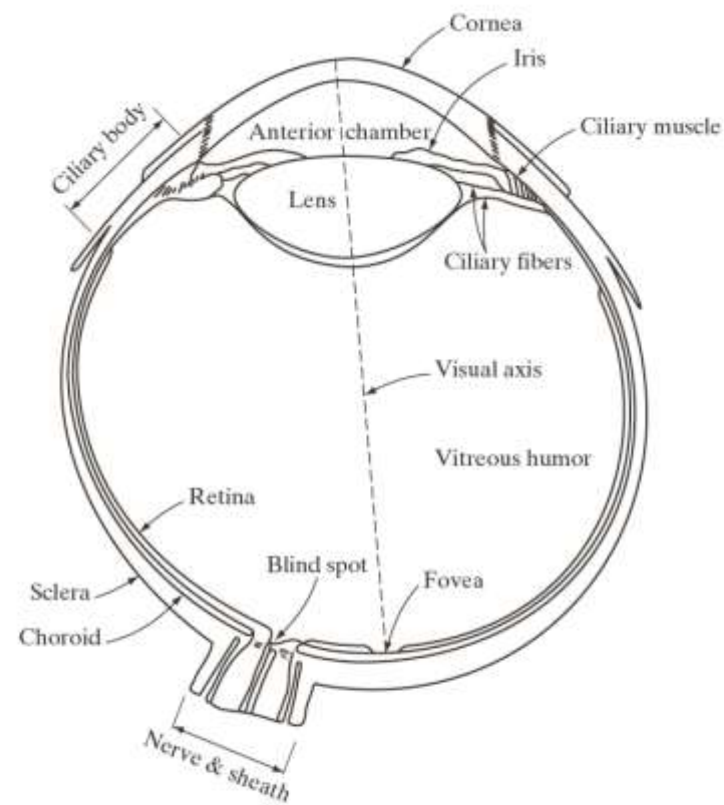
Structure of Human Eye

- Sphere in shape
- 20mm Average diameter
- Three membranes
  - Cornea and sclera
  - Choroid
  - Retina
- Light receptors over retina
  - Cones
  - rods



Cones and Rodes

- Cones are highly distributed at central portion of retina called fovea and less distributed over other regions of retina.
- 6 – 7 million
- Each cone is connected to a nerve end.
- Highly sensitive to color
- Photopic vision or Bright light vision or Day light vision

- Rodes are highly distributed over retina
- 75 to 150 million
- Several rods are connected to single nerve
- Overall picture of field of view
- Scotopic vision or Dimlight vision or Moon light vision

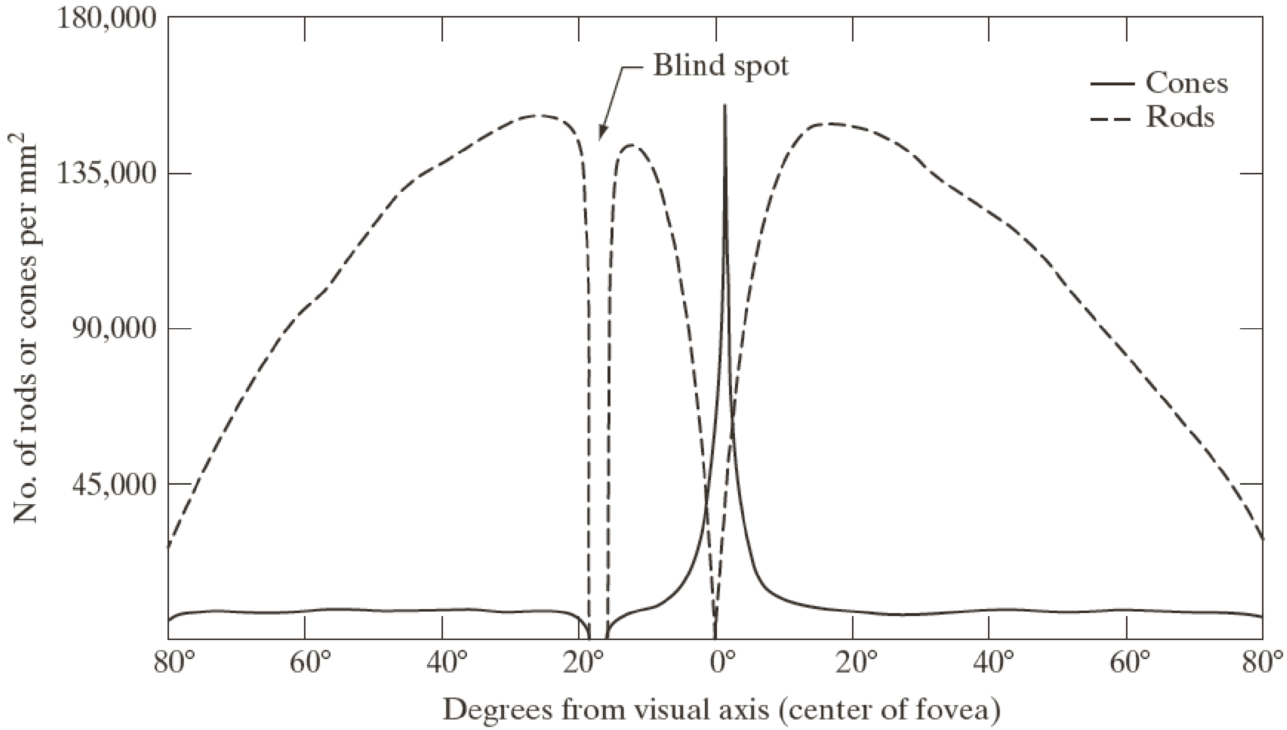


FIGURE 2.2 Distribution of rods and cones in the retina.

Image formation in the Eye

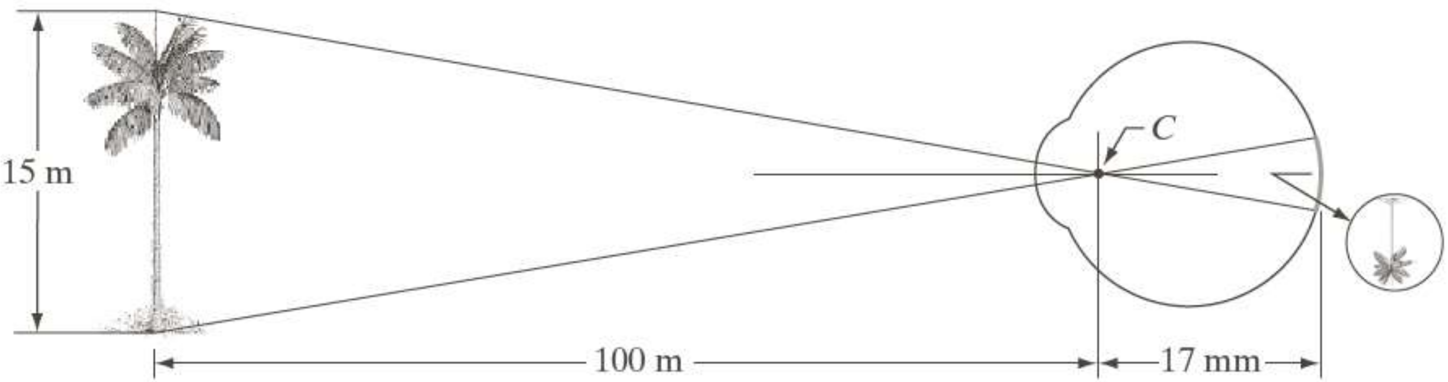


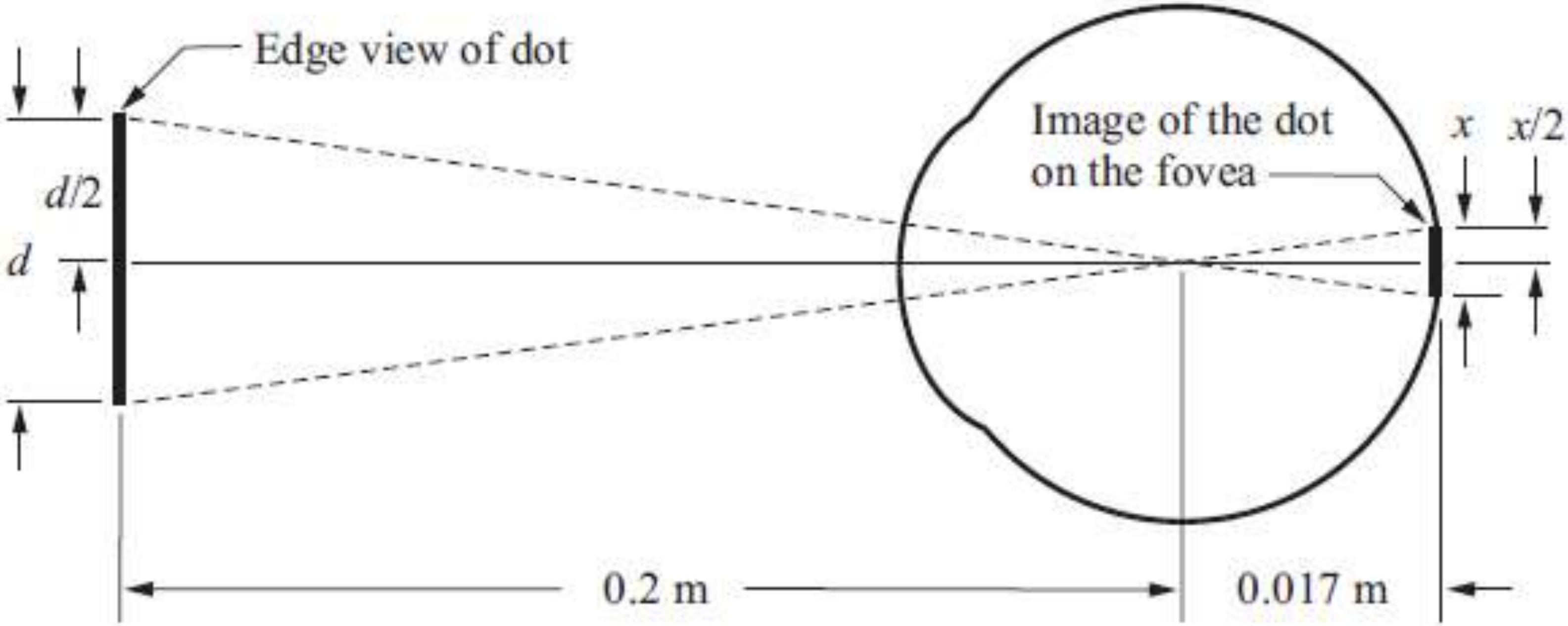
FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point *C* is the optical center of the lens.

- Let ‘h’ denote the height of the object in the retinal image.
- The geometry of the figure yields 15/100 = h/17
- So h = 2.55 mm

- Estimate the diameter of the smallest printed dot that eye can discern if the page on which the dot is printed is 0.2m away from the eyes.

  Assume that the visual system ceases to detect the dot when the image of the dot on the fovea becomes smaller than the diameter of one receptor(cone) in that area of the retina.

  Assume further that fovea can be modelled as square array of dimensions 1.5mm X 1.5mm, and that the cones and spaces between the cones are distributed uniformly through out the array.


Edge view of dot
d/2
d
Image of the dot
on the fovea
x
x/2
0.2 m
0.017 m

The diameter, x, of the retinal image corresponding to the dot is obtained from similar triangles, as shown in Fig. P2.1. That is,

$$\frac{(d/2)}{0.2} = \frac{(x/2)}{0.017}$$

which gives $x = 0.085d$. From the discussion in Section 2.1.1, and taking some liberties of interpretation, we can think of the fovea as a square sensor array having on the order of 337,000 elements, which translates into an array of size 580×580 elements. Assuming equal spacing between elements, this gives 580 elements and 579 spaces on a line 1.5 mm long. The size of each element and each space is then $s = [(1.5\text{mm})/1,159] = 1.3 \times 10^{-6}$ m. If the size (on the fovea) of the imaged dot is less than the size of a single resolution element, we assume that the dot will be invisible to the eye. In other words, the eye will not detect a dot if its diameter, d, is such that $0.085(d) < 1.3 \times 10^{-6}$ m, or $d < 15.3 \times 10^{-6}$ m.

Brightness Adaptation and Discrimination

- The range of light intensity levels to which human system can adapt is from scotopic threshold to Glare limit.
- Subjective brightness is a logarithmic function of the light incident on the eye.
- The long solid curve represents the range of intensities to which the visual system can adapt.

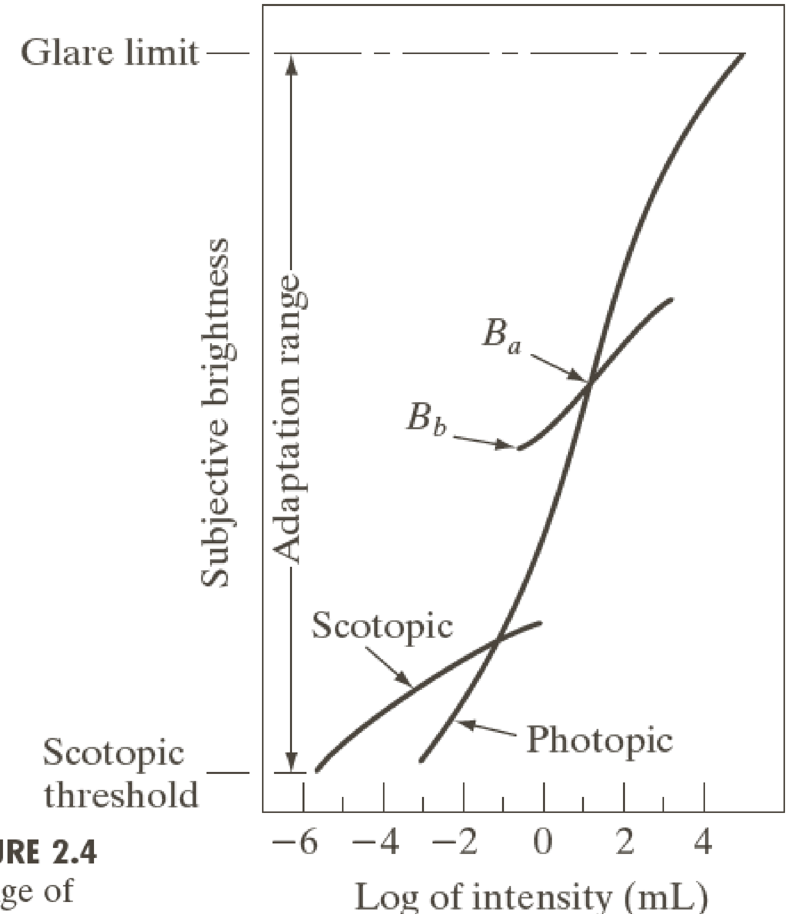
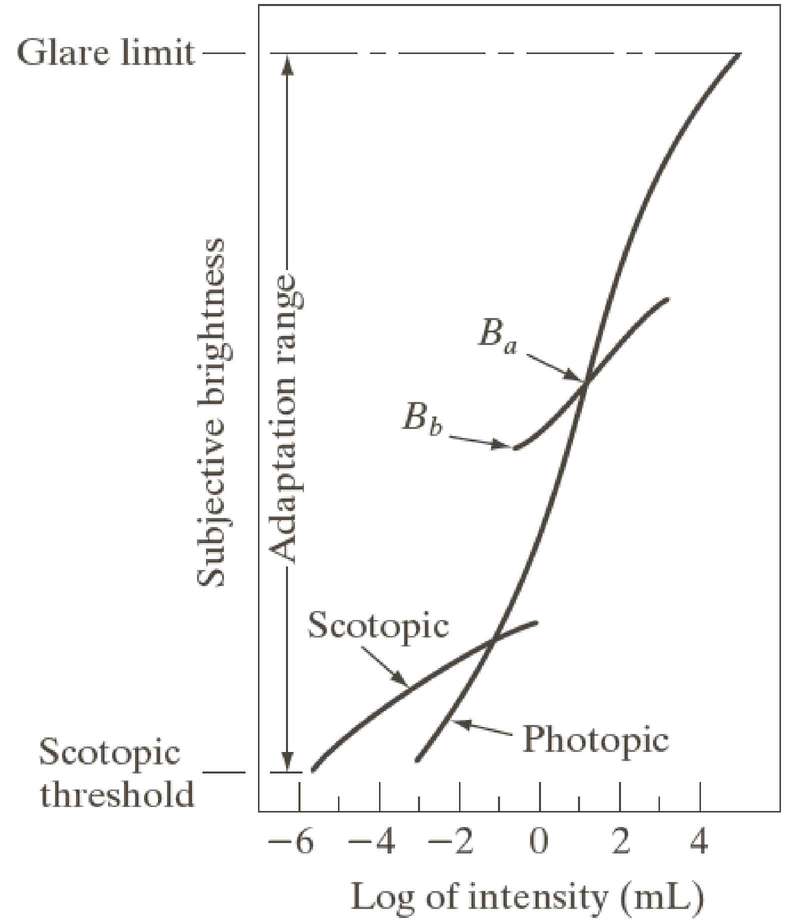
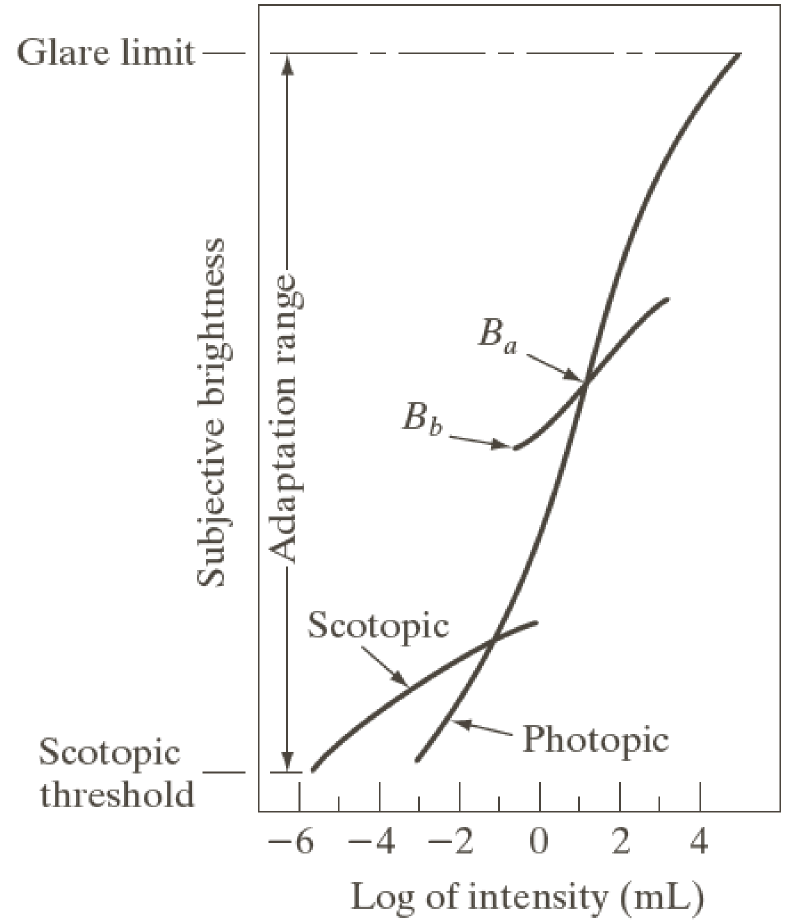


FIGURE 2.4 Range of subjective brightness sensations showing a particular adaptation level.

- The transition from scotopic to photopic vision is gradual over the approximate range from 0.001 to 0.1 millilambert (-3 to -1 mL in the log scale)
- The total range of distinct intensity levels a visual system can discriminate simultaneously is small when compared with the total adaptation range



- For any given set of conditions B_a is the brightness adaptation level.
- The range of subjective brightness that the eye can perceive when adapted to this level B_a is $B_a - B_b$
- B_b is the adaptation level at which all stimuli are perceived as indistinguishable blacks.



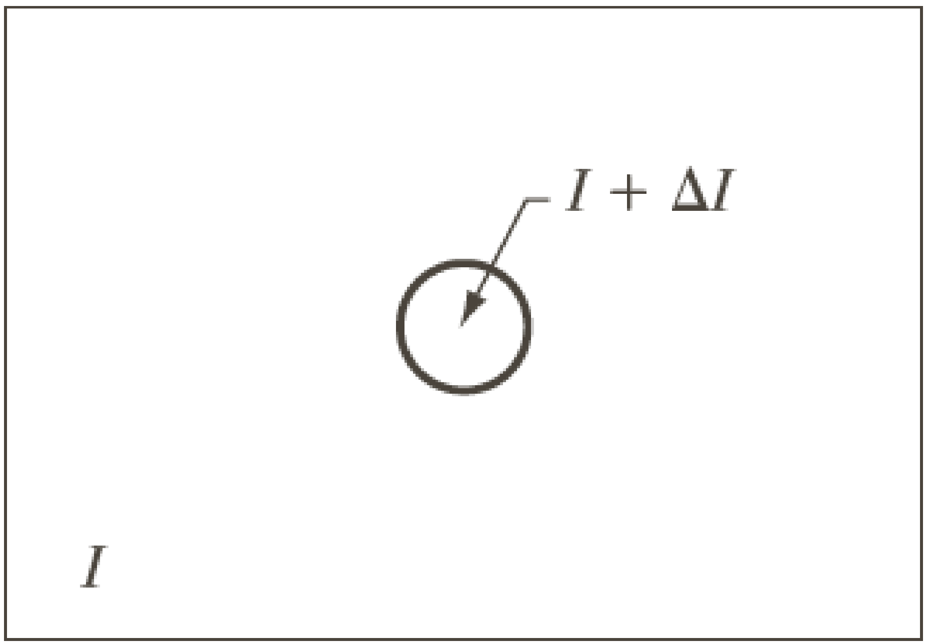


FIGURE 2.5 Basic experimental setup used to characterize brightness discrimination.

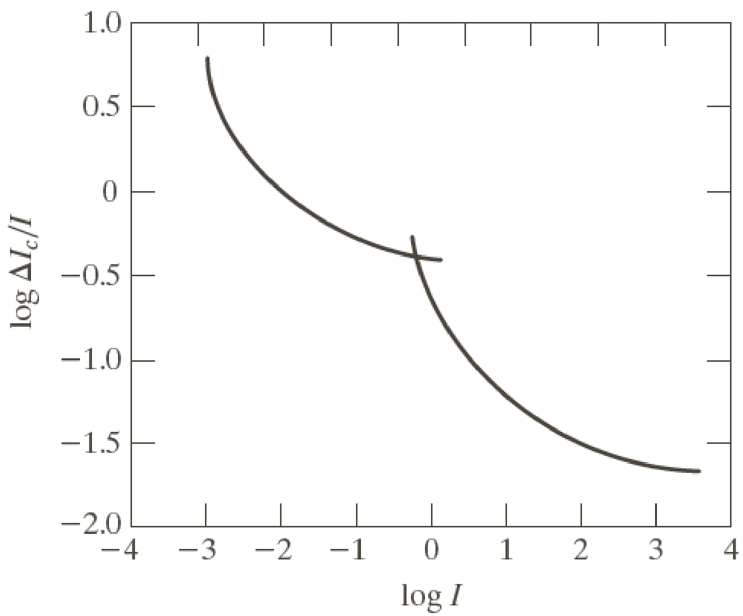
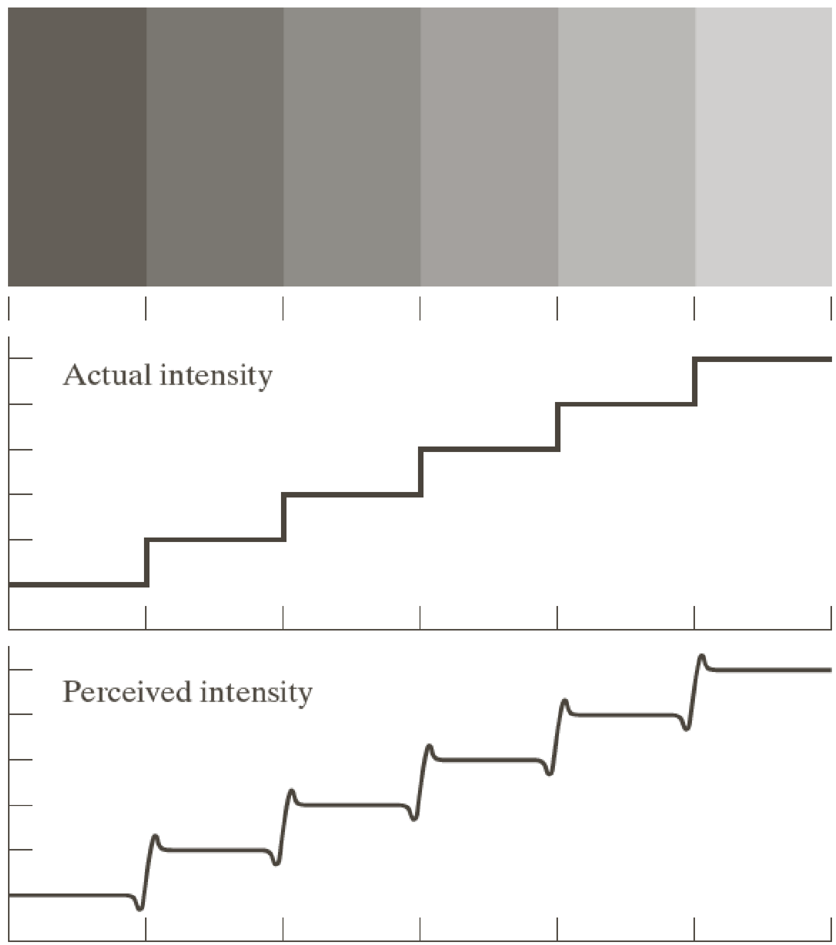
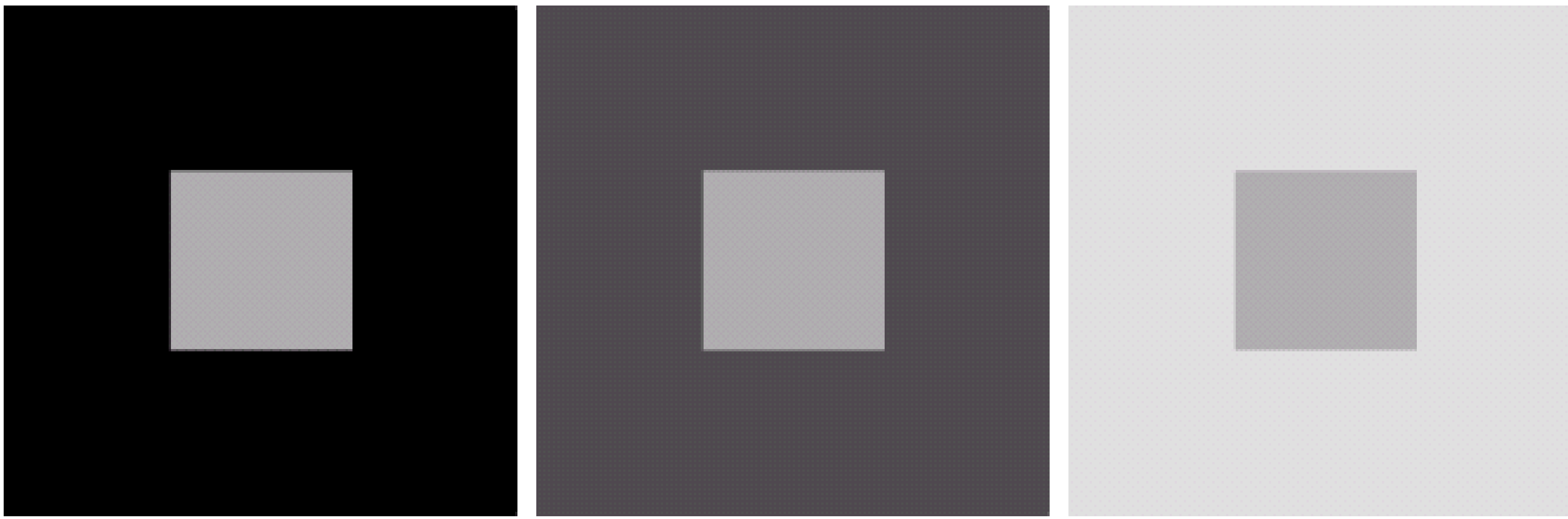


FIGURE 2.6 Typical Weber ratio as a function of intensity.



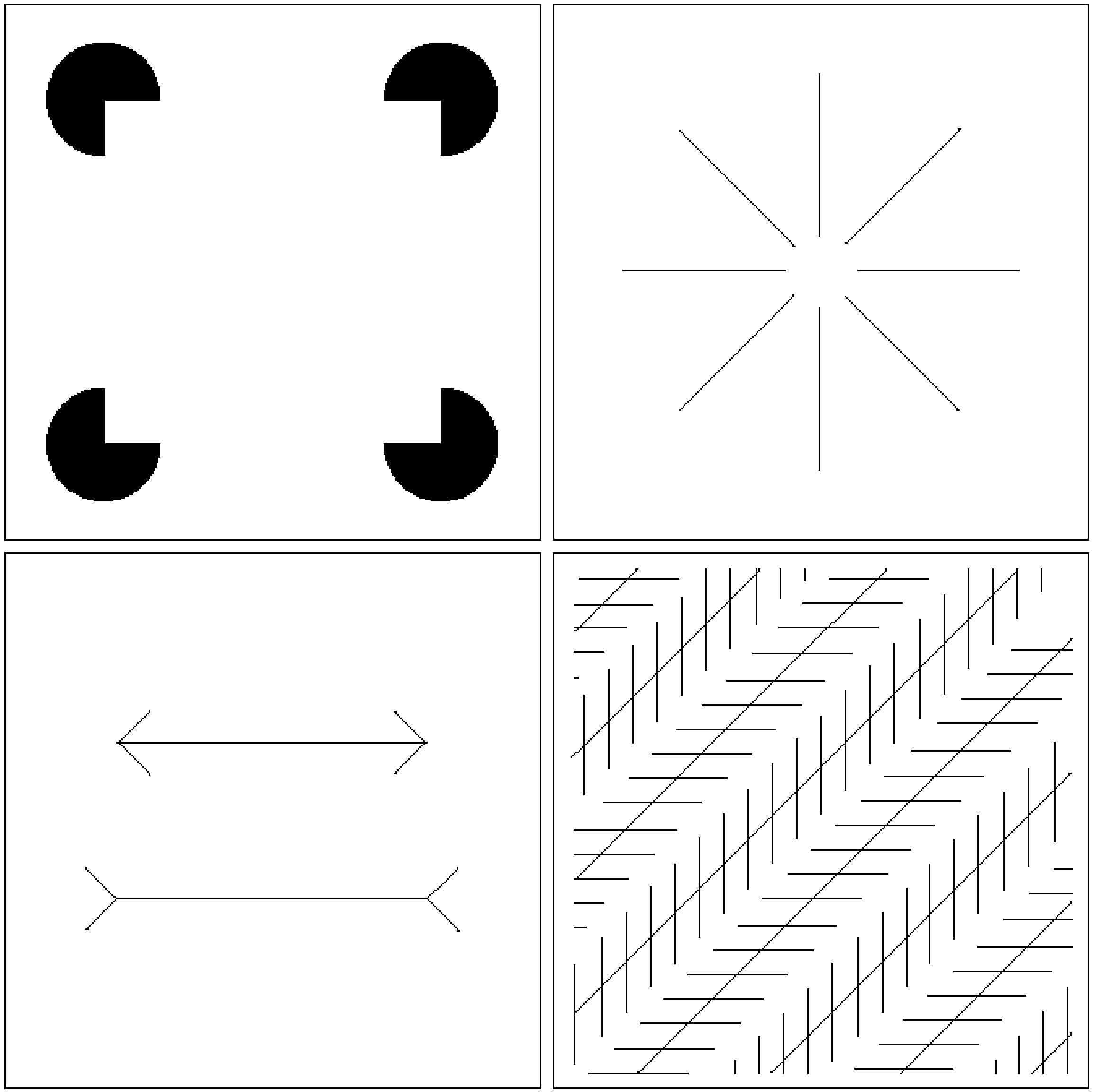
a
b
c

FIGURE 2.7 Illustration of the Mach band effect. Perceived intensity is not a simple function of actual intensity.



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.



a b
c d

FIGURE 2.9 Some well-known optical illusions.

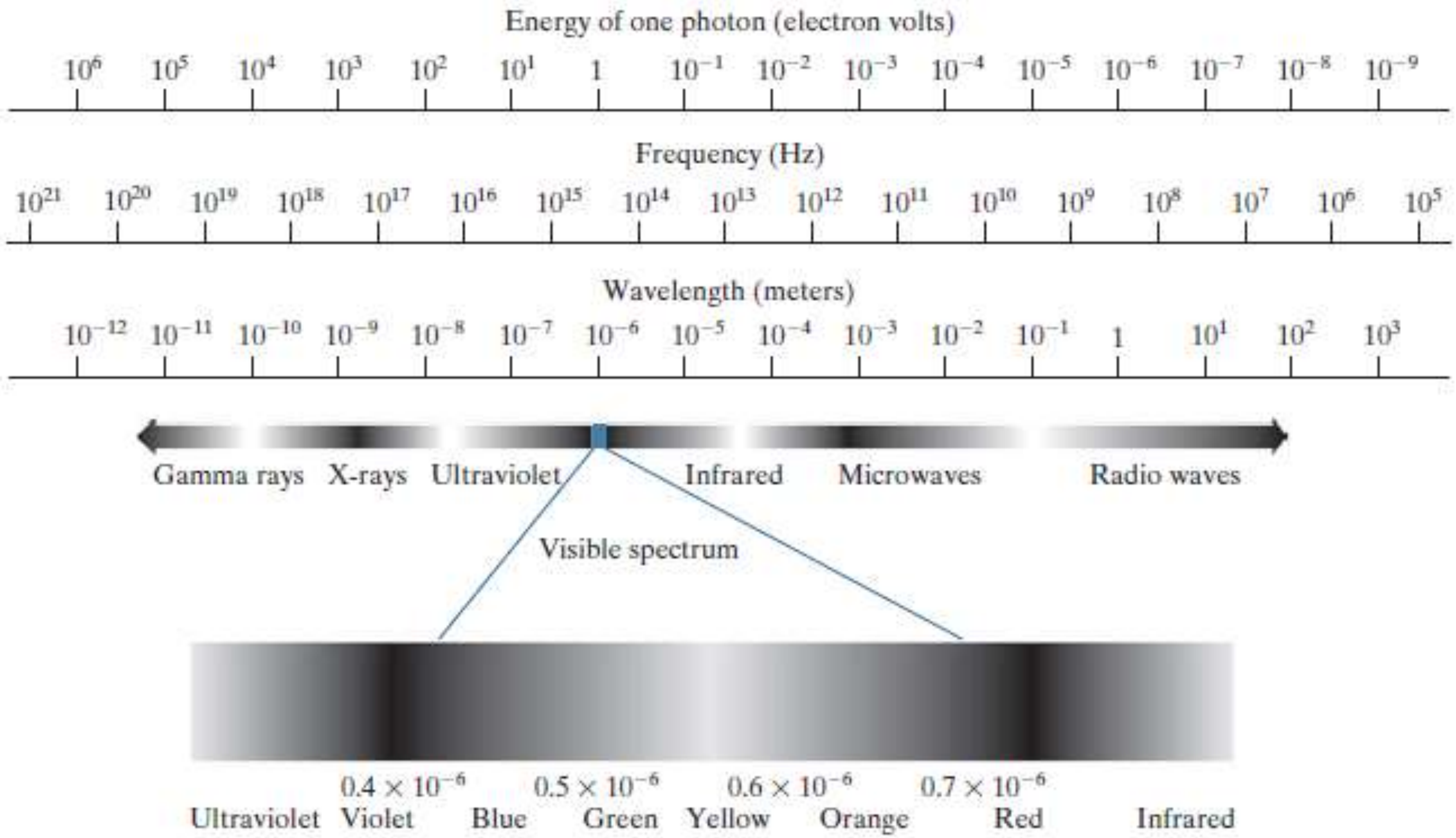
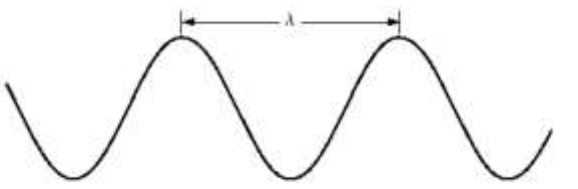


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanations, but note that it encompasses a very narrow range of the total EM spectrum.

- Wavelength(λ)and frequency(ν)are related by the expression

$$\lambda = \frac{c}{\nu}$$

FIGURE 2.11 Graphical representation of one wavelength.



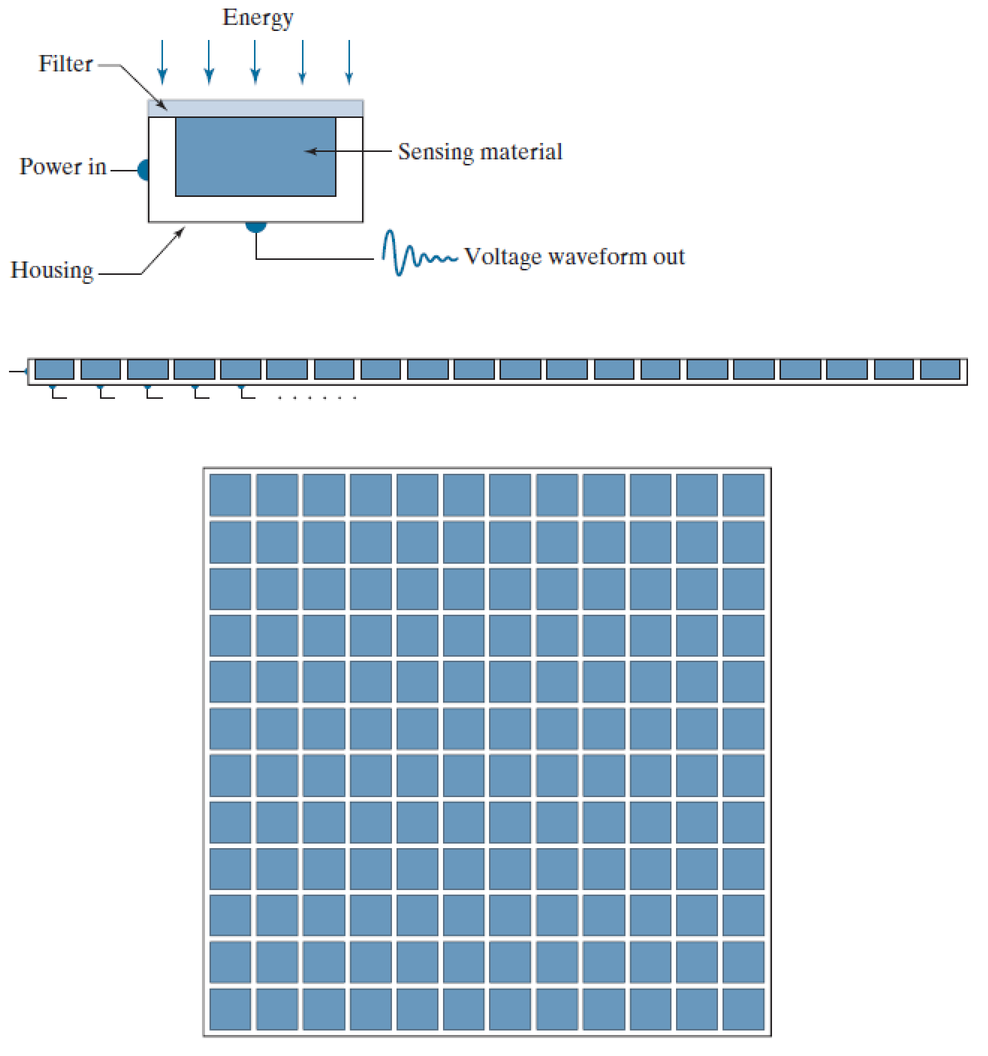
Monochromatic light

- Light that is void of color is called monochromatic (or achromatic) light.
- The only attribute of monochromatic light is its intensity.
- Vary from black to grays and finally to white.

Chromatic Light

- Light having colors
- Three basic quantities are used to describe the quality of a chromatic light
  - Radiance: is the total amount of energy that flows from the light source , measured in watts
  - Luminance : an amount of energy an observer perceives from a light source, measured in lumens
  - Brightness : is a subjective descriptor of light perception that is practically impossible to measure.

Image Sensing and Acquisition



a
b
c

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

IMAGE ACQUISITION USING A SINGLE SENSING ELEMENT

- Figure 2.12(a) shows the components of a single sensing element.
- A familiar sensor of this type is the photodiode, whose output is a voltage proportional to light intensity.
- In order to generate a 2-D image using a single sensing element, there has to be relative displacements in both the *x- and y-directions between the sensor and* the area to be imaged.
- Figure 2.13 shows an arrangement used in high-precision scanning, where a film negative is mounted onto a drum whose mechanical rotation provides displacement in one dimension.
- The sensor is mounted on a lead screw that provides motion in the perpendicular direction.
- A light source is contained inside the drum.
- As the light passes through the film, its intensity is modified by the film density before it is captured by the sensor.
- This "modulation" of the light intensity causes corresponding variations in the sensor voltage, which are ultimately converted to image intensity levels by digitization.

FIGURE 2.13 Combining a single sensing element with mechanical motion to generate a 2-D image.

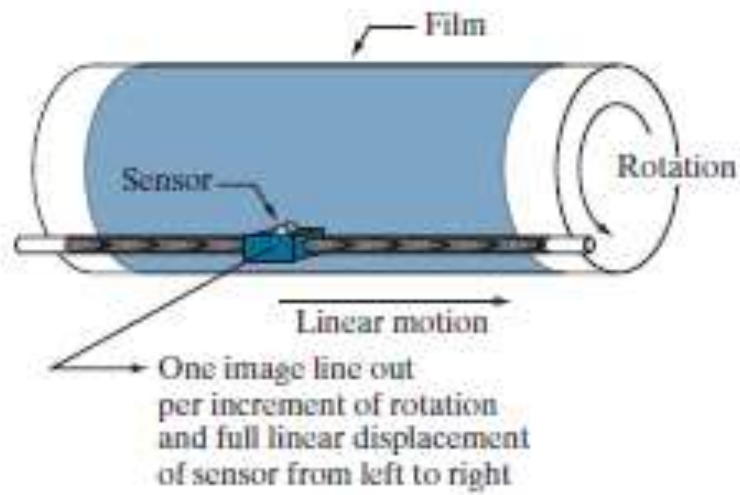


IMAGE ACQUISITION USING SENSOR STRIPS

- The strip provides imaging elements in one direction. Motion perpendicular to the strip provides imaging in the other direction, as shown in Fig. 2.14(a).
- In-line sensors are used routinely in airborne imaging applications, in which the imaging system is mounted on an aircraft that flies at a constant altitude and speed over the geographical area to be imaged.
- An imaging strip gives one line of an image at a time, and the motion of the strip relative to the scene completes the other dimension of a 2-D image.
- Sensor strips in a ring configuration are used in medical and industrial imaging to obtain cross-sectional (“slice”) images of 3-D objects, as Fig. 2.14(b) shows.
- A rotating X-ray source provides illumination, and X-ray sensitive sensors opposite the source collect the energy that passes through the object.
- This is the basis for medical and industrial computerized axial tomography (CAT) imaging.
- The output of the sensors is processed by reconstruction algorithms whose objective is to transform the sensed data into meaningful cross sectional images.

a b

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

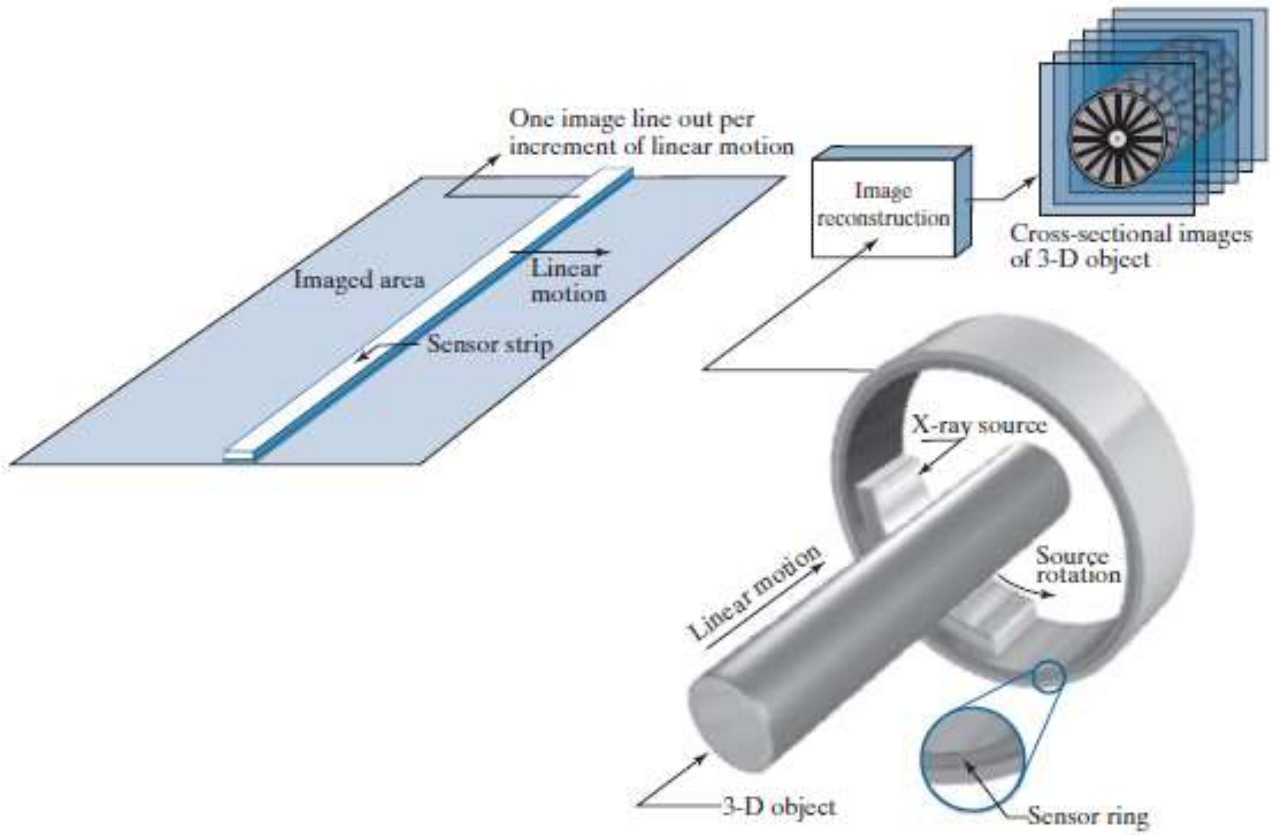


IMAGE ACQUISITION USING SENSOR ARRAYS

- Figure 2.12(c) shows individual sensing elements arranged in the form of a 2-D array.
- This is also the predominant arrangement found in digital cameras.
- A typical sensor for these cameras is a CCD (charge-coupled device) array, which can be manufactured with a broad range of sensing properties and can be packaged in rugged arrays of 4000 * 4000 elements or more.
- The response of each sensor is proportional to the integral of the light energy projected onto the surface of the sensor, a property that is used in astronomical and other applications requiring low noise images.
- Noise reduction is achieved by letting the sensor integrate the input light signal over minutes or even hours.
- Because the sensor array in Fig. 2.12(c) is two dimensional, its key advantage is that a complete image can be obtained by focusing the energy pattern onto the surface of the array.
- Motion obviously is not necessary, as is the case with the sensor arrangements discussed in the preceding two sections.

- Figure 2.15 shows the principal manner in which array sensors are used.
- This figure shows the energy from an illumination source being reflected from a scene.
- The first function performed by the imaging system in Fig.2.15(c) is to collect the incoming energy and focus it onto an image plane.
- If the illumination is light, the front end of the imaging system is an optical lens that projects the viewed scene onto the focal plane of the lens, as Fig. 2.15(d) shows.
- The sensor array, which is coincident with the focal plane, produces outputs proportional to the integral of the light received at each sensor.
- Digital and analog circuitry sweep these outputs and convert them to an analog signal, which is then digitized by another section of the imaging system.
- The output is a digital image, as shown diagrammatically in Fig. 2.15(e).

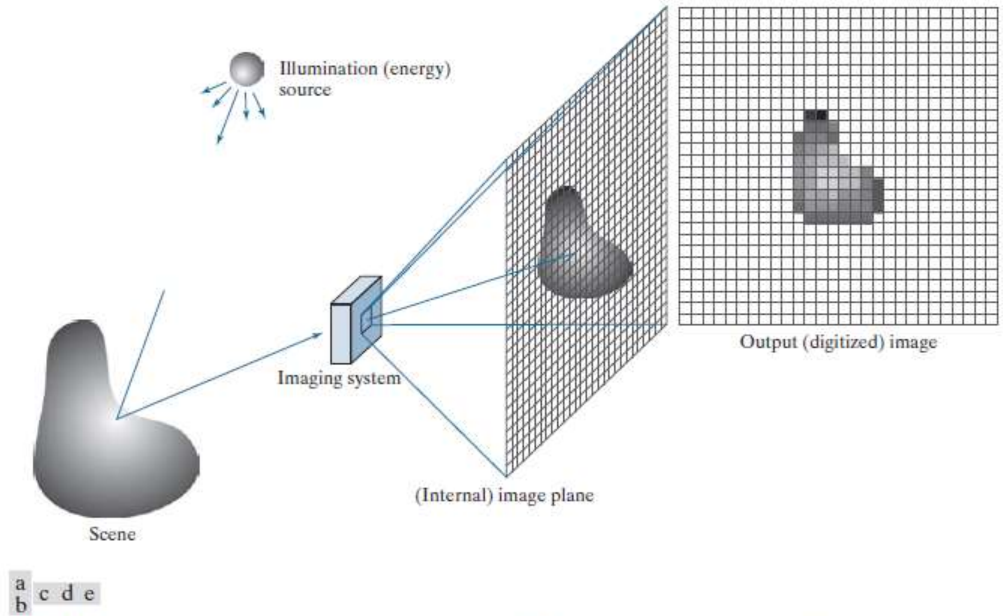


FIGURE 2.15 An example of digital image acquisition. (a) Illumination (energy) source. (b) A scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

A Simple Image Formation Model

- we denote images by two-dimensional functions of the form $f(x, y)$.
- *The value of f at spatial coordinates (x, y) is a scalar quantity*.
- As a consequence, *$f(x, y)$ must be nonnegative and finite; that is,*

  $0 \leq f(x, y) < \infty$
- Function *$f(x, y)$ is characterized by illumination and reflectance components; that is,*

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

  where $0 \leq i(x, y) < \infty$

  and $0 \leq r(x, y) \leq 1$

Image Sampling and Quantization

- An image may be continuous with respect to the *x- and y- coordinates, and also in* amplitude.
- To digitize it, we have to sample the function in both coordinates and also in amplitude.
- Digitizing the coordinate values is called *sampling*.
- *Digitizing the* amplitude values is called *quantization*

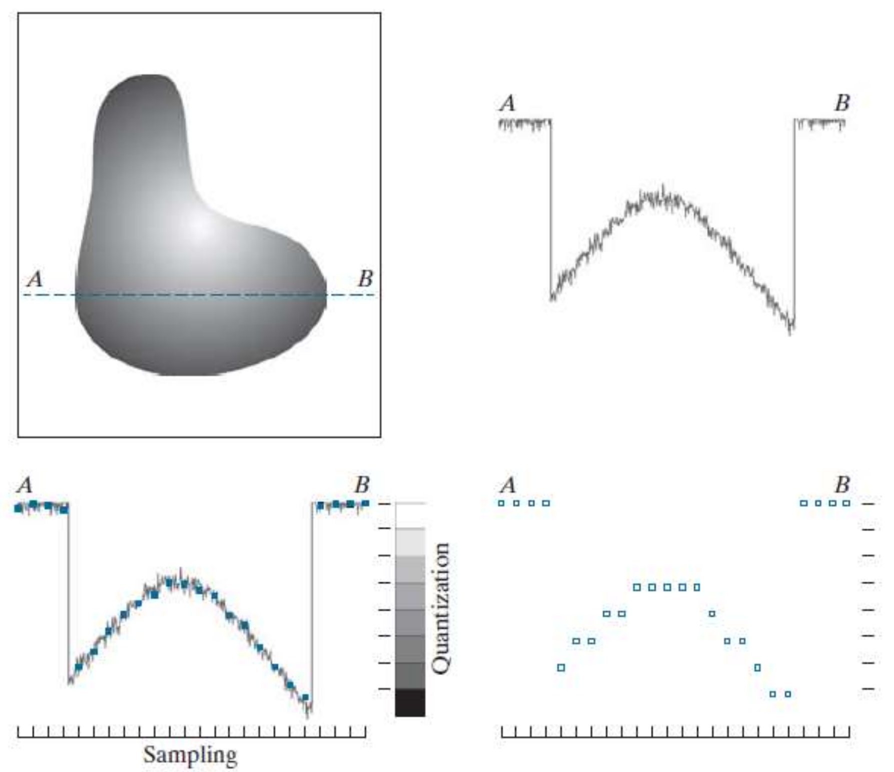
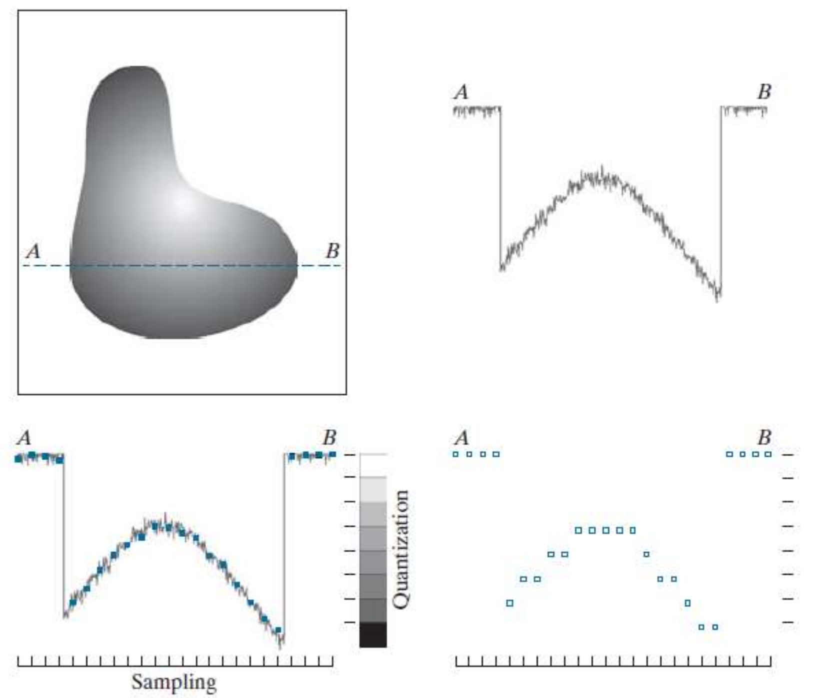


FIGURE 2.16 (a) Continuous image. (b) A scan line showing intensity variations along line *AB* in the continuous image. (c) Sampling and quantization. (d) Digital scan line. (The black border in (a) is included for clarity. It is not part of the image).

- The one-dimensional function in Fig. 2.16(b) is a plot of amplitude (intensity level) values of the continuous image along the line segment *AB in Fig. 2.16(a).*
- *The* random variations are due to image noise.
- To sample this function, we take equally spaced samples along line *AB, as shown in Fig. 2.16(c).*
- *The samples are shown as* small dark squares superimposed on the function, and their (discrete) spatial locations are indicated by corresponding tick marks in the bottom of the figure.



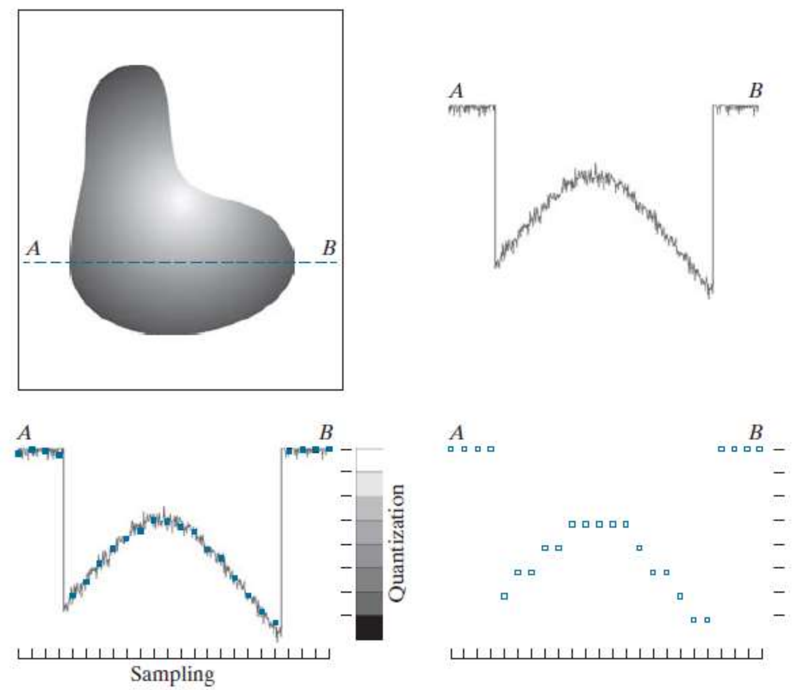
a b
c d

FIGURE 2.16 (a) Continuous image. (b) A scan line showing intensity variations along line *AB* in the continuous image. (c) Sampling and quantization. (d) Digital scan line. (The black border in (a) is included for clarity. It is not part of the image).

- The set of dark squares constitute the *sampled function. However, the values of the samples* still span (vertically) a continuous range of intensity values.
- In order to form a digital function, the intensity values also must be converted (*quantized) into discrete* quantities.
- The vertical gray bar in Fig. 2.16(c) depicts the intensity scale divided into eight discrete intervals, ranging from black to white.
- The vertical tick marks indicate the specific value assigned to each of the eight intensity intervals.

a b
c d

FIGURE 2.16 (a) Continuous image. (b) A scan line showing intensity variations along line *AB* in the continuous image. (c) Sampling and quantization. (d) Digital scan line. (The black border in (a) is included for clarity. It is not part of the image).



- The continuous intensity levels are quantized by assigning one of the eight values to each sample, depending on the vertical proximity of a sample to a vertical tick mark.
- The digital samples resulting from both sampling and quantization are shown as white squares in Fig. 2.16(d). Starting at the top of the continuous image and carrying out this procedure downward, line by line, produces a two-dimensional digital image

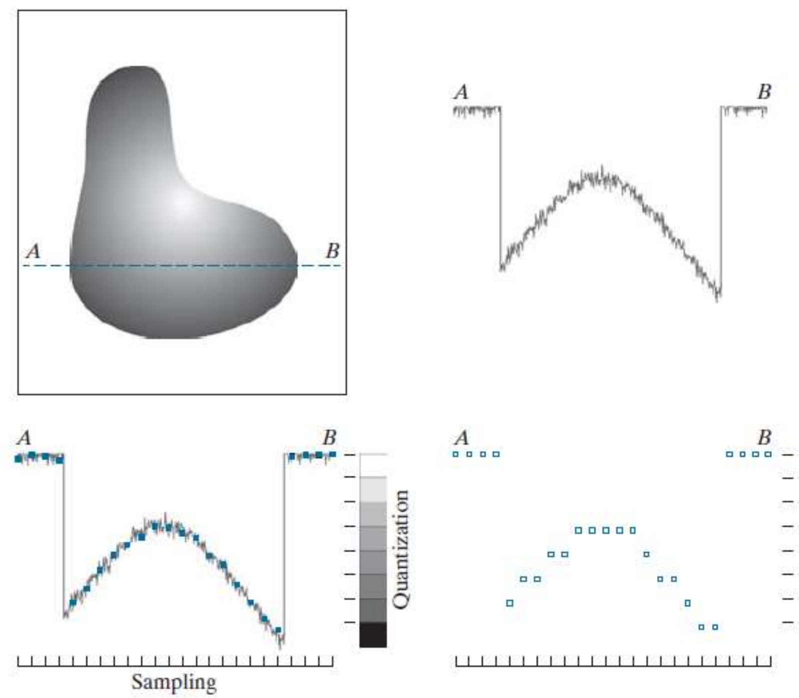


FIGURE 2.16 (a) Continuous image. (b) A scan line showing intensity variations along line AB in the continuous image. (c) Sampling and quantization. (d) Digital scan line. (The black border in (a) is included for clarity. It is not part of the image).

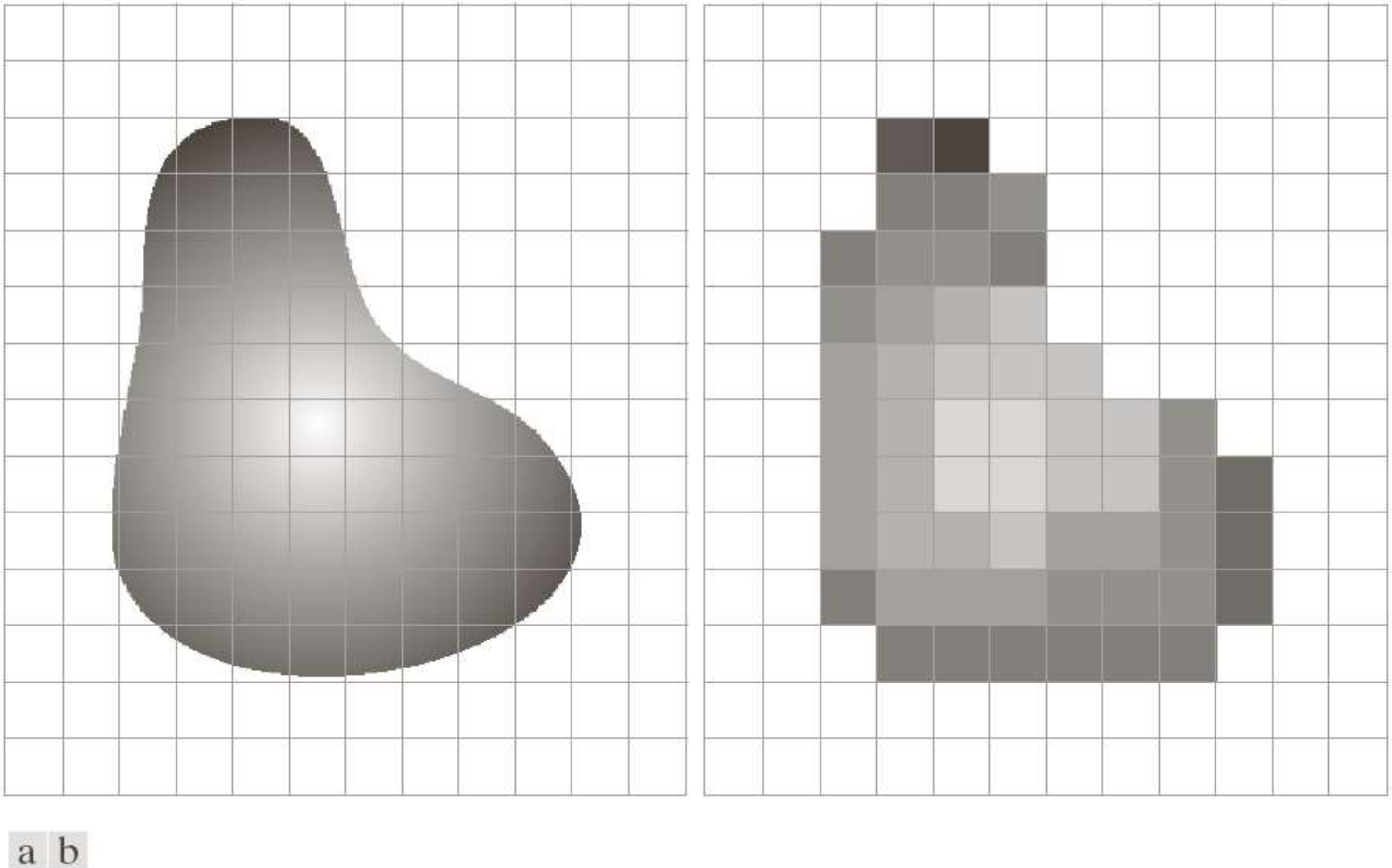


FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

Representing digital image

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

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

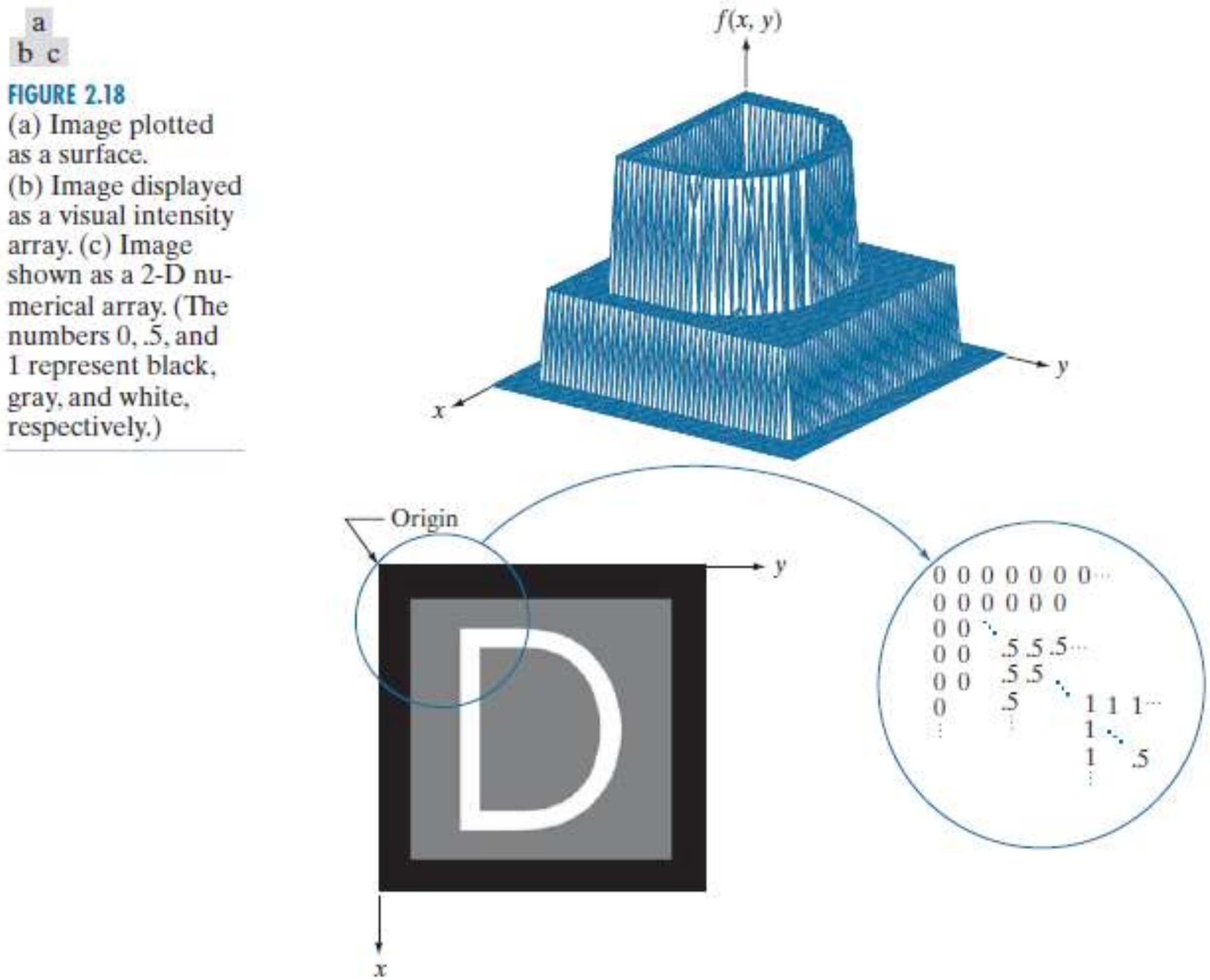


FIGURE 2.18 (a) Image plotted as a surface. (b) Image displayed as a visual intensity array. (c) Image shown as a 2-D numerical array. (The numbers 0, .5, and 1 represent black, gray, and white, respectively.)

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

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

Where M is the no. Of rows, N is the no. Of columns in the image and k is the number of bits to store a pixel.

The number of intensity levels in an image is L = 2^k

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

- Generally image transmission is accomplished in packets consisting of start bit, a byte of information and a stop bit. How many minutes would it take to transmit a 1024x1024 Image with 256 intensity levels using 56 K baud modem?

Sol:

The total amount of data (including the start and stop bit) in an 8-bit, 1024×1024 image, is

$$(1024\times1024)\times[8+2] \text{ bits.}$$

The total time required to transmit this image over a 56K baud link is

$(1024\times1024)\times[8+2] / 56000 = 187.25$ sec or about 3.1 min.

- *The difference in intensity between* the highest and lowest intensity levels in an image is called *image contrast*.
- The *contrast ratio is the ratio of* these two quantities.

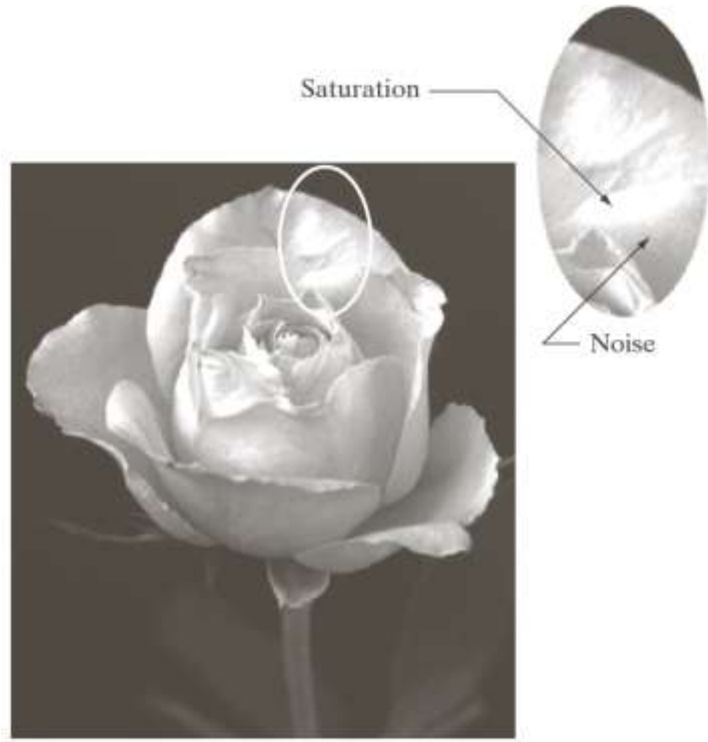


FIGURE 2.19 An image exhibiting saturation and noise. Saturation is the highest value beyond which all intensity levels are clipped (note how the entire saturated area has a high, *constant* intensity level). Noise in this case appears as a grainy texture pattern. Noise, especially in the darker regions of an image (e.g., the stem of the rose) masks the lowest detectable true intensity level.

Spatial Resolution

- It is a measure of the smallest discernable detail in an image.
- Quantitatively
  - Line pairs per unit distance
  - Dots (pixels) per unit distance
- Printing and publishing industry uses *dpi* (dots per inch)

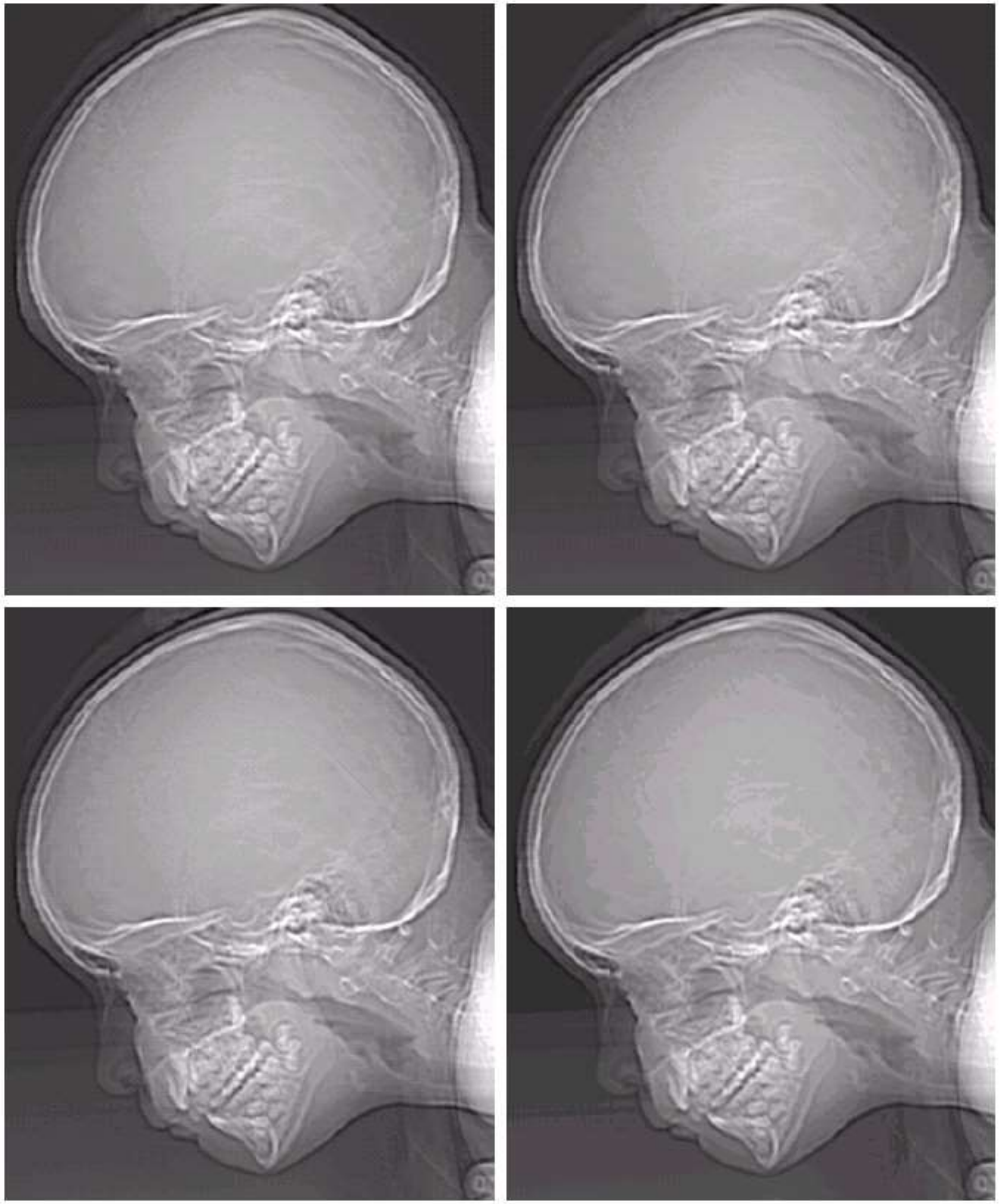
- Original image is of size 3692*2812 pixels
- Shown at 1250, 300, 150, and 72 dpi respectively
- 72 dpi image is an array of size 213*162 pixels.
- 3692/height = 1250/72 , so height at 72 dpi is 213.
- Similarly for width
- All the images are zoomed back to their original size for comparision purpose

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.

Intensity resolution

- It is the smallest discernible change in intensity level.
- Based on hardware, the number of intensity levels usually is an integer power of two.
- The most common number is 8 bits.
- 16 bits is used in some applications where enhancement of some intensity ranges is necessary.
- 32 bits is rare



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.

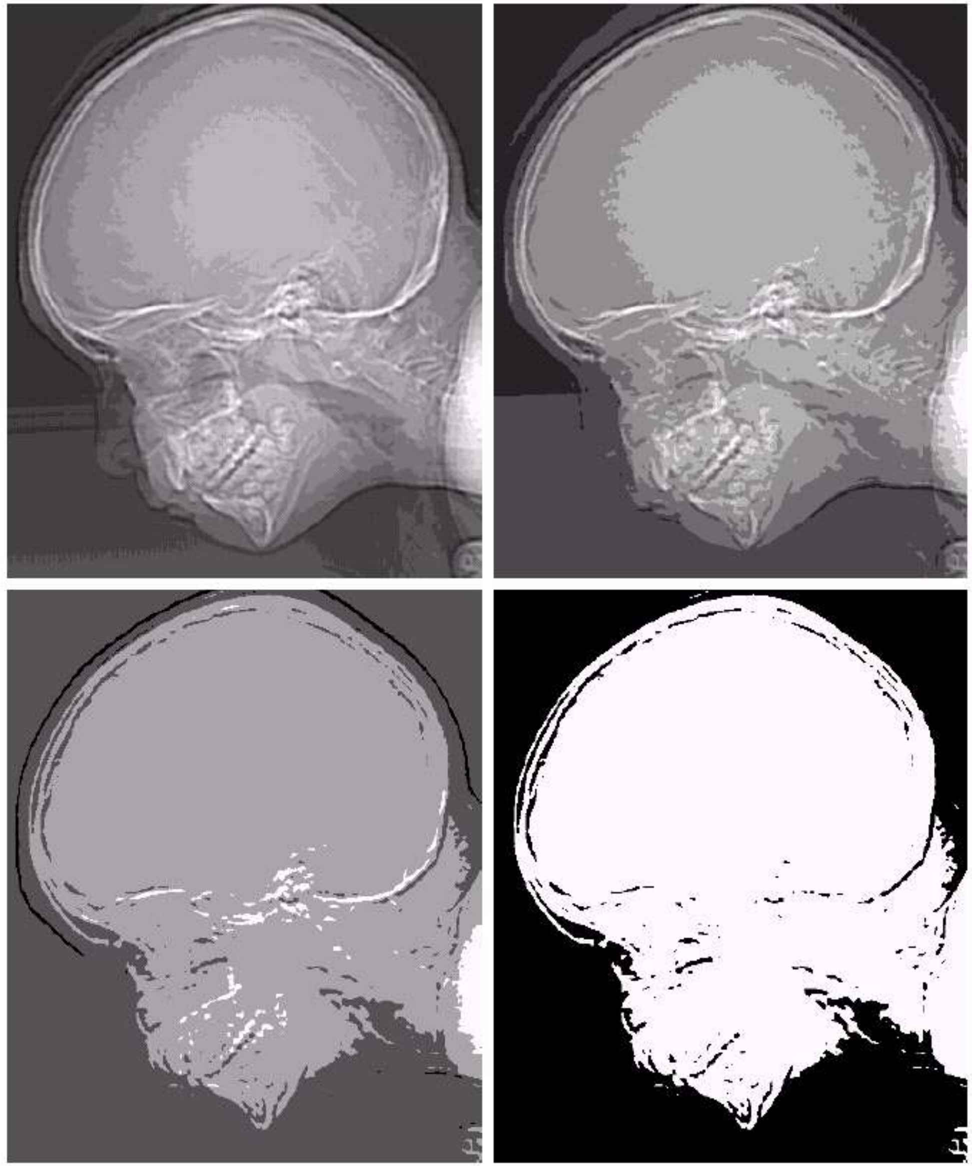


FIGURE 2.21 *(Continued)* (e)–(h) Image displayed in 16, 8, 4, and 2 gray levels. (Original courtesy of Dr. David R. Pickens, Department of Radiology & Radiological Sciences, Vanderbilt University Medical Center.)

Image interpolation

- Used in tasks like zooming, shrinking, rotation, and geometrically correcting digital images.
- Interpolation is the process of using known data to estimate values at unknown locations.
- Nearest neighbour interpolation
- Bilinear interpolation – four nearest neighbours

  $v(x,y) = ax + by + cxy + d$
- where the four coefficients are determined from the four equations in four unknowns that can be written using the *four nearest neighbours of point (x, y).*
- Bilinear interpolation gives much better results than nearest neighbour interpolation,
- with a modest increase in computational burden.
- Bicubic interpolation- sixteen nearest neighbours

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

EXAMPLE 2.4: Comparison of interpolation approaches for image shrinking and zooming.

Figure 2.27(a) is the same as Fig. 2.23(d), which was obtained by reducing the resolution of the 930 dpi image in Fig. 2.23(a) to 72 dpi (the size shrank from 2136×2140 to 165×166 pixels) and then zooming the reduced image back to its original size. To generate Fig. 2.23(d) we used nearest neighbor interpolation both to shrink and zoom the image. As noted earlier, the result in Fig. 2.27(a) is rather poor. Figures 2.27(b) and (c) are the results of repeating the same procedure but using, respectively, bilinear and bicubic interpolation for both shrinking and zooming. The result obtained by using bilinear interpolation is a significant improvement over nearest neighbor interpolation, but the resulting image is blurred slightly. Much sharper results can be obtained using bicubic interpolation, as Fig. 2.27(c) shows.

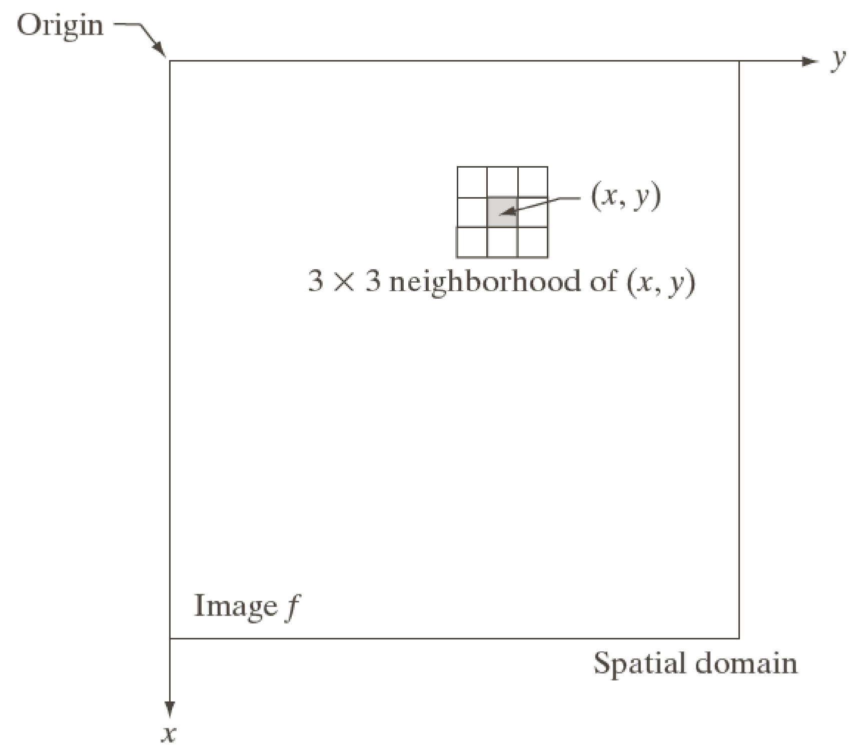
a b c

FIGURE 2.27 (a) Image reduced to 72 dpi and zoomed back to its original 930 dpi using nearest neighbor interpolation. This figure is the same as Fig. 2.23(d). (b) Image reduced to 72 dpi and zoomed using bilinear interpolation. (c) Same as (b) but using bicubic interpolation.

Neighbors of a pixel

- 4-neighbors of a pixel p at (x,y) are

  (x+1,y), (x-1,y), (x,y+1), (x,y-1)
- The four diagonal neighbors of p are (x+1,y+1), (x+1,y-1), (x-1,y+1),(x-1,y-1)
- All together called 8-neighbors of a pixel
- For a pixel at border of an image some of its neibors fall outside the image.



Adjacency

- Let V be the set of intensity values used to define adjacency.
- In a binary image, V = {1} if we are referring to adjacency of pixels with value 1.
- In a grayscale image, the idea is the same, but set V typically contains more elements.
- For example, if *we* are dealing with the adjacency of pixels whose values are in the range 0 to 255, set *V* could be any subset of these 256 values.
- We consider three types of adjacency:

1. 4-*adjacency*. Two pixels p and q with values from V are 4-adjacent if q is in the set $N_4(p)$.
2. 8-*adjacency*. Two pixels p and q with values from V are 8-adjacent if q is in the set $N_8(p)$.
3. *m-adjacency* (also called *mixed adjacency*). Two pixels p and q with values from V are m-adjacent if

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

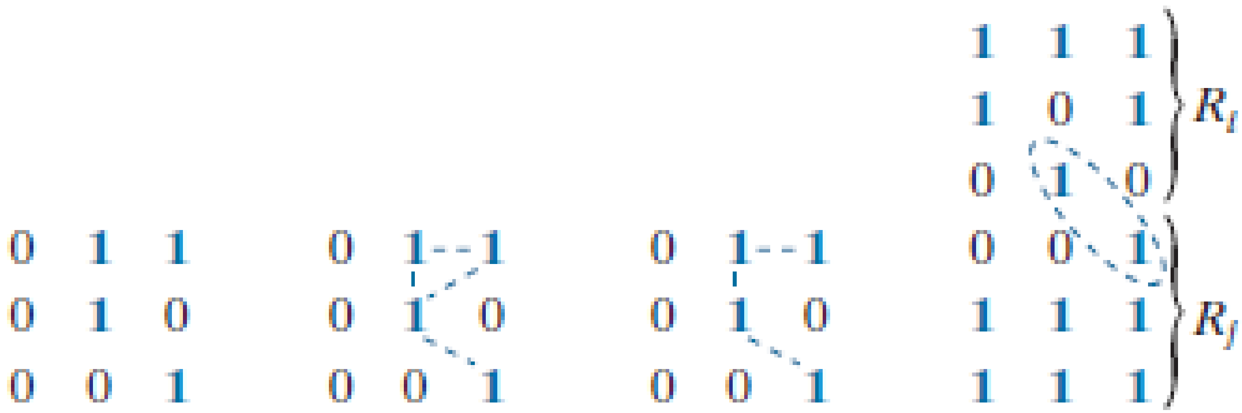
   (b) q is in $N_D(p)$ *and* the set $N_4(p) \cap N_4(q)$ has no pixels whose values are from V.

- Mixed adjacency is a modification of 8-adjacency, and is introduced to eliminate the ambiguities that may result from using 8-adjacency.

Path, Connectivity

- We can define 4-, 8-, or m- paths depending on the type of adjacency specified
- Let S represent a subset of pixels in an image.
- Two pixels are said to be connected in S if there exists a path between them consisting entirely of pixels in S.
- For any pixel p in S, the set of pixels that are connected to it in S is called a connected component of S.

4- , 8-, or m-paths, adjacent regions



- (a) An arrangement of pixels in a binary image
- (b) Pixels that are 8-adjacent
- (c) m-adjacency
- (d) Two regions that are 8-adjacent

Region

- If it only has one connected component, then the set S is called a connected set.
- Let R be a subset of pixels in an image.
- We call R a region of the image, if R is a connected set.
- Two regions, Ri and Rj are said to be adjacent if their union forms a connected set.