CHAPTER 2

DIGITAL IMAGE FUNDAMENTALS

CHAPTER 2: DIGITAL IMAGE FUNDAMENTALS

Cornea: tough, transparent tissue that covers the anterior surface of the eye.

Sclera: opaque membrane.

Lens: suspended by fibers attached to the ciliary body.

Absorbs ~8% of the visible light spectrum.

Infrared and ultraviolet light are also absorbed.

Choroid: contains a network of blood vessels.

Structure of the human eye

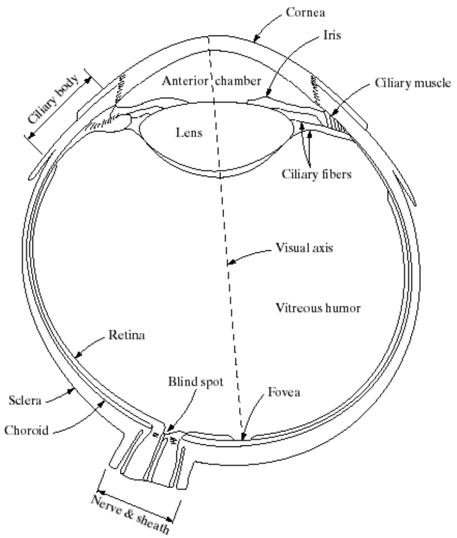


FIGURE 2.1 Simplified diagram of a cross section of the human eye.

Iris diaphragm: contracts or expands to control the amount of light.

Retina: innermost membrane.

Two types of receptors: cones and rods.

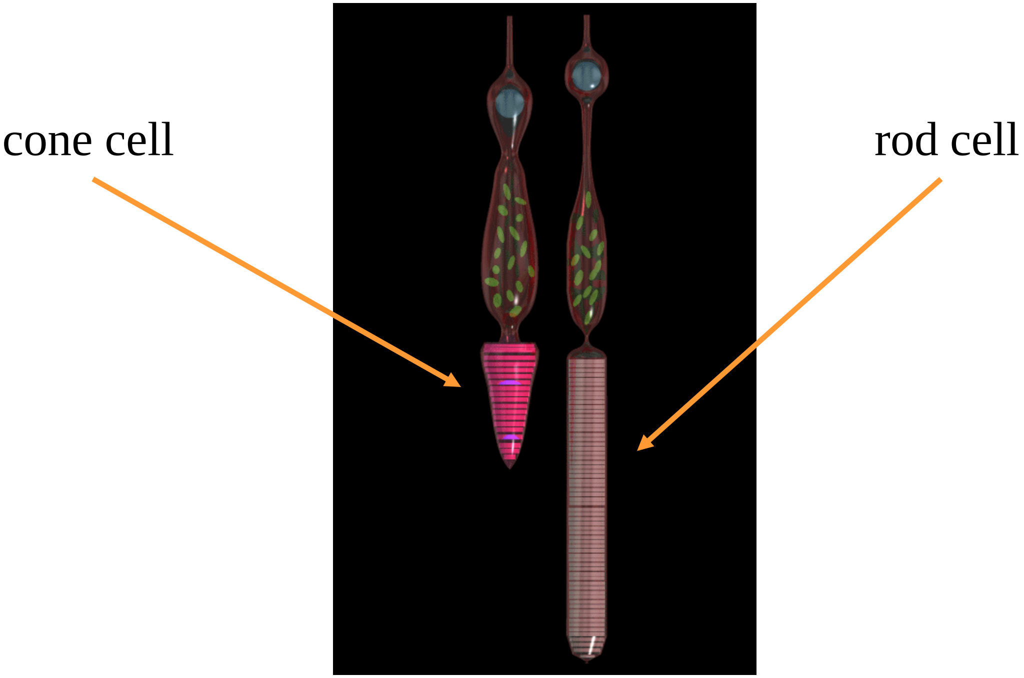
Cones: 6-7 million. Each connected to its own nerve end. Highly sensitive to color. Cone vision is called ***photopic*** vision.

Rods: 75-150 million. Several are connected to a single nerve end. Serve to give an overall picture of the field of view. Not involved in color vision. Rod vision is called ***scotopic*** vision.

Blind spot: the area on the retina without receptors that respond to light.

Fovea: Circular indentation in the retina (~1.5mm in diameter)

CONE AND ROD CELLS



DISTRIBUTION OF RODS AND CONES

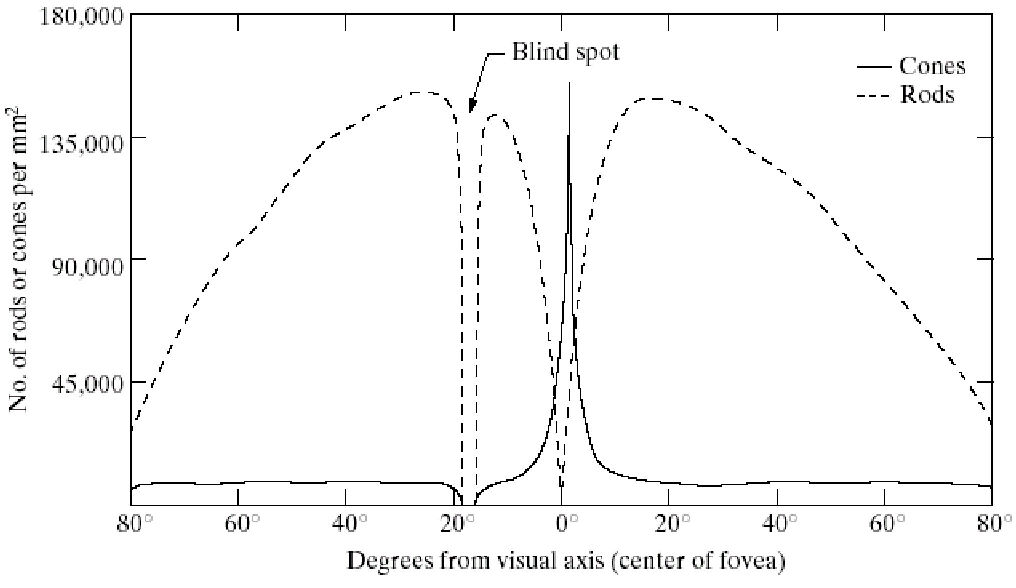


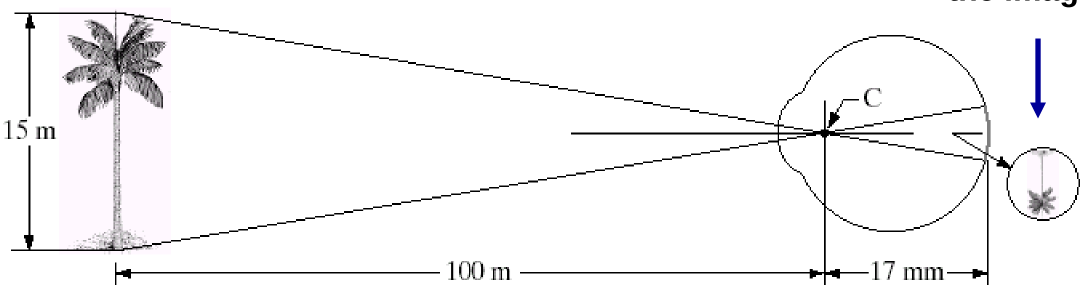
FIGURE 2.2 Distribution of rods and cones in the retina.

IMAGE FORMATION IN THE EYE

The receptors transform radiant energy into electrical impulses that are decoded by the brain.

What is the height of the image?

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



Focal length varies from 14mm to 17mm.

BRIGHTNESS ADAPTATION

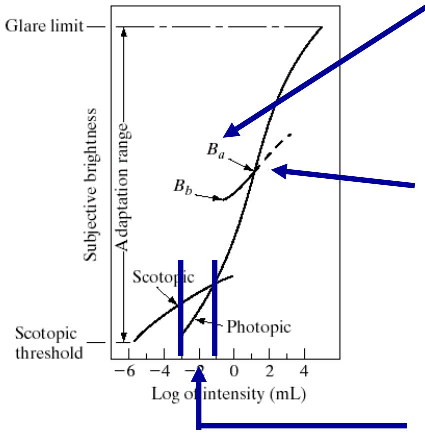
The range of light intensity levels to which the HVS can adapt is enormous – on the order of 10^{10}!

Experimental evidence indicates that subjective brightness is a logarithmic function of the light intensity.

However, the HVS cannot operate over such a range simultaneously.

Brightness adaptation: the total range of distinct intensity levels that can be discriminated is rather small.

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



Brightness adaptation level: the current sensitivity level of the HVS for any given set of conditions.

Short curve represents the range of subjective brightness the eye can perceive at this level.

The transition from scotopic to photopic vision is gradual (-3 to -1 mL in log scale).

BRIGHTNESS DISCRIMINATION

How does the eye discriminate between changes in light intensity at a specific adaptation level?

A classical experiment:

- **A subject looks at a flat, uniformly illuminated area (large enough to occupy the entire field of view).**
- **The intensity *I* can be varied.**
- **ΔI is added in the form of a short-duration flash that appears as a circle in the middle.**
- **If ΔI is not bright enough, the subject says "no."**
- **As ΔI gets stronger, the subject may say "yes."**
- **When ΔI is stronger enough, the subject will say "yes" all the time.**
- **Weber ratio: $\Delta I_c / I$, ΔI_c: increment of illumination discriminable 50% of the time with background illumination *I*.**

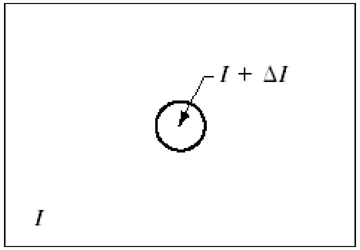
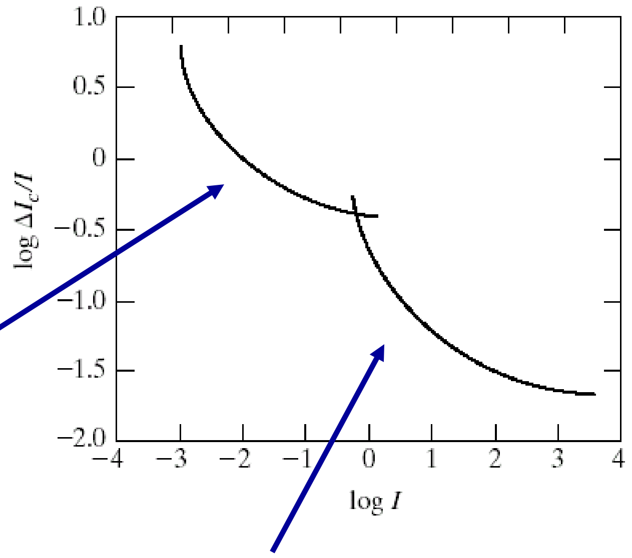


FIGURE 2.5 Basic experimental setup used to characterize brightness discrimination.

WEBER RATIO AS FUNCTION OF INTENSITY

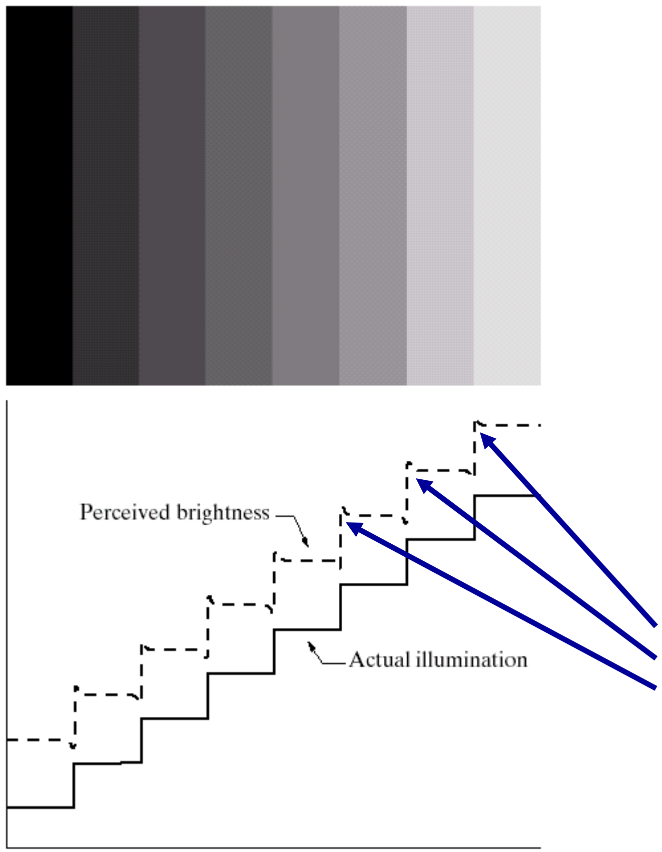
FIGURE 2.6
Typical Weber ratio as a function of intensity.



Poor brightness discrimination: A large value of $\Delta I_c / I$ means a large percentage change in intensity is discriminable.

Good brightness discrimination: A small value of $\Delta I_c / I$ means a small percentage change in intensity is discriminable.

PERCEIVED BRIGHTNESS: NOT A SIMPLE FUNCTION OF INTENSITY – MACH BANDS



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.

The HVS tends to undershoot or overshoot around the boundary of regions of different intensities.

The intensities of the stripes is constant but we perceive a brightness pattern that is strongly scalloped, especially near the boundaries.

PERCEIVED BRIGHTNESS: NOT A SIMPLE FUNCTION OF INTENSITY – SIMULTANEOUS CONTRAST

A region's perceived brightness does not simply depend on its intensity.

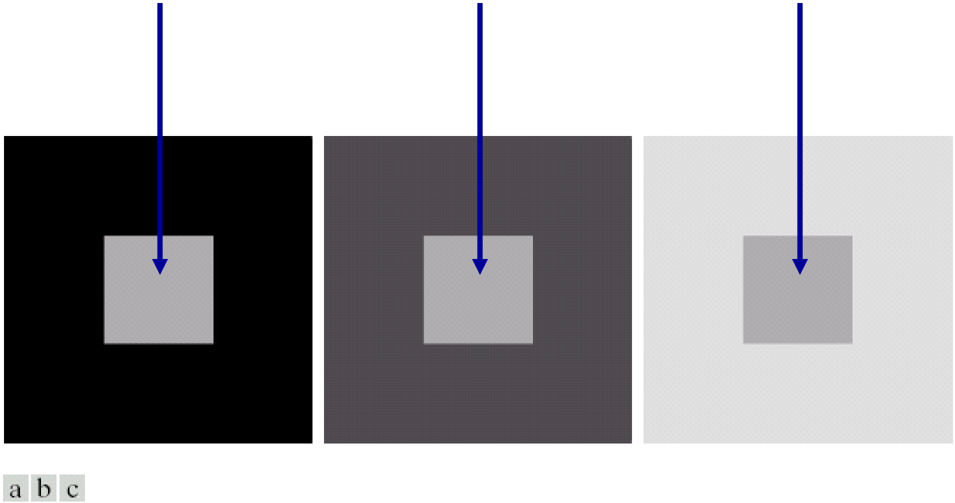


FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

OPTICAL ILLUSIONS: OTHER EXAMPLES OF HUMAN PERCEPTION PHENOMENA

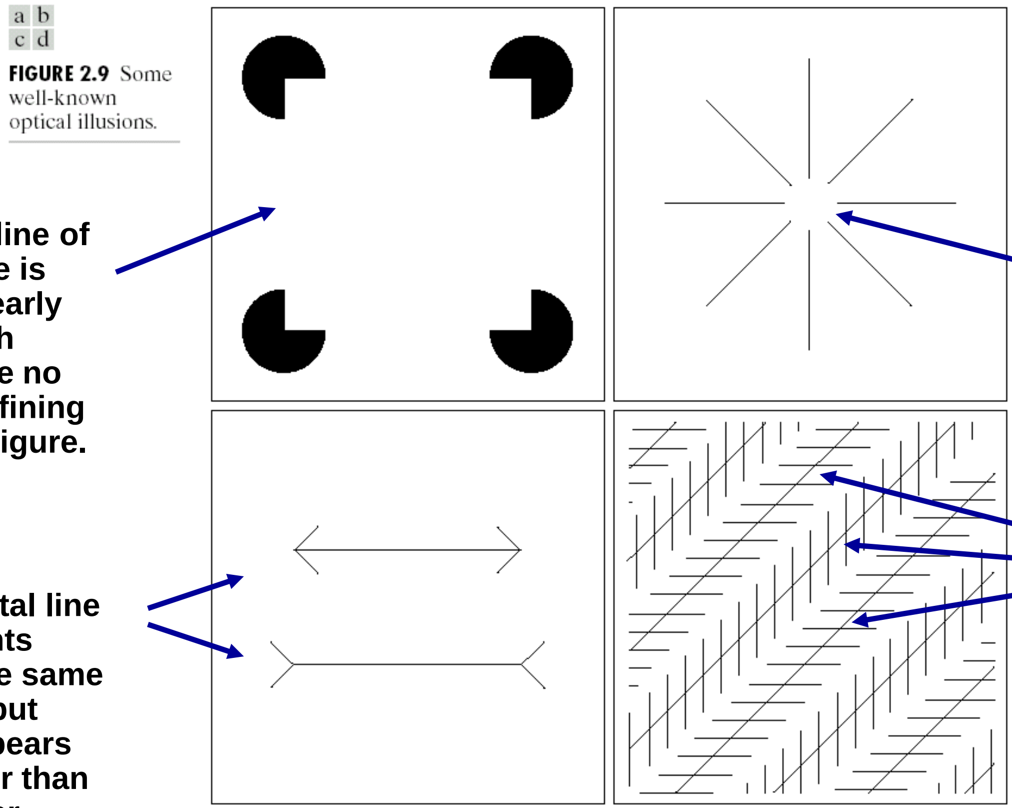


FIGURE 2.9 Some well-known optical illusions.

The outline of a square is seen clearly although there are no lines defining such a figure.

A few lines are sufficient to give the illusion of a complete circle.

Two horizontal line segments have the same length but one appears shorter than the other.

All lines that are oriented at 45^0 are equidistant and parallel.

LIGHT AND ELECTROMAGNETIC SPECTRUM

- **Electromagnetic spectrum**
  - **The range of colors we perceive in visible light represents a very small portion of the spectrum.**
  - **Radio waves with wavelengths billions of times longer.**
  - **Gamma rays with wavelengths billions of smaller.**
- **Wavelength, frequency and energy**
  - **$\lambda = c/v$, c: speed of light (2.998×10^8 m/s)**
  - **$E = hv$, h: Planck's constant**
- **Electromagnetic waves can be visualized as**
  - **propagating sinusoidal waves with wavelength λ.**
  - **a stream of massless particles, each traveling in a wavelike pattern and moving at the speed of light.**
    - **Each massless particle contains a bundle of energy called a photon.**
    - **Higher frequency electromagnetic phenomena carry more energy per photon.**
- **The visible band: 0.43 μm (violet) – 0.79 μm (red)**
- **Six broad color regions: violet, blue, green, yellow, orange, red.**

ELECTROMAGNETIC SPECTRUM

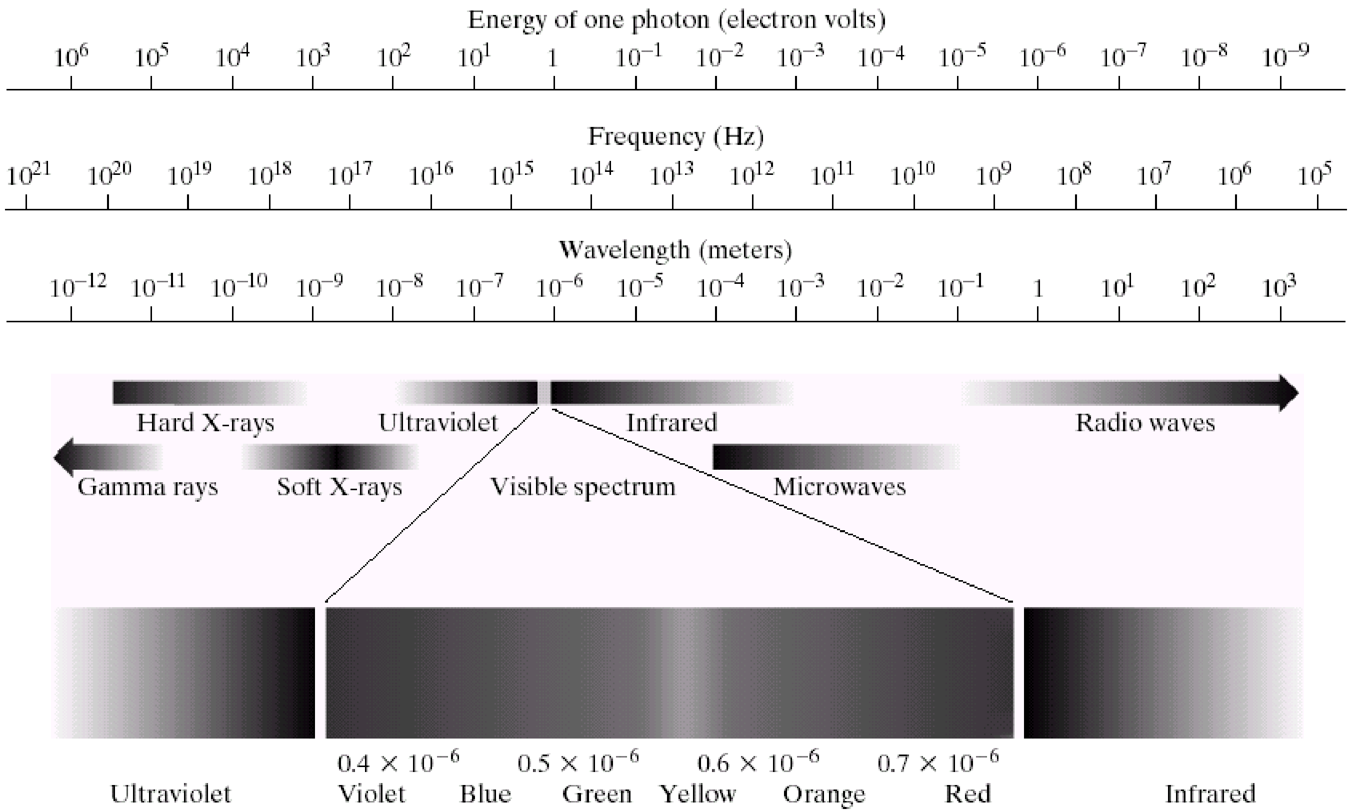


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

COLOR PERCEPTION

- The colors perceived in an object are determined by the nature of light reflected from the object.
- A body that reflects light and is relatively balanced in all visible wavelengths appears white.
- A green object reflects light with wavelengths primarily in [500-570] nm range, and absorb most of the energy at other wavelengths.
- Achromatic or monochromatic light: light that is void of color.
- Three basic quantities to describe the quality of a chromatic light source
  - Radiance: total amount of energy that flows from the light source (usually measured in watts)
  - Luminance: a measure of the amount of energy an observer perceives from a light source.
  - Brightness: a subjective descriptor of light perception that is impossible to measure.

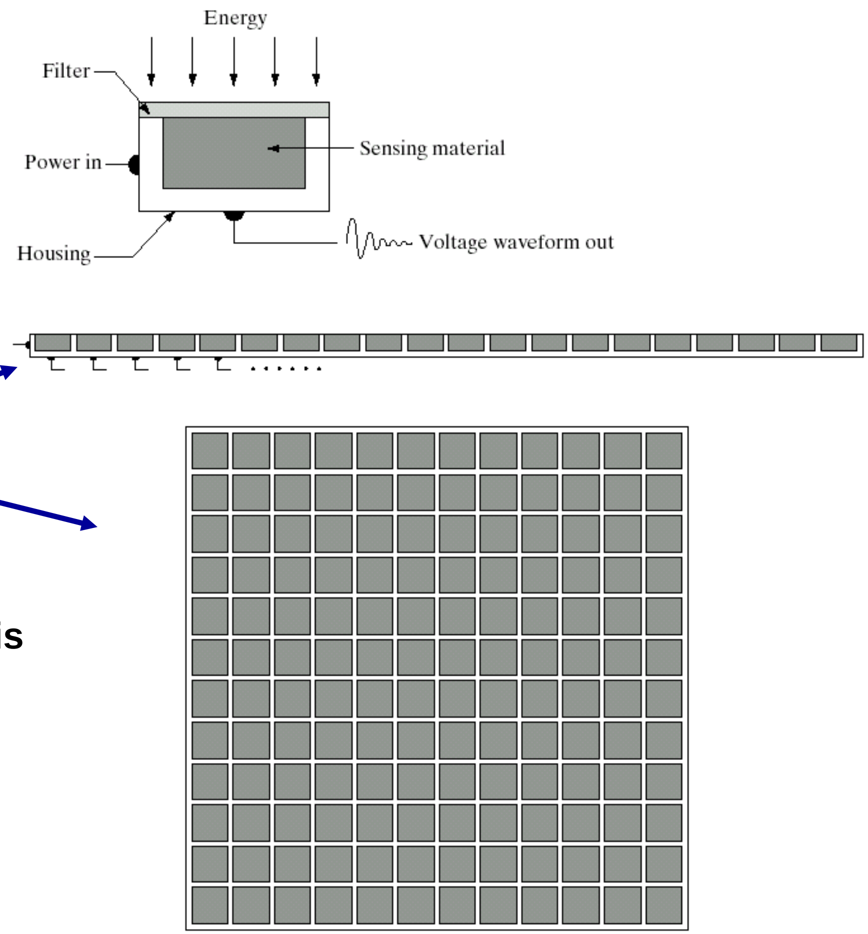
IMAGE SENSING AND ACQUISITION

- If a sensor can be developed with the capability of detecting energy radiated by a band of the EM spectrum, we can image events in that band!
- The wavelength of am EM wave required to see an object <= the size of the object!
  - A water molecule's diameter ~$10^{-10.}$
  - To study molecules, we need a source capable of emitting in the far ultraviolet or soft X-ray region!
- Illumination
  - Visible light
  - Radar, infrared, X-ray, etc.
- Scene elements
  - Familiar 3-D objects
  - Molecules, buried rock formations, human brain
- Illumination energy
  - Reflected from objects: light reflected from a planar object
  - Transmitted through objects: X-ray through a patient's body

SENSORS

a
b
c

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



3 principal sensor arrangements

Illumination energy is transformed into digital images.

SINGLE SENSOR

Arrangement used in high-precision scanning

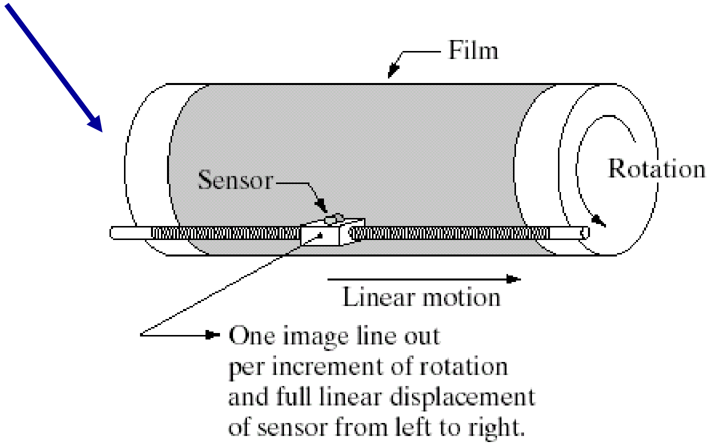
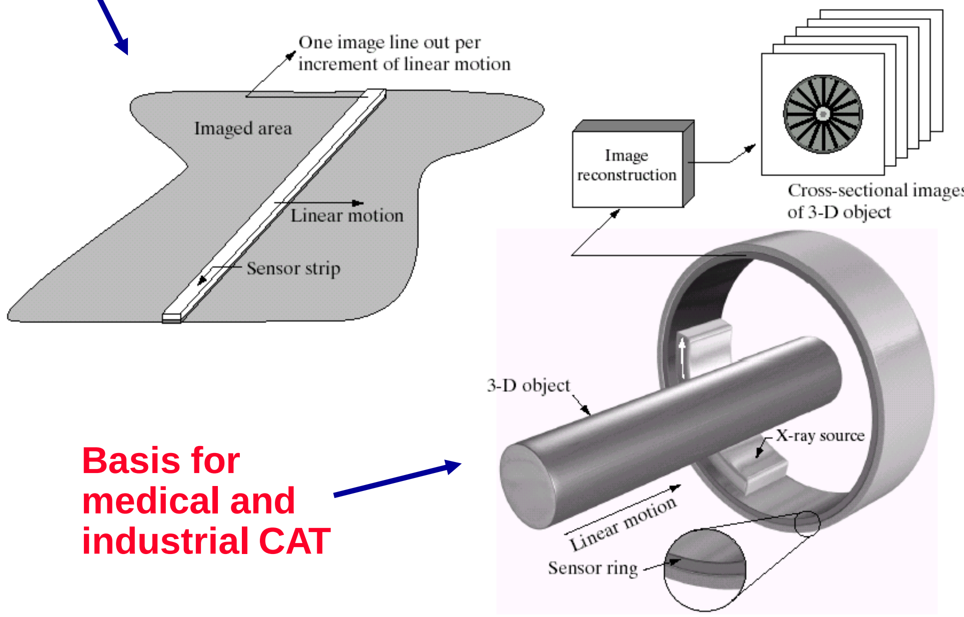


FIGURE 2.13 Combining a single sensor with motion to generate a 2-D image.

SENSOR STRIPS

Typical arrangement in most flat bed scanners

Basis for medical and industrial CAT



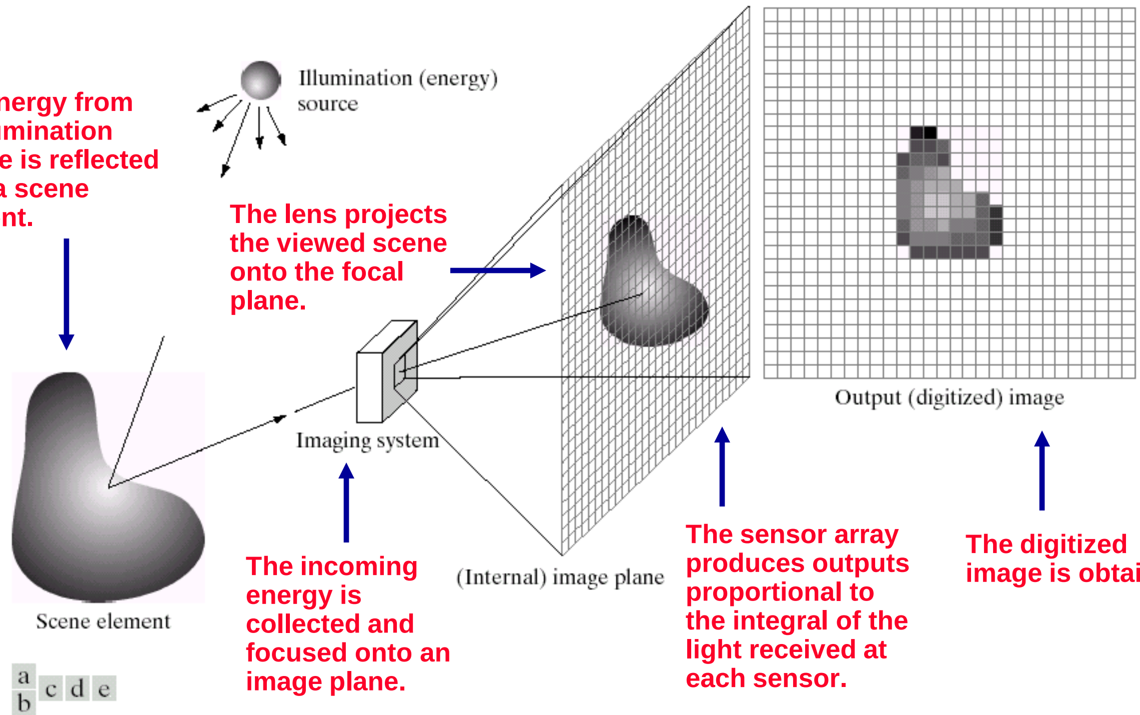
a b

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

SENSOR ARRAYS

The energy from an illumination source is reflected from a scene element.

The lens projects the viewed scene onto the focal plane.



The incoming energy is collected and focused onto an image plane.

The sensor array produces outputs proportional to the integral of the light received at each sensor.

The digitized image is obtained.

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

- **When an image is generated from a physical process, its values are proportional to energy radiated by a physical source.**
- **Hence, $0 < f(x,y) < \infty$**
- **$f(x,y)$ may be characterized by 2 components:**
  - **Amount of source illumination incident on the scene being viewed – illumination $i(x,y)$**
  - **Amount of illumination reflected by the objects in the scene – reflectance $r(x,y)$**
  - **The 2 functions combine as a product: $f(x,y) = i(x,y)r(x,y)$**
  - **$0 < i(x,y) < \infty$ (theoretical bound)**
    - **Typical values of $i(x,y)$**
      - **On a clear day: 90,000 lm/m^2**
      - **On a cloudy day: 10,000 lm/m^2**
      - **On a clear evening: 0.1 lm/m^2**
  - **$0 < r(x,y) < 1$ (theoretical bound)**
    - **Typical values of $r(x,y)$**
      - **0.01 for black velvet**
      - **0.65 for stainless steel**
      - **0.80 for flat-white wall paint**

GRAY-SCALE IMAGES

- $(x_0,y_0) \Rightarrow l = f(x_0,y_0)$
- L_{min} , L_{max}
- L_{min}: positive, L_{max}: finite
- $L_{\text{min}} = i_{min} r_{\text{min}}$
- $L_{\text{max}} = i_{max} r_{\text{max}}$
- $L_{\text{min}} = 10$, $L_{\text{max}} = 1000$: typical limits for indoor values
- $[L_{\text{min}}, L_{\text{max}}]$: gray scale
- $[0, L-1]$, $l = 0$ is black and $l = L-1$ is white.
- Intermediate values: shades of gray

SAMPLING AND QUANTIZATION

- The output of most sensors is continuous voltage waveform.
- To create a digital image, continuous sensed data should be converted into digital form.
- Two processes: sampling and quantization.
- Consider a function $f(x,y)$ representing an image.
- $f(x,y)$ is continuous w.r.t.
  - x and y coordinates
  - Amplitude
- Sampling: digitizing the coordinate values
- Quantization: digitizing the amplitude values

GENERATING A DIGITAL IMAGE

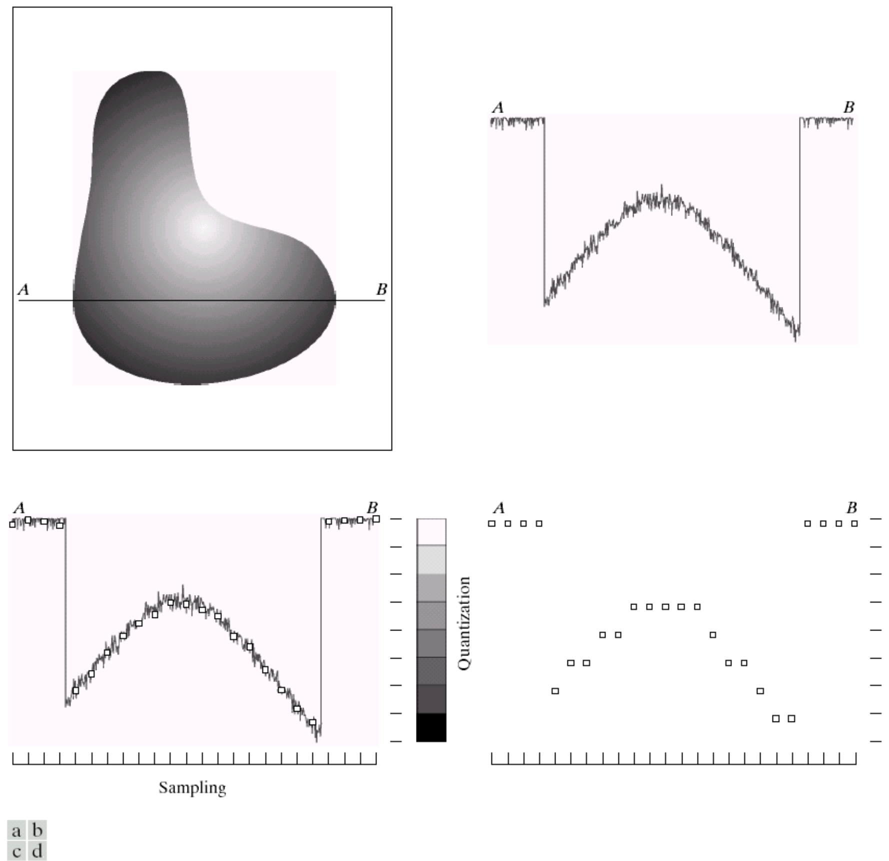
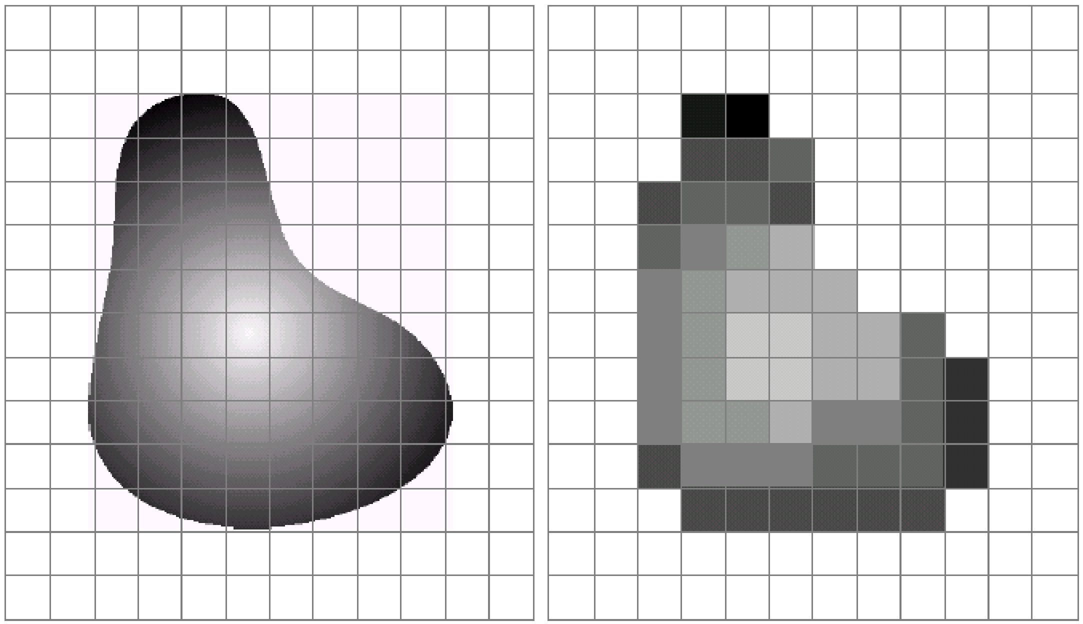


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

IMAGE ACQUISITION WITH A SENSING ARRAY



a b

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

DIGITAL IMAGE REPRESENTATION

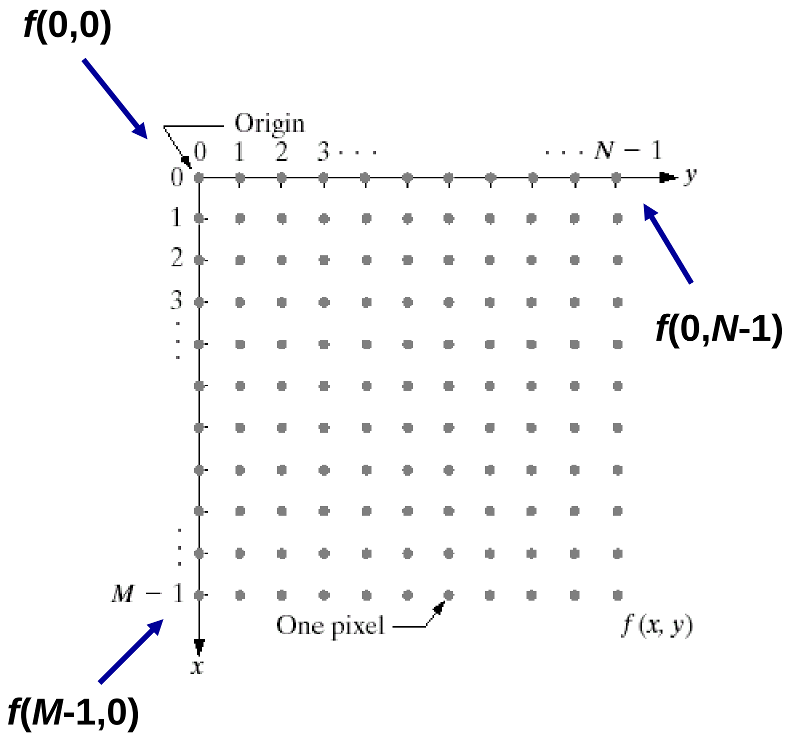


FIGURE 2.18 Coordinate convention used in this book to represent digital images.

***L*: # of discrete gray levels**

$L = 2^k$

$b = M \times N \times k$

STORAGE REQUIREMENTS

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 GRAY LEVEL RESOLUTION

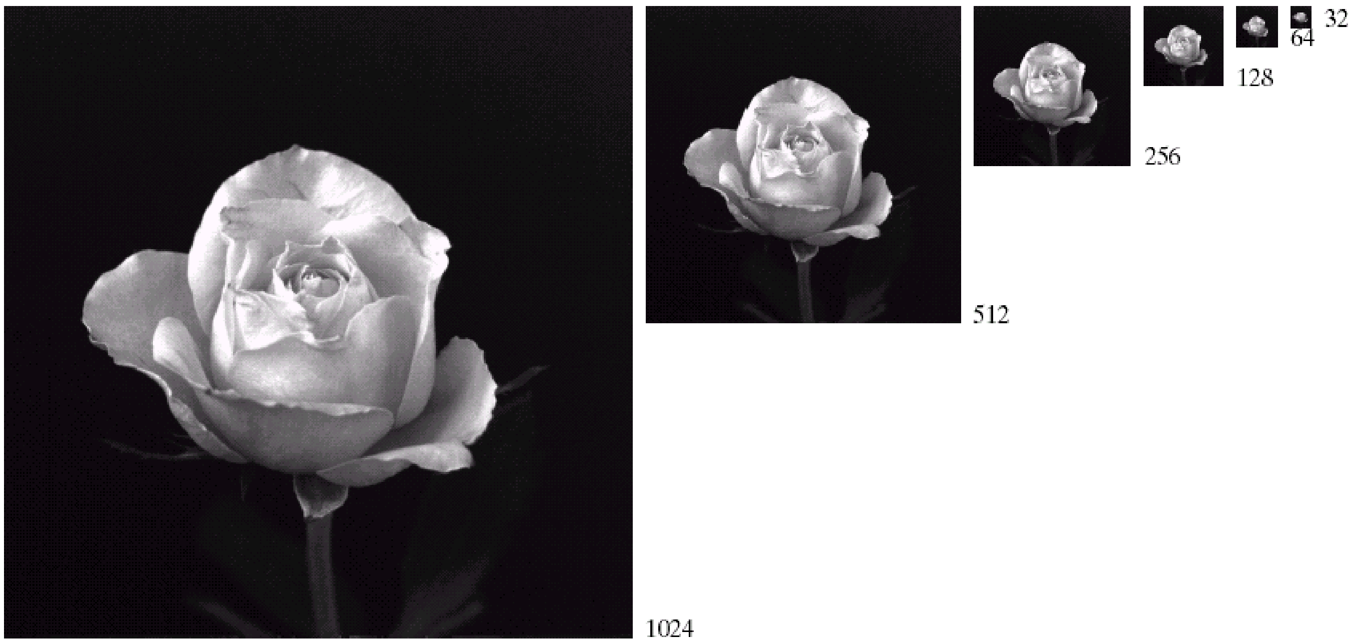
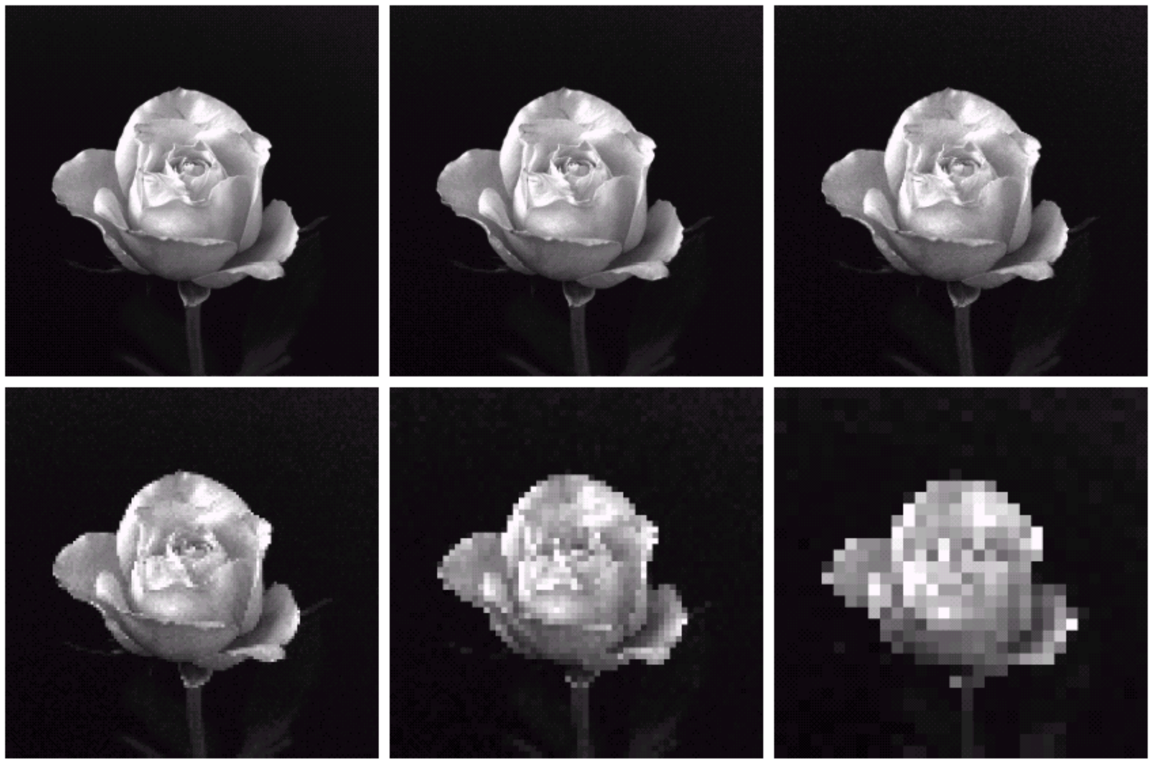


FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

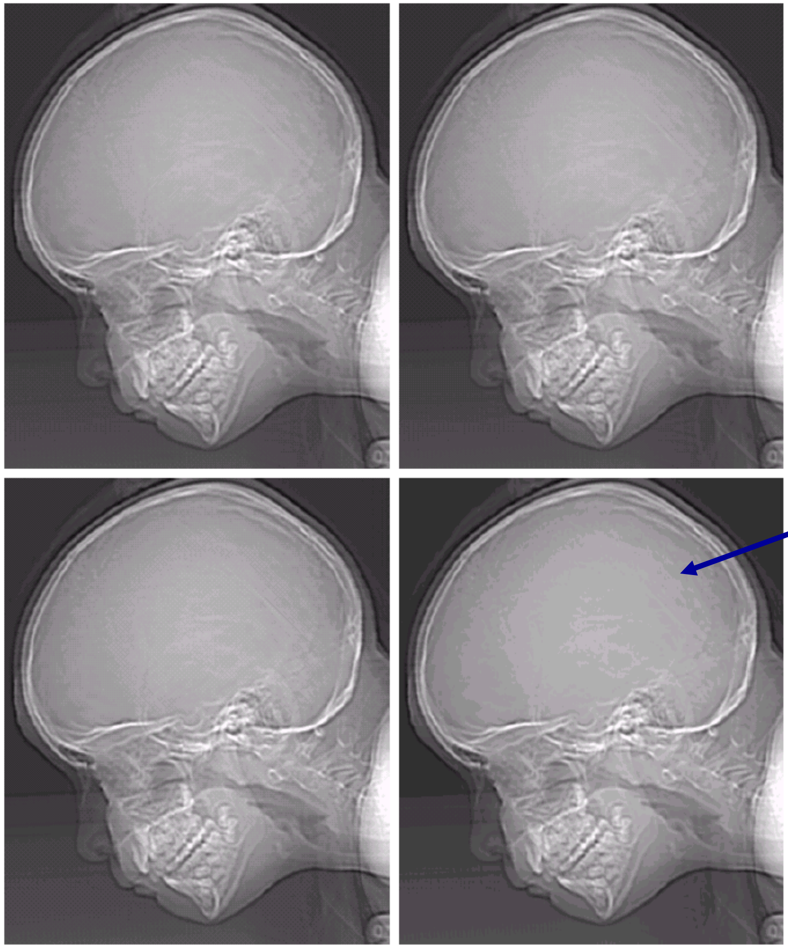
RESAMPLING INTO 1024X1024 PIXELS



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.

256/128/64/32 GRAY LEVELS



a b
c d

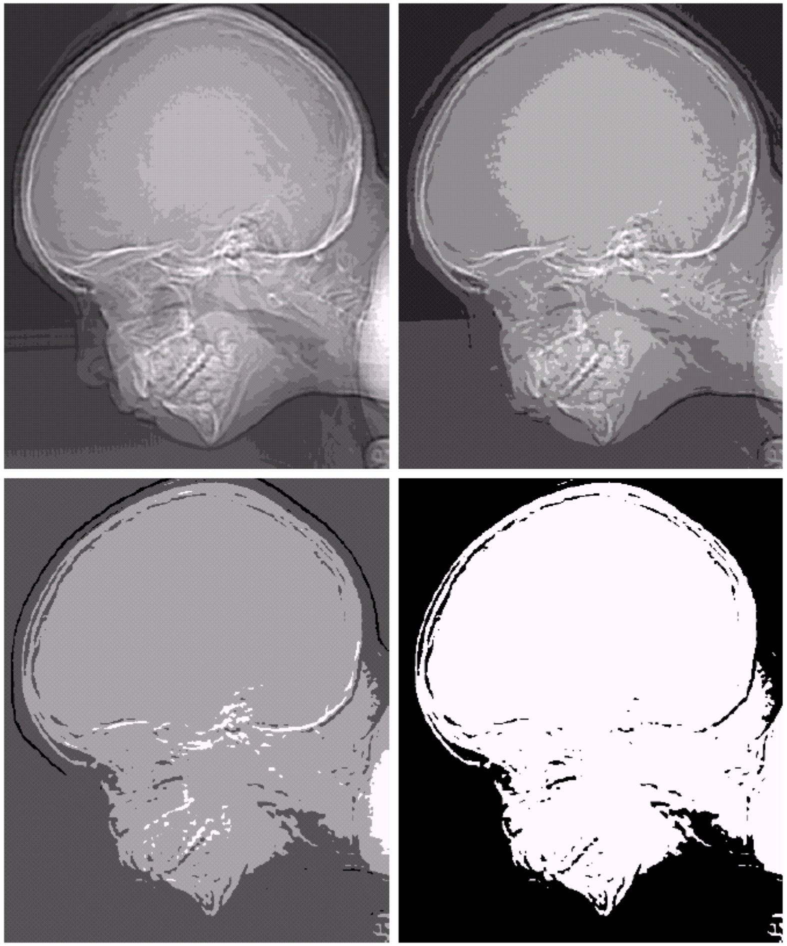
FIGURE 2.21 (a) 452 × 374, 256-level image. (b)–(d) Image displayed in 128, 64, and 32 gray levels, while keeping the spatial resolution constant.

False contouring

16/8/4/2 GRAY LEVELS

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.)



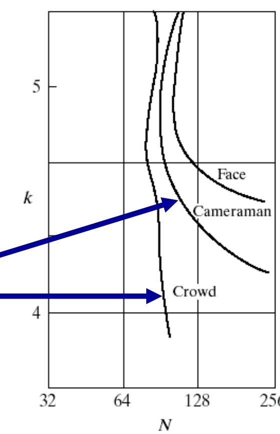
ISOPREFERENCE CURVES

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.)

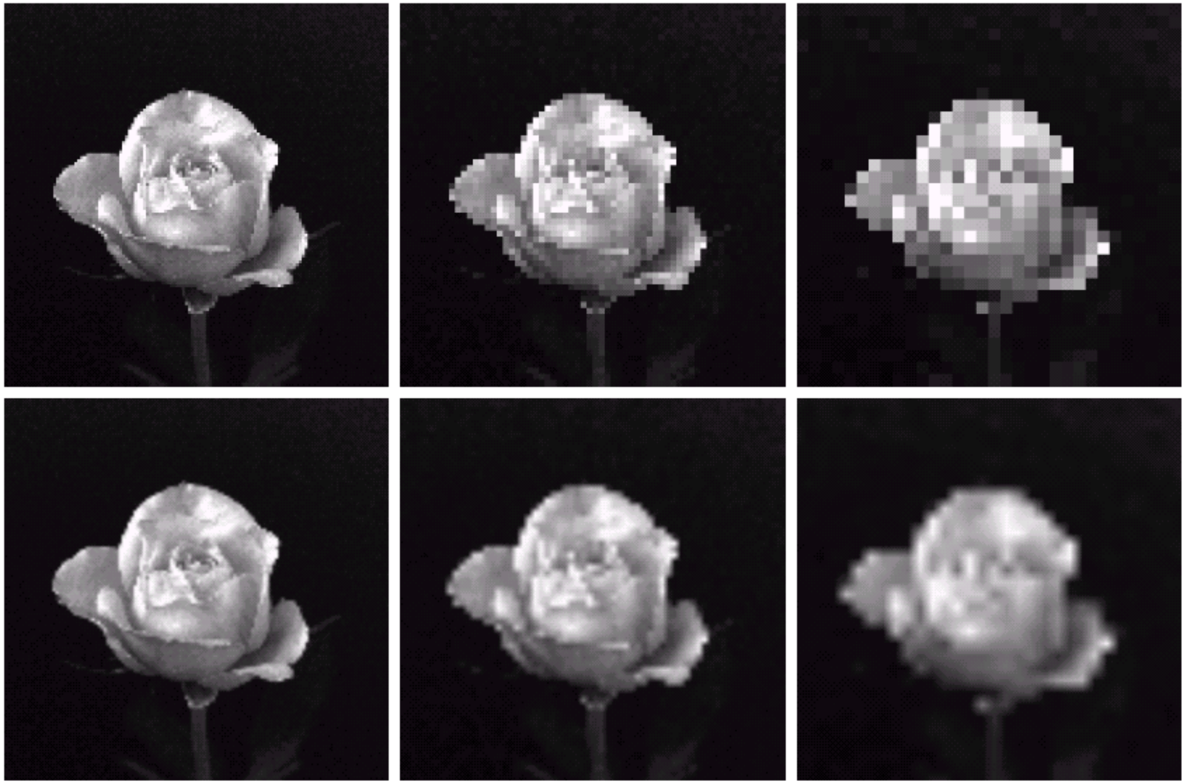
Huang (1965) varied *N* and *k* simultaneously, and attempted to quantify the effects on image quality.

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



Conclusions?

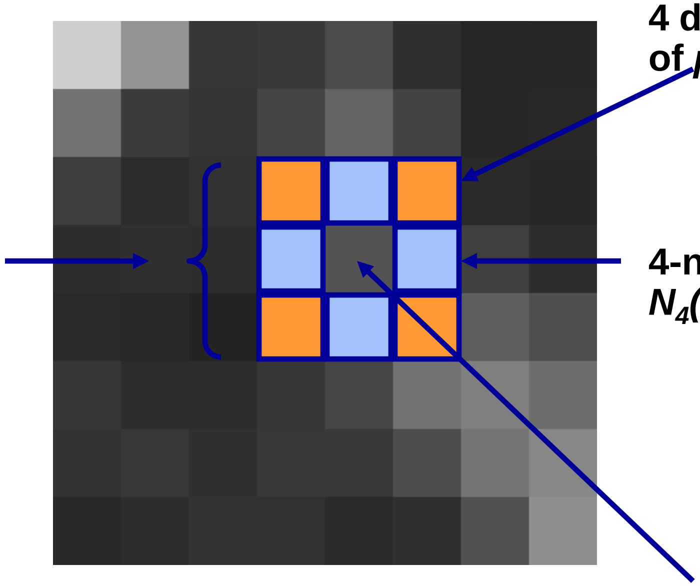
ZOOMING AND SHRINKING DIGITAL IMAGES



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.

NEIGHBORS OF A PIXEL



ADJACENCY, CONNECTIVITY

- 3 types of adjacency
  - 4- adjacency: 2 pixels *p* and *q* with values from *V* are 4-adjacent if *q* is in the set $N_4(p)$
  - 8- adjacency: 2 pixels *p* and *q* with values from *V* are 8-adjacent if *q* is in the set $N_8(p)$
  - *m*- adjacency: 2 pixels *p* and *q* with values from *V* are *m*-adjacent if *q* is in the set $N_4(p)$ if
    - *q* is in $N_4(p)$
    - *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 digital path 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), …, (x_n,y_n), where $(x_0,y_0)= (x,y)$ and $(x_n,y_n)=(s,t)$, and pixels (x_i,y_i) and (x_{i-1},y_{i-1}) are adjacent for $1 \le i \le n$.

REGIONS, BOUNDARIES

- *S*: a subset of pixels in an image. Two pixels *p* and *q* 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*.
  - If S has only one connected component, it is called a connected set.
- *R*: a subset of pixels in an image. *R* is a region of the image if *R* is a connected set.
- The boundary of a region *R* is the set of pixels in the region that have one or more neighbors that are not in *R*.

DISTANCE MEASURES

- p with (x,y)
- q with (s,t)
- z with (v,w)

$D(p,q) = 0$ iff $p = q$
$D(p,q) = D(q,p)$
$D(p,z) \leq D(p,q) + D(q,z)$

- **Euclidean distance** between p and q: $D_e(p,q) = [(x-s)^2 + (y-t)^2]^{1/2}$
- **D_4 distance**: $D_4(p,q) = |x-s| + |y-t|$
- **D_8 distance**: $D_8(p,q) = \max(|x-s| + |y-t|)$
- D_4 and D_8 distances between p and q are independent of any paths that might exist between the points.
- For m-adjacency, **D_m distance** between two points is defined as the shortest m-path between the points.

LINEAR AND NONLINEAR OPERATIONS

- H: an operator whose I and O are images.
- f and g: any two images
- a and b: two scalars
- H is a **linear operator** if $H(af + bg) = aH(f) + bH(g)$.
- Examples
  - Sum of K images: operator is linear.
  - Absolute value of the difference of 2 images: operator is not linear.
- Linear operations are very important in image processing because the **theory is well-established**.
- Nonlinear operations sometimes offer better performance but the **theory is not understood well**!