CS633:Image Processing
Module 1: Digital Image Fundamentals

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Module - 1
Digital Image Fundamentals

- **Topics Covered**
  - Introduction
    - What is Digital Image Processing?
    - The Origin of Digital Image Processing
    - Fundamental Steps in Digital Image Processing
    - Components of an Image Processing System
  - Digital Image Fundamentals
    - Elements of Visual Perception
    - Image Sensing and Acquisition
    - Image Sampling and Quantization
    - Some Basic Relationships Between Pixels
  - Color Models

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- **Introduction**
  - One picture is worth more than ten thousand words
  - Interest in digital image processing methods stems from two principal application areas
    - Improvement of pictorial information for human interpretation
    - Processing of image data for tasks such as storage, transmission, and extraction of pictorial information

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- **What is Digital Image Processing?**
  - An Image
    - A two-dimensional function, f (x, y)
    - Where x and y are spatial (plane) coordinates
    - The amplitude of f at any pair of coordinates (x, y) is called the intensity or gray level
  - A Digital Image
    - When x, y, and the intensity values of f are all finite, discrete quantities, image is called as a digital image
    - Composed of a finite number of elements, each of which has a particular location and value
    - These elements are called picture elements, image elements, pels, and pixels

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- **What is Digital Image Processing?**
  - A Digital Image
    - Pixel is the term used most widely to denote the elements of a digital image
  - Digital Image Processing
    - Processing digital images by means of a digital computer
    - A discipline in which both the input and output of a process are images
    - Includes processes that extract attributes from images
    - Including the recognition of individual objects

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- **What is Digital Image Processing?**
  - Digital Image Processing
    - Three types of computerized processes
      - Low Level Processes
      - Mid Level Processes,
      - High Level Processes
    - Low Level Processes
      - Involve primitive operations such as image preprocessing to reduce noise, contrast enhancement, and image sharpening
      - Characterized by the fact that both its inputs and outputs are images

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- **What is Digital Image Processing?**
  - Digital Image Processing
    - Mid Level Processes
      - Involves tasks such as segmentation (partitioning an image into regions or objects)
      - Description of those objects to reduce them to a form suitable for computer processing
      - Classification (recognition) of individual objects
      - Characterized by the fact that its inputs generally are images, but its outputs are attributes extracted from those images (e.g., edges, contours, and the identity of individual objects)

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- **What is Digital Image Processing?**
  - Digital Image Processing
    - High Level Processes
      - Involves “making sense” of an ensemble of recognized objects, as in image analysis,
      - Performing the cognitive functions normally associated with human vision

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- **The Origin of Digital Image Processing**
  - Introduction of the Bartlane cable picture transmission system in the early ***1920s*** reduced the time required to transport a picture across the Atlantic from more than a week to less than three hours
  - Specialized printing equipment coded pictures for cable transmission, then reconstructed them at the receiving end
  - Figure 1.1 was transmitted in this way and reproduced on a telegraph printer fitted with typefaces simulating a halftone pattern

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- **The Origin of Digital Image Processing**

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.]

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- **The Origin of Digital Image Processing**
  - Some of the initial problems in improving the visual quality of these early digital pictures were related to the selection of printing procedures and the distribution of intensity levels
  - The printing method used to obtain Fig. 1.1 was abandoned toward the end of ***1921*** in favor of a technique based on photographic reproduction made from tapes perforated at the telegraph receiving terminal
  - Figure 1.2 shows an image obtained using this method
  - The improvements over Fig. 1.1 are evident, both in tonal quality and in resolution

- **The Origin of Digital Image Processing**

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

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- **The Origin of Digital Image Processing**
  - The early Bartlane systems were capable of coding images in five distinct levels of gray.
  - This capability was increased to 15 levels in ***1929***
  - Figure 1.3 is typical of the type of images that could be obtained using the 15-tone equipment.
  - During this period, introduction of a system for developing a film plate via light beams that were modulated by the coded picture tape improved the reproduction process considerably

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- **The Origin of Digital Image Processing**

FIGURE 1.3 Unretouched cable picture of Generals Pershing (right) and Foch, transmitted in 1929 from London to New York by 15-tone equipment. (McFarlane.)

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- **The Origin of Digital Image Processing**
  - All the examples just cited involve digital images
  - Not considered digital image processing results
  - Digital computers were not used in their creation
  - History of digital image processing is intimately tied to the development of the digital computer
  - Digital images require so much storage and computational power
  - Progress in the field of digital image processing has been dependent on the development of digital computers and of supporting technologies that include data storage, display, and transmission

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- **The Origin of Digital Image Processing**
  - A modern digital computer dates back to only the 1940s, with the introduction by John von Neumann of two key concepts
    - A memory to hold a stored program and data
    - Conditional branching
  - These two ideas are the foundation of a central processing unit (CPU), which is at the heart of computers today
  - Starting with von Neumann, there were a series of key advances that led to computers powerful enough to be used for digital image processing

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- **The Origin of Digital Image Processing**
  - Briefly, these advances may be summarized as follows
    - The invention of the transistor at Bell Laboratories in 1948
    - The development in the 1950s and 1960s of the high-level programming languages COBOL (Common Business-Oriented Language) and FORTRAN (Formula Translator)
    - The invention of the integrated circuit (IC) at Texas Instruments in 1958

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- **The Origin of Digital Image Processing**
  - Briefly, these advances may be summarized as follows
    - The development of operating systems in the early 1960s
    - The development of the microprocessor (a single chip consisting of a CPU, memory, and input and output controls) by Intel in the early 1970s
    - The introduction by IBM of the personal computer in 1981

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- **The Origin of Digital Image Processing**
  - Briefly, these advances may be summarized as follows
    - Progressive miniaturization of components, starting with large-scale integration (LI) in the late 1970s, then very-large-scale integration (VLSI) in the 1980s, to the present use of ultra-large-scale integration (ULSI) and experimental nono technologies
    - Concurrent with these advances were developments in the areas of mass storage and display systems, both of which are fundamental requirements for digital image processing

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- **The Origin of Digital Image Processing**
  - The first computers powerful enough to carry out meaningful image processing tasks appeared in the early 1960s
  - The birth of what we call digital image processing today can be traced to the availability of those machines, and to the onset of the space program during that period
  - It took the combination of those two developments to bring into focus the potential of digital image processing for solving problems of practical significance

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- **The Origin of Digital Image Processing**
  - Work on using computer techniques for improving images from a space probe began at the Jet Propulsion Laboratory (Pasadena, California) in 1964
  - Pictures of the moon transmitted by Ranger 7 were processed by a computer to correct various types of image distortion inherent in the on-board television camera
  - Figure 1.4 shows the first image of the moon taken by Ranger 7 on July 31, 1964 at 9:09 A.M. Eastern Daylight Time (EDT), about 17 minutes before impacting the lunar surface

- **The Origin of Digital Image Processing**

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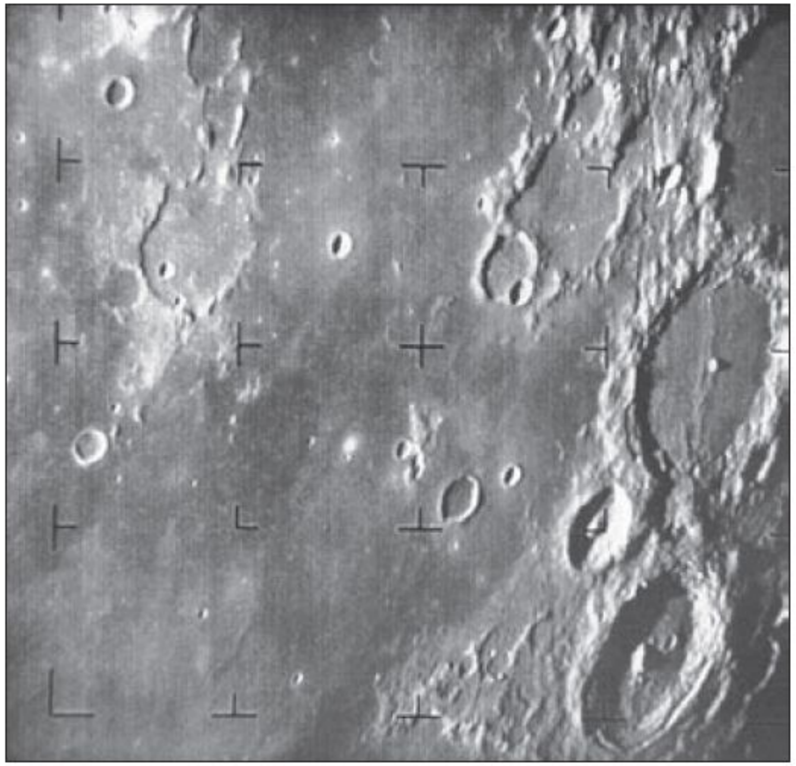
FIGURE 1.4
The first picture of the moon by a U.S. spacecraft. *Ranger 7* took this image on July 31, 1964 at 9:09 A.M. EDT, about 17 minutes before impacting the lunar surface. (Courtesy of NASA.)



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- **The Origin of Digital Image Processing**
  - This also is the first image of the moon taken by a U.S. spacecraft
  - The imaging lessons learned with Ranger 7 served as the basis for improved methods used to enhance and restore images from the Surveyor missions to the moon, the Mariner series of flyby missions to Mars, the Apollo manned flights to the moon, and others
  - In parallel with space applications, digital image processing techniques began in the late 1960s and early 1970s to be used in medical imaging, remote Earth resources observations, and astronomy

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- **Fundamental Steps in Digital Image Processing**

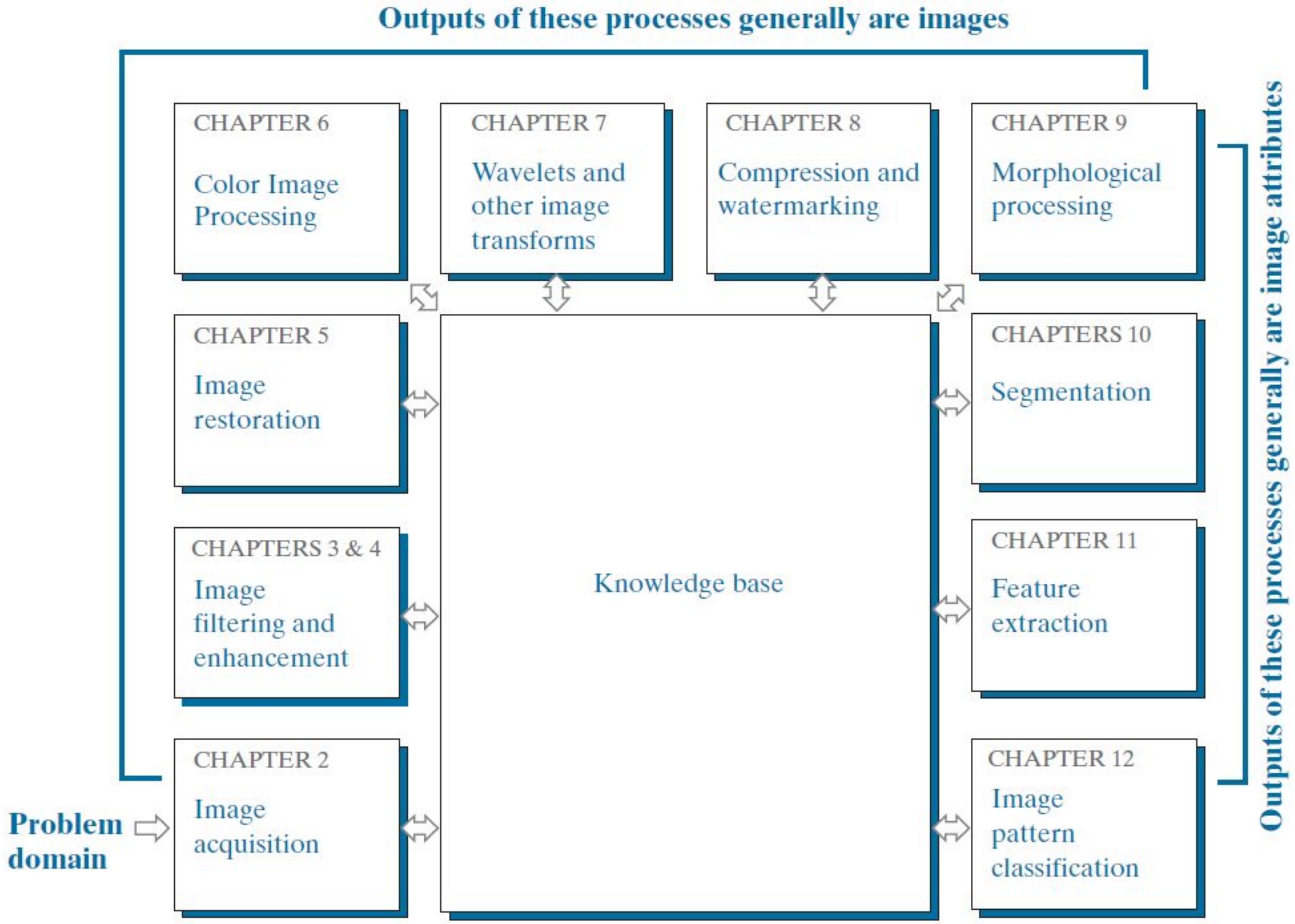

FIGURE 1.23 Fundamental steps in digital image processing.

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- **Fundamental Steps in Digital Image Processing**
  - Divide the material into the two broad categories
    - Methods whose input and output are images
    - Methods whose inputs may be images, but whose outputs are attributes extracted from those image
  - This organization is summarized in Fig. 1.23
  - The diagram does not imply that every process is applied to an image
  - All the methodologies that can be applied to images for different purposes, and possibly with different objectives

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- **Fundamental Steps in Digital Image Processing**
  - **Image acquisition**
    - Given an image that is already in digital form
    - The image acquisition stage involves preprocessing, such as scaling
  - **Image enhancement**
    - The process of manipulating an image so the result is more suitable than the original for a specific application
    - Enhancement techniques are problem oriented
    - for example, a method that is quite useful for enhancing X-ray images may not be the best approach for enhancing satellite images

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- **Fundamental Steps in Digital Image Processing**
  - **Image restoration**
    - Deals with improving the appearance of an image
    - Unlike enhancement, which is subjective, image restoration is objective
    - Restoration techniques tend to be based on mathematical or probabilistic models of image degradation
    - Enhancement is based on human subjective preferences regarding what constitutes a “good” enhancement result
  - **Color image processing**
    - Fundamental concepts in color models
    - Basic color processing in a digital domain
    - Color is used as the basis for extracting features of interest in an image

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- **Fundamental Steps in Digital Image Processing**
  - **Wavelets**
    - Foundation for representing images in various degrees of resolution
    - Used for image data compression and for pyramidal representation, in which images are subdivided successively into smaller regions
  - **Compression**
    - Deals with techniques for reducing the storage required to save an image, or the bandwidth required to transmit it
    - Image compression is familiar to most users of computers in the form of image file extensions, such as the jpg file extension used in the JPEG (Joint Photographic Experts Group) image compression standard

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- **Fundamental Steps in Digital Image Processing**
  - **Morphological**
    - Deals with tools for extracting image components that are useful in the representation and description of shape
  - **Segmentation**
    - Partitions an image into its constituent parts or objects
    - Autonomous segmentation is one of the most difficult tasks in digital image processing
    - A rugged segmentation procedure brings the process a long way toward successful solution of imaging problems that require objects to be identified individually
    - Weak or erratic segmentation algorithms almost always guarantee eventual failure
    - The more accurate the segmentation, the more likely automated object classification is to succeed

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- **Fundamental Steps in Digital Image Processing**
  - **Feature extraction**
    - Follows the output of a segmentation stage, which usually is raw pixel data, constituting either the boundary of a region (i.e., the set of pixels separating one image region from another) or all the points in the region itself
    - Consists of feature detection and feature description
    - Feature detection refers to finding the features in an image, region, or boundary
    - Feature description assigns quantitative attributes to the detected features
    - For example, we might detect corners in a region, and describe those corners by their orientation and location; both of these descriptors are quantitative attributes

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- **Fundamental Steps in Digital Image Processing**
  - **Feature extraction**
    - Feature processing methods are subdivided into three principal categories, depending on whether they are applicable to boundaries, regions, or whole images
    - Some features are applicable to more than one category
    - Feature descriptors should be as insensitive as possible to variations in parameters such as scale, translation, rotation, illumination, and viewpoint
  - **Image pattern classification**
    - The process that assigns a label (e.g., “vehicle”) to an object based on its feature descriptors
    - Methods of image pattern classification ranging from “classical” approaches such as minimum-distance, correlation, and Bayes classifiers

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- **Fundamental Steps in Digital Image Processing**
  - **Image pattern classification**
    - Modern approaches implemented using deep neural networks
    - Deep convolutional neural networks, which are ideally suited for image processing work
  - **Knowledge base**
    - Knowledge about a problem domain is coded into an image processing system in the form of a knowledge database
    - This knowledge may be as simple as detailing regions of an image where the information of interest is known to be located, thus limiting the search that has to be conducted in seeking that information

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- **Fundamental Steps in Digital Image Processing**
  - **Knowledge base**
    - The knowledge base can also be quite complex, such as an interrelated list of all major possible defects in a materials inspection problem, or an image database containing high-resolution satellite images of a region in connection with change-detection applications
    - It controls the interaction between modules
    - This distinction is made in Fig. 1.23 by the use of double-headed arrows between the processing modules and the knowledge base, as opposed to single-headed arrows linking the processing modules

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- **Fundamental Steps in Digital Image Processing**
  - viewing the results of image processing can take place at the output of any stage in Fig. 1.23
  - Not even all those modules are needed in many cases
  - As the complexity of an image processing task increases, so does the number of processes required to solve the problem

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- **Components of an Image Processing System**
  - General-purpose small computers with specialized image processing hardware and software
  - Figure 1.24 shows the basic components comprising a typical general-purpose system used for digital image processing
  - **Image Sensors**
    - Two subsystems are required to acquire digital images
    - **Physical Sensor**
      - Responds to the energy radiated by the object we wish to image
    - **Digitizer**
      - Device for converting the output of the physical sensing device into digital form
  - **Specialized image processing hardware**
    - **Digitizer**

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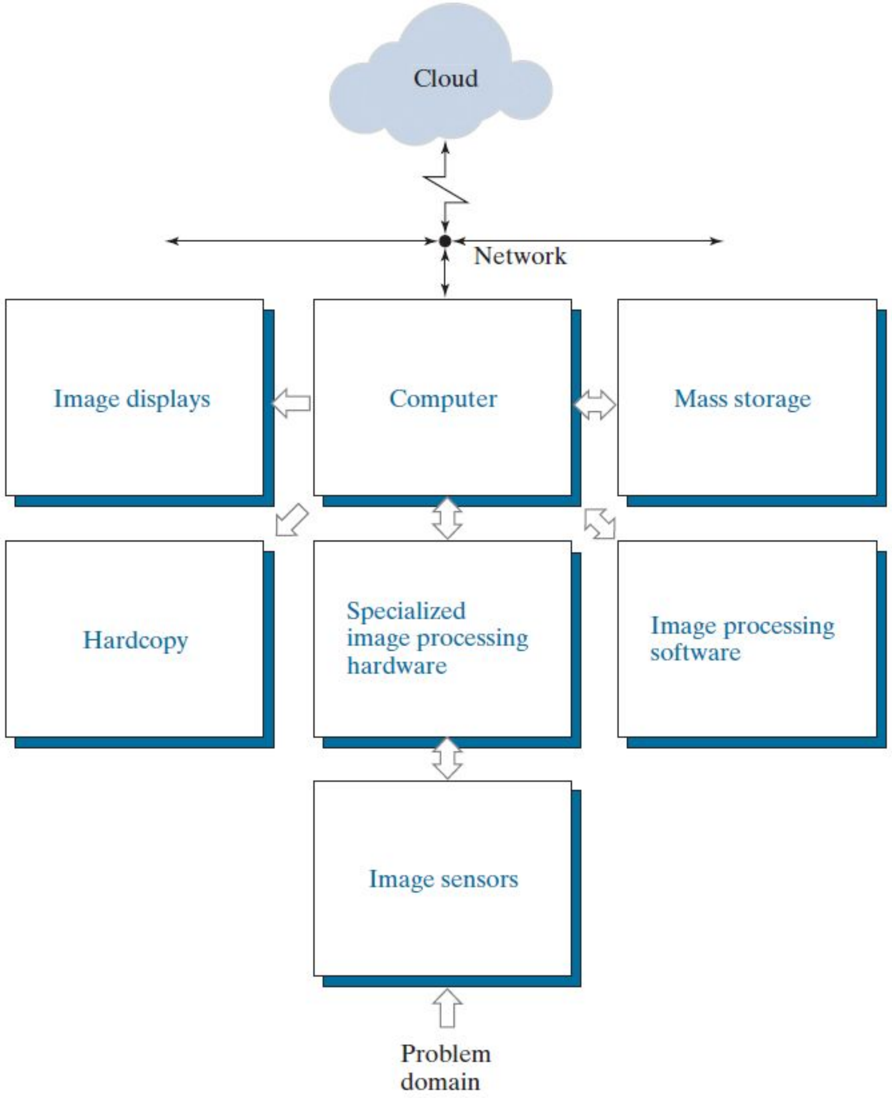

FIGURE 1.24 Components of a general-purpose image processing system.

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- **Components of an Image Processing System**
  - **Specialized image processing hardware**
    - **ALU(Arithmetic Logic Unit)**
      - Performs arithmetic and logical operations in parallel on entire images
      - One example of how an ALU is used is in averaging images for the purpose of noise reduction
      - Called a front-end subsystem
      - Most distinguishing characteristic is speed
      - Performs functions that require fast data throughputs (e.g., digitizing and averaging video images at 30 frames/s)
    - **One or more GPUs (Graphics Processing Units)**
      - Perform intensive matrix operations

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- **Components of an Image Processing System**
  - **Computer**
    - A general-purpose computer
    - Range from a PC to a supercomputer
  - **Software**
    - Consists of specialized modules that perform specific tasks
    - A well-designed package
      - Includes the capability for the user to write code
      - Allow the integration of those modules and general-purpose software commands from at least one computer language
    - Commercially available image processing software, MATLAB® Image Processing Toolbox

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- **Components of an Image Processing System**
  - **Mass Storage**
    - Dealing with image databases that contain thousands, or even millions of images
    - Required adequate storage
    - Digital storage for image processing applications falls into three principal categories
      - Short-Term Storage
      - On-Line Storage
      - Archival Storage
    - Storage is measured
      - Bytes (Eight Bits)
      - Kbytes (10^3 bytes)
      - Mbytes (10^6 bytes)
      - Gbytes (10^9 bytes)
      - Tbytes (10^{12} bytes)

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- **Components of an Image Processing System**
  - **Mass Storage**
    - Short-Term Storage
      - Use during processing
      - Method of providing short-term storage
        - Computer Memory
        - Frame Buffers
          - Store one or more images
          - Accessed rapidly, usually at video rates (e.g., at 30 complete images per second)
        - The latter method allows virtually instantaneous image zoom, as well as scroll (vertical shifts) and pan (horizontal shifts)
        - Frame buffers usually are housed in the specialized image processing hardware unit
    - On-Line Storage
      - Relatively fast recall
      - Takes the form of magnetic disks or optical-media storage
      - Frequent access to the stored data

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- **Components of an Image Processing System**
  - **Mass Storage**
    - Archival Storage
      - Characterized by infrequent access
      - Characterized by massive storage requirements
      - Magnetic tapes and optical disks housed in “jukeboxes” are the usual media for archival applications
  - **Image displays**
    - Use today mainly color, flat screen monitors
    - Monitors are driven by the outputs of image and graphics display cards that are an integral part of the computer system
  - **Hardcopy devices**
    - Recording images include laser printers, film cameras, heat sensitive devices, ink-jet units, and digital units, such as optical and CD-ROM disks

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- **Components of an Image Processing System**
  - **Networking and cloud communication**
    - Almost default functions in any computer system in use today
    - Because of the large amount of data inherent in image processing applications, the key consideration in image transmission is bandwidth
    - In dedicated networks, this typically is not a problem, but communications with remote sites via the internet are not always as efficient
    - Fortunately, transmission bandwidth is improving quickly as a result of optical fiber and other broadband technologies
    - Image data compression continues to play a major role in the transmission of large amounts of image data

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- **Elements of Visual Perception**
  - Developing a basic understanding of human visual perception
  - Mechanics and parameters related to how images are formed and perceived by humans
  - Physical limitations of human vision in terms of factors that also are used in our work with digital images
  - Factors such as how human and electronic imaging devices compare in terms of resolution and ability to adapt to changes in illumination
  - **Structure of the Human Eye**
    - The eye is nearly a sphere
    - An average diameter of approximately 20 mm
    - Three membranes enclose the eye:
      - The cornea and sclera outer cover
      - The choroid
      - The retina

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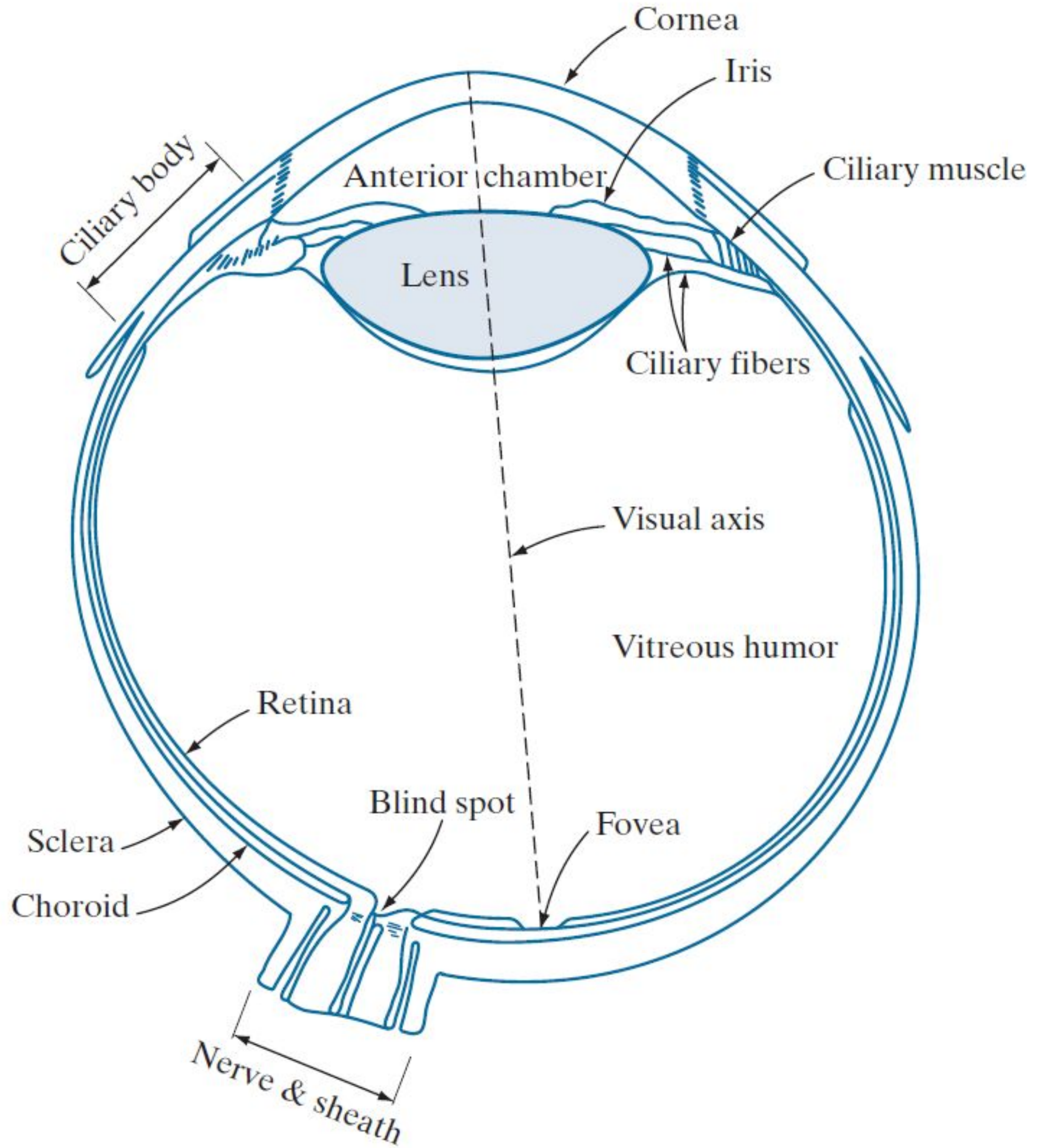

FIGURE 2.1 Simplified diagram of a cross section of the human eye.

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- **Structure of the Human Eye**
  - The cornea and sclera outer cover
    - The cornea is a tough, transparent tissue that covers the anterior surface of the eye
    - The sclera is an opaque membrane that encloses the remainder of the optic globe
  - The choroid
    - Lies directly below the sclera
    - This membrane contains a network of blood vessels that serve as the major source of nutrition to the eye
  - The retina
    - The innermost membrane of the eye is the *retina*, which lines the inside of the wall’s entire posterior portion
    - When the eye is properly focused, light from an object outside the eye is imaged on the retina
  - The eye ball
    - The eye ball is approximately spherical
    - The vertical measure of an eye ball is approximately 24 mm and is slightly less than the horizontal width
    - The eye offers a field of view covering 160^{o}(width) × 135^{o} height area

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- **Structure of the Human Eye**
  - Iris
    - The light entering the cornea is blocked by the visible colored and opaque surface of the iris
    - The back of the iris is coated with a black pigment
  - Pupil
    - The pupil is the opening at the center of the iris
    - The pupil controls the amount of light entering the eye ball
    - Its diameter varies from 1 to 8 mm in response to illumination changes
    - In low light conditions it dilates to increase the amount of light reaching the retina
    - Behind the pupil is the lens of the eye
  - Lens
    - The lens is suspended to the ciliary body by the suspensory ligament (Zonule of Zinn), made up of fine transparent fibers
    - The lens is transparent (has 70% water) and absorbs approximately 8% of the visible light spectrum
    - The protein in the lens absorbs the harmful infrared and ultraviolet light and prevents damage to the eye

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- **Structure of the Human Eye**
  - Fovea
    - The central portion of the retina at the posterior part is the fovea
    - It is about 1.5 mm in diameter
  - Cones
    - There are about 6 million cones in the eye
    - The cones help in the bright-light (photopic) vision
    - These are highly sensitive to color
    - They are located primarily in the fovea where the image is focused by the lens
    - Each cone cell is connected to its separate nerve ending
    - Hence they have the ability to resolve fine details
  - Rods
    - There about 100 million rods in the eye
    - The rods help in the dim-light (scotopic) vision
    - Their spatial distribution is radially symmetric about the fovea, but varies across the retina
    - They are distributed over a larger area in the retina
    - The rods are extremely sensitive and can respond even to a single photon
    - However they are not involved in color vision

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- **Structure of the Human Eye**
  - Rods
    - They cannot resolve fine spatial detail despite high number because many rods are connected to a single nerve
  - Blind spot
    - Though the photo-receptors are distributed in radially symmetric manner about the fovea, there is a region near the fovea where there are no receptors
    - This region is called as the blind spot
    - This is the region where the optic nerve emerges from the eye
    - Light falling on this region cannot be sensed
  - **Image Formation in the Eye**
    - Ordinary photographic camera
      - The lens has a fixed focal length
      - Focusing at various distances is achieved by varying the distance between the lens and the imaging plane, where the film (or imaging chip in the case of a digital camera) is located

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- **Image Formation in the Eye**
  - Human eye
    - The converse is true
    - The distance between the lens and the imaging region (the retina) is fixed
    - The focal length needed to achieve proper focus is obtained by varying the shape of the lens
    - The fibers in the ciliary body accomplish this, flattening or thickening the lens for distant or near objects, respectively
    - The retinal image is focused primarily on the region of the fovea
    - Perception then takes place by the relative excitation of light receptors, which transform radiant energy into electrical impulses that ultimately are decoded by the brain

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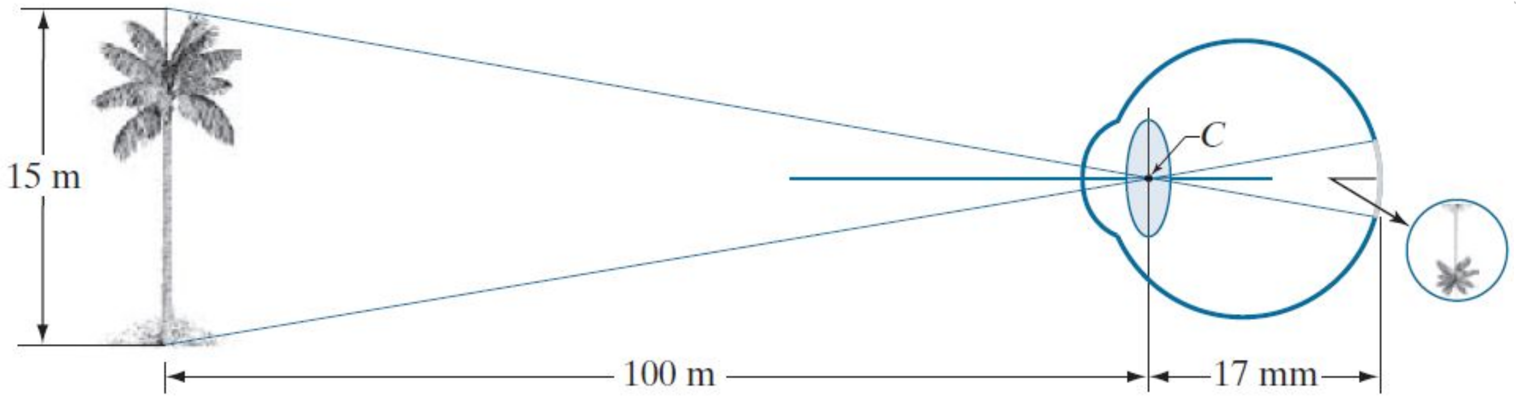

FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point C is the focal center of the lens.

- **Brightness Adaptation and Discrimination**
  - Digital images are displayed as a discrete set of intensities
    - The eye's ability to discriminate between different intensity levels is an important consideration in presenting image processing results
    - The range of light intensity levels to which the human visual system can adapt is enormous on the order of 10^{10}
    - Experimental evidence indicates that *subjective brightness* (intensity as *perceived* by the human visual system) is a logarithmic function of the light intensity incident on the eye

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- **Brightness Adaptation and Discrimination**
  - Brightness Adaptation
    - The human visual sensory mechanisms adapt to different lighting conditions
    - The sensitivity level for a given lighting condition is called as the brightness adaptation level
    - As the lighting condition changes, our visual sensory mechanism will adapt by changing its sensitivity
    - The human eye cannot respond to the entire range of intensity levels at a given level of sensitivity
    - If we stand in a brightly lit area we cannot discern details in a dark area since it will appear totally dark.
    - Our photo-receptors cannot respond to the low level of intensity because the level of sensitivity has been adapted to the bright light
    - However a few minutes after moving into the dark room, our eyes would adapt to the required sensitivity level and we would be able to see in the dark area
    - This shows that though our visual system can respond to a wide dynamic range, it is possible only by adapting to different lighting conditions
    - At a given point of time our eye can respond well to only particular brightness levels
    - The response of the visual system can be characterized with respect to a particular brightness adaptation level

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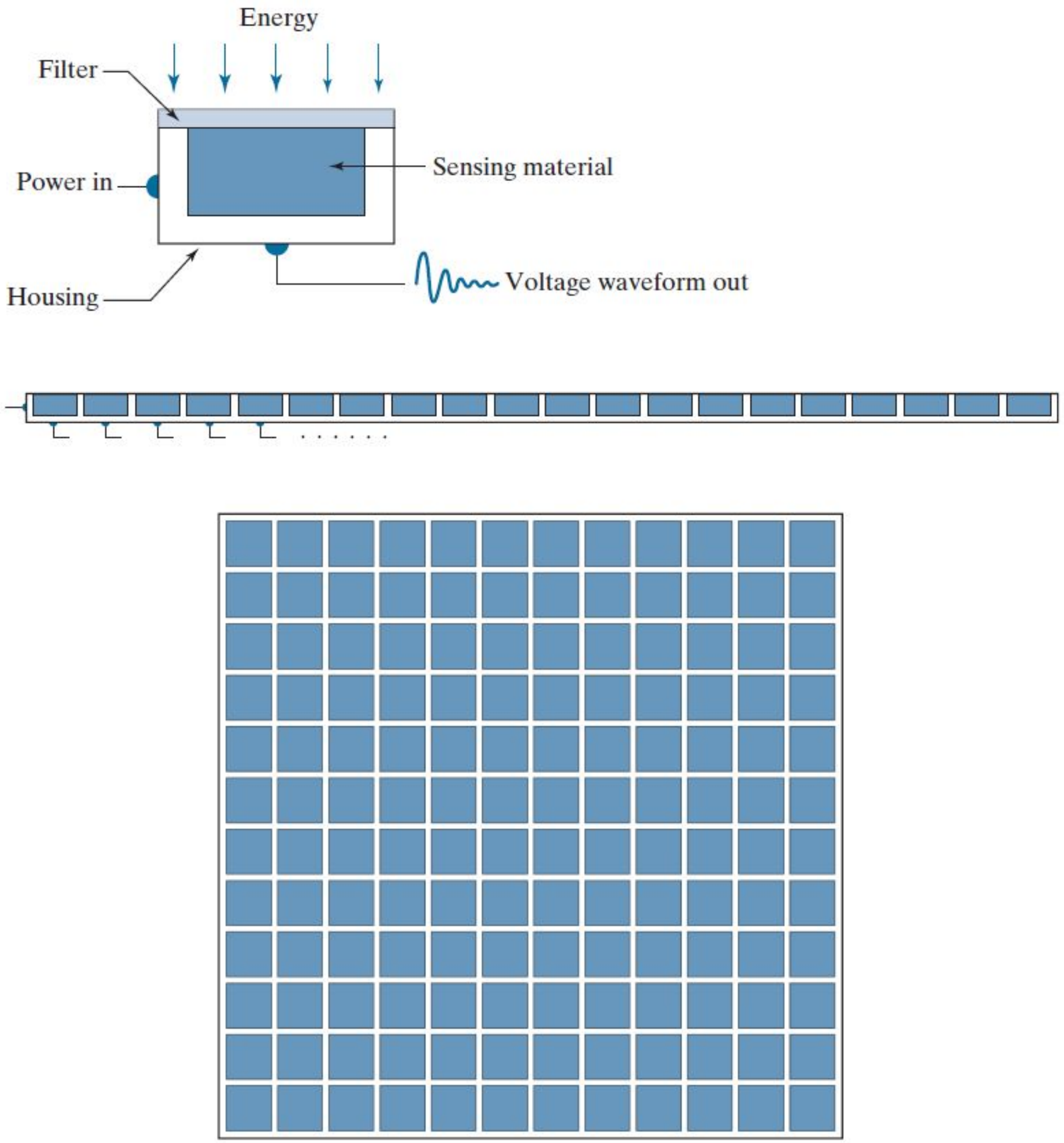
- **Image Sensing and Acquisition**
  - Most images generated
    - “illumination” source + the reflection or absorption of energy from that source
    - Elements of the “scene” being imaged
  - Illumination may originate
    - Source of electromagnetic energy, such as a radar, infrared, or X-ray system
    - Less traditional sources, such as ultrasound or even a computer-generated illumination pattern
  - Scene elements
    - Familiar objects
  - Depending on the nature of the source, illumination energy is reflected from, or transmitted through, objects
  - An example in the first category
    - Light reflected from a planar surface
  - An example in the second category
    - When X-rays pass through a patient’s body for the purpose of generating a diagnostic X-ray image

Module - 1 ***Digital Image Fundamentals***

a
b
c

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



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- **Image Sensing and Acquisition**
  - Figure 2.12 shows the three principal sensor arrangements used to transform incident energy into digital images
    - Image Acquisition Using a Single Sensing Element
    - Image Acquisition Using Sensor Strips
    - Image Acquisition Using Sensor Arrays
  - ***The idea***
    - *Incoming energy is transformed into a voltage by a combination of the input electrical power and sensor material that is responsive to the type of energy being detected*
    - *The output voltage waveform is the response of the sensor*
    - *A digital quantity is obtained by digitizing that response*

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- **Image Sensing and Acquisition**
  - **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*
      - *Constructed of silicon materials*
      - *Output is a voltage proportional to light intensity*
    - Using a filter in front of a sensor
      - Improves its selectivity
    - For example
      - An optical green-transmission filter favors light in the green band of the color spectrum
      - The sensor output would be stronger for green light than for other visible light components
    - To generate a 2-D image
      - 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
      - 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

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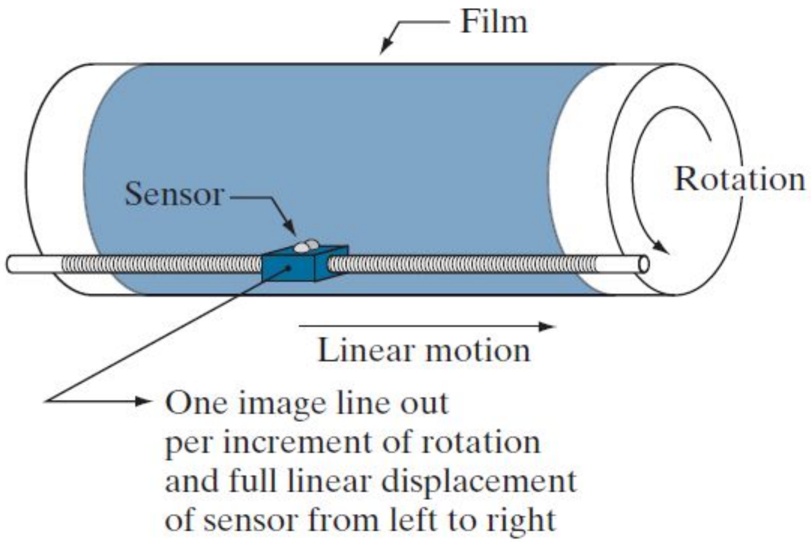
- **Image Sensing and Acquisition**
  - **Image Acquisition Using a Single Sensing Element**
    - **Figure 2.13**
      - A light source is contained inside the drum
      - As the light passes through the film, its intensity is modified by the film density before it is captured by the sensor
      - 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.



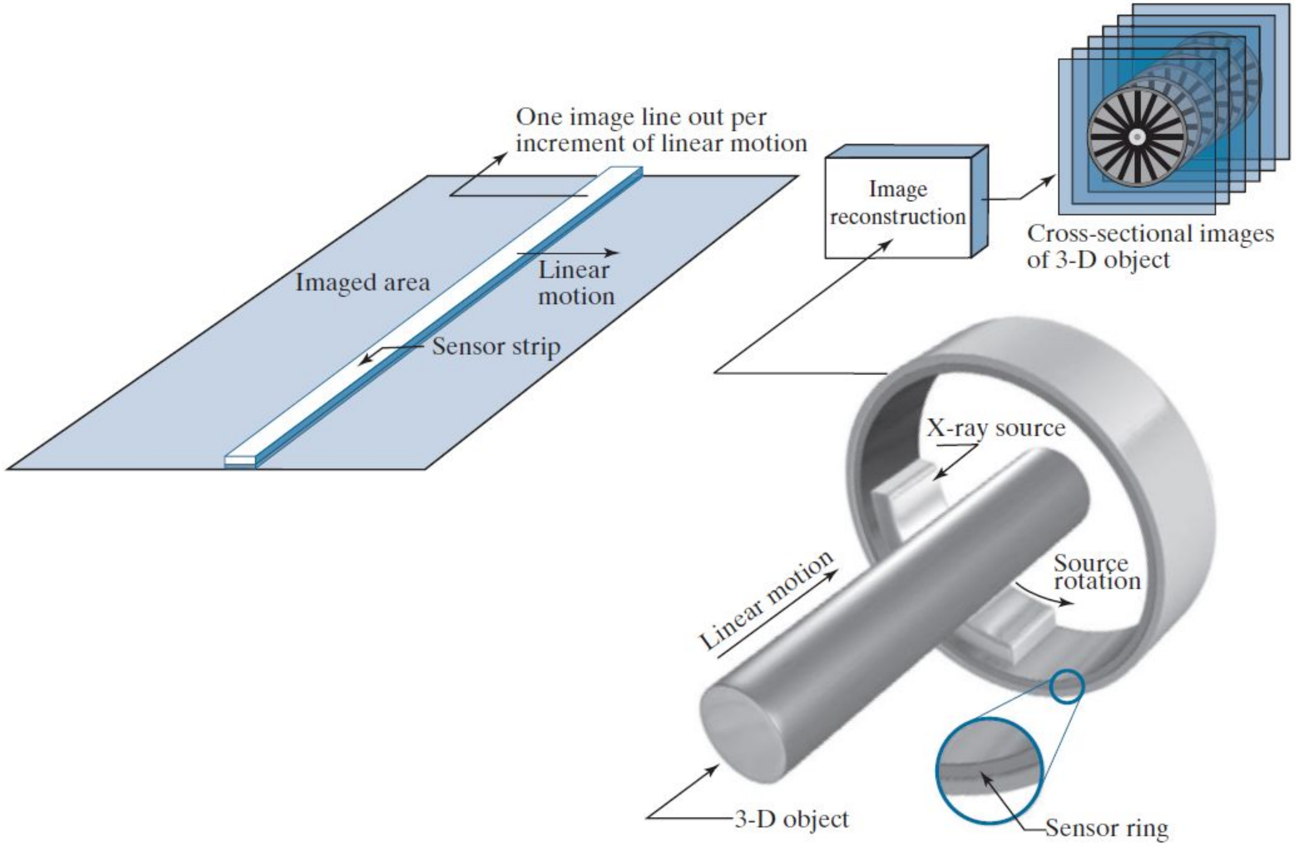
Module - 1 *Digital Image Fundamentals*

- **Image Sensing and Acquisition**
  - **Image Acquisition Using a Single Sensing Element**
    - Advantage
      - Inexpensive way to obtain high-resolution images because mechanical motion can be controlled with high precision
    - Disadvantages
      - Slow
      - Not portable
    - Other similar mechanical arrangements use a flat imaging bed, with the sensor moving in two linear directions
      - These types of mechanical digitizers sometimes are referred to as *transmission microdensitometers*
      - Systems in which light is reflected from the medium, instead of passing through it, are called *reflection microdensitometers*
    - Another example of imaging with a single sensing element
      - Places a laser source coincident with the sensor
      - Moving mirrors are used to control the outgoing beam in a scanning pattern and to direct the reflected laser signal onto the sensor

Module - 1
Digital Image Fundamentals

a b

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



Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **Image Acquisition Using Sensor Strips**
    - Fig. 2.12(b)
      - A geometry used more frequently
      - The strip provides imaging elements in one direction
    - Fig. 2.14(a)
      - Motion perpendicular to the strip provides imaging in the other direction
      - This arrangement is used in most flat bed scanners
      - Sensing devices with 4000 or more in-line sensors are possible
      - 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
      - One dimensional imaging sensor strips that respond to various bands of the electromagnetic spectrum are mounted perpendicular to the direction of flight
      - 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
      - Lenses or other focusing schemes are used to project the area to be scanned onto the sensors

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **Image Acquisition Using Sensor Strips**
    - Fig. 2.14(b)
      - Sensor strips in a ring configuration are used in medical and industrial imaging to obtain cross-sectional ("slice") images of 3-D objects
      - 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
      - In other words, images are not obtained directly from the sensors by motion alone; they also require extensive computer processing
      - A 3-D digital volume consisting of stacked images is generated as the object is moved in a direction perpendicular to the sensor ring

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **Image Acquisition Using Sensor Strips**
    - Fig. 2.14(b)
      - Other modalities of imaging based on the CAT principle include magnetic resonance imaging (MRI) and positron emission tomography (PET)
      - The illumination sources, sensors, and types of images are different, but conceptually their applications are very similar to the basic imaging approach shown in Fig. 2.14(b).

Module - 1
Digital Image Fundamentals

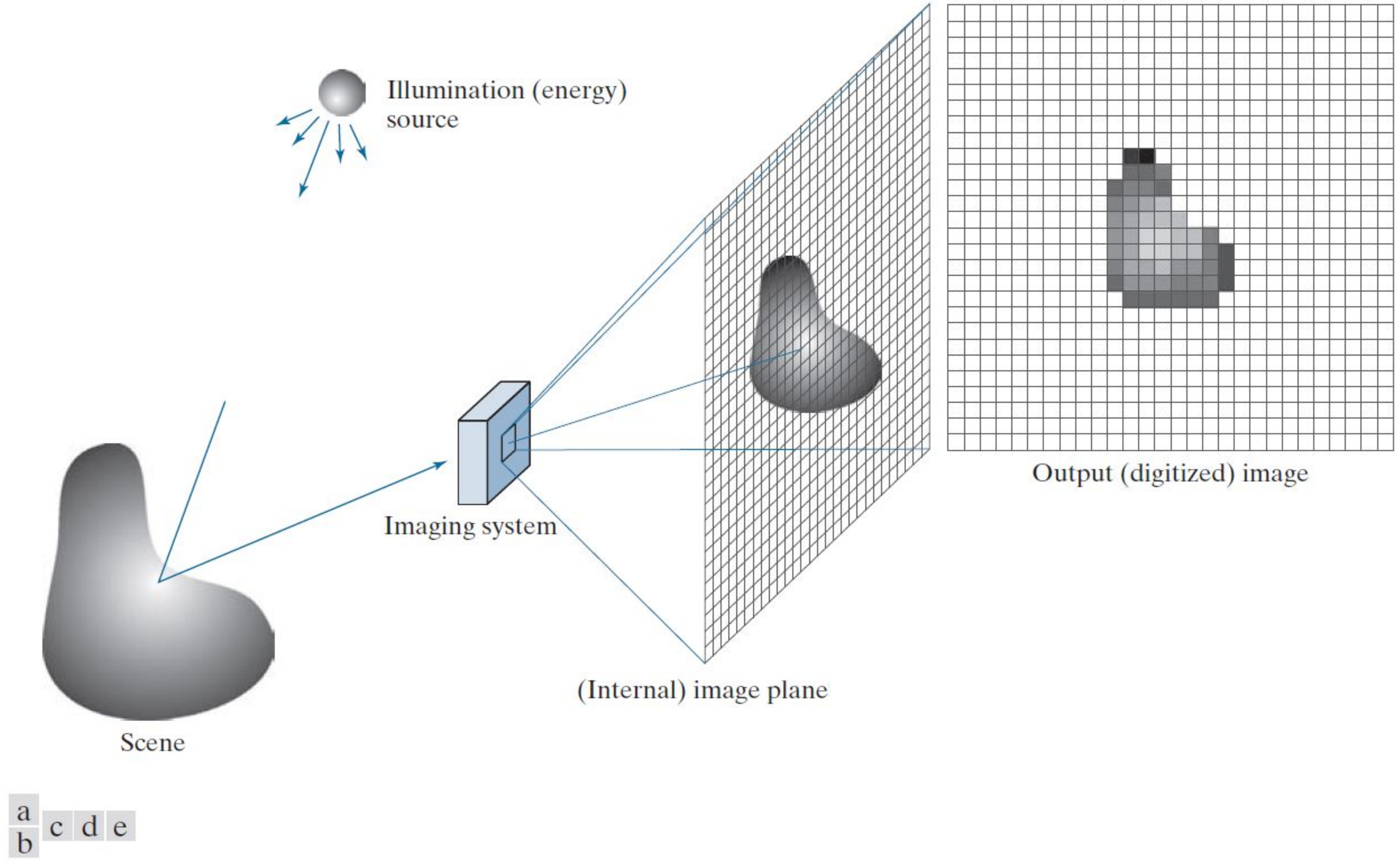


FIGURE 2.15 An example of digital image acquisition. (a) Illumination (energy) source. (b) A scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **Image Acquisition Using Sensor Arrays**
    - Figure 2.12(c)
      - Shows individual sensing elements arranged in the form of a 2-D array
      - Electromagnetic and ultrasonic sensing devices frequently are arranged in this manner
      - 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
      - CCD sensors are used widely in digital cameras and other light-sensing instruments
      - 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
      - Its key advantage is that a complete image can be obtained by focusing the energy pattern onto the surface of the array

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **Image Acquisition Using Sensor Arrays**
    - Figure 2.15
      - Shows the principal manner in which array sensors are used
      - 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)

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **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 whose physical meaning is determined by the source of the image, and whose values are proportional to energy radiated by a physical source (e.g., electromagnetic waves)
    - 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 two components
      - The amount of source illumination incident on the scene being viewed, called the illumination, denoted by i(x, y)
      - The amount of illumination reflected by the objects in the scene, called reflectance, denoted by r(x, y)
    - The two functions combine as a product to form f (x, y): $f(x, y) = i(x, y)r(x, y)$, where $0 \leq i(x, y) < \infty$ and $0 \leq r(x, y) \leq 1$

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **A Simple Image Formation Model**
    - Reflectance is bounded by 0 (total absorption) and 1 (total reflectance)
    - The nature of i(x, y) is determined by the illumination source, and r(x, y) is determined by the characteristics of the imaged objects
    - These expressions are applicable also to images formed via transmission of the illumination through a medium, such as a chest X-ray
    - In this case, we would deal with a transmissivity instead of a reflectivity function, but the limits would be the same as in Eq. , and the image function formed would be modeled as the product in Eq.
    - EXAMPLE 2.1
      - Some typical values of illumination and reflectance
      - The following numerical quantities illustrate some typical values of illumination and reflectance for visible light
      - On a clear day, the sun may produce in excess of 90,000 lm/m^2 of illumination on the surface of the earth
      - This value decreases to less than 10,000 lm/m^2 on a cloudy day

Module - 1 *Digital Image Fundamentals*

- **Image Sensing and Acquisition**
  - **A Simple Image Formation Model**
    - EXAMPLE 2.1
      - On a clear evening, a full moon yields about 0.1 lm/m^2 of illumination
      - The typical illumination level in a commercial office is about 1,000 lm/m^2
      - Similarly, the following are typical values of r(x, y): 0.01 for black velvet, 0.65 for stainless steel, 0.80 for flat-white wall paint, 0.90 for silver-plated metal, and 0.93 for snow
    - Let the intensity (gray level) of a monochrome image at any coordinates (x, y) be denoted by $l = f(x, y)$
    - From Eqs. it is evident that l lies in the range $L_{min} \leq l \leq L_{max}$
    - In theory, the requirement on L_{min} is that it be nonnegative, and on L_{max} that i be finite.
    - In practice, $L_{min} = i_{min}\, r_{min}$ and $L_{max} = i_{max}\, r_{max}$
    - From Example 2.1, using average office illumination and reflectance values as guidelines, we may expect $L_{min} \approx 10$ and $L_{max} \approx 1000$ to be typical indoor values in the absence of additional illumination

Module - 1
Digital Image Fundamentals

- **Image Sensing and Acquisition**
  - **A Simple Image Formation Model**
    - The units of these quantities are lum/m^2
    - However, actual units seldom are of interest, except in cases where photometric measurements are being performed
    - The interval $[L_{min}, L_{max}]$ is called the intensity (or gray) scale
    - Common practice is to shift this interval numerically to the interval [0, 1], or [0, C], where l = 0 is considered black and l = 1 (or C) is considered white on the scale
    - All intermediate values are shades of gray varying from black to white

Module - 1
Digital Image Fundamentals

- **Image Sampling and Quantization**
  - **Done**
    - To generate digital images from sensed data
    - The output of most sensors is a continuous voltage waveform whose amplitude and spatial behavior are related to the physical phenomenon being sensed
  - **Sampling and Quantization**
    - To create a digital image, we need to convert the continuous sensed data into a digital format
  - **Basic Concepts**
    - Figure 2.16(a) shows a continuous image f that we want to convert to digital form
    - 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
    - *Sampling*
      - *Digitizing the coordinate values*
    - *Quantization*
      - *Digitizing the amplitude values*

Module - 1
Digital Image Fundamentals

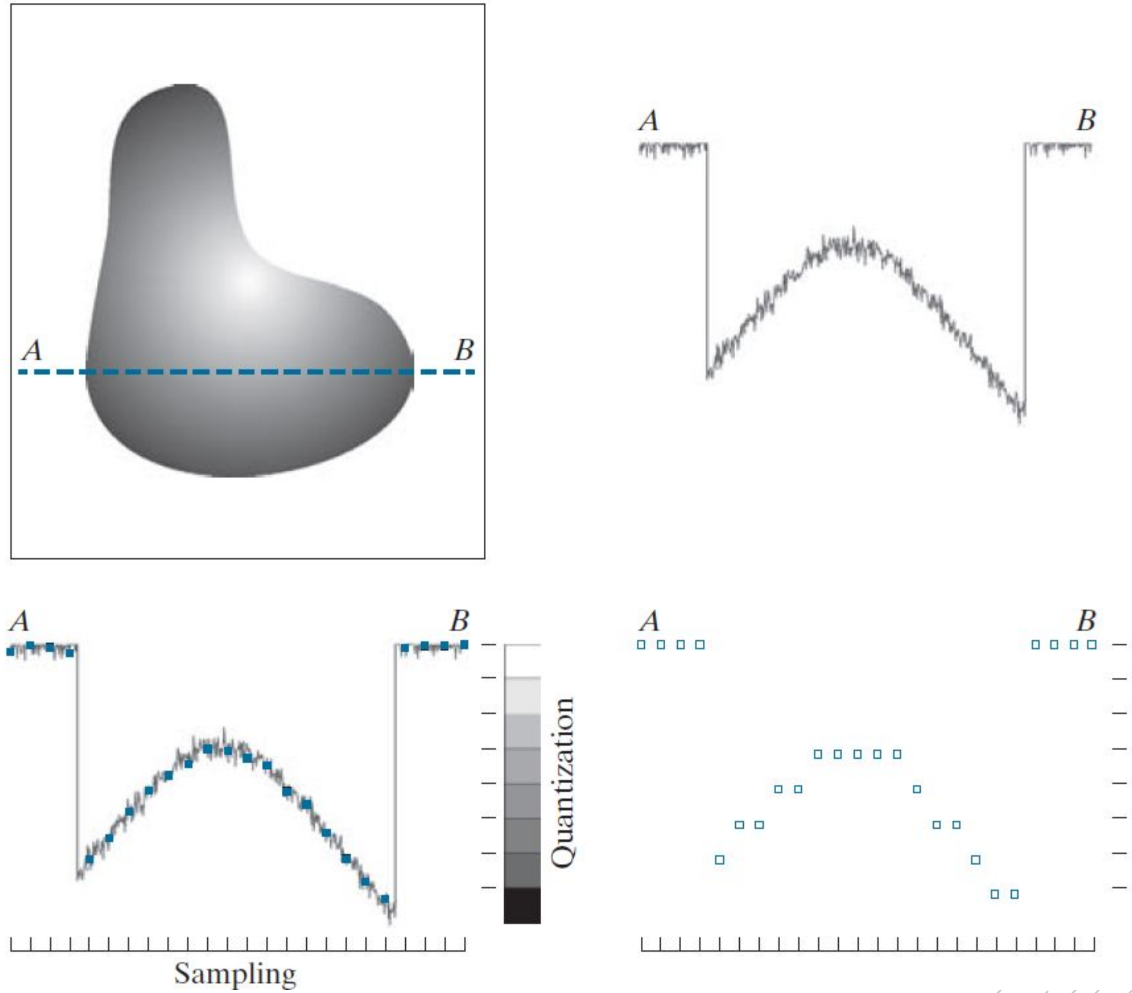


FIGURE 2.16 (a) Continuous image. (b) A scan line showing intensity variations along line AB in the continuous image. (c) Sampling and quantization. (d) Digital scan line. (The black border in (a) is included for clarity. It is not part of the image).

Module - 1
Digital Image Fundamentals

- **Image Sampling and Quantization**
  - **Basic Concepts**
    - Fig. 2.16(b)
      - The one-dimensional function 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
    - Fig. 2.16(c)
      - To sample this function, we take equally spaced samples along line AB
      - 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
      - The set of dark squares constitute the sampled function
      - 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

Module - 1
Digital Image Fundamentals

- **Image Sampling and Quantization**
  - **Basic Concepts**
    - Fig. 2.16(c)
      - The vertical gray bar 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
      - 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
    - Fig. 2.16(d)
      - The digital samples resulting from both sampling and quantization are shown as white squares
    - Starting at the top of the continuous image and carrying out this procedure downward, line by line, produces a two-dimensional digital image
    - It is implied in Fig. 2.16 that, in addition to the number of discrete levels used, the accuracy achieved in quantization is highly dependent on the noise content of the sampled signal

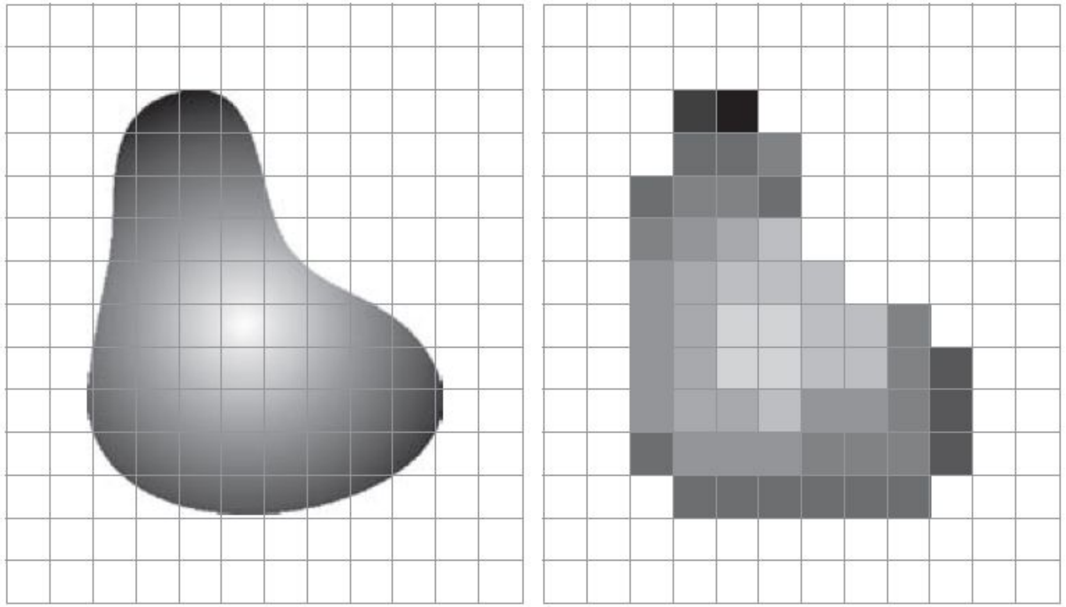
Module - 1
Digital Image Fundamentals

- **Image Sampling and Quantization**
  - Method of sampling
    - Determined by the sensor arrangement used to generate the image
    - When an image is generated by a single sensing element combined with mechanical motion
      - The output of the sensor is quantized in the manner described above
    - When a sensing strip is used for image acquisition**,**
      - The number of sensors in the strip establishes the samples in the resulting image in one direction
      - Mechanical motion establishes the number of samples in the other
      - Quantization of the sensor outputs completes the process of generating a digital image
    - When a sensing array is used for image acquisition
      - No motion is required
      - The number of sensors in the array establishes the limits of sampling in both directions
      - Quantization of the sensor outputs is as explained above
      - Figure 2.17 illustrates this concept
        - Figure 2.17(a) shows a continuous image projected onto the plane of a 2-D sensor
        - Figure 2.17(b) shows the image after sampling and quantization

Module - 1
Digital Image Fundamentals

a b

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



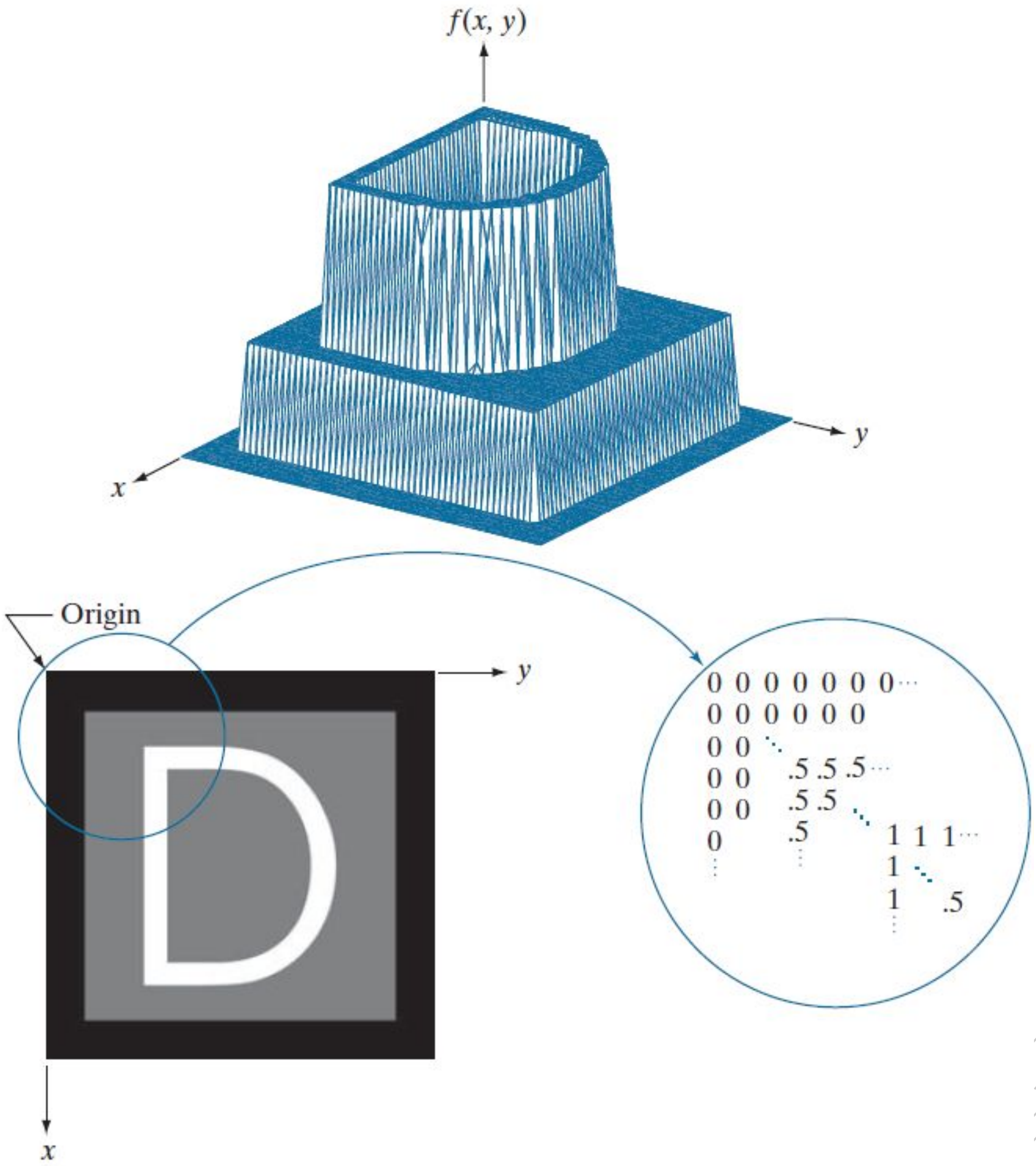
Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - Let f (s, t) represent a continuous image function of two continuous variables, s and t
  - Convert this function into a digital image by sampling and quantization
    - Suppose that we sample the continuous image into a digital image, f (x, y)
      - Containing M rows and N columns
      - Where (x, y) are discrete coordinates
      - x = 0, 1, 2,…,M − 1 and y = 0, 1, 2,…, N − 1
      - for example, the value of the digital image at the origin is f (0,0)
      - its value at the next coordinates along the first row is f (0,1)
      - The notation (0, 1) is used to denote the second sample along the first row
      - Does not the values of the physical coordinates
      - In general, the value of a digital image at any coordinates (x, y) is denoted f (x, y), where x and y are integers
      - When we need to refer to specific coordinates (i, j), we use the notation f (i, j), where the arguments are integers

Module - 1 ***Digital Image Fundamentals***

- **Representing Digital Images**
  - *Spatial Domain*
    - The section of the real plane spanned by the coordinates of an image
    - With x and y being referred to as *spatial variables* or *spatial coordinates*
  - Figure 2.18
    - Shows three ways of representing f (x, y)
  - Figure 2.18(a)
    - A plot of the function
    - Two axes determining spatial location
    - The third axis being the values of f as a function of x and y
    - This representation is useful when working with grayscale sets
    - Elements are expressed as triplets of the form (x, y,z)
    - Where x and y are spatial coordinates and z is the value of f at coordinates (x, y)
  - Figure 2.18(b)
    - Shows f (x, y) as it would appear on a computer display or photograph
    - Intensity of each point in the display is proportional to the value of f at that point

Module - 1
Digital Image Fundamentals



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. (The numbers 0, .5, and 1 represent black, gray, and white, respectively.)

Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - Figure 2.18(b)
    - Only three equally spaced intensity values
    - If the intensity is normalized to the interval [0,1]
    - Each point in the image has the value 0, 0.5, or 1
    - A monitor or printer converts these three values to black, gray, or white, respectively
    - This type of representation includes color images, and allows us to view results at a glance
  - Figure 2.18(c)
    - Shows, the third representation is an array (matrix) composed of the numerical values of f (x, y)
    - Representation used for computer processing
    - In equation form, we write the representation of an M * N numerical array as

$$f(x,y) = \begin{bmatrix} f(0,0) & f(0,1) & \cdots & f(0,N-1) \\ f(1,0) & f(1,1) & \cdots & f(1,N-1) \\ \vdots & \vdots & & \vdots \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1) \end{bmatrix} \tag{2-9}$$

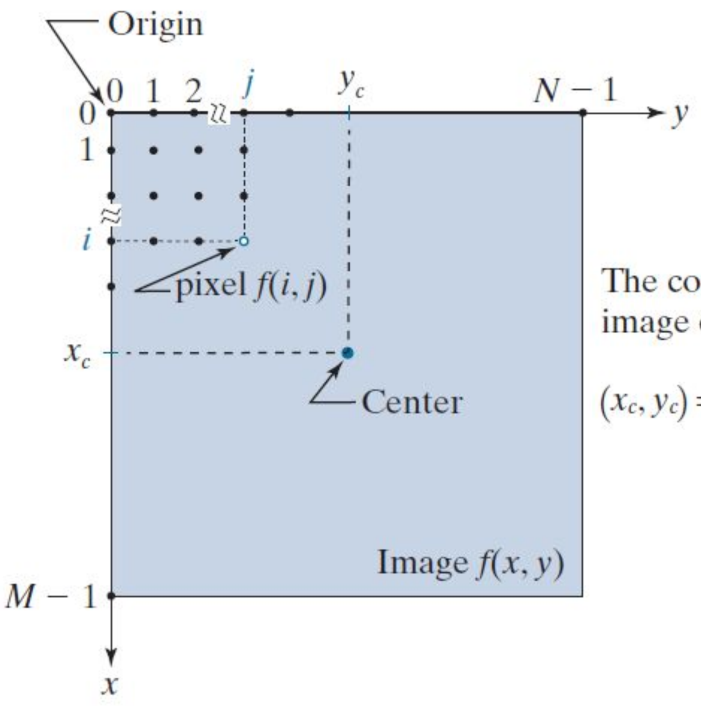
Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - Figure 2.18(c)
    - The right side of this equation is a digital image represented as an array of real numbers
    - Each element of this array is called an *image element, picture element, pixel,* or *pel*
    - We use the terms *image* and pixel throughout the book to denote a digital image and its elements
  - Figure 2.19
    - Shows a graphical representation of an image array,
    - Where the x- and y-axis are used to denote the rows and columns of the array
    - Specific pixels are values of the array at a fixed pair of coordinates
    - Generally use f (i, j) when referring to a pixel with coordinates (i, j)
    - Represent a digital image in a traditional matrix form:

$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix} \qquad (2\text{-}10)$$

Module - 1 *Digital Image Fundamentals*

FIGURE 2.19 Coordinate convention used to represent digital images. Because coordinate values are integers, there is a one-to-one correspondence between x and y and the rows (r) and columns (c) of a matrix.



The coordinates of the image center are

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

Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - Figure 2.19
    - Clearly, $a_{i, j} = f(i, j)$, so Eqs. (2-9) and (2-10) denote identical arrays
    - Define the origin of an image at the top left corner
    - This is a convention based on the fact that many image displays (e.g., TV monitors) sweep an image starting at the top left and moving to the right, one row at a time
    - The fact that the first element of a matrix is by convention at the top left of the array
    - Choosing the origin of f (x, y) at that point makes sense mathematically because digital images in reality are matrices
    - In fact,sometimes we use x and y interchangeably in equations with the rows (r) and columns (c) of a matrix
    - The positive x-axis extends downward and the positive y-axis extends to the right, is precisely the right-handed Cartesian coordinate system with which you are familiar, but shown rotated by 90° so that the origin appears on the top, left

Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - Figure 2.19
    - An M × N digital image with origin at (0,0)
    - Range to (M − 1,N − 1)
    - Center is obtained by dividing M and N by 2 and rounding down to the nearest integer
    - This operation sometimes is denoted using the floor operator
    - This holds true for M and N even or odd
    - For example, the center of an image of size 1023 × 1024 is at (511, 512)
    - Some programming languages (e.g., MATLAB) start indexing at 1 instead of at 0
    - The center of an image in that case is found at (x_c, y_c) = (floor(M/2) + 1 , floor(N/2) + 1)
  - To express sampling and quantization in more formal mathematical terms
    - let Z = the set of integers and R = the set of real numbers
    - The sampling process may be viewed as partitioning the xy-plane into a grid

Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - To express sampling and quantization in more formal mathematical terms
    - The coordinates of the center of each cell in the grid being a pair of elements from the Cartesian product Z^2 (also denoted Z × Z) which, as you may recall, is the set of all ordered pairs of elements (z_i, z_j) with z_i and z_j being integers from set
    - Hence, f (x, y) is a digital image if (x, y) are integers from Z^2 and f is a function that assigns an intensity value (that is, a real number from the set of real numbers, R) to each distinct pair of coordinates (x, y)
    - This functional assignment is the quantization process
    - If the intensity levels also are integers, then R = Z, and a digital image becomes a 2-D function whose coordinates and amplitude values are integers
  - Image digitization requires that decisions be made regarding the values for M, N, and for the number, L, of discrete intensity levels

Module - 1
Digital Image Fundamentals

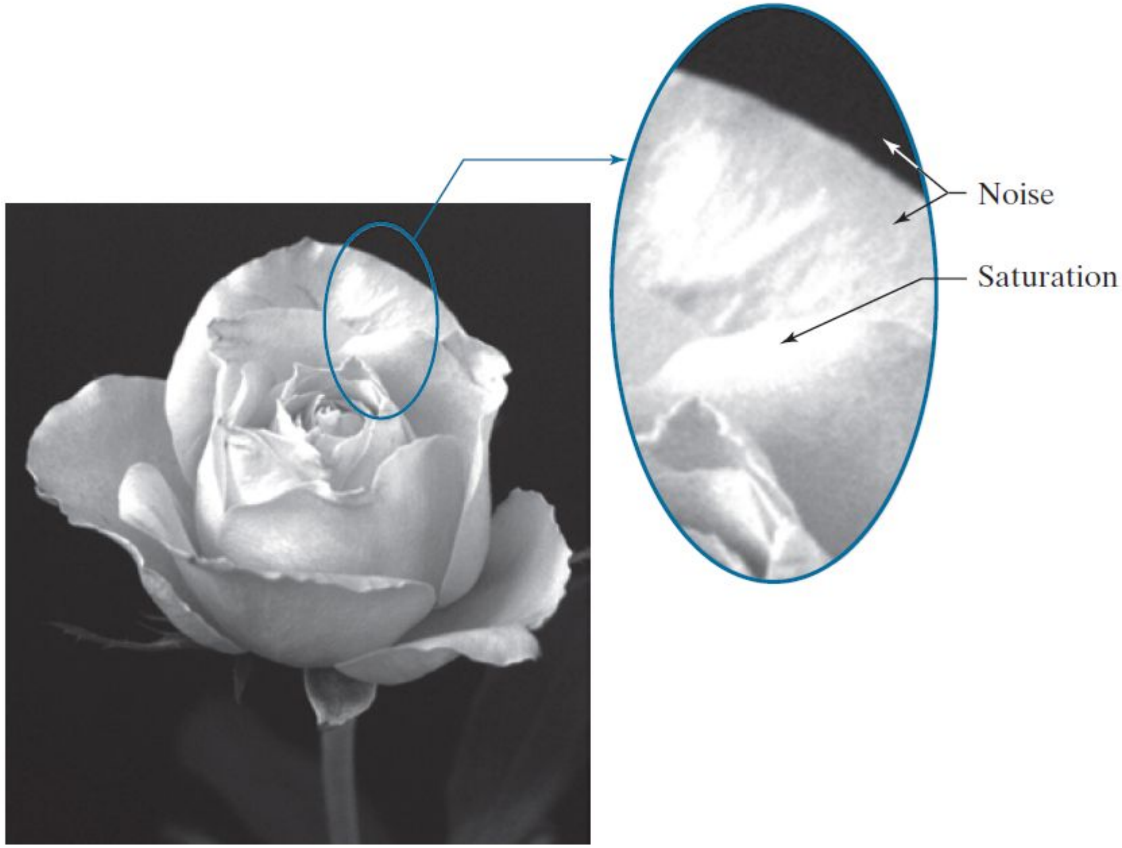
- **Representing Digital Images**
  - There are no restrictions placed on M and N, other than they have to be positive integers
  - However, digital storage and quantizing hardware considerations usually lead to the number of intensity levels, L, being an integer power of two; that is $L = 2^k$ where k is an integer
  - We assume that the discrete levels are equally spaced and that they are integers in the range $[0, L - 1]$
  - Sometimes, the range of values spanned by the gray scale is referred to as the dynamic range, a term used in different ways in different fields
  - The dynamic range of an imaging system to be the ratio of the maximum measurable intensity to the minimum detectable intensity level in the system
  - As a rule, the upper limit is determined by saturation and the lower limit by noise, although noise can be present also in lighter intensities

Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - Figure 2.20 shows examples of saturation and slight visible noise
  - Because the darker regions are composed primarily of pixels with the minimum detectable intensity, the background in Fig. 2.20 is the noisiest part of the image; however, dark background noise typically is much harder to see
  - The dynamic range establishes the lowest and highest intensity levels that a system can represent and, consequently, that an image can have
  - Closely associated with this concept is *image contrast*, which we define as the difference in intensity between the highest and lowest intensity levels in an image
  - The *contrast ratio* is the ratio of these two quantities
  - When an appreciable number of pixels in an image have a high dynamic range, we can expect the image to have high contrast
  - Conversely, an image with low dynamic range typically has a dull, washed-out gray look

Module - 1
Digital Image Fundamentals

FIGURE 2.20
An image exhibiting saturation and noise. Saturation is the highest value beyond which all intensity values are clipped (note how the entire saturated area has a high, constant intensity level). Visible noise in this case appears as a grainy texture pattern. The dark background is noisier, but the noise is difficult to see.

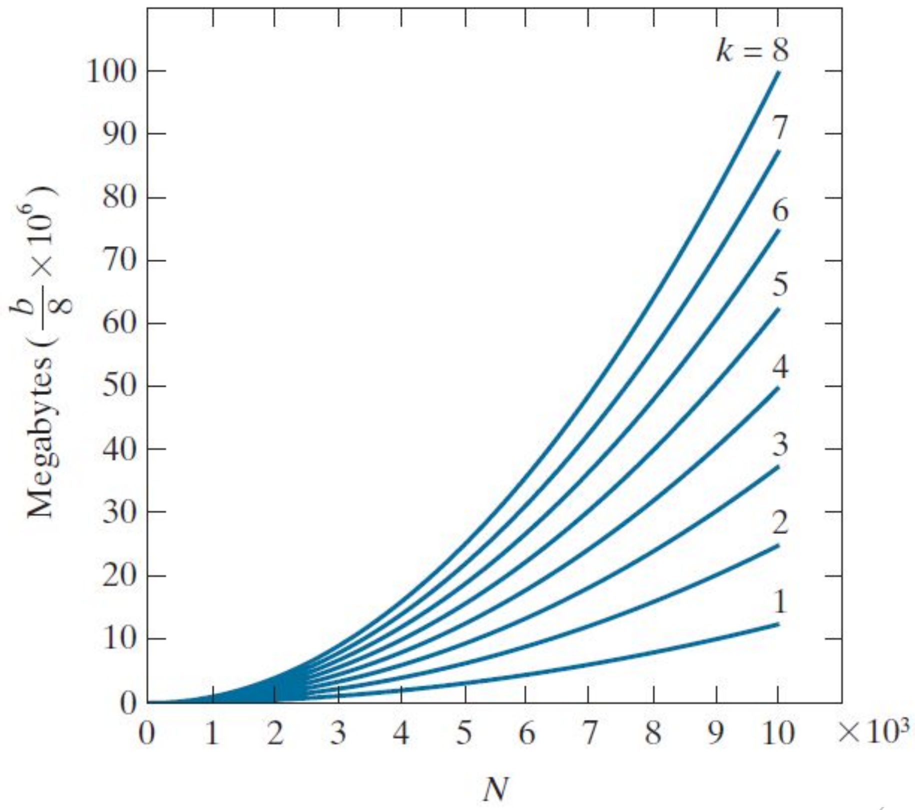


Module - 1
Digital Image Fundamentals

- **Representing Digital Images**
  - The number, b, of bits required to store a digital image is $b = M * N * k$
  - When M = N, this equation becomes $b = N^2 k$
  - Figure 2.21 shows the number of megabytes required to store square images for various values of N and k (as usual, one byte equals 8 bits and a megabyte equals 10^6 bytes)
  - When an image can have 2^k possible intensity levels, it is common practice to refer to it as a "k-bit image," (e,g., a 256-level image is called an 8-bit image)

Module - 1
Digital Image Fundamentals

FIGURE 2.21 Number of megabytes required to store images for various values of *N* and *k*.



Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - Relationships between pixels in a digital image
  - Use lowercase letters, such as p and q
  - Neighbours of a Pixel
    - A pixel p at coordinates (x, y) has two horizontal and two vertical neighbors with coordinates

      $(x + 1, y), (x - 1, y), (x, y + 1), (x, y - 1)$
    - This set of pixels, called the *4-neighbors* of p, is denoted $N_4(p)$
    - The four diagonal neighbors of p have coordinates

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

      and are denoted $N_D(p)$
    - These neighbors, together with the 4-neighbors, are called the 8-neighbors of p, denoted by $N_8(p)$

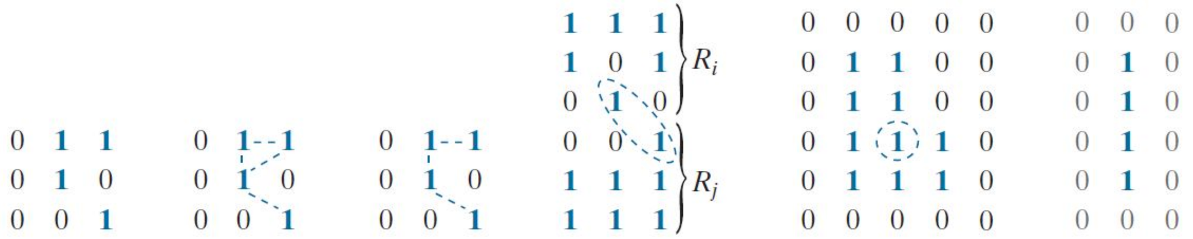
Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - The set of image locations of the neighbors of a point p is called the *neighborhood* of p
  - The *neighborhood* is said to be *closed* if it *contains p*
  - Otherwise, the *neighborhood* is said to be *open*
  - *Adjacency, Connectivity, Regions, and Boundaries*
    - 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, set V typically contains more elements, 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:

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Adjacency*
    - 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 $N_8(p)$
    - m-adjacency (also called mixed adjacency)
      - Two pixels p and q with values from V are m-adjacent if
        - q is in $N_4(p)$, or
        - q is in $N_D(p)$ and the set $N_4(p) \cap N_4(q)$ has no pixels whose values are from V
    - For example, consider the pixel arrangement in Fig. 2.28(a) and let V = {1}
    - The three pixels at the top of Fig. 2.28(b) show multiple (ambiguous) 8-adjacency, as indicated by the dashed lines
    - This ambiguity is removed by using m-adjacency, as in Fig. 2.28(c)

Module - 1
Digital Image Fundamentals



a b c d e f

FIGURE 2.28 (a) An arrangement of pixels. (b) Pixels that are 8-adjacent (adjacency is shown by dashed lines). (c) m-adjacency. (d) Two regions (of 1's) that are 8-adjacent. (e) The circled point is on the boundary of the 1-valued pixels only if 8-adjacency between the region and background is used. (f) The inner boundary of the 1-valued region does not form a closed path, but its outer boundary does.

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Connectivity*
    - A *digital path* (or curve) from pixel p with coordinates (x_o , y_o) to pixel q with coordinates (x_n , y_n) is a sequence of distinct pixels with coordinates

      $$(x_o , y_o), (x_1 , y_1),\ldots (x_n , y_n)$$

      where points (x_i , y_i) and (x_{i-1} , y_{i-1}) are adjacent for $1 \leq i \leq n$
    - n is the *length* of the path
    - If$(x_o , y_o) = (x_n , y_n)$ the path is a *closed* path
    - We can define 4-, 8-, or m-paths, depending on the type of adjacency specified
    - For example, the paths in Fig. 2.28(b) between the top right and bottom right points are 8-paths, and the path in Fig. 2.28(c) is an m-path

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Connectivity*
    - Let S represent 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 it only has one component, and that component is connected, then S is called a *connected set*
  - *Regions*
    - Let R represent a subset of pixels in an image
    - 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 adjacent are said to be *disjoint*
    - We consider 4- and 8-adjacency when referring to regions

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Regions*
    - The type of adjacency used must be specified
    - For example, the two regions of 1's in Fig. 2.28(d) are adjacent only if 8-adjacency is used
    - Suppose an image contains K disjoint regions, R_k , k =1, 2,…, K, none of which touches the image border
    - Let R_u denote the union of all the K regions, and let $(R_u)^c$ denote its complement
    - We call all the points in R_u the *foreground*, and all the points in $(R_u)^c$ the *background* of the image
  - *Boundaries*
    - The *boundary* (also called the *border* or *contour*) of a region R is the set of pixels in R that are adjacent to pixels in the complement of R
    - Stated another way, the border of a region is the set of pixels in the region that have at least one background neighbor

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Boundaries*
    - We must specify the connectivity being used to define adjacency
    - For example, the point circled in Fig. 2.28(e) is not a member of the border of the 1-valued region if 4-connectivity is used between the region and its background, because the only possible connection between that point and the background is diagonal
    - As a rule, adjacency between points in a region and its background is defined using 8-connectivity to handle situations such as this
    - The preceding definition sometimes is referred to as the *inner border* of the region to distinguish it from its *outer border*, which is the corresponding border in the background
    - This distinction is important in the development of border-following algorithms

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Boundaries*
    - Such algorithms usually are formulated to follow the outer boundary in order to guarantee that the result will form a closed path
    - For instance, the inner border of the 1-valued region in Fig. 2.28(f) is the region itself
    - This border does not satisfy the definition of a closed path
    - On the other hand, the outer border of the region does form a closed path around the region
    - If R happens to be an entire image, then its boundary (or border) is defined as the set of pixels in the first and last rows and columns of the image
    - This extra definition is required because an image has no neighbors beyond its border
    - Normally, when we refer to a region, we are referring to a subset of an image, and any pixels in the boundary of the region that happen to coincide with the border of the image are included implicitly as part of the region boundary

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Boundaries*
    - The boundary of a finite region forms a closed path and is thus a "global" concept
    - Edges are formed from pixels with derivative values that exceed a preset threshold
    - Thus, an edge is a "local" concept that is based on a measure of intensity-level discontinuity at a point
    - It is possible to link edge points into edge segments, and sometimes these segments are linked in such a way that they correspond to boundaries, but this is not always the case
  - *Distance Measures*
    - For pixels p, q, and s, with coordinates (x, y), (u,v), and (w,z), respectively, D is a distance function or metric if

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Distance Measures*
    - For pixels p, q, and s, with coordinates (x, y), (u,v), and (w,z), respectively, D is a distance function or metric if
      - $D(p,q) \geq 0$ ($D(p,q) = 0$ iff $p = q$) ,
      - $D(p,q) = D(q, p)$, and
      - $D(p, s) \leq D(p, q) + D(q, s)$.
    - The Euclidean distance between p and q is defined as

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

    - The pixels having a distance less than or equal to some value r from (x, y) are the points contained in a disk of radius r centered at (x, y)
    - The D4 distance, (called the city-block distance) between p and q is defined as

$$D_4(p, q) = |(x - u)| + |(y - v)|$$

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Distance Measures*
    - Pixels having a D_4 distance from (x, y) that is less than or equal to some value d form a diamond centered at (x, y)
    - For example, the pixels with D_4 distance ≤ 2 from (x, y) (the center point) form the following contours of constant distance:

$$
\begin{array}{ccccc}
 & & 2 & & \\
 & 2 & 1 & 2 & \\
2 & 1 & 0 & 1 & 2 \\
 & 2 & 1 & 2 & \\
 & & 2 & &
\end{array}
$$

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Distance Measures*
    - The pixels with $D_4 = 1$ are the 4-neighbors of (x, y).
    - The D_8 distance (called the *chessboard distance*) between p and q is defined as

$$D_8(p, q) = \max(|(x - u)|, |(y - v)|)$$

    - The pixels with D_8 distance from (x, y) less than or equal to some value d form a square centered at (x, y)
    - For example, the pixels with D_8 distance ≤ 2 form the following contours of constant distance:

$$\begin{matrix} 2 & 2 & 2 & 2 & 2 \\ 2 & 1 & 1 & 1 & 2 \\ 2 & 1 & 0 & 1 & 2 \\ 2 & 1 & 1 & 1 & 2 \\ 2 & 2 & 2 & 2 & 2 \end{matrix}$$

Module - 1

Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Distance Measures*
    - The pixels with $D_8 = 1$ are the 8-neighbors of the pixel at (x, y)
    - Note that the D_4 and D_8 distances between p and q are independent of any paths that might exist between these points because these distances involve only the coordinates of the points
    - In the case of m-adjacency, however, the D_m distance between two points is defined as the shortest m-path between the points
    - In this case, the distance between two pixels will depend on the values of the pixels along the path, as well as the values of their neighbors
    - For instance, consider the following arrangement of pixels and assume that p, p_2 , and p_4 have a value of 1, and that p_1 and p_3 can be 0 or 1:

Module - 1
Digital Image Fundamentals

- **Some Basic Relationships Between Pixels**
  - *Distance Measures*

$$\begin{array}{ccc} & p_3 & p_4 \\ p_1 & p_2 & \\ p & & \end{array}$$

- Suppose that we consider adjacency of pixels valued 1 (i.e.,V = {1}). If p_1 and $p_3$are 0, the length of the shortest m-path (the D_m distance) between p and p_4 is 2
- If p_1 is 1, then p_2 and p will no longer be m-adjacent and the length of the shortest m-path becomes 3 (the path goes through the points $pp_1p_2p_4$)
- Similar comments apply if p_3 is 1 (and p_1 is 0);
- In this case, the length of the shortest m-path also is 3
- Finally, if both p_1 and p_3 are 1, the length of the shortest m-path between p and p_4 is 4
- In this case, the path goes through the sequence of points $pp_1p_2p_3p_4$

Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color in Image Processing
    - Color is a powerful descriptor that often simplifies object identification and extraction from a scene
    - Humans can detect thousands of color shades, compared to only two dozen shades of gray
  - Divided into two major areas
    - Pseudo-Color Processing
      - Assigning color(s) to a particular grayscale intensity or range of intensities
    - Full-Color Processing
      - Images are acquired using a full-color sensor, such as a digital camera, or color scanner
  - Color Fundamentals
    - In 1666, Sir Isaac Newton discovered
      - When a beam of sunlight passes through a glass prism
      - The emerging light is not white
      - Consists a continuous spectrum of colors ranging from violet at one end to red at the other

Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - In 1666, Sir Isaac Newton discovered
      - In Fig. 6.1, the color spectrum may be divided into six regions: violet, blue, green, yellow, orange, and red
    - The colors that humans and some other animals perceive in an object
      - Determined by the nature of the light reflected from the object
    - In Fig. 6.2, visible light is composed of a relatively narrow band of frequencies in the electromagnetic spectrum
      - A body that reflects light that is balanced in all visible wavelengths appears white to the observer
      - A body that favors reflectance in a limited range of the visible spectrum exhibits some shades of color

Module - 1
Digital Image Fundamentals

FIGURE 6.1
Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lighting Division.)

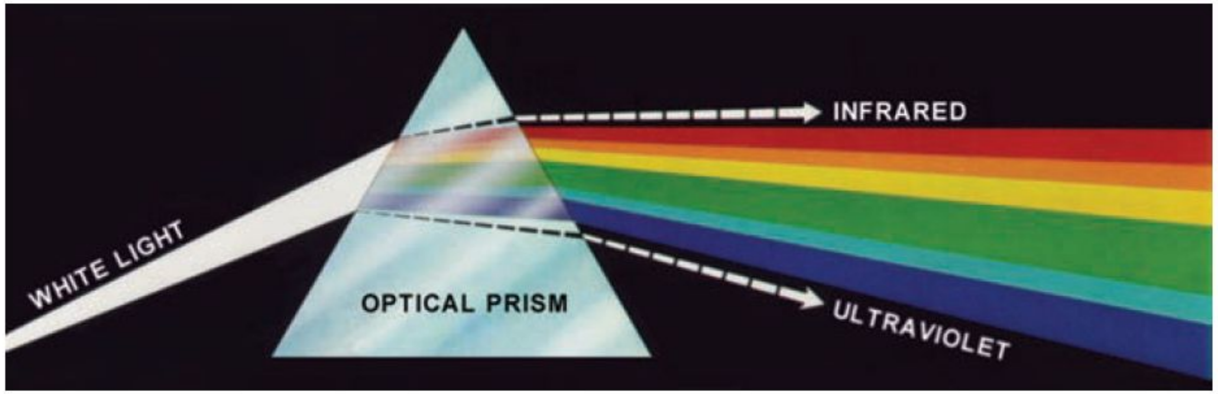
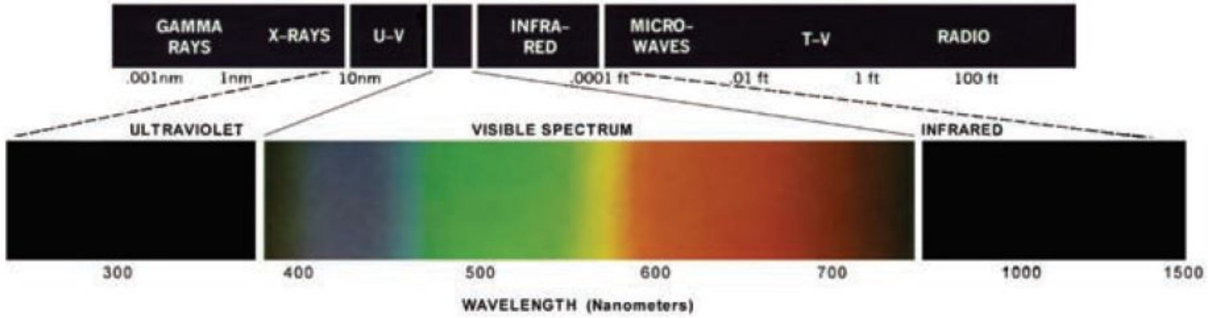


FIGURE 6.2
Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lighting Division.)



Module - 1
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- **Color Image Processing**
  - Color Fundamentals
    - Science of Color
      - Characterization of light
    - *Achromatic* Light (without color)
      - Only attribute is its intensity, or amount
      - Gray (or intensity) level
        - A scalar measure of intensity that ranges from black, to grays, and finally to white
      - What you see on movie films made before the 1930s
    - *Chromatic* Light
      - Spans the electromagnetic spectrum from approximately 400 to 700 nm
      - Describe the quality of a chromatic light source
        - Radiance
        - Luminance
        - Brightness
      - Radiance
        - Total amount of energy that flows from the light source
        - Measured in watts (W)

Module - 1

Digital Image Fundamentals

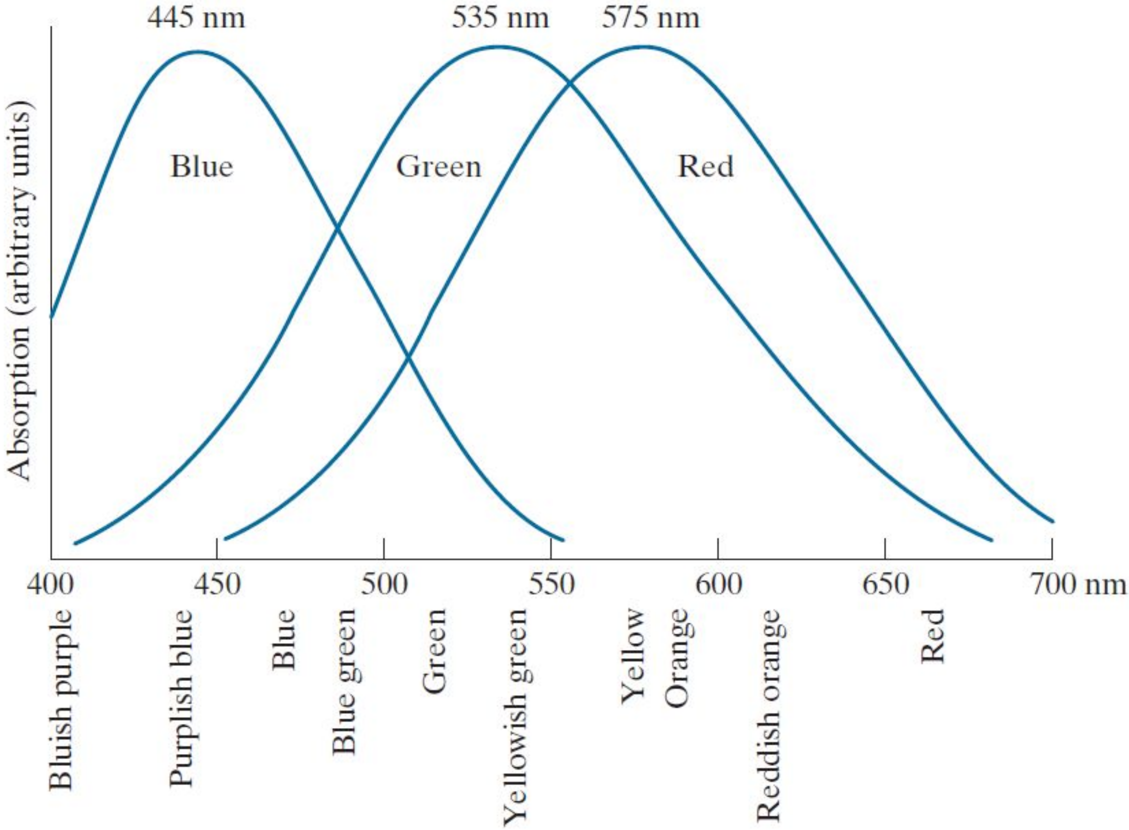
- **Color Image Processing**
  - Color Fundamentals
    - *Chromatic* Light
      - Luminance
        - Measure of the amount of energy that an observer perceives from a light source
        - Measured in lumens (lm)
      - Brightness
        - Subjective descriptor that is practically impossible to measure
        - Embodies the achromatic notion of intensity
        - Describing color sensation
    - Cones
      - The sensors in the eye responsible for color vision
      - 6 to 7 million cones in the human eye
      - Divided into three principal sensing categories
        - Red, Green, and Blue
        - Approximately 65% of all cones are sensitive to red light
        - 33% are sensitive to green light
        - Only about 2% are sensitive to blue
        - The blue cones are the most sensitive

Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - Figure 6.3 shows
      - Average experimental curves
      - Absorption of light by the red, green, and blue cones in the eye
      - The human eye sees colors as variable combinations of ***Red (R), Green (G), and Blue (B)***
      - ***Called Primary Colors***
      - As per the CIE (Commission Internationale del' Eclairage—the International Commission on Illumination) standardization following specific wavelength values to the three primary colors
        - Blue = 435.8 nm
        - Green = 546.1 nm
        - Red = 700 nm
      - ***Secondary Colors*** of light
        - The primary colors can be added together
        - ***Magenta = Red + Blue***
        - ***Cyan = Green + Blue***
        - ***Yellow = Red + Green***

Module - 1 *Digital Image Fundamentals*

FIGURE 6.3
Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.



Module - 1
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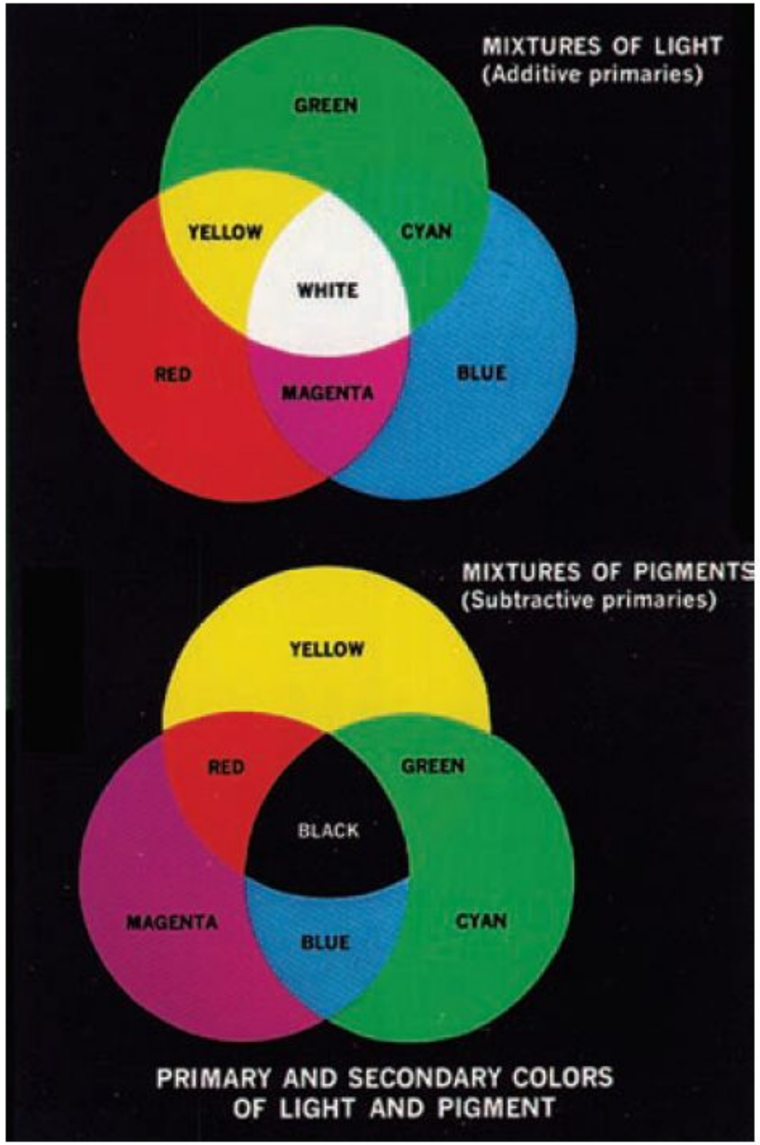
- **Color Image Processing**
  - Color Fundamentals
    - ***Secondary Colors*** of light
      - ***Mixing the three primaries, or a secondary with its opposite primary color, in the right intensities produces white light***
      - Fig. 6.4(a) shows the three primary colors and their combinations to produce the secondary colors of light
      - The primary colors of ***pigments or colorants***
      - A primary color is defined as one that subtracts or absorbs a primary color of light, and reflects or transmits the other two
      - The primary colors of pigments are magenta, cyan, and yellow, and the secondary colors are red, green, and blue
      - These colors are shown in Fig. 6.4(b)
      - ***A proper combination of the three pigment primaries, or a secondary with its opposite primary, produces black***

Module - 1
Digital Image Fundamentals

a
b

FIGURE 6.4
Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lighting Division.)



Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - Characteristics used to distinguish one color from another are ***brightness***, ***hue***, and ***saturation***
    - ***Brightness***
      - Embodies the achromatic notion of intensity
    - ***Hue***
      - Represents dominant color as perceived by an observer
      - When we call an object red, orange, or yellow, we are referring to its hue
    - ***Saturation***
      - Refers to the relative purity or the amount of white light mixed with a hue
      - The pure spectrum colors are fully saturated
      - Colors such as pink (red and white) and lavender (violet and white) are less saturated
      - The degree of saturation being inversely proportional to the amount of white light added

Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - ***Chromaticity***
      - Hue and saturation taken together
      - A color may be characterized by its brightness and chromaticity
    - ***Tristimulus*** values
      - The amounts of red, green, and blue needed to form any particular color
      - Denoted, X, Y, and Z, respectively
    - ***Trichromatic Coefficients***
      - Specified a color and defined as

$$x = \frac{X}{X+Y+Z} \quad (6\text{-}1)$$

$$y = \frac{Y}{X+Y+Z} \quad (6\text{-}2)$$

$$z = \frac{Z}{X+Y+Z} \quad (6\text{-}3)$$

Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - ***Trichromatic Coefficients***

$$x + y + z = 1 \qquad (6\text{-}4)$$

    - ***CIE Chromaticity Diagram***
      - Another approach for specifying colors
      - Fig. 6.5
        - Shows color composition as a function of x (red) and y (green)
      - For any value of x and y
        - The corresponding value of z (blue) is obtained from Eq. (6-4) by noting that $z = 1 - (x + y)$
      - The point marked green in Fig. 6.5
        - Approximately 62% green
        - 25% red content
        - from Eq. (6-4) that the composition of blue is approximately 13%
      - The positions of the various spectrum colors
        - from violet at 380 nm to red at 780 nm
        - Indicated around the boundary of the tongue-shaped chromaticity diagram.

Module - 1

Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - ***CIE Chromaticity Diagram***
      - These are the pure colors shown in the spectrum of Fig. 6.2
      - Any point not actually on the boundary, but within the diagram
        - Represents some mixture of the pure spectrum colors
      - The point of equal energy shown in Fig. 6.5
        - Corresponds to equal fractions of the three primary colors
        - Represents the CIE standard for white light
      - Any point located on the boundary of the chromaticity chart
        - Fully saturated
      - As a point leaves the boundary and approaches the point of equal energy
        - More white light is added to the color
        - Becomes less saturated
      - The saturation at the point of equal energy
        - Zero

Module - 1
Digital Image Fundamentals

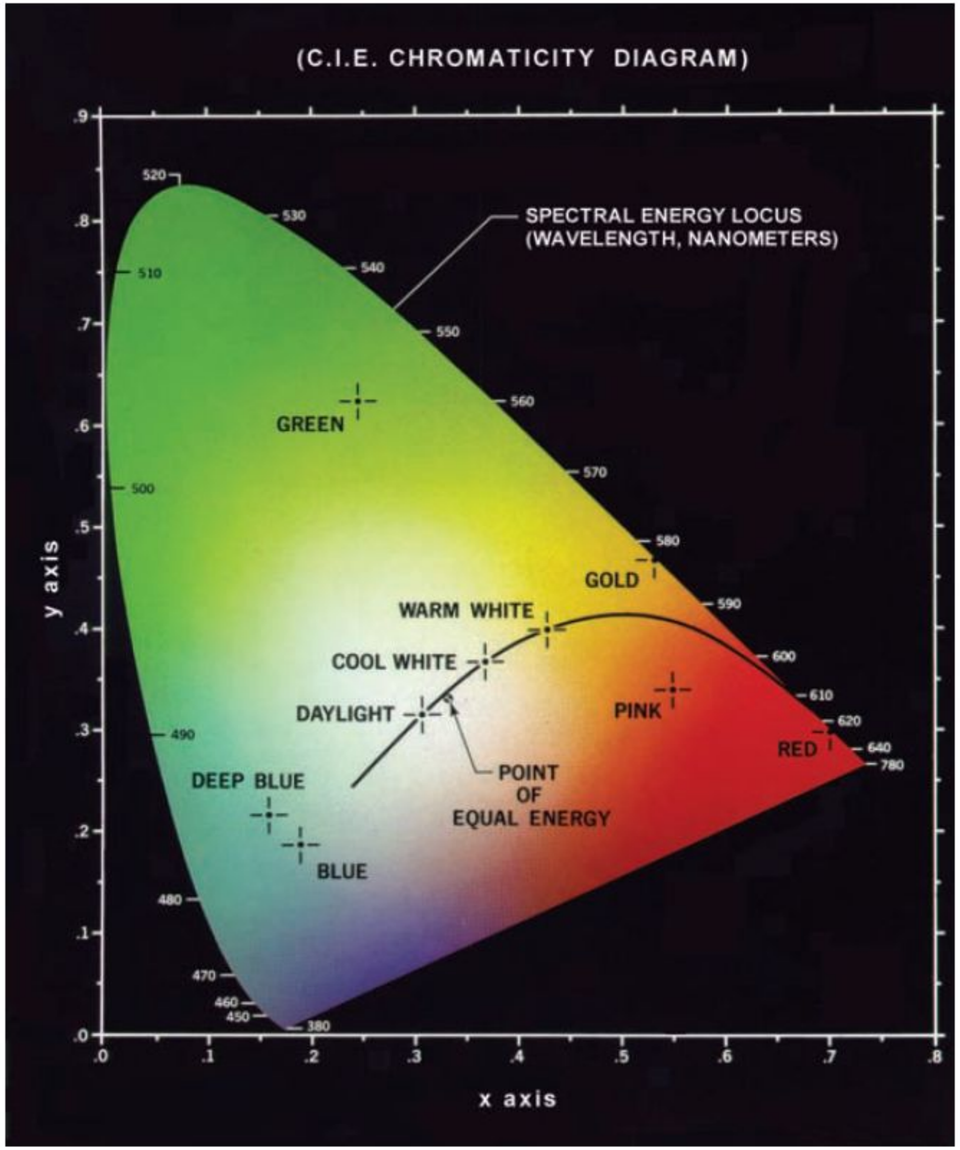
- **Color Image Processing**
  - Color Fundamentals
    - ***CIE Chromaticity Diagram***
      - Useful for color mixing
      - Straight-line segment joining any two points
        - Defines all the different color variations
        - Obtained by combining these two colors additively
      - Consider, for example, a straight line drawn from the red to the green points shown in Fig. 6.5
      - If there is more red than green light
        - The exact point representing the new color will be on the line segment
        - Closer to the red point than to the green point
      - A line drawn from the point of equal energy to any point on the boundary
        - Define all the shades of that particular spectrum color
      - To determine the range of colors that can be obtained from any three given colors
        - Simply draw connecting lines to each of the three color points
        - The result is a triangle
        - Any color inside the triangle, or on its boundary, can be produced by various combinations of the three vertex colors

Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - ***CIE Chromaticity Diagram***
      - A triangle with vertices at any three fixed colors
        - Cannot enclose the entire color region in Fig. 6.5
      - Not all colors can be obtained with three single, fixed primaries, because three colors form a triangle
      - The triangle in Fig. 6.6
        - Shows a range of colors (called the ***color gamut***) produced by RGB monitors
      - The shaded region inside the triangle
        - Illustrates the color gamut of today's high-quality color printing devices
      - The boundary of the color printing gamut
        - Irregular
        - Color printing is a combination of additive and subtractive color mixing
        - Process that is much more difficult to control than that of displaying colors on a monitor
        - Based on the addition of three highly controllable light primaries

Module - 1
Digital Image Fundamentals

FIGURE 6.5
The CIE chromaticity diagram. (Courtesy of the General Electric Co., Lighting Division.)



Module - 1
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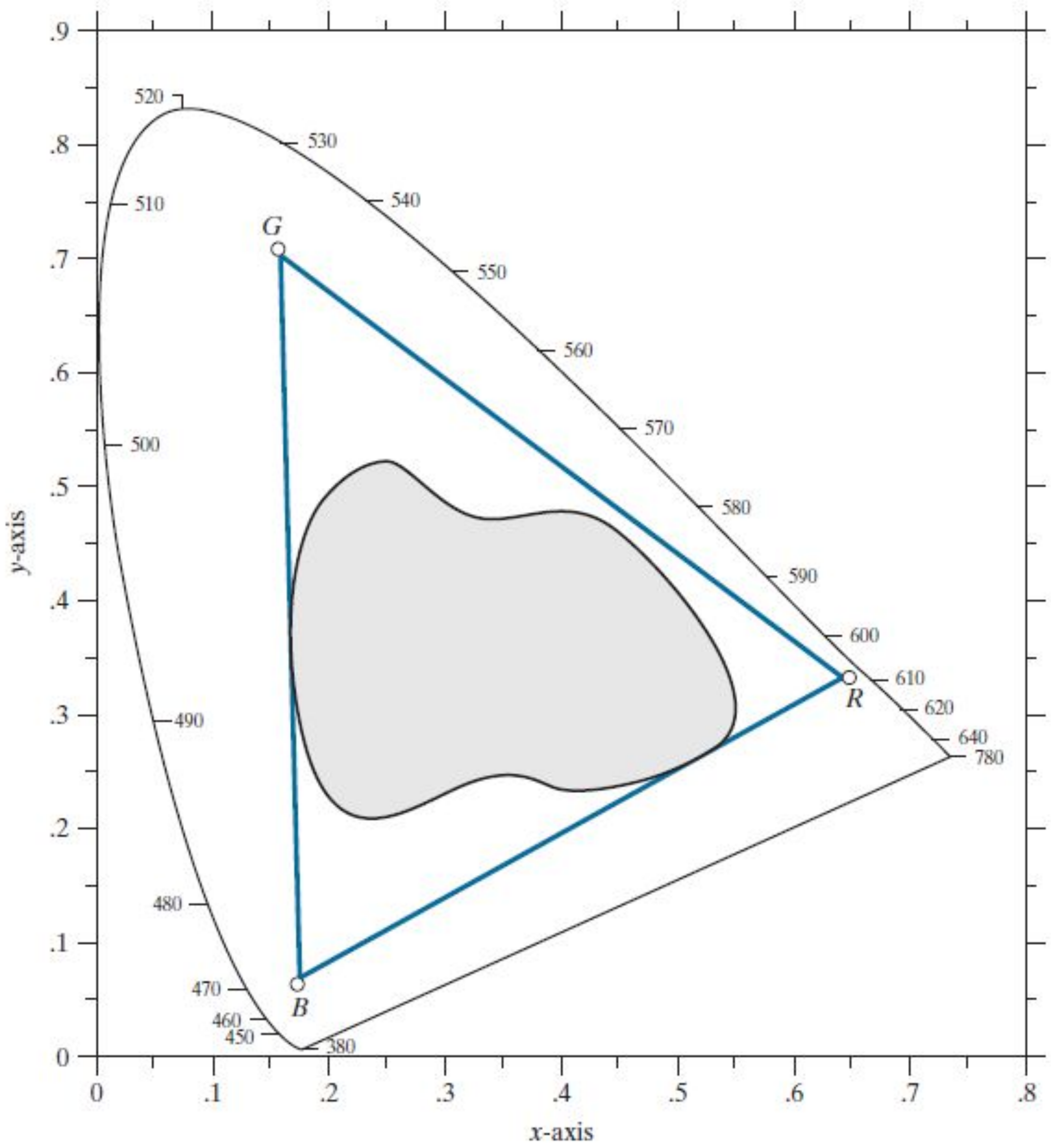
FIGURE 6.6 Illustrative color gamut of color monitors (triangle) and color printing devices (shaded region).



Module - 1
Digital Image Fundamentals

- **Color Image Processing**
  - Color Fundamentals
    - ***CIE Chromaticity Diagram***
      - A triangle with vertices at any three fixed colors
        - Cannot enclose the entire color region in Fig. 6.5
      - Not all colors can be obtained with three single, fixed primaries, because three colors form a triangle
      - The triangle in Fig. 6.6
        - Shows a range of colors (called the ***color gamut***) produced by RGB monitors
      - The shaded region inside the triangle
        - Illustrates the color gamut of today's high-quality color printing devices
      - The boundary of the color printing gamut
        - Irregular
        - Color printing is a combination of additive and subtractive color mixing
        - Process that is much more difficult to control than that of displaying colors on a monitor
        - Based on the addition of three highly controllable light primaries