Digital Image Processing

Lecture 1: Introduction

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Readings: Chapter 1, Chapter 2 (sections 2.1 to 2.4)
How to read: laid-back with pen and paper for occasional notes!

Table of Content

What is Digital Image Processing (DIP)?

- What is an image?
  - A two-dimensional function, ***f(x, y)***, with ***x*** and ***y*** as ***spatial*** coordinates, and the amplitude of ***f*** at any pair of coordinates ***(x, y)*** as the ***intensity*** or ***gray level*** of the image at that point.
- When ***x***, ***y*** and intensity values ***f*** are all finite, discrete quantities, image is a digital image.
- Digital Image Processing (DIP) is to process digital images by digital computers.
- Each digital image is composed of a finite number of elements called picture elements, image elements, pels, or ***pixels***.
- How is DIP different than image analysis and computer vision?
  - DIP is when both input and output of an algorithm are images? Maybe!

What is Digital Image Processing (DIP)?

- Better categorization:
  - **Low-level processes**: both input and output are images
    - Noise reduction
    - Contrast enhancement
    - Image sharpening
  - **Mid-level processes**: inputs are images, outputs are image attributes
    - Segmentation
    - Classification of objects
  - **High-level processes**: “making sense” of the ensemble of recognized objects, for performing cognitive functions.
- DIP consists of processes whose inputs and outputs are images, and of processes that extract attributes from images.

The Origins of DIP

- Earliest applications of digital images were in the newspaper industry, when pictures were sent by submarine cables across the Atlantic Ocean.
- Specialized printing equipment coded pictures for transmission, then reconstructed at the receiving end.
- Early systems were coding images in five distinct levels of gray. By end of 1920s the capability increased to 15 levels.

FIGURE 1.1 A digital picture produced in 1921 from a coded tape by a telegraph printer with special typefaces. (McFarlane.) [References in the bibliography at the end of the book are listed in alphabetical order by authors' last names.]

FIGURE 1.2 A digital picture made in 1922 from a tape punched after the signals had crossed the Atlantic twice. (McFarlane.)

The Origins of DIP

- The basis for digital computers dates back to 1940s with introduction of the concepts for memories that could hold programs and data, and conditional branching.
  - Invention of transistors at Bell Lab, 1948;
  - Common Business-Oriented Language (COBOL) and Formula Translator (FORTRAN) programming languages, 1950s and 1960s;
  - Inventions of Integrated Circuits (IC) by Texas Instruments, 1958;
  - Operating systems, 1960s;
  - Microprocessors by Intel, 1970s;
  - Personal computers by IBM, 1981;
  - Large-scale integration (LI) and very-large-scale integration (VLSI) in 1970s and 1980s;
  - Ultra-large-scale integration (ULSI), present.

The Origins of DIP

- Early examples of DIP dates back to Jet Propulsion Lab in 1964 for processing images of moon captured by Ranger 7.

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.)

- The invention of Computerized Axial Tomography (CAT), or Computerized Tomography (CT) in 1970s is one of the most important events in the application of DIP in medical diagnosis.

DIP Applications

- The areas of applications of DIP are numerous.
- To categorize them, let’s focus on the images according to their sources.
  - Electromagnetic;
  - Acoustic;
  - Ultrasonic;
  - Electronics;
  - Synthetic.

DIP Applications

- Electromagnetic (EM) waves are propagating sinusoidal waves of varying wavelength, or stream of mass-less particles traveling in a wavelike pattern, moving at the speed of light.
- Each mass-less particle contains a certain amount or bundle of energy called a photon.
- Energy of a photon:

$$E = hf = {hc}/{\lambda}$$

$$\begin{aligned}
&h : \textit{Planck constant}\ (6.63\ x\ 10^{-34}\ Js) \\
&f : \textit{frequency} \\
&c : \textit{speed of light}\ (3\ x\ 10^{8}\ m/s) \\
&\lambda : \textit{wavelength of photon}
\end{aligned}$$

DIP Applications

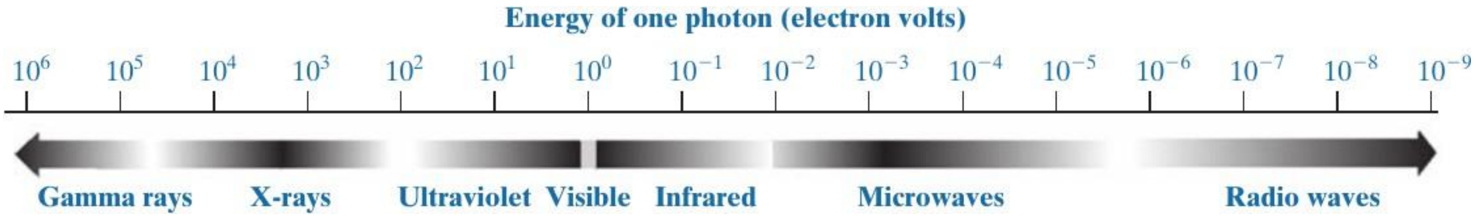
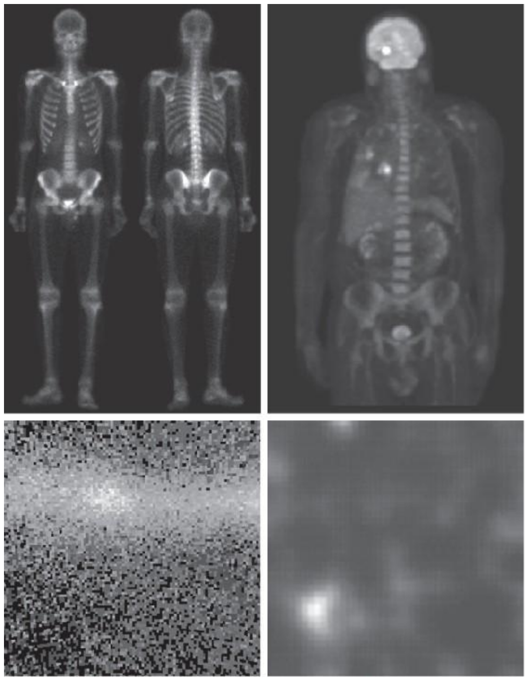
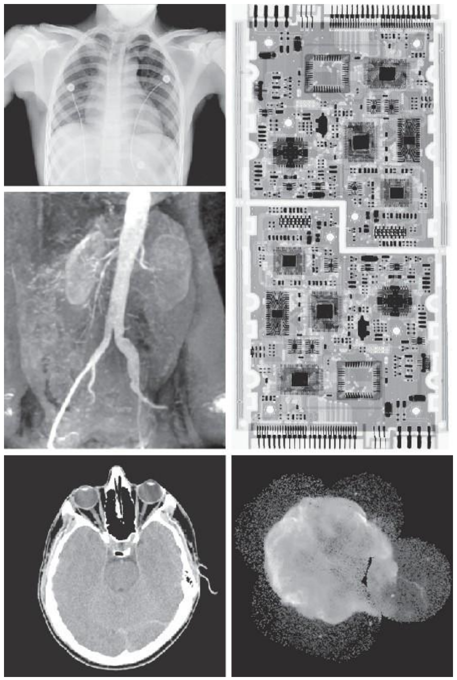


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

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.)





a d
c
b 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, Univ. of Michigan Medical School; (d) Mr. Joseph E. Pascente, Lixi, Inc.; and (e) NASA.)

DIP Applications

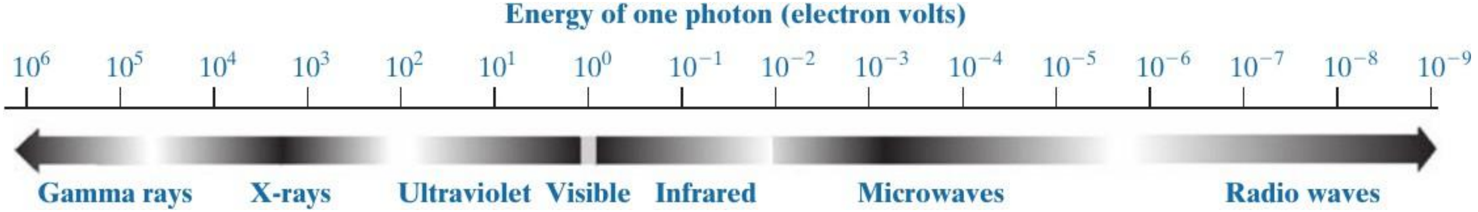
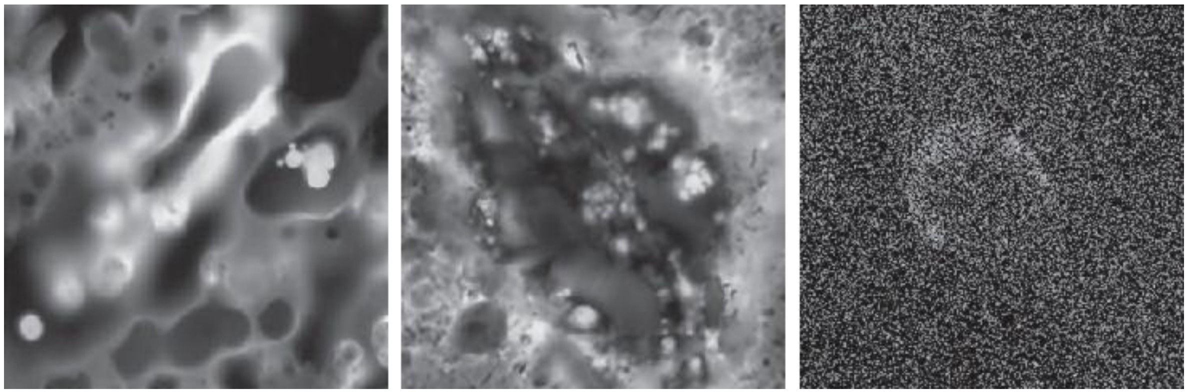


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.



a b c

FIGURE 1.8 Examples of ultraviolet imaging. (a) Normal corn. (b) Corn infected by smut. (c) Cygnus Loop. (Images (a) and (b) courtesy of Dr. Michael W. Davidson, Florida State University, (c) NASA.)

DIP Applications

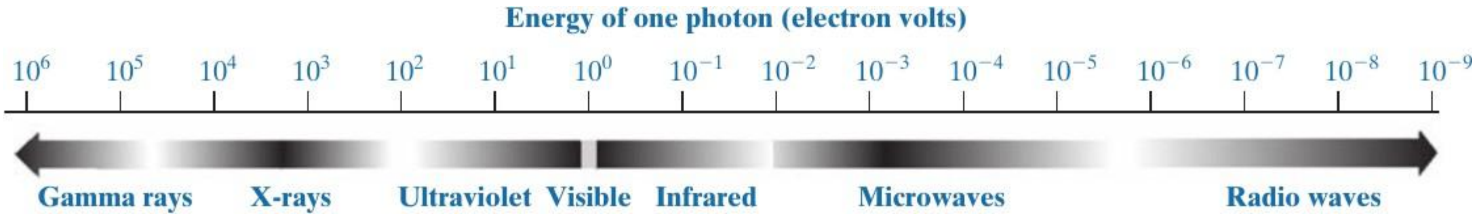
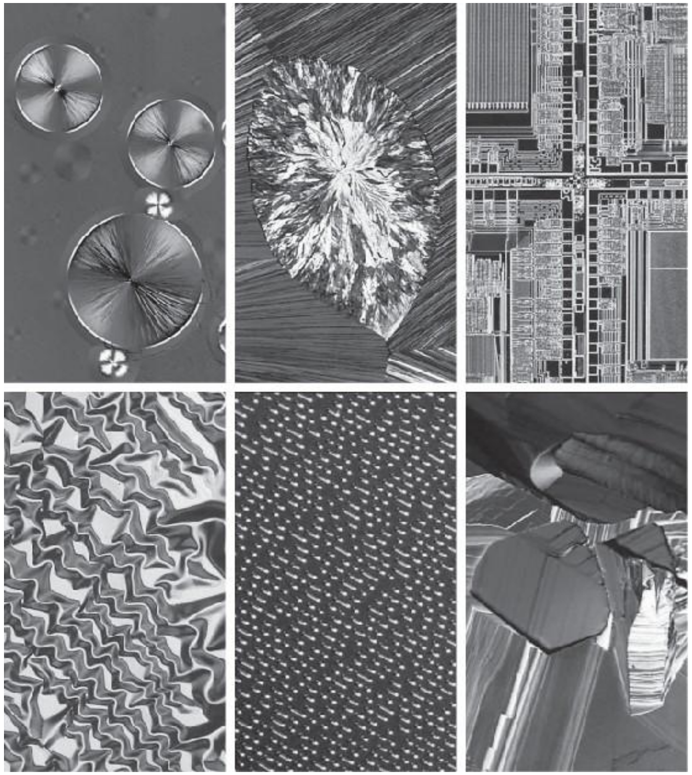


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

a b c
d e f

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



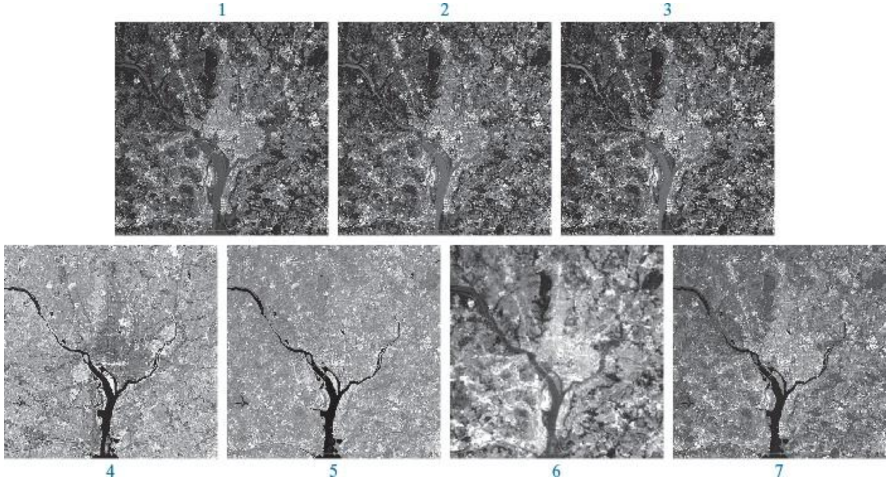


FIGURE 1.10 LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

TABLE 1.1 Thematic bands of 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	0.53–0.61	Measures plant vigor
3	Visible red	0.63–0.69	Vegetation discrimination
4	Near infrared	0.78–0.90	Biomass and shoreline mapping
5	Middle infrared	1.55–1.75	Moisture content: soil/vegetation
6	Thermal infrared	10.4–12.5	Soil moisture; thermal mapping
7	Short-wave infrared	2.09–2.35	Mineral mapping

DIP Applications

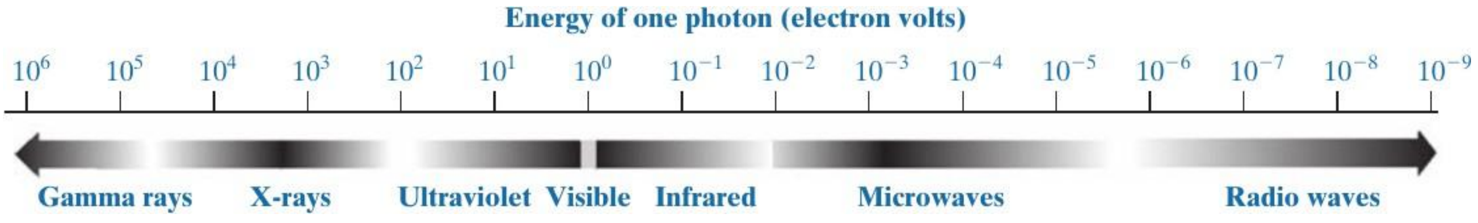


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

FIGURE 1.12 Infrared satellite images of the Americas. The small shaded map is provided for reference. (Courtesy of NOAA.)

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

DIP Applications

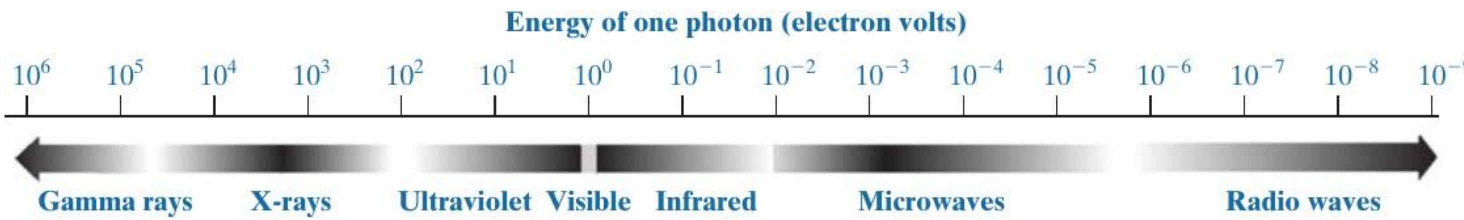
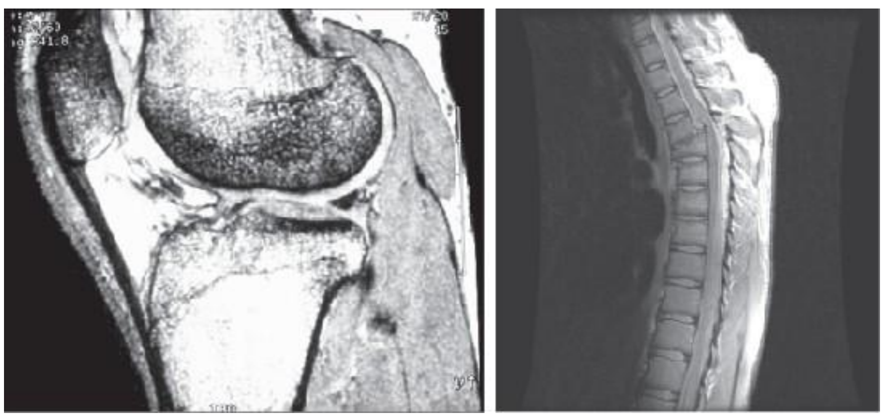


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.



a b

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

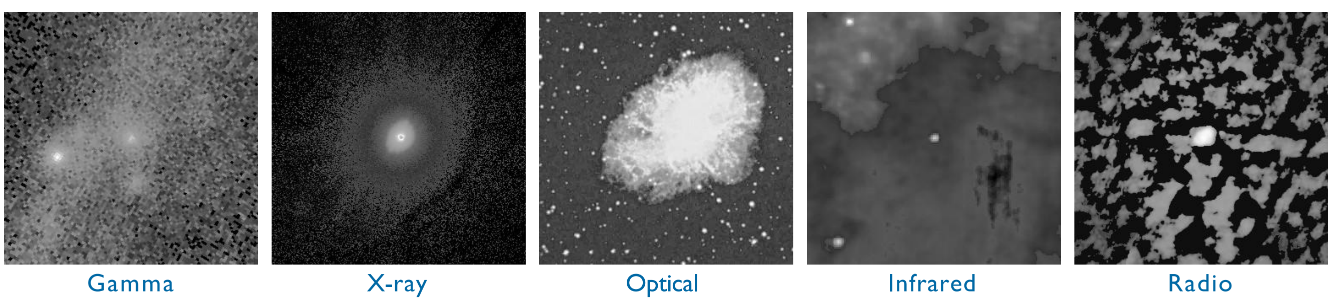


FIGURE 1.18 Images of the Crab Pulsar (in the center of each image) covering the electromagnetic spectrum. (Courtesy of NASA.)

DIP Applications

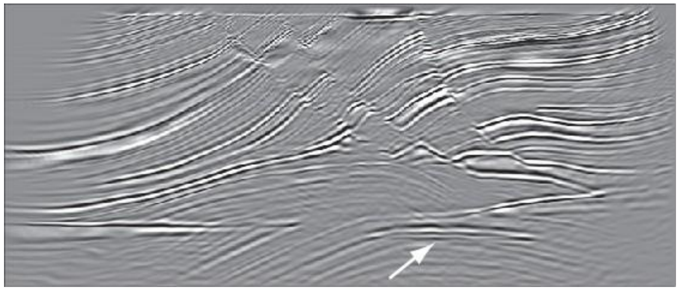
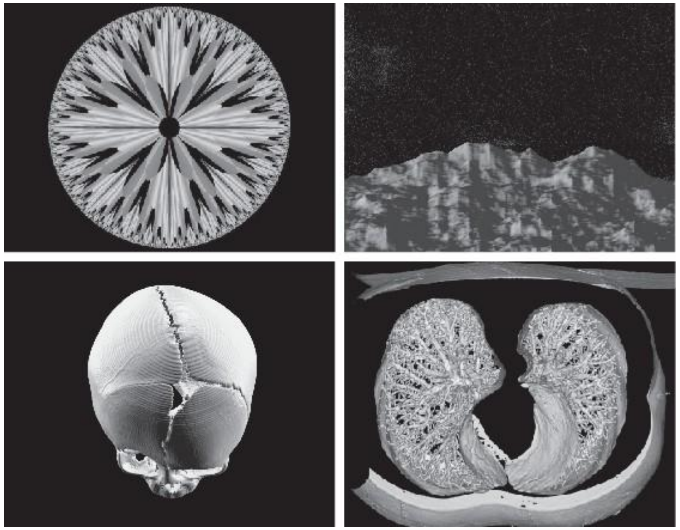
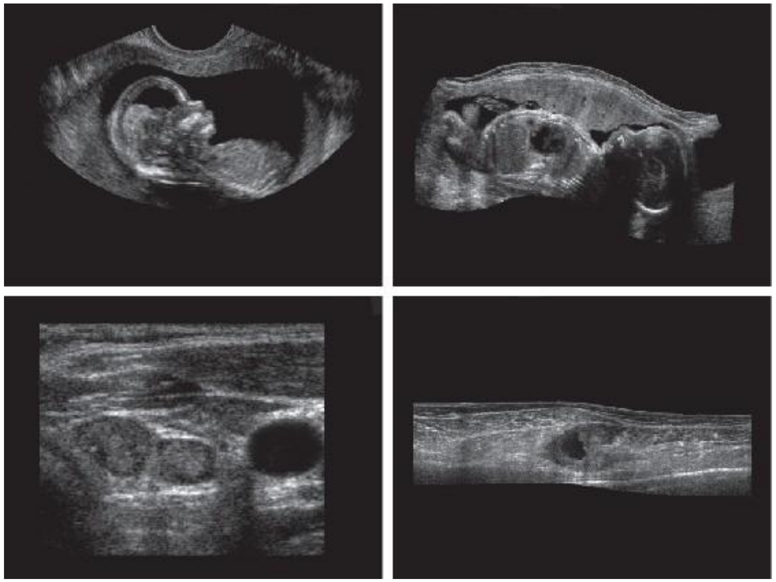


FIGURE 1.19 Cross-sectional image of a seismic model. The arrow points to a hydrocarbon (oil and/or gas) trap. (Courtesy of Dr. Curtis Ober, Sandia National Laboratories.)



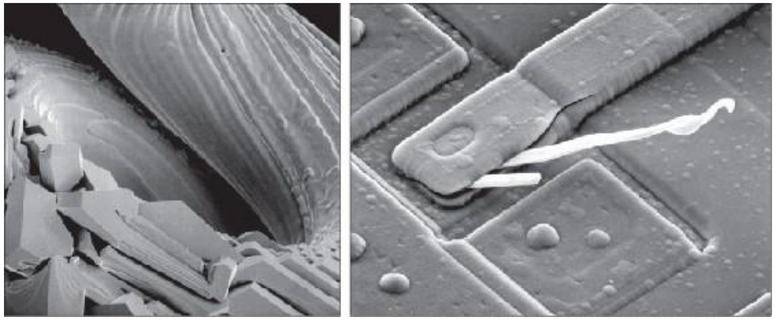
a b
c d

FIGURE 1.22 (a) and (b) Fractal images. (c) and (d) Images generated from 3-D computer models of the objects shown. (Figures (a) and (b) courtesy of Ms. Melissa D. Binde, Swarthmore College; (c) and (d) courtesy of NASA.)



a b
c d

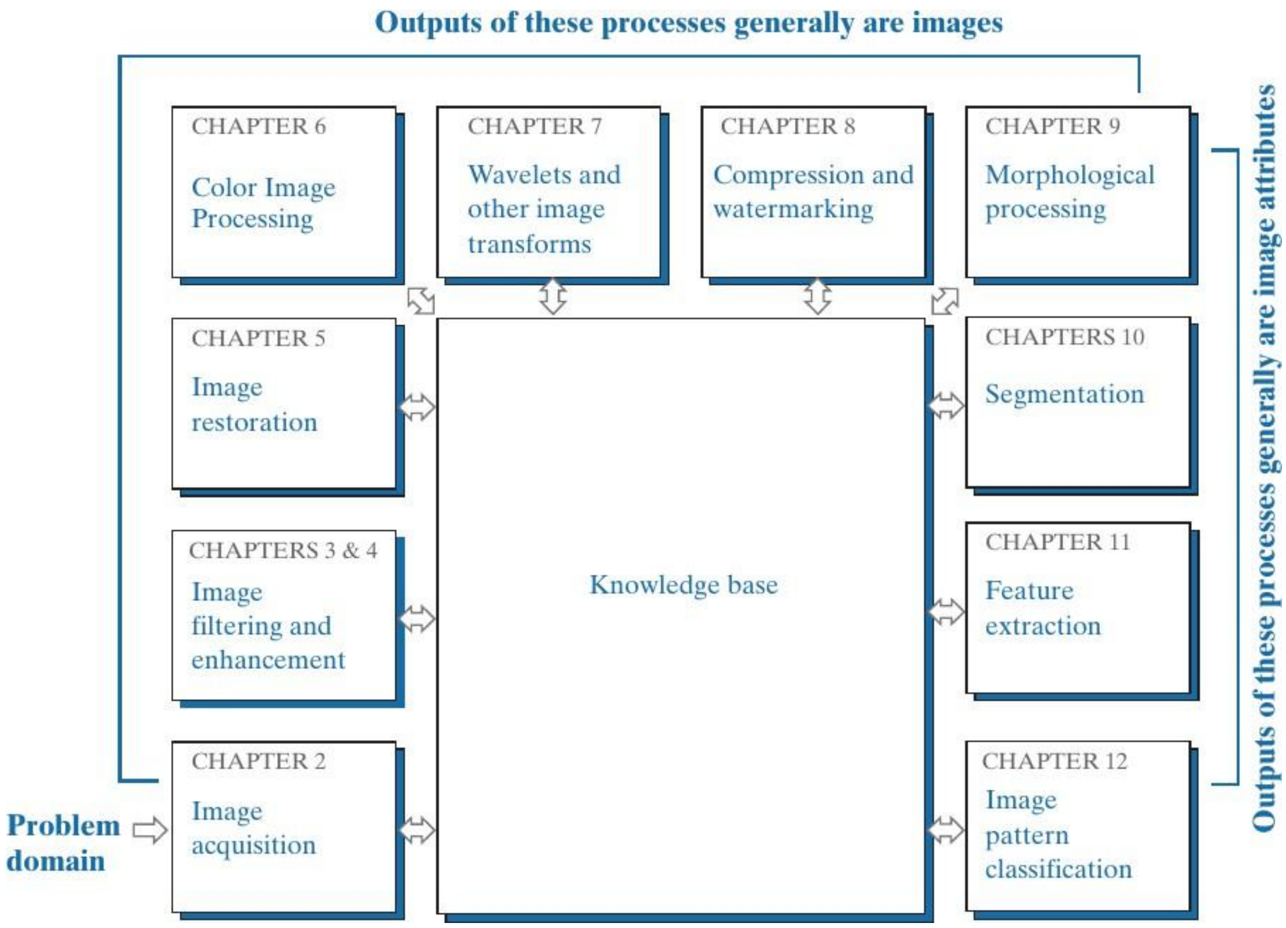
FIGURE 1.20 Examples of ultrasound imaging. (a) A fetus. (b) Another view of the fetus. (c) Thyroids. (d) Muscle layers showing lesion. (Courtesy of Siemens Medical Systems, Inc., Ultrasound Group.)



a b

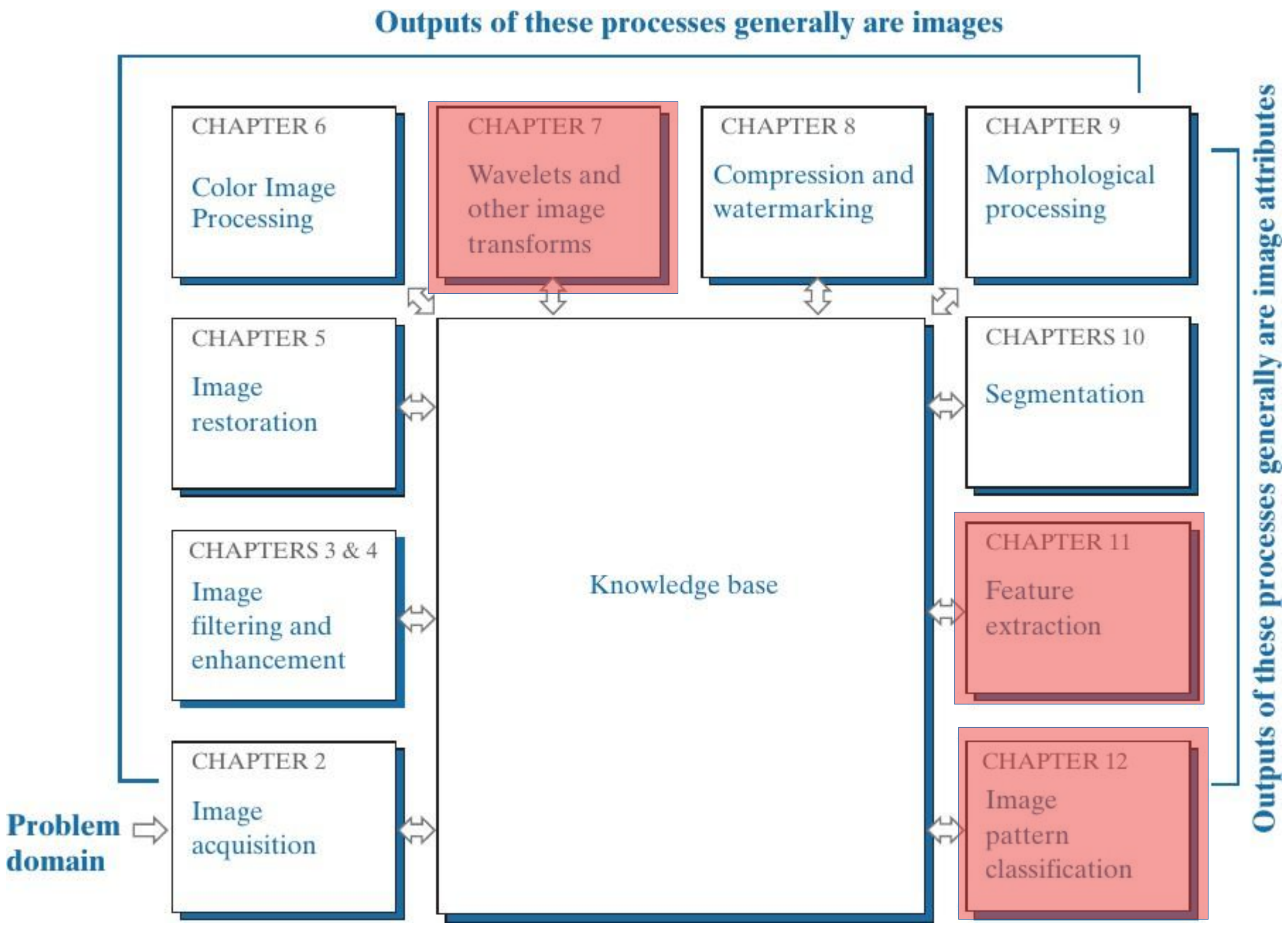
FIGURE 1.21 (a) 250 × SEM image of a tungsten filament following thermal failure (note the shattered pieces on the lower left). (b) 2500 × SEM image of a damaged integrated circuit. The white fibers are oxides resulting from thermal destruction. (Figure (a) courtesy of Mr. Michael Shaffer, Department of Geological Sciences, University of Oregon, Eugene; (b) courtesy of Dr. J. M. Hudak, McMaster University, Hamilton, Ontario, Canada.)

Fundamental Steps in DIP



* Note 1: this is from the international version of the book. The US version is slightly different.
* Note 2: not all sections of chapters are discussed.

Fundamental Steps in DIP



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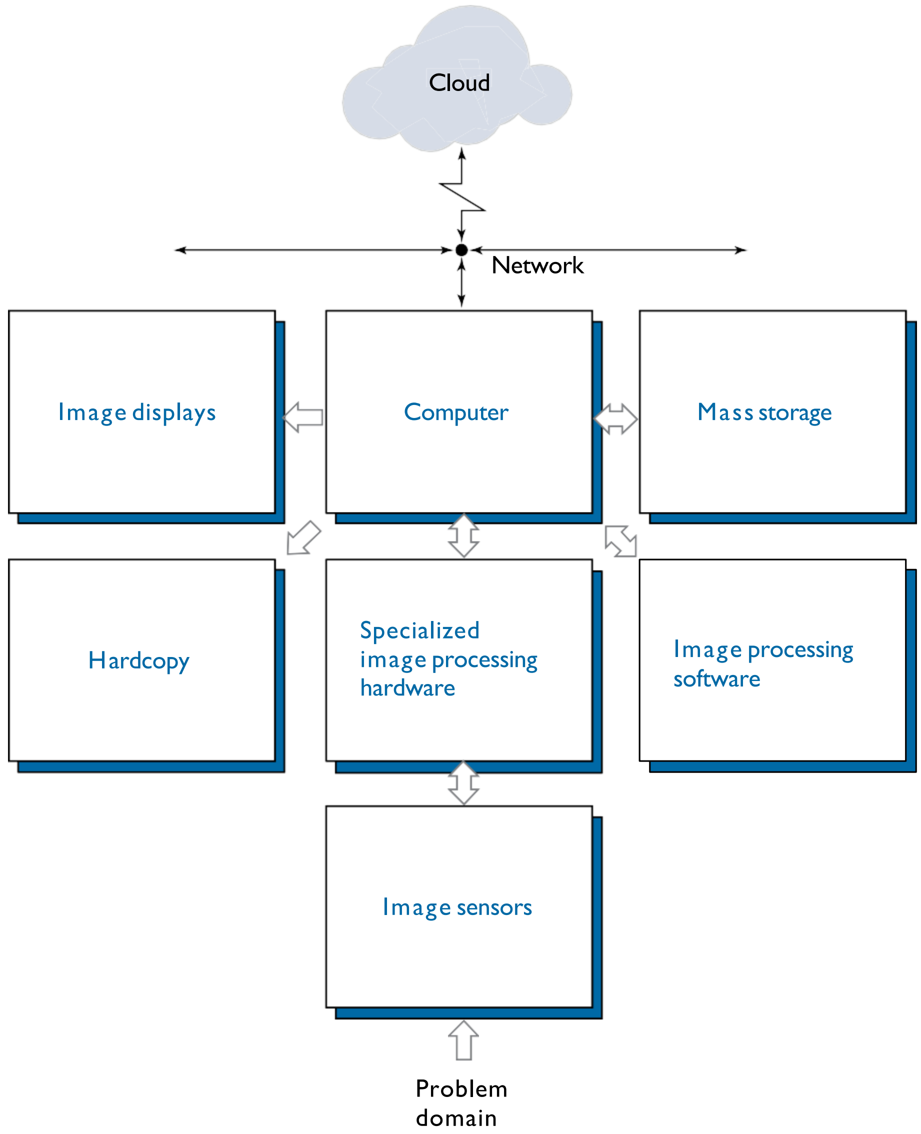
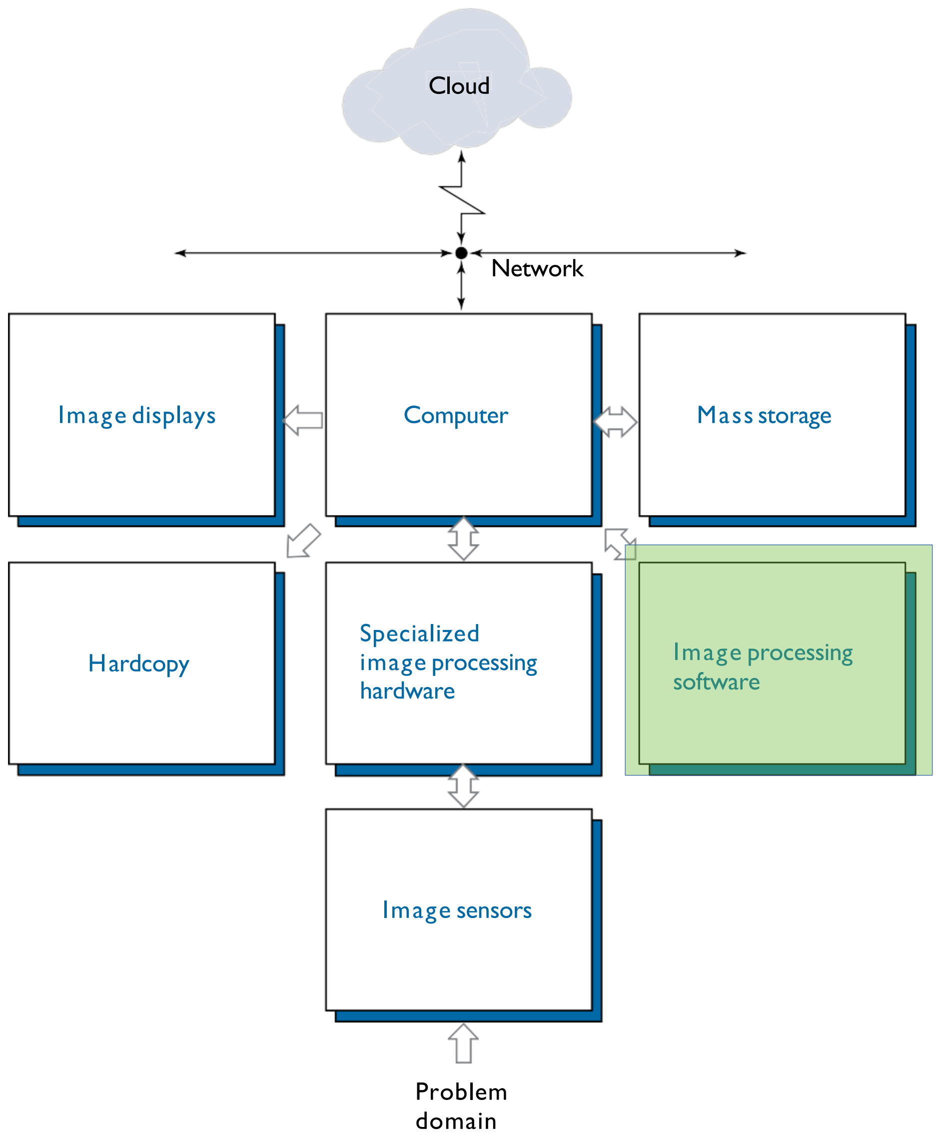
Components of a DIP System

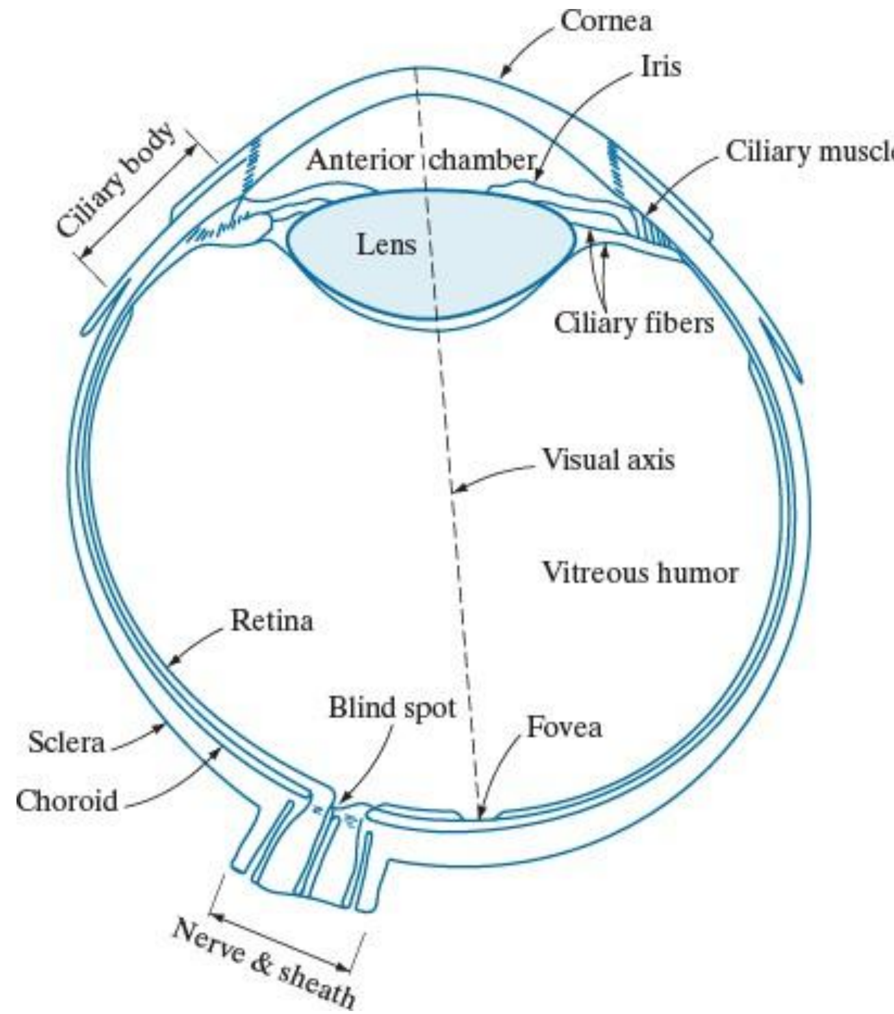


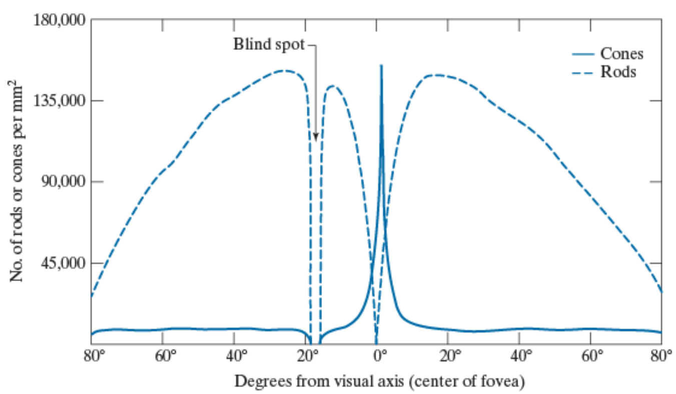
Components of a DIP System



Elements of Visual Perception
Human Eye

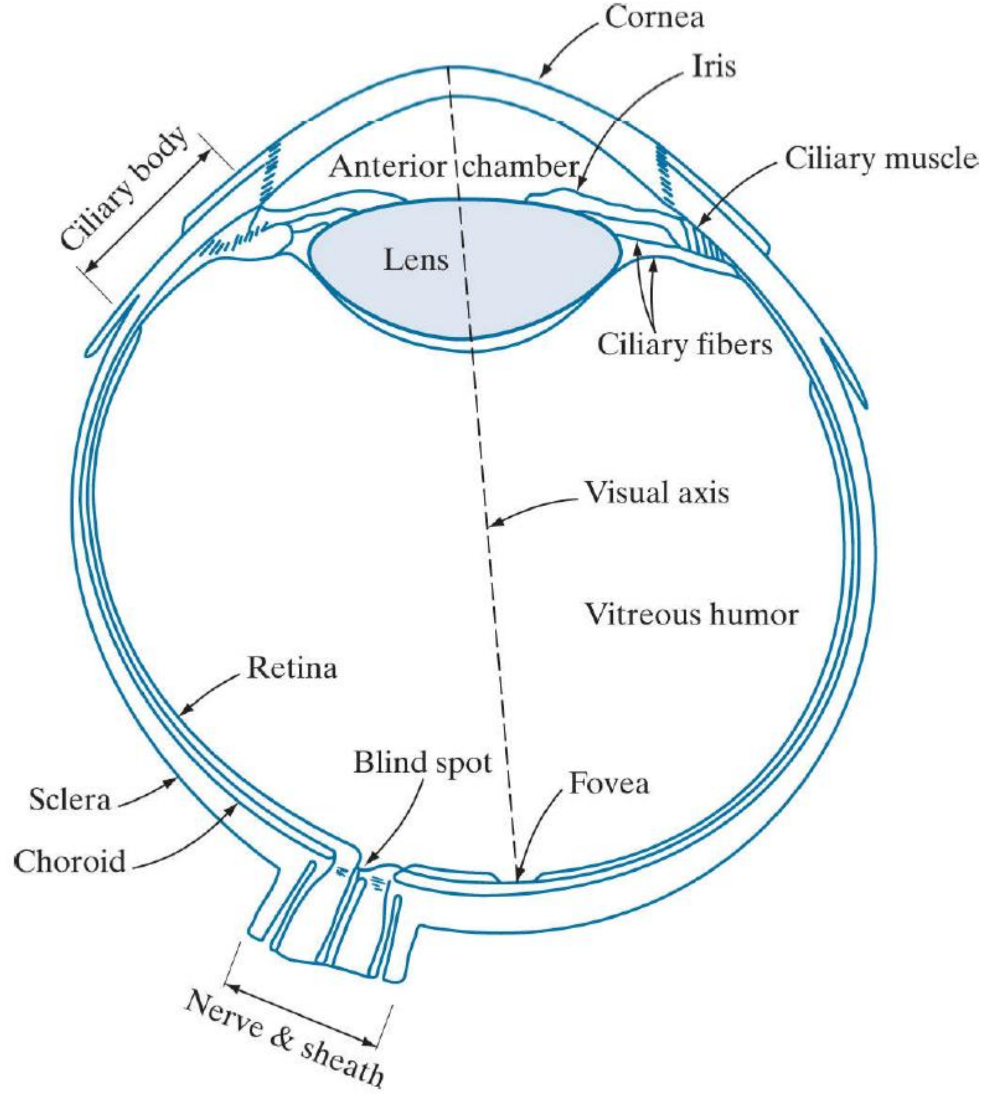
- Like a sphere with a diameter of 20 mm
- Key components
  - Lens & muscles
  - Retina (with receptors)
  - Cones in fovea.
    - 6-7 millions of cone cells.
    - Very sensitive to color.
    - ***Photopic*** or bright-light vision.
  - Rods in the rest of retina.
    - 75-150 millions of rod cells.
    - No color sensitivity.
    - Sensitive to low-level illumination.
    - ***Scotoptic*** or dim-light vision





Human vision

- **Cornea** acts as a protective lens that roughly focuses
- incoming light
- **Iris** controls the amount of light that enters the eye
- Iris is the colored part in the eye

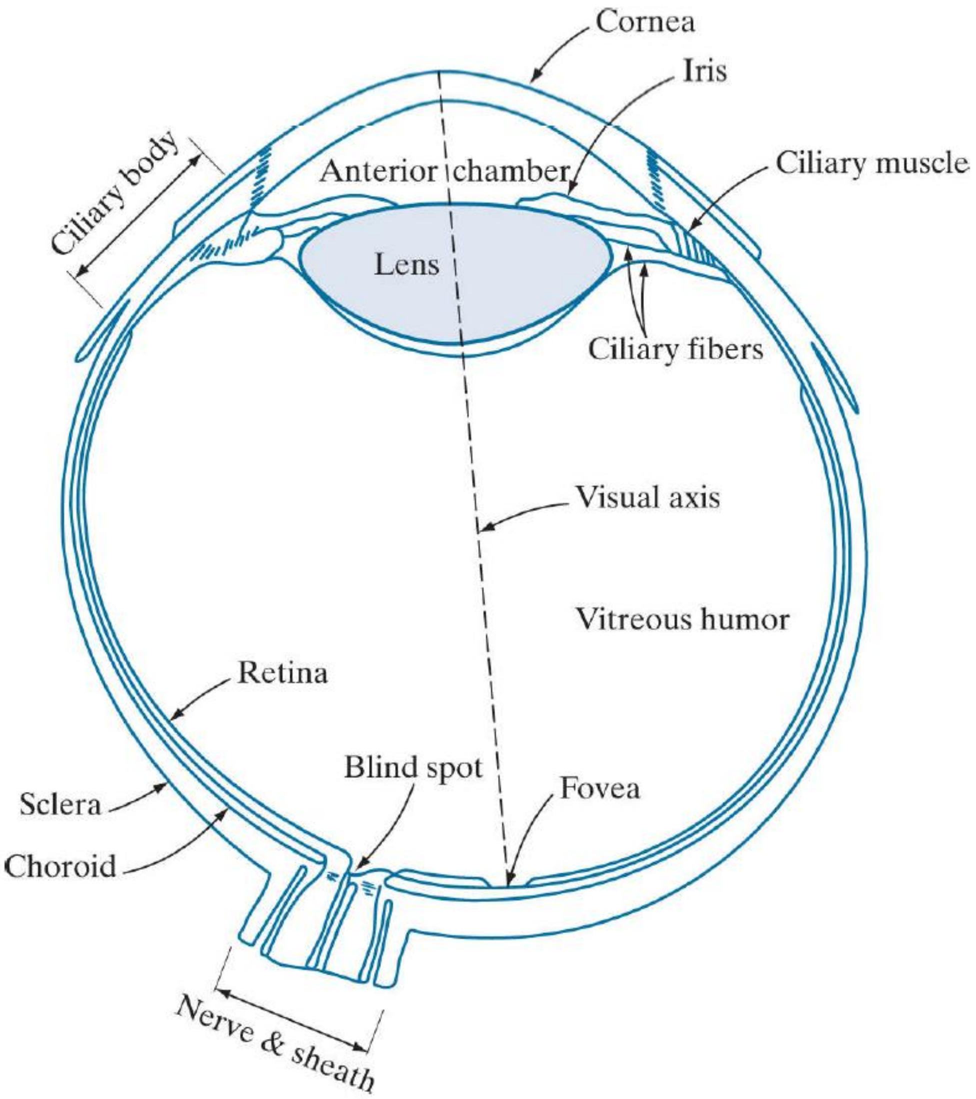


Human vision

The **lens** sharply focuses incoming light onto the retina,

Absorbs both infra-red and ultra-violet light.

The **retina** is covered by **photoreceptors** (light sensors) which measure light



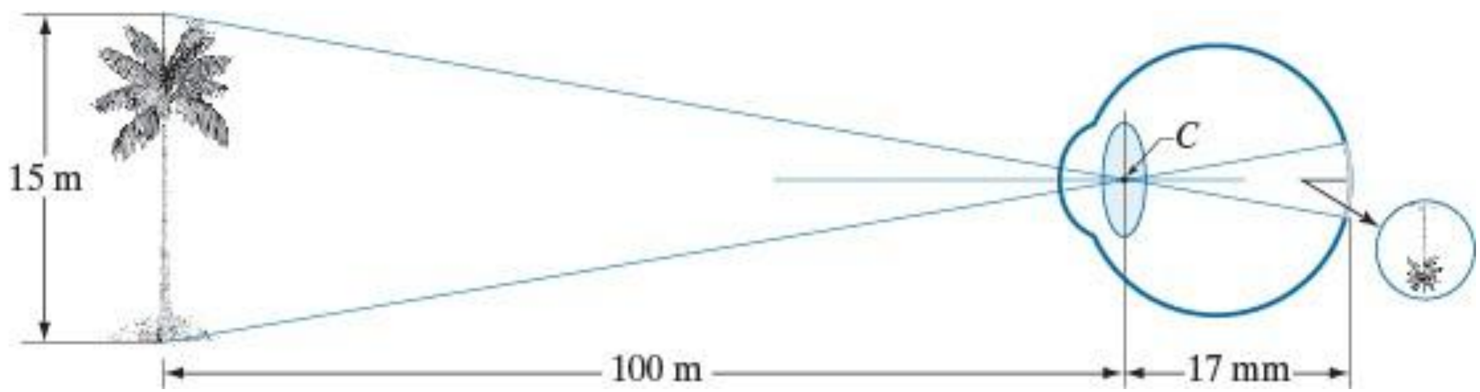
Cones

- Approximately 6-7 million cones
- Sensitive to higher-light levels
- High resolution
- Detect color by the use of 3 different kinds of cones each of which is sensitive to red, green, or blue frequencies
  - **Red (L cone)** : 564-580 nm wavelengths (65% of all cones)
  - **Green (M cone)** : 534-545 nm wavelengths (30% of all cones)
  - **Blue (S cone)** : 420-440 nm wavelengths (5% of all cones)

Rods	Cones
Used for night vision	Used for day vision
Loss causes night blindness	Loss causes legal blindness
Low spatial resolution with higher noise	High spatial resolution with lower noise
Not present in fovea	Concentrated in fovea
Slower time response to light	Quicker time response to light
One type of photosensitive pigment	Three types of photosensitive pigment
Emphasis on motion detection	Emphasis on detecting fine detail

Elements of Visual Perception
Human Eye

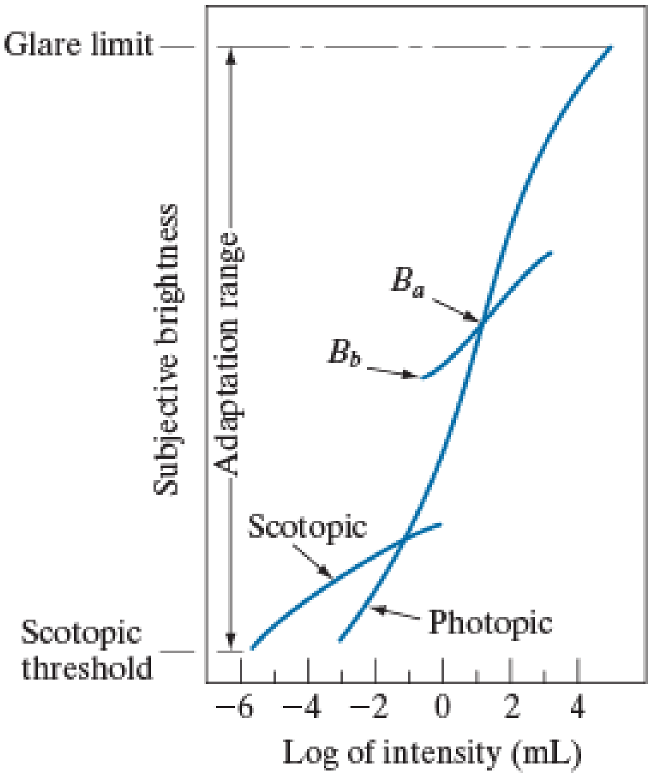
- In regular cameras, the lens has a fixed focal length, and focusing achieved by varying the distance between the lens and the imaging plane.
- In human eye, however, the distance between the center of the lens and the retina is fixed (approximately 17 mm), and the focal length is changed by varying the shape of the lens (14-17 mm)!



Elements of Visual Perception

Human Eye

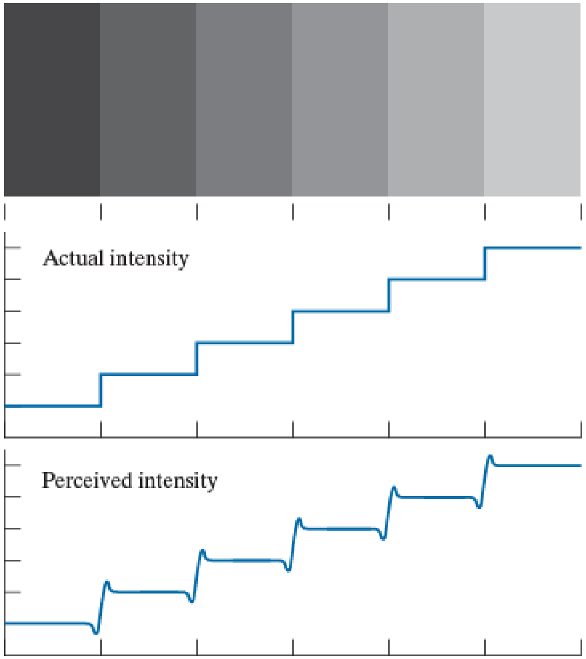
- The light intensity
  - Measured by energy of the incoming light
  - Human eyes can adapt to an enormous range of intensities.
- The subjective brightness
  - Perceived by human eyes
  - A logarithmic function of the light intensity.
- Adaptation is based on brightness levels.

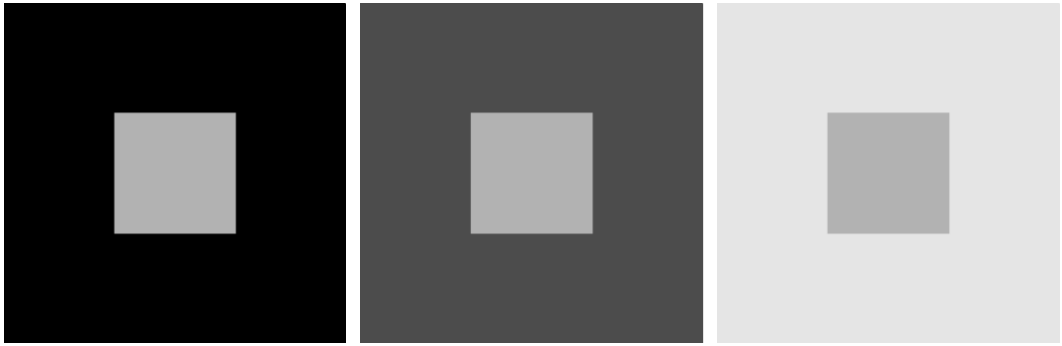


Elements of Visual Perception

Human Eye

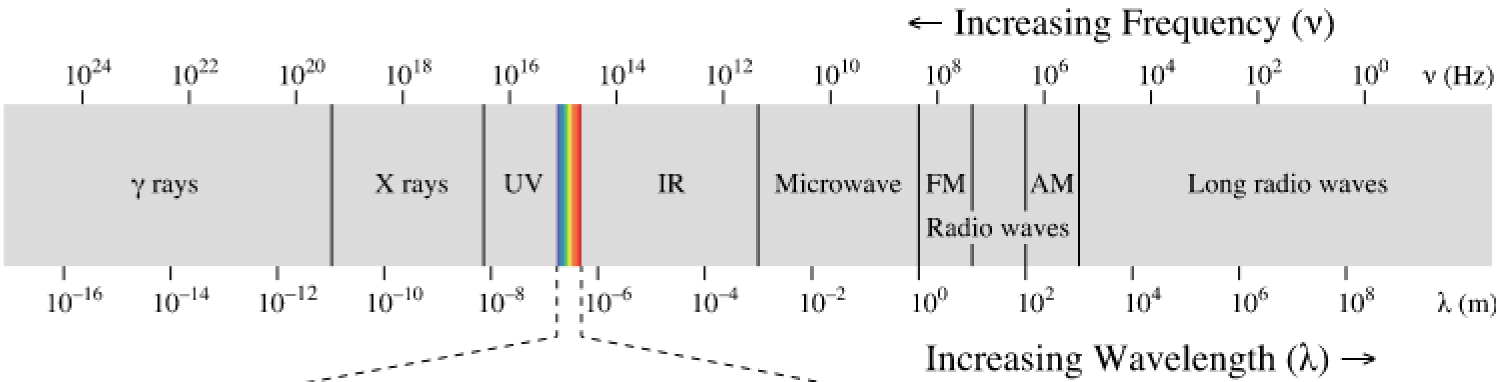
- Perceived brightness depends on two phenomena:
  - Visual system tends to undershoot or overshoot around the boundary of regions in different intensities.
  - A region's perceived brightness does not depend only on its intensity (simultaneous contrast).

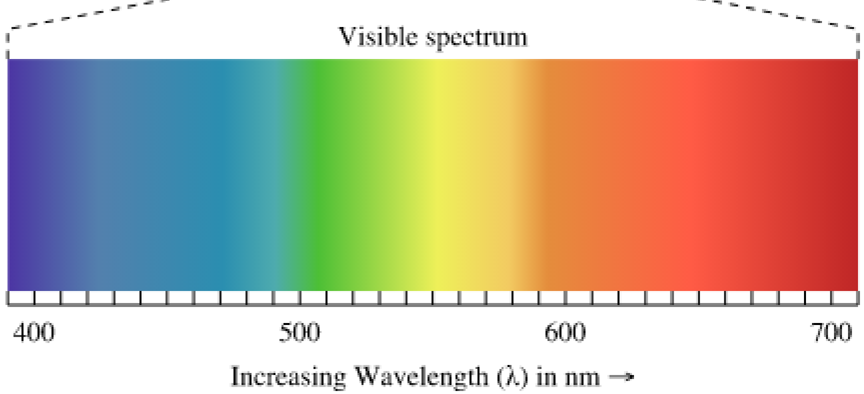


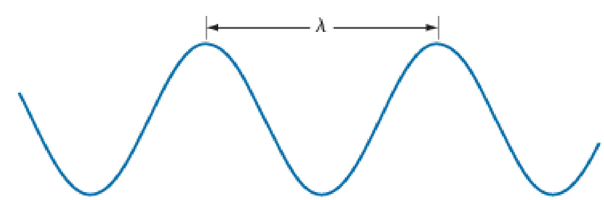


Light and the Electromagnetic Spectrum

- In 1666, Isaac Newton discovered that when a beam of sunlight passes through a glass prism, it is decomposed into a continuous spectrum of colors ranging from violet to red.





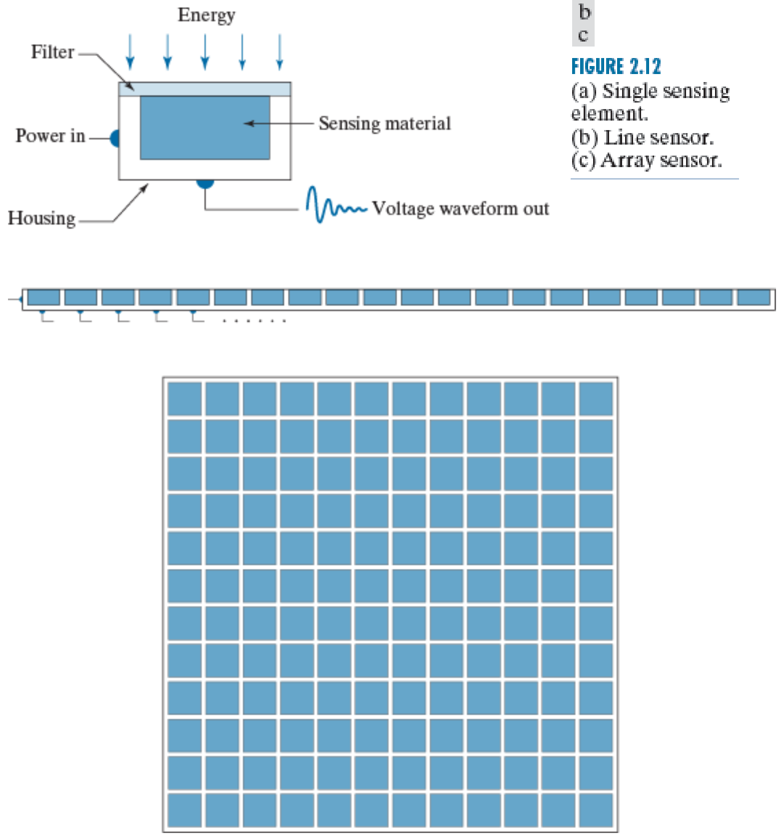


Light and the Electromagnetic Spectrum

- The colors perceived in an object are determined by the nature of the light reflected by it.
- **Monochromatic** (*achromatic*) light, is a light that is void of color, represented only by its intensity (gray level), ranging from black to white.
- **Chromatic** light spans the electromagnetic energy spectrum from 0.43 to 0.79 micro-meter.
- **Radiance**: total amount of energy that flows from the light source, measured in watts (W).
- **Luminance**: amount of energy an observer perceives from a light source, measured in lumens (lm).
- **Brightness**: a subjective descriptor of light perception, impossible to measure, representing the achromatic notion of intensity.

Image Sensing and Acquisition

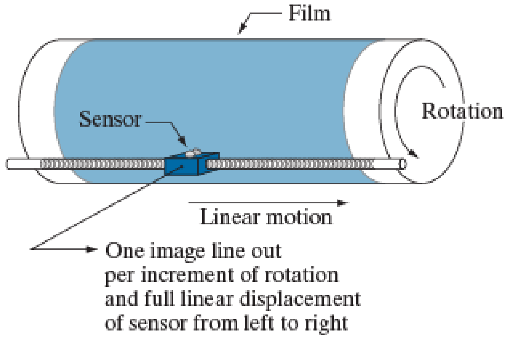
- Images are generated by the combination of an “illumination” source and the reflection or absorption of energy from the source by the elements of the “scene”.
- Illumination can be from a source of electromagnetic energy, or from less traditional sources such as ultrasound, acoustics, or even computer-generated.
- Scene elements can be familiar objects, or molecules, rock formations, human brain etc.

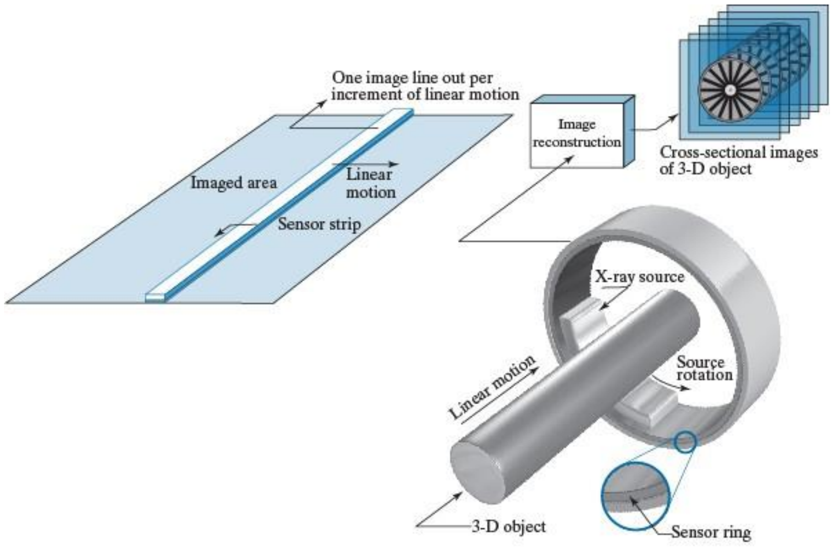


a
b
c
FIGURE 2.12
(a) Single sensing element.
(b) Line sensor.
(c) Array sensor.

Image Sensing and Acquisition

FIGURE 2.13 Combining a single sensing element with mechanical 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 Sensing and Acquisition

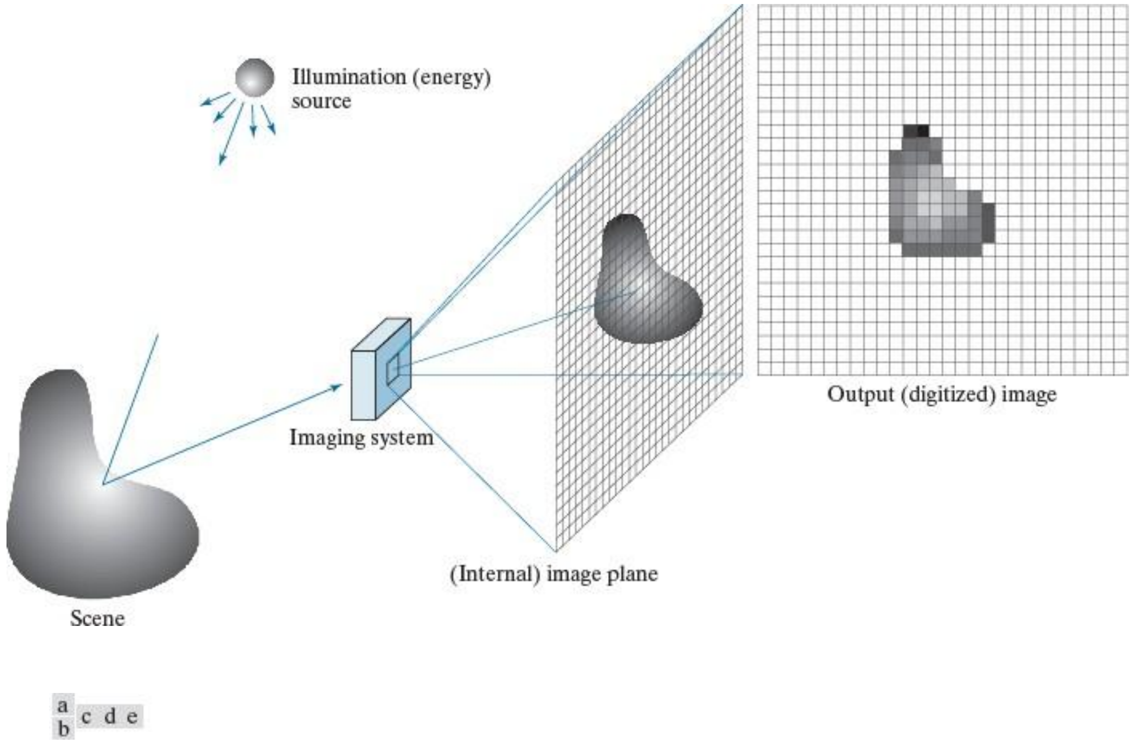


FIGURE 2.15 An example of digital image acquisition. (a) Illumination (energy) source. (b) A scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

Image Formation Model

- An image is denoted by a function ***f(x, y)***, which the value of ***f*** at spatial coordinates ***(x, y)*** is a scalar quantity proportional to energy radiated by a physical source.
- The values of ***f*** are non-negative, and finite: ***0 ≤ f(x,y) < inf***.
- Function ***f(x, y)*** is characterized by two components:
  - **Illumination**: the amount of source illumination incident on the scene being viewed, represented by ***i(x, y)***.
  - **Reflectance**: the amount of illumination reflected by the objects in the scene, ***r(x,y)***.

$$f(x,y)=i(x,y)*r(x,y)$$
$$0\leq i(x,y)\in inf$$
$$0\leq r(x,y)\leq 1$$

- In some cases, for example X-ray imaging, we have transmissivity instead of reflectance.

Image Sampling and Quantization

- To create a digital image, we need to convert the continuous sensed data into a digital format.
- Two processes are required:
  - Sampling: digitization in the spatial domain
  - Quantization: digitization in the function domain

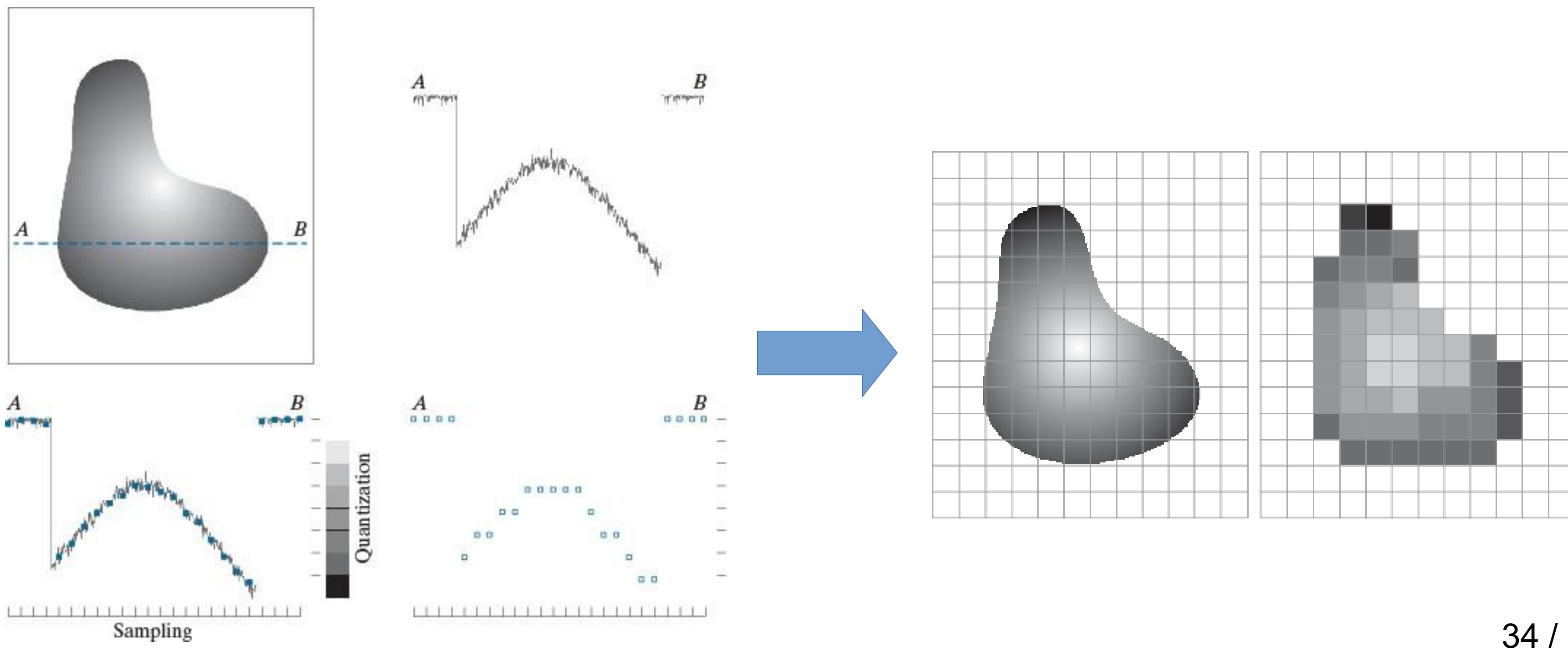


Image Sampling and Quantization

- Assuming ***f(s, t)*** as a continuous image function, using sampling and digitization, we create the image ***f(x, y)***, containing ***M*** rows and ***N*** columns.
- The spatial coordinate values are shown by integers as: ***x=0, 1, 2, …, M-1*** and ***y=0, 1, 2, …, N-1***.
- For image ***f(x, y)***, we have ***L*** number of intensity levels, represented as a power of 2. For example, in an 8-bit image, we have 256 intensity levels:

$$L = 2^k$$

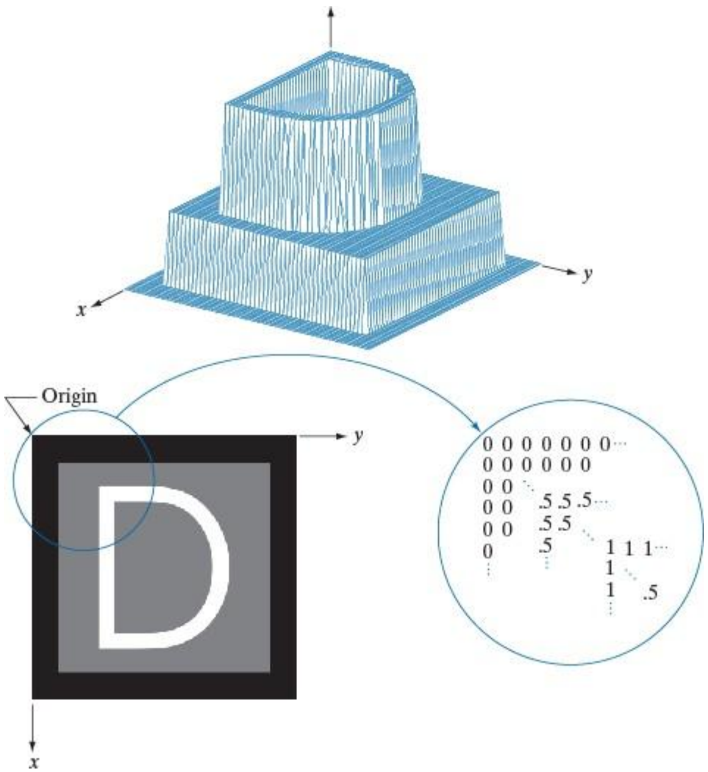
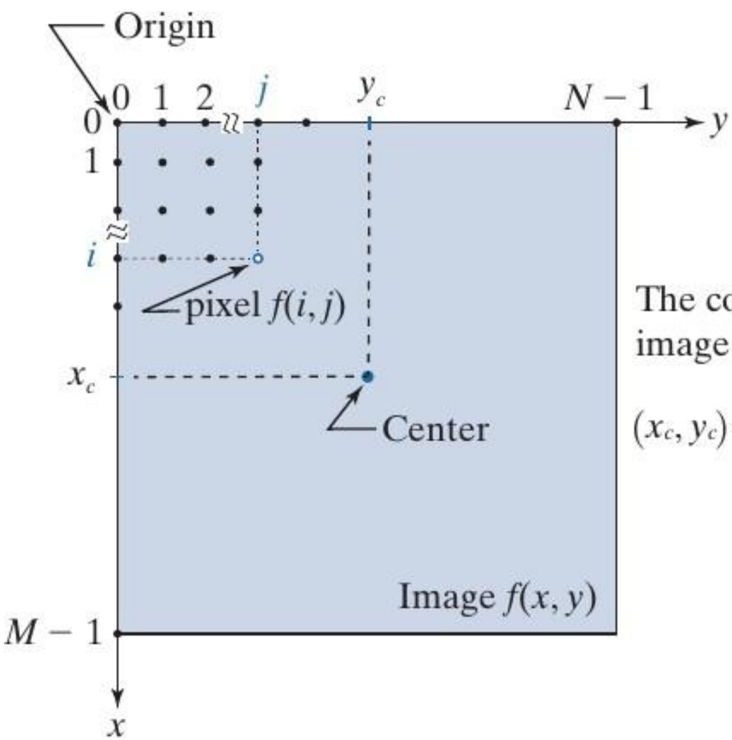


Image Sampling and Quantization

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



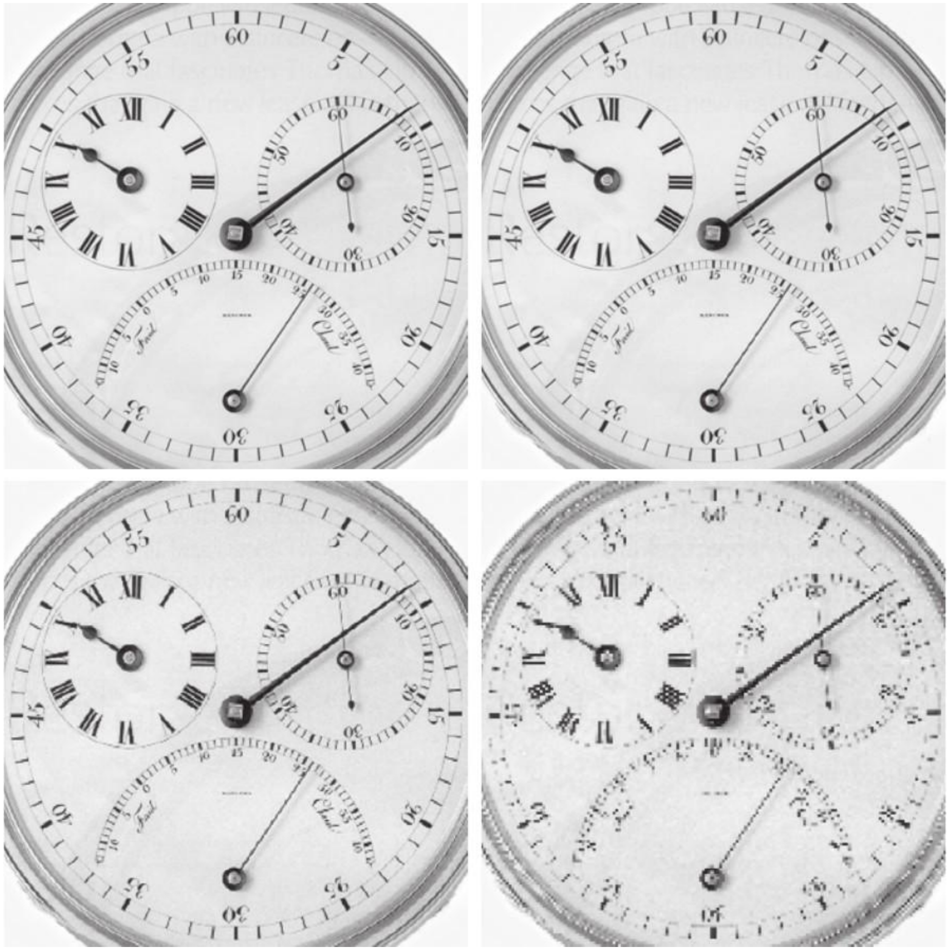
$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}$$

The coordinates of the image center are

$$(x_c, y_c) = \left(\text{floor}\left(\frac{M}{2}\right), \text{floor}\left(\frac{N}{2}\right)\right)$$

Spatial and Intensity Resolution

- Spatial resolution: the size of the smallest perceptible details in an image
- May be measured by the number of pixels per unit distance.
- Spatial resolution is dependent on the sampling rate.



a b
c d

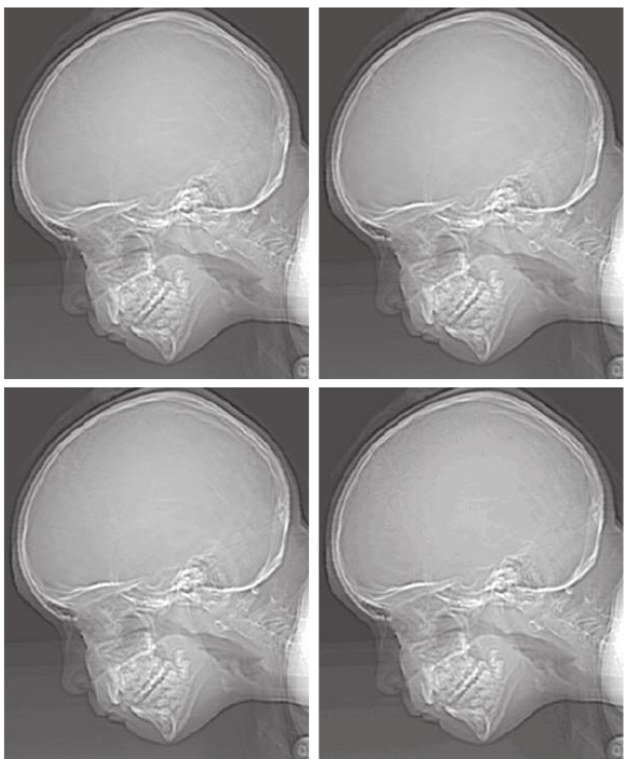
FIGURE 2.23 Effects of reducing spatial resolution. The images shown are at:
(a) 930 dpi,
(b) 300 dpi,
(c) 150 dpi, and
(d) 72 dpi.

Spatial and Intensity Resolution

- Intensity resolution: the smallest discernible change in the intensity level.
- Measured in the number of bits used for quantization.

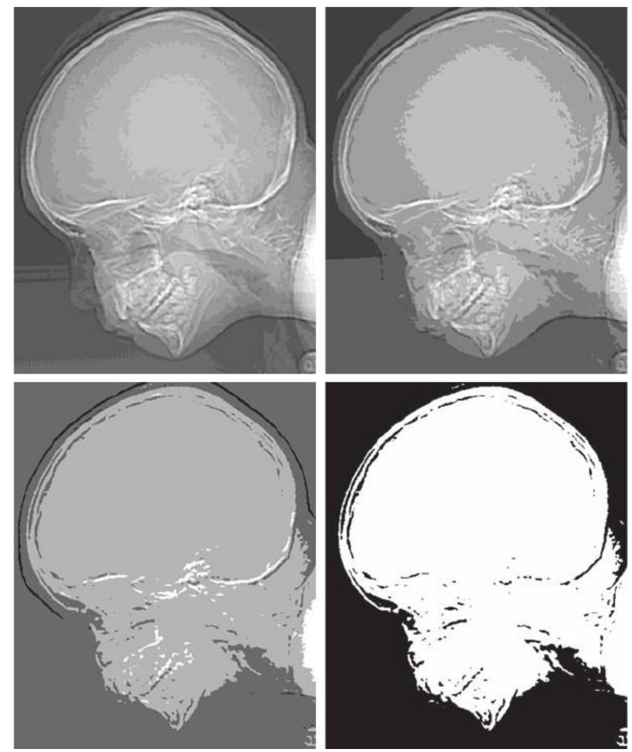
a b
c d

FIGURE 2.24
(a) 774 × 640, 256-level image. (b)-(d) Image displayed in 128, 64, and 32 intensity levels, while keeping the spatial resolution constant. (Original image courtesy of the Dr. David R. Pickens, Department of Radiology & Radiological Sciences, Vanderbilt University Medical Center.)



e f
g h

FIGURE 2.24
(*Continued*) (e)-(h) Image displayed in 16, 8, 4, and 2 intensity levels.



Spatial and Intensity Resolution

- Both are digitization-dependent:
  - Spatial resolution depends on the number of samples (N)
  - Intensity resolution depends on the number of bits (k)

- Different artifacts:
  - Too low spatial resolution results in jagged lines
  - Too low intensity resolution results in false contouring

- Sensitivity:
  - Spatial resolution is more sensitive to the shape variations
  - Intensity resolution is more sensitive to the lighting variations

Spatial and Intensity Resolution

- Left: Least geometric details but more lighting information
- Middle: More details but less lighting information
- Right: Most geometric details but least lighting information

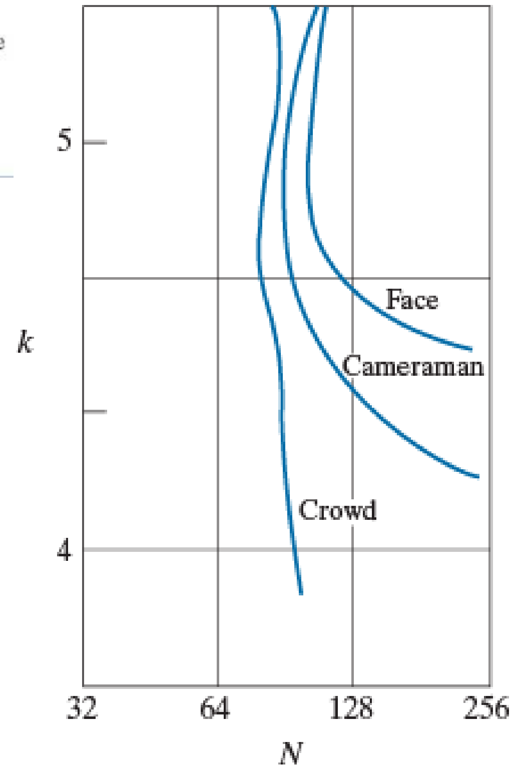
What would be good digitization schemes for these images?

Spatial and Intensity Resolution

- The iso-preference curves
  - Change N and k values and compare the quality of the images obtained.
  - Each curve shows the images with the same quality judged by observers

- We can see:
  - Images with more shape detail (e.g., crowd) need fewer intensity levels to achieve the same quality
  - Images with less shape detail (e.g., face) are more sensitive to the intensity resolution but less sensitive to spatial resolution

FIGURE 2.26 Representative isopreference curves for the three types of images in Fig. 2.25.



Questions?

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DATA-DRIVEN SCIENCE AND ENGINEERING
Machine Learning, Dynamical Systems, and Control
Steven L. Brunton · J. Nathan Kutz
Shannon Nyquist Sampling Theorem
"Aliasing"
PSD
true
freq

Sampling Theory & Nyquist Principle

What is Sampling?

The process of converting a continuous-time signal (analog) into a discrete-time signal (digital) by taking measurements at discrete time intervals.

- **Nyquist-Shannon Sampling Theorem:** To accurately reconstruct a bandlimited continuous signal, the sampling rate must be at least twice the highest frequency component in the signal. $f_s \geq 2 \cdot f_{max}$ Where f_s = sampling frequency, f_{max} = highest frequency in the signal
- **Critical Sampling Rate:** The minimum sampling rate ($2 \cdot f_{max}$) is known as the Nyquist rate
- **Aliasing:** When the sampling rate is below the Nyquist rate, high-frequency components appear as lower frequencies in the sampled signal, causing distortion
- **Preventing Aliasing:** Use anti-aliasing filters before sampling to remove frequency components above $f_s/2$

Proper Sampling

ECG signal with 100 Hz maximum frequency:
Sampling rate should be ≥ 200 Hz
Accurate reconstruction possible

Under-Sampling

EEG signal with 70 Hz frequency components:
Sampling at 100 Hz (below Nyquist rate)
Aliasing occurs, distorted signal

Over-Sampling

PPG signal with 10 Hz maximum frequency:
Sampling at 100 Hz (5× Nyquist rate)
Better noise immunity, higher resolution