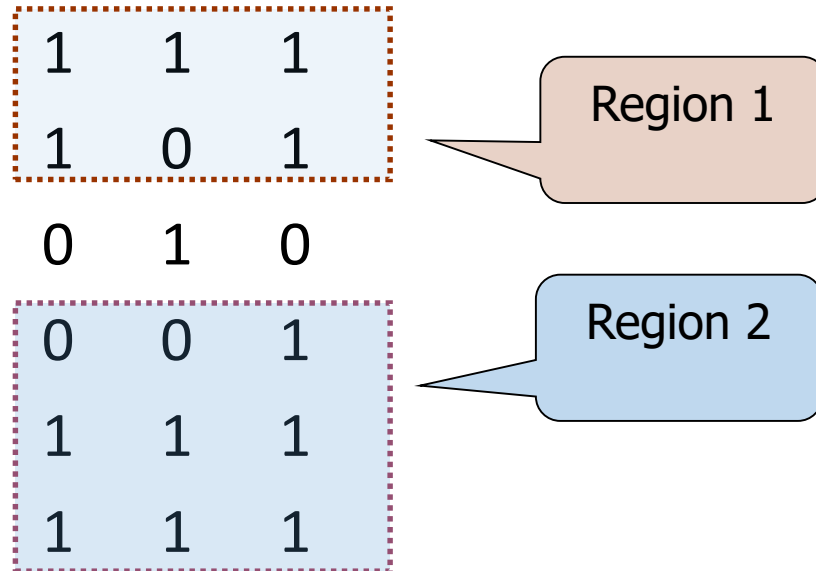


Question 2

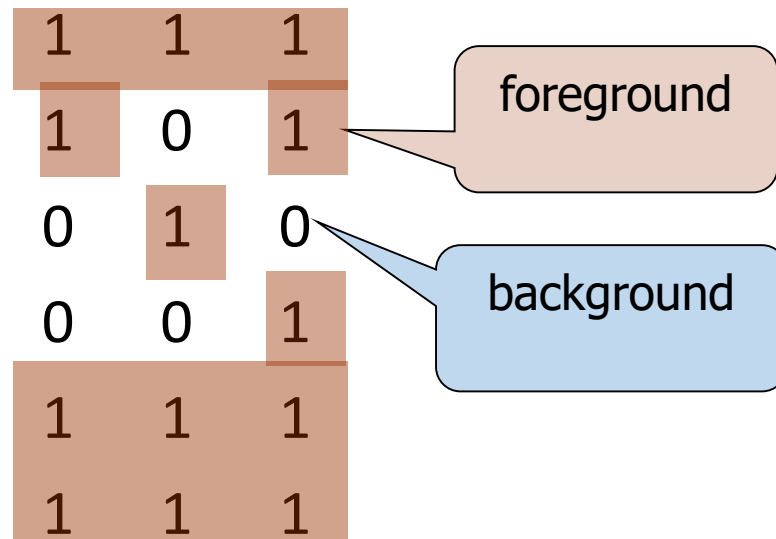
- In the following arrangement of pixels, are the two parts (of 1s) adjacent? (if 4-adjacency is used)



- In the following arrangement of pixels, the two regions (of 1s) are disjoint (if 4-adjacency is used)



- In the following arrangement of pixels, the two regions (of 1s) are disjoint (if 4-adjacency is used)



Question 3

- In the following arrangement of pixels, the circled point is part of the boundary of the 1-valued pixels if 8-adjacency is used, true or false?

0	0	0	0	0
0	1	1	0	0
0	1	1	0	0
0	1	1	1	0
0	1	1	1	0
0	0	0	0	0

Question 4

- In the following arrangement of pixels, the circled point is part of the boundary of the 1-valued pixels if 4-adjacency is used, true or false?

0	0	0	0	0
0	1	1	0	0
0	1	1	0	0
0	1	1	1	0
0	1	1	1	0
0	0	0	0	0

Distance Measures

- Given pixels p , q and z with coordinates (x, y) , (s, t) , (u, v) respectively, the distance function D has following properties:
 - a. $D(p, q) \geq 0$ [$D(p, q) = 0$, iff $p = q$]
 - b. $D(p, q) = D(q, p)$
 - c. $D(p, z) \leq D(p, q) + D(q, z)$

Distance Measures

The following are the different Distance measures:

a. Euclidean Distance :

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

b. City Block Distance:

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

		2		
	2	1	2	
2	1	0	1	2
	2	1	2	
		2		

c. Chess Board 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

Question 5

- In the following arrangement of pixels, what's the value of the chessboard distance between the circled two points?

0	0	0	0	0
0	0	1	1	0
0	1	1	0	0
0	1	0	0	0
0	0	0	0	0
0	0	0	0	0

Question 6

- In the following arrangement of pixels, what's the value of the city-block distance between the circled two points?

0	0	0	0	0
0	0	1	1	0
0	1	1	0	0
0	1	0	0	0
0	0	0	0	0
0	0	0	0	0

Question 7

- In the following arrangement of pixels, what's the value of the length of the m-path between the circled two points?

0	0	0	0	0
0	0	1	1	0
0	1	1	0	0
0	1	0	0	0
0	0	0	0	0
0	0	0	0	0