



Introduction

One picture is worth more than ten thousand words.

Anonymous

Preview

Interest in digital image processing methods stems from two principal application areas: improvement of pictorial information for human interpretation, and processing of image data for tasks such as storage, transmission, and extraction of pictorial information. This chapter has several objectives: (1) to define the scope of the field that we call image processing; (2) to give a historical perspective of the origins of this field; (3) to present an overview of the state of the art in image processing by examining some of the principal areas in which it is applied; (4) to discuss briefly the principal approaches used in digital image processing; (5) to give an overview of the components contained in a typical, general-purpose image processing system; and (6) to provide direction to the literature where image processing work is reported. The material in this chapter is extensively illustrated with a range of images that are representative of the images we will be using throughout the book.

Upon completion of this chapter, readers should:

- Understand the concept of a digital image.
- Have a broad overview of the historical underpinnings of the field of digital image processing.
- Understand the definition and scope of digital image processing.
- Know the fundamentals of the electromagnetic spectrum and its relationship to image generation.
- Be aware of the different fields in which digital image processing methods are applied.
- Be familiar with the basic processes involved in image processing.
- Be familiar with the components that make up a general-purpose digital image processing system.
- Be familiar with the scope of the literature where image processing work is reported.

1.1 WHAT IS DIGITAL IMAGE PROCESSING?

An image may be defined as a two-dimensional function, $f(x, y)$, where x and y are *spatial* (plane) coordinates, and the amplitude of f at any pair of coordinates (x, y) is called the *intensity* or *gray level* of the image at that point. When x , y , and the intensity values of f are all finite, discrete quantities, we call the image a *digital image*. The field of *digital image processing* refers to processing digital images by means of a digital computer. Note that a digital image is 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*. *Pixel* is the term used most widely to denote the elements of a digital image. We will consider these definitions in more formal terms in Chapter 2.

Vision is the most advanced of our senses, so it is not surprising that images play the single most important role in human perception. However, unlike humans, who are limited to the visual band of the electromagnetic (EM) spectrum, imaging machines cover almost the entire EM spectrum, ranging from gamma to radio waves. They can operate on images generated by sources that humans are not accustomed to associating with images. These include ultrasound, electron microscopy, and computer-generated images. Thus, digital image processing encompasses a wide and varied field of applications.

There is no general agreement among authors regarding where image processing stops and other related areas, such as *image analysis* and *computer vision*, start. Sometimes, a distinction is made by defining image processing as a discipline in which both the input and output of a process are images. We believe this to be a limiting and somewhat artificial boundary. For example, under this definition, even the trivial task of computing the average intensity of an image (which yields a single number) would not be considered an image processing operation. On the other hand, there are fields such as computer vision whose ultimate goal is to use computers to emulate human vision, including learning and being able to make inferences and take actions based on visual inputs. This area itself is a branch of *artificial intelligence* (AI) whose objective is to emulate human intelligence. The field of AI is in its earliest stages of infancy in terms of development, with progress having been much slower than originally anticipated. The area of image analysis (also called *image understanding*) is in between image processing and computer vision.

There are no clear-cut boundaries in the continuum from image processing at one end to computer vision at the other. However, one useful paradigm is to consider three types of computerized processes in this continuum: low-, mid-, and high-level processes. Low-level processes involve primitive operations such as image preprocessing to reduce noise, contrast enhancement, and image sharpening. A low-level process is characterized by the fact that both its inputs and outputs are images. Mid-level processing of images 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, and classification (recognition) of individual objects. A mid-level process is 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). Finally, higher-level processing

involves “making sense” of an ensemble of recognized objects, as in image analysis, and, at the far end of the continuum, performing the cognitive functions normally associated with human vision.

Based on the preceding comments, we see that a logical place of overlap between image processing and image analysis is the area of recognition of individual regions or objects in an image. Thus, what we call in this book *digital image processing* encompasses processes whose inputs and outputs are images and, in addition, includes processes that extract attributes from images up to, and including, the recognition of individual objects. As an illustration to clarify these concepts, consider the area of automated analysis of text. The processes of acquiring an image of the area containing the text, preprocessing that image, extracting (segmenting) the individual characters, describing the characters in a form suitable for computer processing, and recognizing those individual characters are in the scope of what we call digital image processing in this book. Making sense of the content of the page may be viewed as being in the domain of image analysis and even computer vision, depending on the level of complexity implied by the statement “making sense of.” As will become evident shortly, digital image processing, as we have defined it, is used routinely in a broad range of areas of exceptional social and economic value. The concepts developed in the following chapters are the foundation for the methods used in those application areas.

1.2 THE ORIGINS OF DIGITAL IMAGE PROCESSING

One of the earliest applications of digital images was in the newspaper industry, when pictures were first sent by submarine cable between London and New York. 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.

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



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.)



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 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.

Although the examples just cited involve digital images, they are not considered digital image processing results in the context of our definition, because digital computers were not used in their creation. Thus, the history of digital image processing is intimately tied to the development of the digital computer. In fact, digital images require so much storage and computational power that 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.

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.)



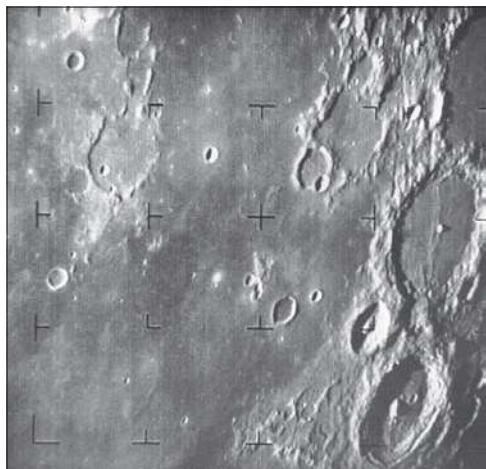
The concept of a computer dates back to the invention of the abacus in Asia Minor, more than 5000 years ago. More recently, there have been developments in the past two centuries that are the foundation of what we call a computer today. However, the basis for what we call a *modern* digital computer dates back to only the 1940s, with the introduction by John von Neumann of two key concepts: (1) a memory to hold a stored program and data, and (2) 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. Briefly, these advances may be summarized as follows: (1) the invention of the transistor at Bell Laboratories in 1948; (2) the development in the 1950s and 1960s of the high-level programming languages COBOL (Common Business-Oriented Language) and FORTRAN (Formula Translator); (3) the invention of the integrated circuit (IC) at Texas Instruments in 1958; (4) the development of operating systems in the early 1960s; (5) the development of the microprocessor (a single chip consisting of a CPU, memory, and input and output controls) by Intel in the early 1970s; (6) the introduction by IBM of the personal computer in 1981; and (7) 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 nonotechnologies. 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.

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. Work on using computer techniques for improving images from a space probe began at the Jet Propulsion Laboratory (Pasadena, California) in 1964, when 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 markers, called *reseau marks*, are used for geometric corrections, as discussed in Chapter 2). 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. The invention in the early 1970s of *computerized axial tomography* (CAT), also called *computerized tomography* (CT) for short, is one of the most important events in the application of image processing in medical diagnosis. Computerized axial tomography is a process in which a ring of detectors

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.)



encircles an object (or patient) and an X-ray source, concentric with the detector ring, rotates about the object. The X-rays pass through the object and are collected at the opposite end by the corresponding detectors in the ring. This procedure is repeated as the source rotates. Tomography consists of algorithms that use the sensed data to construct an image that represents a “slice” through the object. Motion of the object in a direction perpendicular to the ring of detectors produces a set of such slices, which constitute a three-dimensional (3-D) rendition of the inside of the object. Tomography was invented independently by Sir Godfrey N. Hounsfield and Professor Allan M. Cormack, who shared the 1979 Nobel Prize in Medicine for their invention. It is interesting to note that X-rays were discovered in 1895 by Wilhelm Conrad Roentgen, for which he received the 1901 Nobel Prize for Physics. These two inventions, nearly 100 years apart, led to some of the most important applications of image processing today.

From the 1960s until the present, the field of image processing has grown vigorously. In addition to applications in medicine and the space program, digital image processing techniques are now used in a broad range of applications. Computer procedures are used to enhance the contrast or code the intensity levels into color for easier interpretation of X-rays and other images used in industry, medicine, and the biological sciences. Geographers use the same or similar techniques to study pollution patterns from aerial and satellite imagery. Image enhancement and restoration procedures are used to process degraded images of unrecoverable objects, or experimental results too expensive to duplicate. In archeology, image processing methods have successfully restored blurred pictures that were the only available records of rare artifacts lost or damaged after being photographed. In physics and related fields, computer techniques routinely enhance images of experiments in areas such as high-energy plasmas and electron microscopy. Similarly successful applications of image processing concepts can be found in astronomy, biology, nuclear medicine, law enforcement, defense, and industry.

These examples illustrate processing results intended for human interpretation. The second major area of application of digital image processing techniques mentioned at the beginning of this chapter is in solving problems dealing with machine perception. In this case, interest is on procedures for extracting information from an image, in a form suitable for computer processing. Often, this information bears little resemblance to visual features that humans use in interpreting the content of an image. Examples of the type of information used in machine perception are statistical moments, Fourier transform coefficients, and multidimensional distance measures. Typical problems in machine perception that routinely utilize image processing techniques are automatic character recognition, industrial machine vision for product assembly and inspection, military recognition, automatic processing of fingerprints, screening of X-rays and blood samples, and machine processing of aerial and satellite imagery for weather prediction and environmental assessment. The continuing decline in the ratio of computer price to performance, and the expansion of networking and communication bandwidth via the internet, have created unprecedented opportunities for continued growth of digital image processing. Some of these application areas will be illustrated in the following section.

1.3 EXAMPLES OF FIELDS THAT USE DIGITAL IMAGE PROCESSING ■

Today, there is almost no area of technical endeavor that is not impacted in some way by digital image processing. We can cover only a few of these applications in the context and space of the current discussion. However, limited as it is, the material presented in this section will leave no doubt in your mind regarding the breadth and importance of digital image processing. We show in this section numerous areas of application, each of which routinely utilizes the digital image processing techniques developed in the following chapters. Many of the images shown in this section are used later in one or more of the examples given in the book. Most images shown are digital images.

The areas of application of digital image processing are so varied that some form of organization is desirable in attempting to capture the breadth of this field. One of the simplest ways to develop a basic understanding of the extent of image processing applications is to categorize images according to their source (e.g., X-ray, visual, infrared, and so on). The principal energy source for images in use today is the electromagnetic energy spectrum. Other important sources of energy include acoustic, ultrasonic, and electronic (in the form of electron beams used in electron microscopy). Synthetic images, used for modeling and visualization, are generated by computer. In this section we will discuss briefly how images are generated in these various categories, and the areas in which they are applied. Methods for converting images into digital form will be discussed in the next chapter.

Images based on radiation from the EM spectrum are the most familiar, especially images in the X-ray and visual bands of the spectrum. Electromagnetic waves can be conceptualized as propagating sinusoidal waves of varying wavelengths, or they can be thought of as a stream of massless particles, each traveling in a wavelike pattern and moving at the speed of light. Each massless particle contains a certain amount (or bundle) of energy. Each bundle of energy is called a *photon*. If spectral

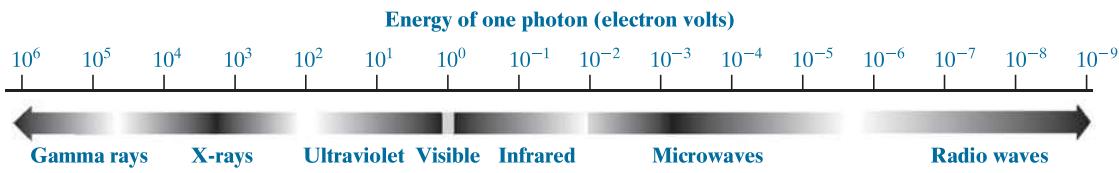


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

bands are grouped according to energy per photon, we obtain the spectrum shown in Fig. 1.5, ranging from gamma rays (highest energy) at one end to radio waves (lowest energy) at the other. The bands are shown shaded to convey the fact that bands of the EM spectrum are not distinct, but rather transition smoothly from one to the other.

GAMMA-RAY IMAGING

Major uses of imaging based on gamma rays include nuclear medicine and astronomical observations. In nuclear medicine, the approach is to inject a patient with a radioactive isotope that emits gamma rays as it decays. Images are produced from the emissions collected by gamma-ray detectors. Figure 1.6(a) shows an image of a complete bone scan obtained by using gamma-ray imaging. Images of this sort are used to locate sites of bone pathology, such as infections or tumors. Figure 1.6(b) shows another major modality of nuclear imaging called *positron emission tomography* (PET). The principle is the same as with X-ray tomography, mentioned briefly in Section 1.2. However, instead of using an external source of X-ray energy, the patient is given a radioactive isotope that emits positrons as it decays. When a positron meets an electron, both are annihilated and two gamma rays are given off. These are detected and a tomographic image is created using the basic principles of tomography. The image shown in Fig. 1.6(b) is one sample of a sequence that constitutes a 3-D rendition of the patient. This image shows a tumor in the brain and another in the lung, easily visible as small white masses.

A star in the constellation of Cygnus exploded about 15,000 years ago, generating a superheated, stationary gas cloud (known as the Cygnus Loop) that glows in a spectacular array of colors. Figure 1.6(c) shows an image of the Cygnus Loop in the gamma-ray band. Unlike the two examples in Figs. 1.6(a) and (b), this image was obtained using the natural radiation of the object being imaged. Finally, Fig. 1.6(d) shows an image of gamma radiation from a valve in a nuclear reactor. An area of strong radiation is seen in the lower left side of the image.

X-RAY IMAGING

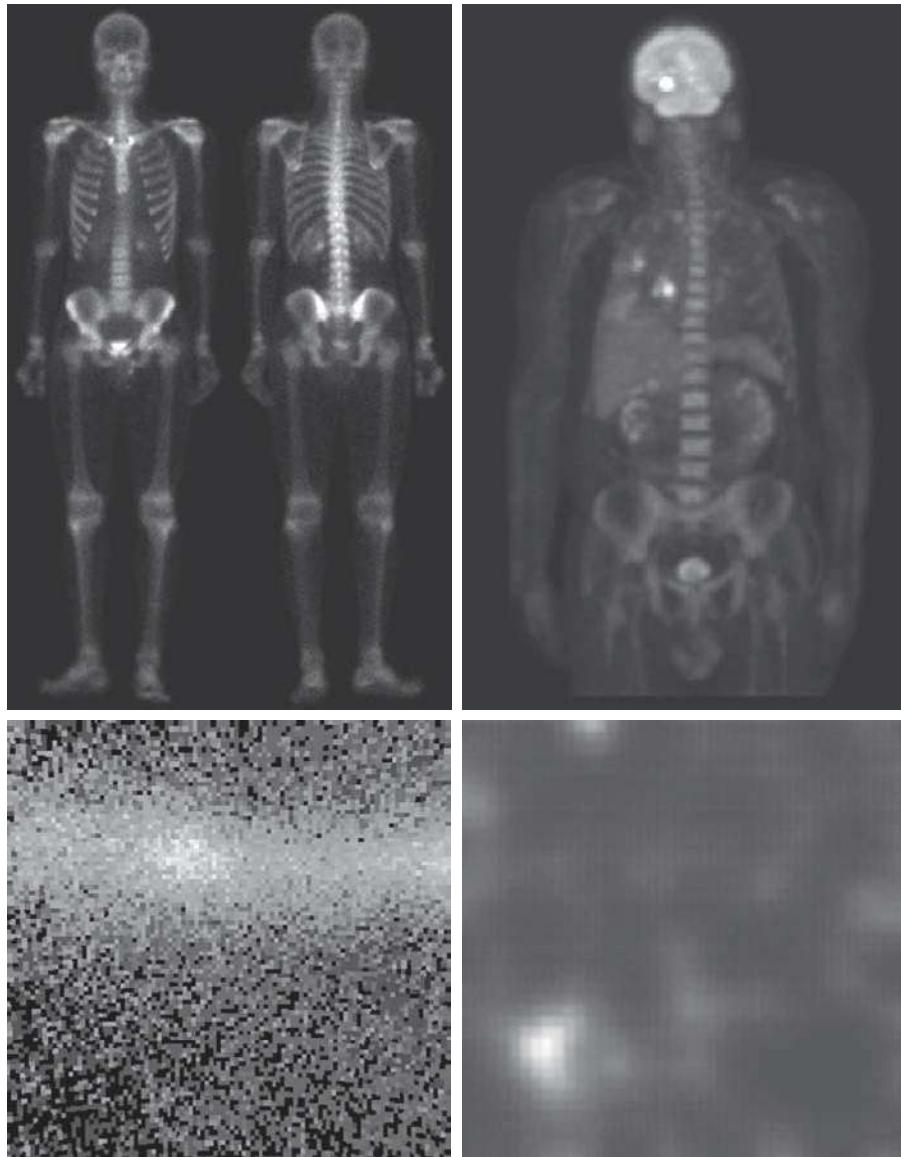
X-rays are among the oldest sources of EM radiation used for imaging. The best known use of X-rays is medical diagnostics, but they are also used extensively in industry and other areas, such as astronomy. X-rays for medical and industrial imaging are generated using an X-ray tube, which is a vacuum tube with a cathode and anode. The cathode is heated, causing free electrons to be released. These electrons flow at high speed to the positively charged anode. When the electrons strike a

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| 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.)

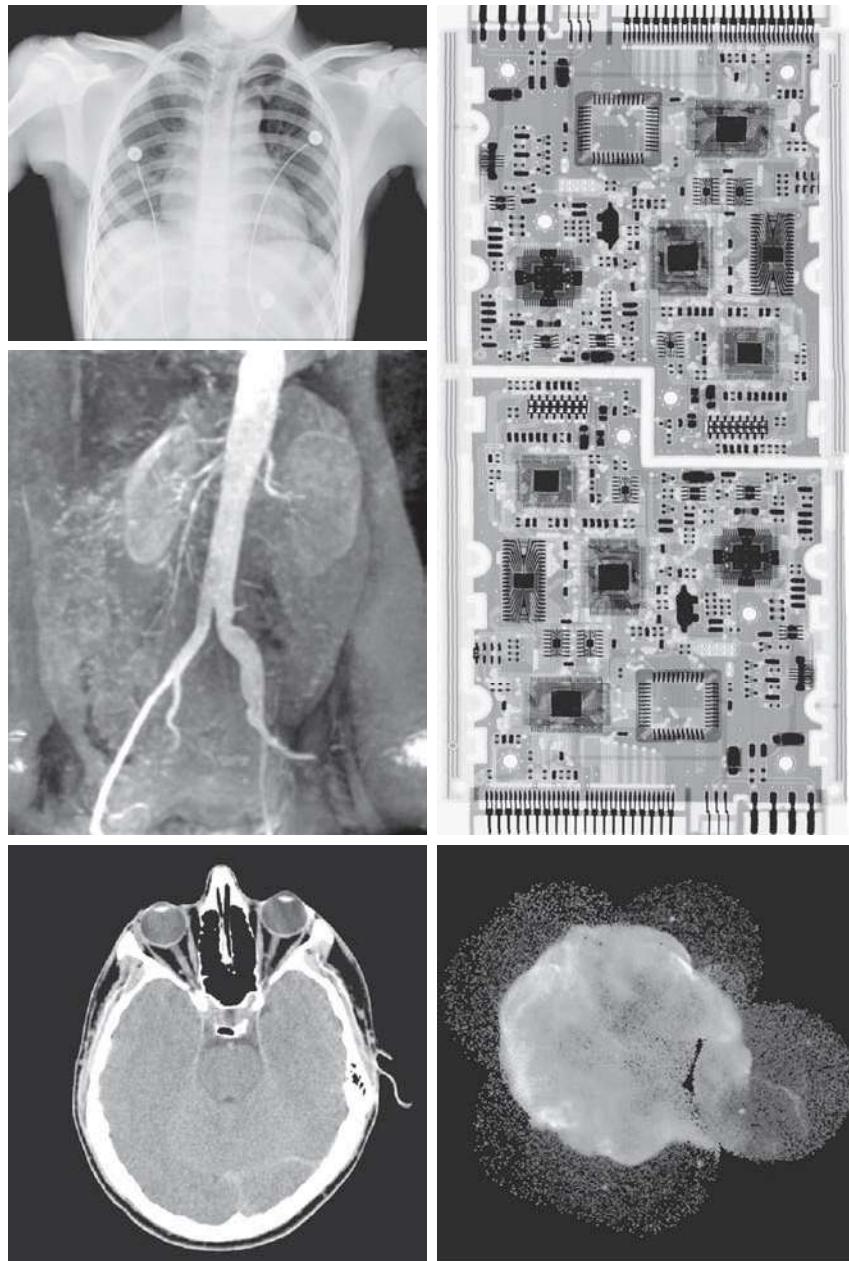


nucleus, energy is released in the form of X-ray radiation. The energy (penetrating power) of X-rays is controlled by a voltage applied across the anode, and by a current applied to the filament in the cathode. Figure 1.7(a) shows a familiar chest X-ray generated simply by placing the patient between an X-ray source and a film sensitive to X-ray energy. The intensity of the X-rays is modified by absorption as they pass through the patient, and the resulting energy falling on the film develops it, much in the same way that light develops photographic film. In digital radiography,

| | |
|---|---|
| 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.)



digital images are obtained by one of two methods: (1) by digitizing X-ray films; or; (2) by having the X-rays that pass through the patient fall directly onto devices (such as a phosphor screen) that convert X-rays to light. The light signal in turn is captured by a light-sensitive digitizing system. We will discuss digitization in more detail in Chapters 2 and 4.

Angiography is another major application in an area called contrast enhancement radiography. This procedure is used to obtain images of blood vessels, called *angiograms*. A catheter (a small, flexible, hollow tube) is inserted, for example, into an artery or vein in the groin. The catheter is threaded into the blood vessel and guided to the area to be studied. When the catheter reaches the site under investigation, an X-ray contrast medium is injected through the tube. This enhances the contrast of the blood vessels and enables a radiologist to see any irregularities or blockages. Figure 1.7(b) shows an example of an aortic angiogram. The catheter can be seen being inserted into the large blood vessel on the lower left of the picture. Note the high contrast of the large vessel as the contrast medium flows up in the direction of the kidneys, which are also visible in the image. As we will discuss further in Chapter 2, angiography is a major area of digital image processing, where image subtraction is used to further enhance the blood vessels being studied.

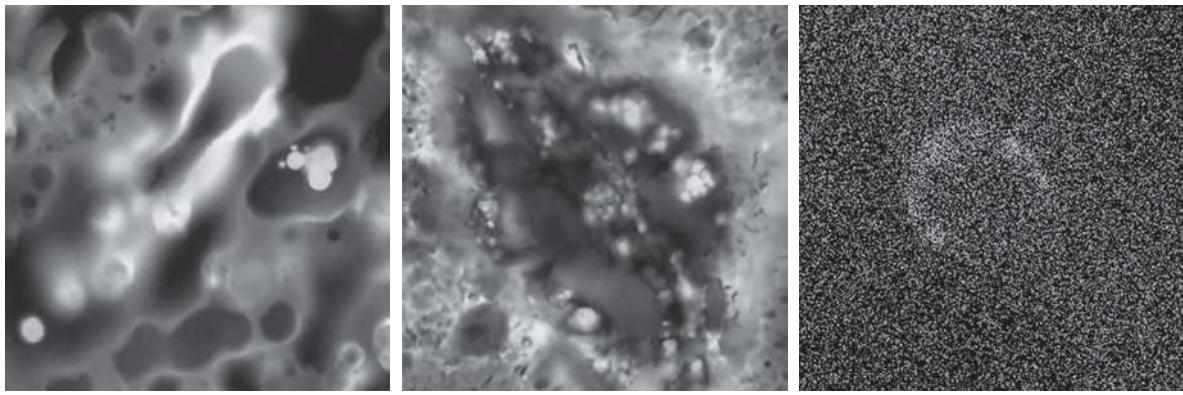
Another important use of X-rays in medical imaging is computerized axial tomography (CAT). Due to their resolution and 3-D capabilities, CAT scans revolutionized medicine from the moment they first became available in the early 1970s. As noted in Section 1.2, each CAT image is a “slice” taken perpendicularly through the patient. Numerous slices are generated as the patient is moved in a longitudinal direction. The ensemble of such images constitutes a 3-D rendition of the inside of the body, with the longitudinal resolution being proportional to the number of slice images taken. Figure 1.7(c) shows a typical CAT slice image of a human head.

Techniques similar to the ones just discussed, but generally involving higher energy X-rays, are applicable in industrial processes. Figure 1.7(d) shows an X-ray image of an electronic circuit board. Such images, representative of literally hundreds of industrial applications of X-rays, are used to examine circuit boards for flaws in manufacturing, such as missing components or broken traces. Industrial CAT scans are useful when the parts can be penetrated by X-rays, such as in plastic assemblies, and even large bodies, such as solid-propellant rocket motors. Figure 1.7(e) shows an example of X-ray imaging in astronomy. This image is the Cygnus Loop of Fig. 1.6(c), but imaged in the X-ray band.

IMAGING IN THE ULTRAVIOLET BAND

Applications of ultraviolet “light” are varied. They include lithography, industrial inspection, microscopy, lasers, biological imaging, and astronomical observations. We illustrate imaging in this band with examples from microscopy and astronomy.

Ultraviolet light is used in fluorescence microscopy, one of the fastest growing areas of microscopy. Fluorescence is a phenomenon discovered in the middle of the nineteenth century, when it was first observed that the mineral fluorspar fluoresces when ultraviolet light is directed upon it. The ultraviolet light itself is not visible, but when a photon of ultraviolet radiation collides with an electron in an atom of a fluorescent material, it elevates the electron to a higher energy level. Subsequently, the excited electron relaxes to a lower level and emits light in the form of a lower-energy photon in the visible (red) light region. Important tasks performed with a fluorescence microscope are to use an excitation light to irradiate a prepared specimen, and then to separate the much weaker radiating fluorescent light from the brighter



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.)

excitation light. Thus, only the emission light reaches the eye or other detector. The resulting fluorescing areas shine against a dark background with sufficient contrast to permit detection. The darker the background of the nonfluorescing material, the more efficient the instrument.

Fluorescence microscopy is an excellent method for studying materials that can be made to fluoresce, either in their natural form (primary fluorescence) or when treated with chemicals capable of fluorescing (secondary fluorescence). Figures 1.8(a) and (b) show results typical of the capability of fluorescence microscopy. Figure 1.8(a) shows a fluorescence microscope image of normal corn, and Fig. 1.8(b) shows corn infected by “smut,” a disease of cereals, corn, grasses, onions, and sorghum that can be caused by any one of more than 700 species of parasitic fungi. Corn smut is particularly harmful because corn is one of the principal food sources in the world. As another illustration, Fig. 1.8(c) shows the Cygnus Loop imaged in the high-energy region of the ultraviolet band.

IMAGING IN THE VISIBLE AND INFRARED BANDS

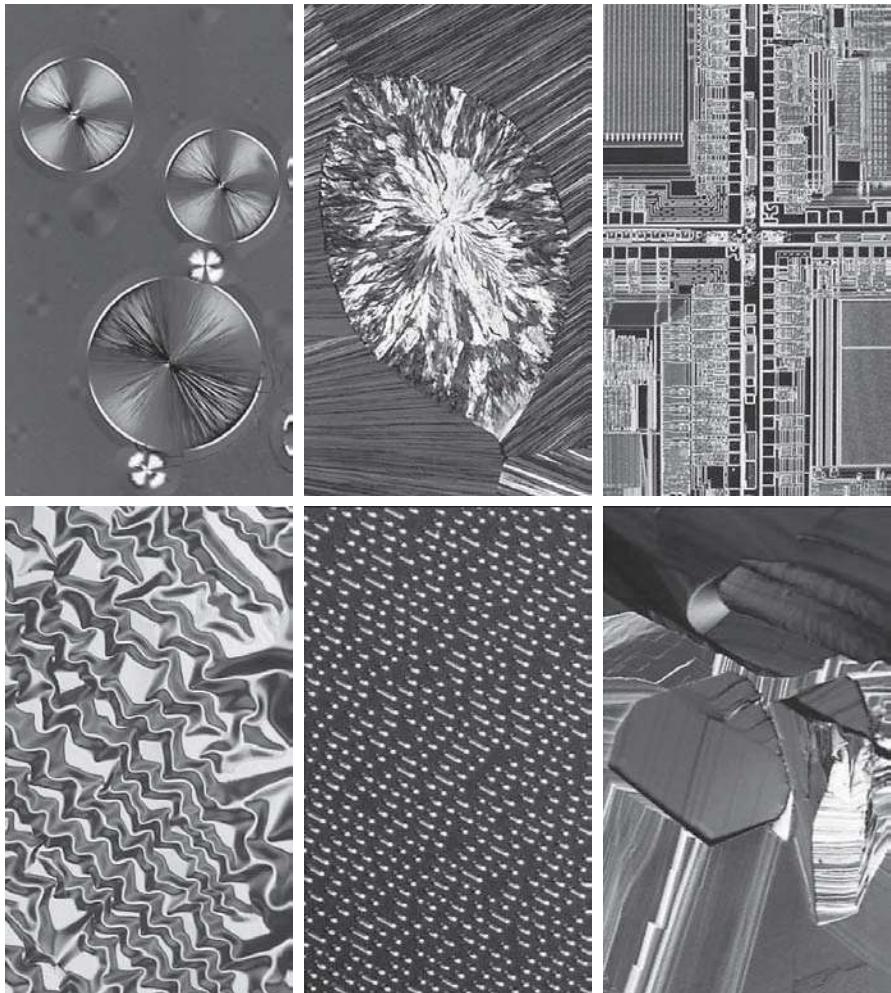
Considering that the visual band of the electromagnetic spectrum is the most familiar in all our activities, it is not surprising that imaging in this band outweighs by far all the others in terms of breadth of application. The infrared band often is used in conjunction with visual imaging, so we have grouped the visible and infrared bands in this section for the purpose of illustration. We consider in the following discussion applications in light microscopy, astronomy, remote sensing, industry, and law enforcement.

Figure 1.9 shows several examples of images obtained with a light microscope. The examples range from pharmaceuticals and microinspection to materials characterization. Even in microscopy alone, the application areas are too numerous to detail here. It is not difficult to conceptualize the types of processes one might apply to these images, ranging from enhancement to measurements.

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| 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.)



Another major area of visual processing is remote sensing, which usually includes several bands in the visual and infrared regions of the spectrum. Table 1.1 shows the so-called *thematic bands* in NASA's LANDSAT satellites. The primary function of LANDSAT is to obtain and transmit images of the Earth from space, for purposes of monitoring environmental conditions on the planet. The bands are expressed in terms of wavelength, with $1\mu\text{m}$ being equal to 10^{-6} m (we will discuss the wavelength regions of the electromagnetic spectrum in more detail in Chapter 2). Note the characteristics and uses of each band in Table 1.1.

In order to develop a basic appreciation for the power of this type of multispectral imaging, consider Fig. 1.10, which shows one image for each of the spectral bands in Table 1.1. The area imaged is Washington D.C., which includes features such as buildings, roads, vegetation, and a major river (the Potomac) going though the city.

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 |

Images of population centers are used over time to assess population growth and shift patterns, pollution, and other factors affecting the environment. The differences between visual and infrared image features are quite noticeable in these images. Observe, for example, how well defined the river is from its surroundings in Bands 4 and 5.

Weather observation and prediction also are major applications of multispectral imaging from satellites. For example, Fig. 1.11 is an image of Hurricane Katrina, one of the most devastating storms in recent memory in the Western Hemisphere. This image was taken by a National Oceanographic and Atmospheric Administration (NOAA) satellite using sensors in the visible and infrared bands. The eye of the hurricane is clearly visible in this image.

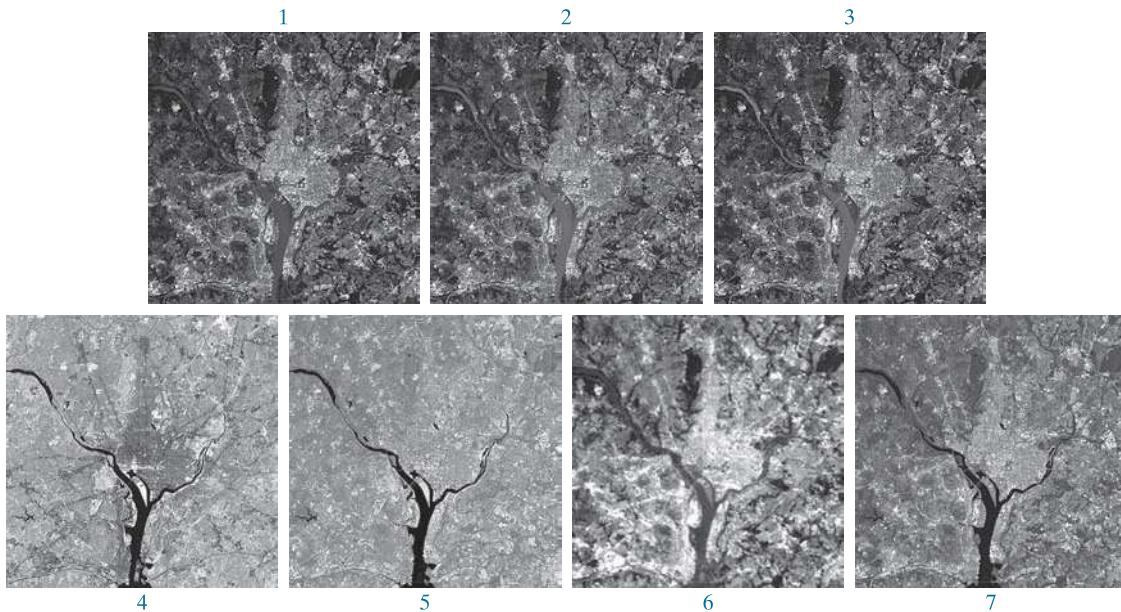


FIGURE 1.10 LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

FIGURE 1.11

Satellite image of Hurricane Katrina taken on August 29, 2005.
(Courtesy of NOAA.)



Figures 1.12 and 1.13 show an application of infrared imaging. These images are part of the Nighttime Lights of the World data set, which provides a global inventory of human settlements. The images were generated by an infrared imaging system mounted on a NOAA/DMSP (Defense Meteorological Satellite Program) satellite. The infrared system operates in the band 10.0 to 13.4 μm , and has the unique capability to observe faint sources of visible, near infrared emissions present on the Earth's surface, including cities, towns, villages, gas flares, and fires. Even without formal training in image processing, it is not difficult to imagine writing a computer program that would use these images to estimate the relative percent of total electrical energy used by various regions of the world.

A major area of imaging in the visible spectrum is in automated visual inspection of manufactured goods. Figure 1.14 shows some examples. Figure 1.14(a) is a controller board for a CD-ROM drive. A typical image processing task with products such as this is to inspect them for missing parts (the black square on the top, right quadrant of the image is an example of a missing component).

Figure 1.14(b) is an imaged pill container. The objective here is to have a machine look for missing, incomplete, or deformed pills. Figure 1.14(c) shows an application in which image processing is used to look for bottles that are not filled up to an acceptable level. Figure 1.14(d) shows a clear plastic part with an unacceptable number of air pockets in it. Detecting anomalies like these is a major theme of industrial inspection that includes other products, such as wood and cloth. Figure 1.14(e) shows a batch of cereal during inspection for color and the presence of anomalies such as burned flakes. Finally, Fig. 1.14(f) shows an image of an intraocular implant (replacement lens for the human eye). A “structured light” illumination technique was used to highlight deformations toward the center of the lens, and other imperfections. For example, the markings at 1 o'clock and 5 o'clock are tweezer damage. Most of the other small speckle detail is debris. The objective in this type of inspection is to find damaged or incorrectly manufactured implants automatically, prior to packaging.

FIGURE 1.12

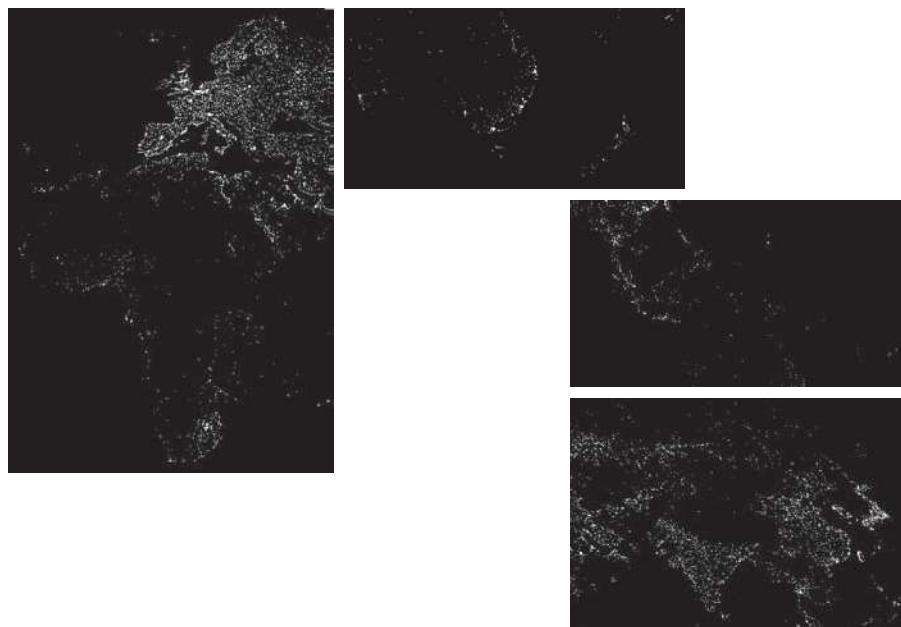
Infrared satellite images of the Americas. The small shaded map is provided for reference.
(Courtesy of NOAA.)



Figure 1.15 illustrates some additional examples of image processing in the visible spectrum. Figure 1.15(a) shows a thumb print. Images of fingerprints are routinely processed by computer, either to enhance them or to find features that aid in the automated search of a database for potential matches. Figure 1.15(b) shows an image of paper currency. Applications of digital image processing in this area

FIGURE 1.13

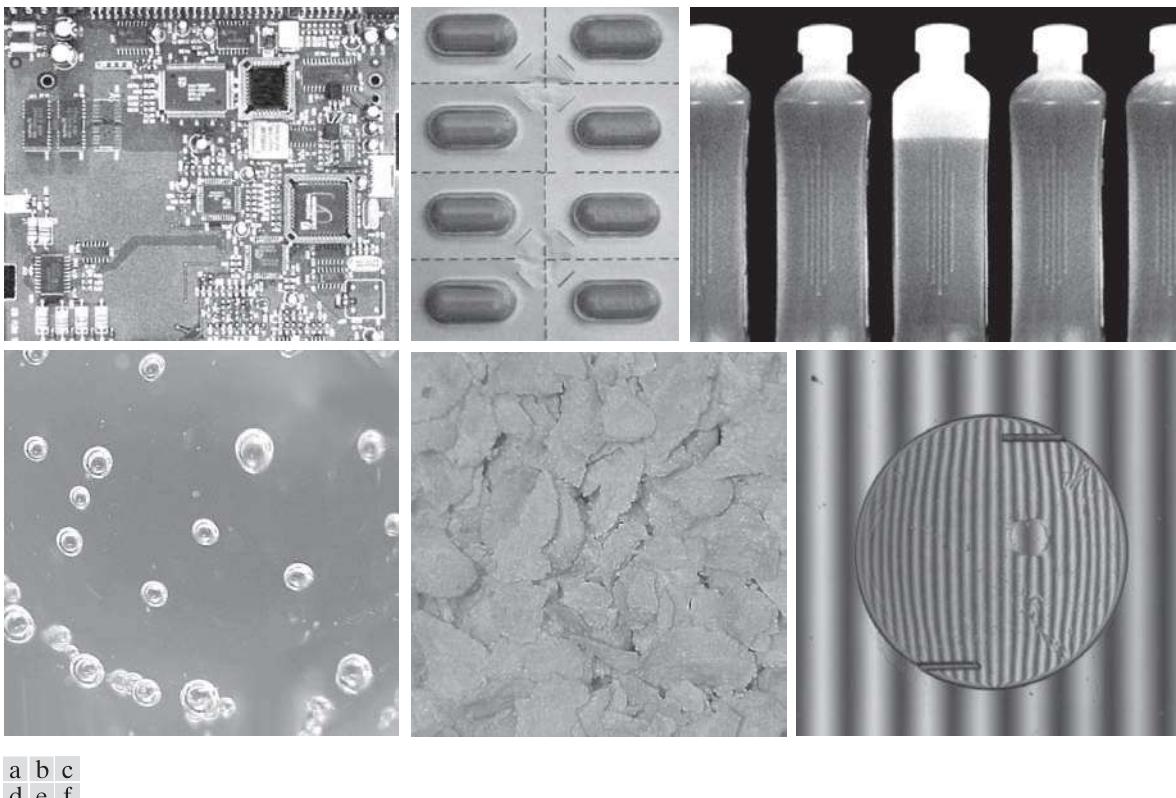
Infrared satellite images of the remaining populated parts of the world. The small shaded map is provided for reference.
(Courtesy of NOAA.)



include automated counting and, in law enforcement, the reading of the serial number for the purpose of tracking and identifying currency bills. The two vehicle images shown in Figs. 1.15(c) and (d) are examples of automated license plate reading. The light rectangles indicate the area in which the imaging system detected the plate. The black rectangles show the results of automatically reading the plate content by the system. License plate and other applications of character recognition are used extensively for traffic monitoring and surveillance.

IMAGING IN THE MICROWAVE BAND

The principal application of imaging in the microwave band is radar. The unique feature of imaging radar is its ability to collect data over virtually any region at any time, regardless of weather or ambient lighting conditions. Some radar waves can penetrate clouds, and under certain conditions, can also see through vegetation, ice, and dry sand. In many cases, radar is the only way to explore inaccessible regions of the Earth's surface. An imaging radar works like a flash camera in that it provides its own illumination (microwave pulses) to illuminate an area on the ground and



a b c

d e f

FIGURE 1.14 Some examples of manufactured goods checked using digital image processing. (a) Circuit board controller. (b) Packaged pills. (c) Bottles. (d) Air bubbles in a clear plastic product. (e) Cereal. (f) Image of intraocular implant. (Figure (f) courtesy of Mr. Pete Sites, Perceptics Corporation.)

take a snapshot image. Instead of a camera lens, a radar uses an antenna and digital computer processing to record its images. In a radar image, one can see only the microwave energy that was reflected back toward the radar antenna.

Figure 1.16 shows a spaceborne radar image covering a rugged mountainous area of southeast Tibet, about 90 km east of the city of Lhasa. In the lower right corner is a wide valley of the Lhasa River, which is populated by Tibetan farmers and yak herders, and includes the village of Menba. Mountains in this area reach about 5800 m (19,000 ft) above sea level, while the valley floors lie about 4300 m (14,000 ft) above sea level. Note the clarity and detail of the image, unencumbered by clouds or other atmospheric conditions that normally interfere with images in the visual band.

IMAGING IN THE RADIO BAND

As in the case of imaging at the other end of the spectrum (gamma rays), the major applications of imaging in the radio band are in medicine and astronomy. In medicine, radio waves are used in magnetic resonance imaging (MRI). This technique places a

a b
c
d

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



patient in a powerful magnet and passes radio waves through the individual's body in short pulses. Each pulse causes a responding pulse of radio waves to be emitted by the patient's tissues. The location from which these signals originate and their strength are determined by a computer, which produces a two-dimensional image of a section of the patient. MRI can produce images in any plane. Figure 1.17 shows MRI images of a human knee and spine.

The rightmost image in Fig. 1.18 is an image of the Crab Pulsar in the radio band. Also shown for an interesting comparison are images of the same region, but taken in most of the bands discussed earlier. Observe that each image gives a totally different "view" of the pulsar.

OTHER IMAGING MODALITIES

Although imaging in the electromagnetic spectrum is dominant by far, there are a number of other imaging modalities that are also important. Specifically, we discuss

FIGURE 1.16

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



in this section acoustic imaging, electron microscopy, and synthetic (computer-generated) imaging.

Imaging using “sound” finds application in geological exploration, industry, and medicine. Geological applications use sound in the low end of the sound spectrum (hundreds of Hz) while imaging in other areas use ultrasound (millions of Hz). The most important commercial applications of image processing in geology are in mineral and oil exploration. For image acquisition over land, one of the main approaches is to use a large truck and a large flat steel plate. The plate is pressed on the ground by

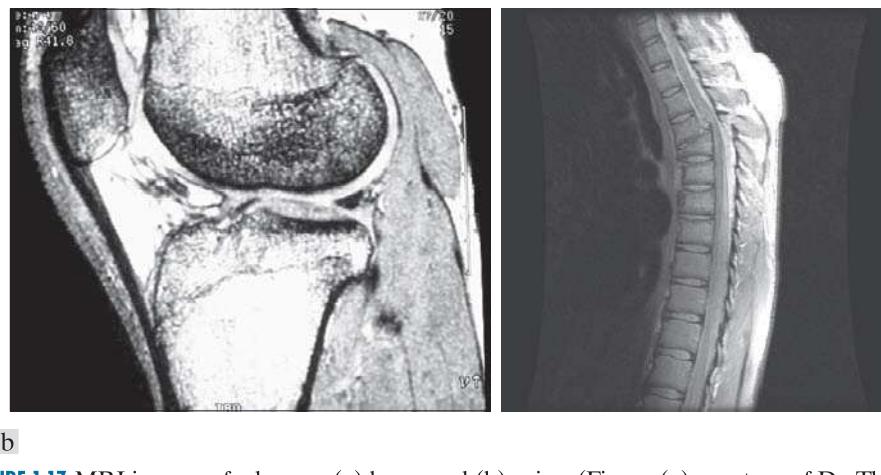


FIGURE 1.17 MRI images of a human (a) knee, and (b) spine. (Figure (a) courtesy of Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School, and (b) courtesy of Dr. David R. Pickens, Department of Radiology and Radiological Sciences, Vanderbilt University Medical Center.)

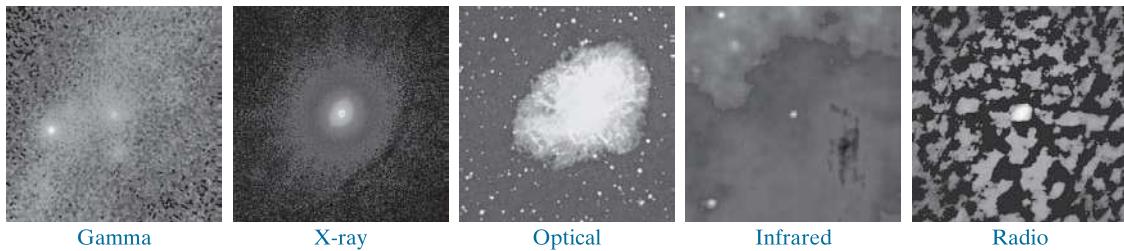


FIGURE 1.18 Images of the Crab Pulsar (in the center of each image) covering the electromagnetic spectrum. (Courtesy of NASA.)

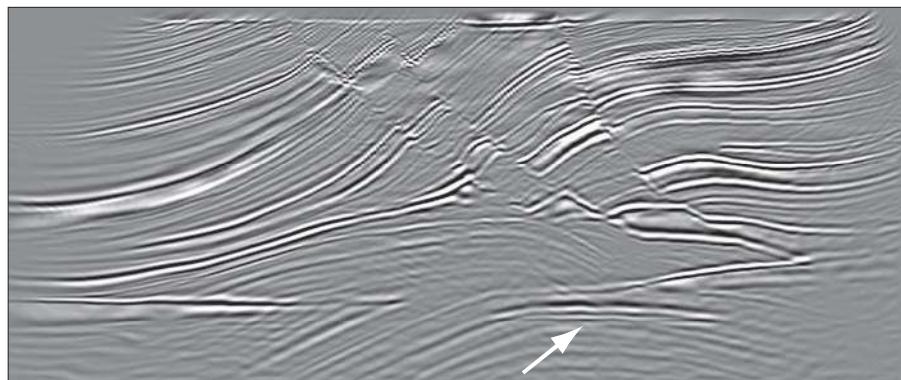
the truck, and the truck is vibrated through a frequency spectrum up to 100 Hz. The strength and speed of the returning sound waves are determined by the composition of the Earth below the surface. These are analyzed by computer, and images are generated from the resulting analysis.

For marine image acquisition, the energy source consists usually of two air guns towed behind a ship. Returning sound waves are detected by hydrophones placed in cables that are either towed behind the ship, laid on the bottom of the ocean, or hung from buoys (vertical cables). The two air guns are alternately pressurized to ~2000 psi and then set off. The constant motion of the ship provides a transversal direction of motion that, together with the returning sound waves, is used to generate a 3-D map of the composition of the Earth below the bottom of the ocean.

Figure 1.19 shows a cross-sectional image of a well-known 3-D model against which the performance of seismic imaging algorithms is tested. The arrow points to a hydrocarbon (oil and/or gas) trap. This target is brighter than the surrounding layers because the change in density in the target region is larger. Seismic interpreters look for these “bright spots” to find oil and gas. The layers above also are bright, but their brightness does not vary as strongly across the layers. Many seismic reconstruction algorithms have difficulty imaging this target because of the faults above it.

Although ultrasound imaging is used routinely in manufacturing, the best known applications of this technique are in medicine, especially in obstetrics, where fetuses are imaged to determine the health of their development. A byproduct of this

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.)



examination is determining the sex of the baby. Ultrasound images are generated using the following basic procedure:

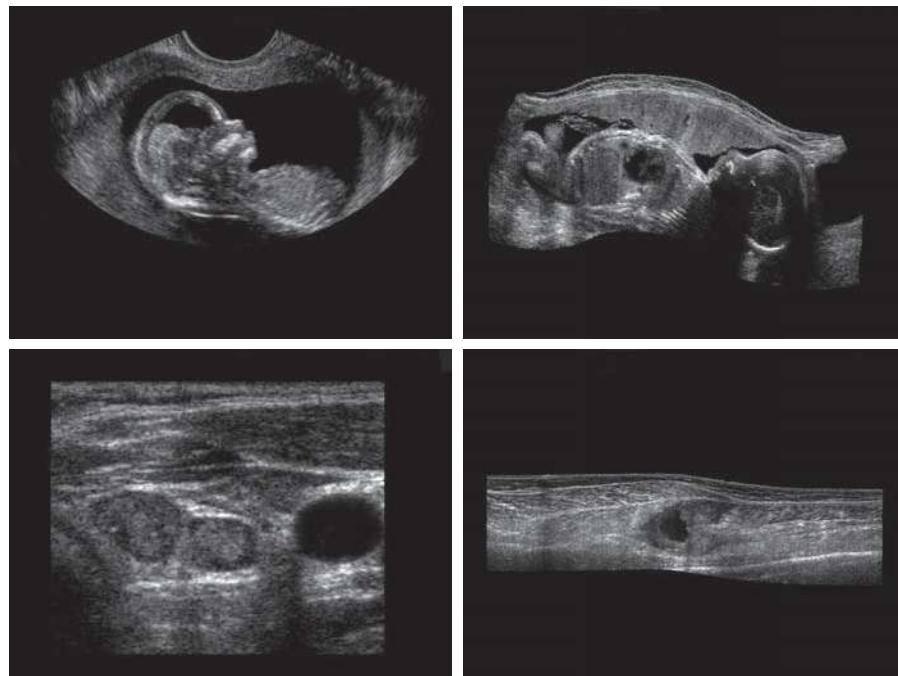
- 1.** The ultrasound system (a computer, ultrasound probe consisting of a source, a receiver, and a display) transmits high-frequency (1 to 5 MHz) sound pulses into the body.
- 2.** The sound waves travel into the body and hit a boundary between tissues (e.g., between fluid and soft tissue, soft tissue and bone). Some of the sound waves are reflected back to the probe, while some travel on further until they reach another boundary and are reflected.
- 3.** The reflected waves are picked up by the probe and relayed to the computer.
- 4.** The machine calculates the distance from the probe to the tissue or organ boundaries using the speed of sound in tissue (1540 m/s) and the time of each echo's return.
- 5.** The system displays the distances and intensities of the echoes on the screen, forming a two-dimensional image.

In a typical ultrasound image, millions of pulses and echoes are sent and received each second. The probe can be moved along the surface of the body and angled to obtain various views. Figure 1.20 shows several examples of medical uses of ultrasound.

We continue the discussion on imaging modalities with some examples of electron microscopy. Electron microscopes function as their optical counterparts, except

| | |
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| 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.)



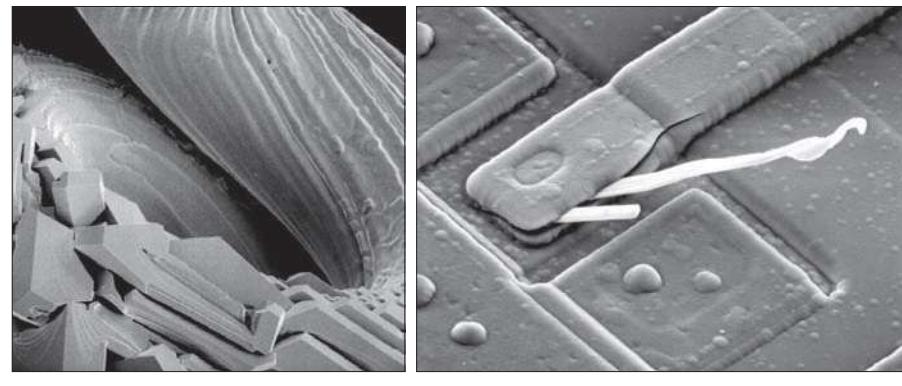
that they use a focused beam of electrons instead of light to image a specimen. The operation of electron microscopes involves the following basic steps: A stream of electrons is produced by an electron source and accelerated toward the specimen using a positive electrical potential. This stream is confined and focused using metal apertures and magnetic lenses into a thin, monochromatic beam. This beam is focused onto the sample using a magnetic lens. Interactions occur inside the irradiated sample, affecting the electron beam. These interactions and effects are detected and transformed into an image, much in the same way that light is reflected from, or absorbed by, objects in a scene. These basic steps are carried out in all electron microscopes.

A *transmission electron microscope* (TEM) works much like a slide projector. A projector transmits a beam of light through a slide; as the light passes through the slide, it is modulated by the contents of the slide. This transmitted beam is then projected onto the viewing screen, forming an enlarged image of the slide. TEMs work in the same way, except that they shine a beam of electrons through a specimen (analogous to the slide). The fraction of the beam transmitted through the specimen is projected onto a phosphor screen. The interaction of the electrons with the phosphor produces light and, therefore, a viewable image. A *scanning electron microscope* (SEM), on the other hand, actually scans the electron beam and records the interaction of beam and sample at each location. This produces one dot on a phosphor screen. A complete image is formed by a raster scan of the beam through the sample, much like a TV camera. The electrons interact with a phosphor screen and produce light. SEMs are suitable for “bulky” samples, while TEMs require very thin samples.

Electron microscopes are capable of very high magnification. While light microscopy is limited to magnifications on the order of $1000\times$, electron microscopes can achieve magnification of $10,000\times$ or more. Figure 1.21 shows two SEM images of specimen failures due to thermal overload.

We conclude the discussion of imaging modalities by looking briefly at images that are not obtained from physical objects. Instead, they are generated by computer. Fractals are striking examples of computer-generated images. Basically, a fractal is nothing more than an iterative reproduction of a basic pattern according to some mathematical rules. For instance, tiling is one of the simplest ways to generate a fractal image. A square can be subdivided into four square subregions, each of which can be further subdivided into four smaller square regions, and so on. Depending on the complexity of the rules for filling each subsquare, some beautiful tile images can be generated using this method. Of course, the geometry can be arbitrary. For instance, the fractal image could be grown radially out of a center point. Figure 1.22(a) shows a fractal grown in this way. Figure 1.22(b) shows another fractal (a “moonscape”) that provides an interesting analogy to the images of space used as illustrations in some of the preceding sections.

A more structured approach to image generation by computer lies in 3-D modeling. This is an area that provides an important intersection between image processing and computer graphics, and is the basis for many 3-D visualization systems (e.g., flight simulators). Figures 1.22(c) and (d) show examples of computer-generated images. Because the original object is created in 3-D, images can be generated in any



a b

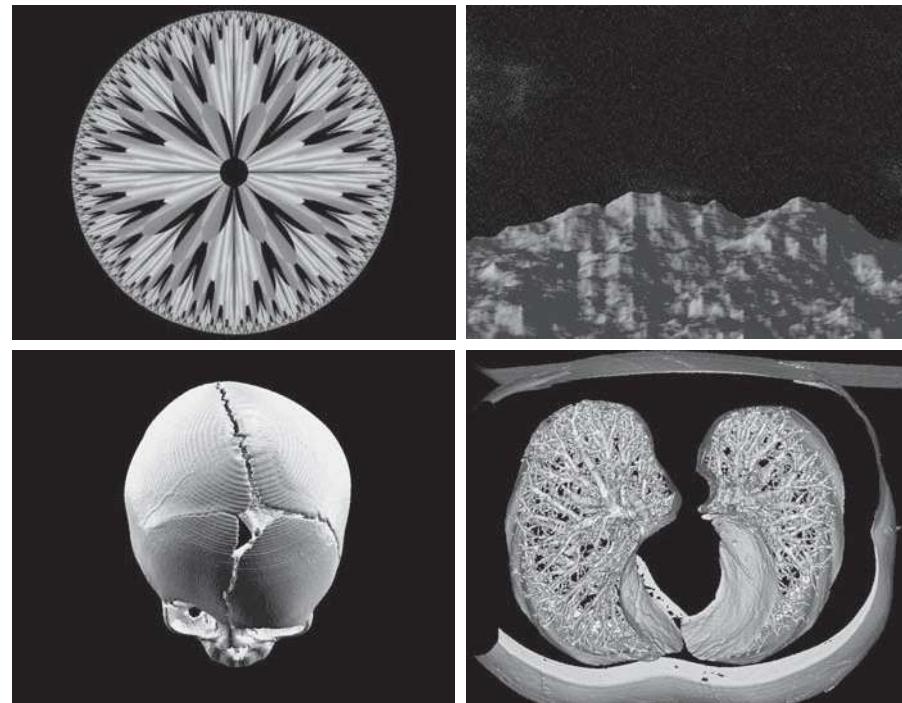
FIGURE 1.21 (a) $250\times$ SEM image of a tungsten filament following thermal failure (note the shattered pieces on the lower left). (b) $2500\times$ SEM image of a damaged integrated circuit. The white fibers are oxides resulting from thermal destruction. (Figure (a) courtesy of Mr. Michael Shaffer,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

perspective from plane projections of the 3-D volume. Images of this type can be used for medical training and for a host of other applications, such as criminal forensics and special effects.

| | |
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| 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.)



1.4 FUNDAMENTAL STEPS IN DIGITAL IMAGE PROCESSING

It is helpful to divide the material covered in the following chapters into the two broad categories defined in Section 1.1: methods whose input and output are images, and methods whose inputs may be images, but whose outputs are attributes extracted from those images. This organization is summarized in Fig. 1.23. The diagram does not imply that every process is applied to an image. Rather, the intention is to convey an idea of all the methodologies that can be applied to images for different purposes, and possibly with different objectives. The discussion in this section may be viewed as a brief overview of the material in the remainder of the book.

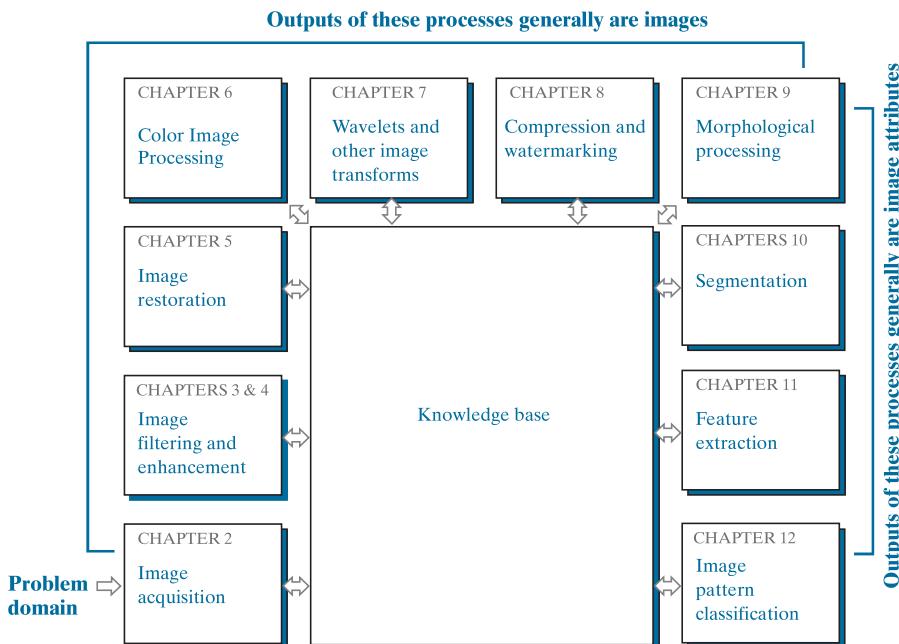
Image acquisition is the first process in Fig. 1.23. The discussion in Section 1.3 gave some hints regarding the origin of digital images. This topic will be considered in much more detail in Chapter 2, where we also introduce a number of basic digital image concepts that are used throughout the book. Acquisition could be as simple as being given an image that is already in digital form. Generally, the image acquisition stage involves preprocessing, such as scaling.

Image enhancement is the process of manipulating an image so the result is more suitable than the original for a specific application. The word *specific* is important here, because it establishes at the outset that enhancement techniques are problem oriented. Thus, for example, a method that is quite useful for enhancing X-ray images may not be the best approach for enhancing satellite images taken in the infrared band of the electromagnetic spectrum.

There is no general “theory” of image enhancement. When an image is processed for visual interpretation, the viewer is the ultimate judge of how well a particular

FIGURE 1.23

Fundamental steps in digital image processing. The chapter(s) indicated in the boxes is where the material described in the box is discussed.



method works. Enhancement techniques are so varied, and use so many different image processing approaches, that it is difficult to assemble a meaningful body of techniques suitable for enhancement in one chapter without extensive background development. For this reason, and also because beginners in the field of image processing generally find enhancement applications visually appealing, interesting, and relatively simple to understand, we will use image enhancement as examples when introducing new concepts in parts of Chapter 2 and in Chapters 3 and 4. The material in the latter two chapters span many of the methods used traditionally for image enhancement. Therefore, using examples from image enhancement to introduce new image processing methods developed in these early chapters not only saves having an extra chapter in the book dealing with image enhancement but, more importantly, is an effective approach for introducing newcomers to the details of processing techniques early in the book. However, as you will see in progressing through the rest of the book, the material developed in Chapters 3 and 4 is applicable to a much broader class of problems than just image enhancement.

Image restoration is an area that also deals with improving the appearance of an image. However, unlike enhancement, which is subjective, image restoration is objective, in the sense that restoration techniques tend to be based on mathematical or probabilistic models of image degradation. Enhancement, on the other hand, is based on human subjective preferences regarding what constitutes a “good” enhancement result.

Color image processing is an area that has been gaining in importance because of the significant increase in the use of digital images over the internet. Chapter 6 covers a number of fundamental concepts in color models and basic color processing in a digital domain. Color is used also as the basis for extracting features of interest in an image.

Wavelets are the foundation for representing images in various degrees of resolution. In particular, this material is used in the book for image data compression and for pyramidal representation, in which images are subdivided successively into smaller regions. The material in Chapters 4 and 5 is based mostly on the Fourier transform. In addition to wavelets, we will also discuss in Chapter 7 a number of other transforms that are used routinely in image processing.

Compression, as the name implies, deals with techniques for reducing the storage required to save an image, or the bandwidth required to transmit it. Although storage technology has improved significantly over the past decade, the same cannot be said for transmission capacity. This is true particularly in uses of the internet, which are characterized by significant pictorial content. Image compression is familiar (perhaps inadvertently) 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.

Morphological processing deals with tools for extracting image components that are useful in the representation and description of shape. The material in this chapter begins a transition from processes that output images to processes that output image attributes, as indicated in Section 1.1.

Segmentation partitions an image into its constituent parts or objects. In general, 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. On the other hand, weak or erratic segmentation algorithms almost always guarantee eventual failure. In general, the more accurate the segmentation, the more likely automated object classification is to succeed.

Feature extraction almost always 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. Feature extraction 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. Feature processing methods discussed in this chapter 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 is the process that assigns a label (e.g., “vehicle”) to an object based on its feature descriptors. In the last chapter of the book, we will discuss methods of image pattern classification ranging from “classical” approaches such as *minimum-distance*, *correlation*, and *Bayes classifiers*, to more modern approaches implemented using *deep neural networks*. In particular, we will discuss in detail *deep convolutional neural networks*, which are ideally suited for image processing work.

So far, we have said nothing about the need for prior knowledge or about the interaction between the knowledge base and the processing modules in Fig. 1.23. *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. 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. In addition to guiding the operation of each processing module, the knowledge base also 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.

Although we do not discuss image display explicitly at this point, it is important to keep in mind that viewing the results of image processing can take place at the output of any stage in Fig. 1.23. We also note that not all image processing applications require the complexity of interactions implied by Fig. 1.23. In fact, not even all those modules are needed in many cases. For example, image enhancement for human visual interpretation seldom requires use of any of the other stages in Fig. 1.23. In general, however, as the complexity of an image processing task increases, so does the number of processes required to solve the problem.

1.5 COMPONENTS OF AN IMAGE PROCESSING SYSTEM

As recently as the mid-1980s, numerous models of image processing systems being sold throughout the world were rather substantial peripheral devices that attached to equally substantial host computers. Late in the 1980s and early in the 1990s, the market shifted to image processing hardware in the form of single boards designed to be compatible with industry standard buses and to fit into engineering workstation cabinets and personal computers. In the late 1990s and early 2000s, a new class of add-on boards, called graphics processing units (GPUs) were introduced for work on 3-D applications, such as games and other 3-D graphics applications. It was not long before GPUs found their way into image processing applications involving large-scale matrix implementations, such as training deep convolutional networks. In addition to lowering costs, the market shift from substantial peripheral devices to add-on processing boards also served as a catalyst for a significant number of new companies specializing in the development of software written specifically for image processing.

The trend continues toward miniaturizing and blending of 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. The function of each component will be discussed in the following paragraphs, starting with image sensing.

Two subsystems are required to acquire digital images. The first is a physical *sensor* that responds to the energy radiated by the object we wish to image. The second, called a *digitizer*, is a device for converting the output of the physical sensing device into digital form. For instance, in a digital video camera, the sensors (CCD chips) produce an electrical output proportional to light intensity. The digitizer converts these outputs to digital data. These topics will be covered in Chapter 2.

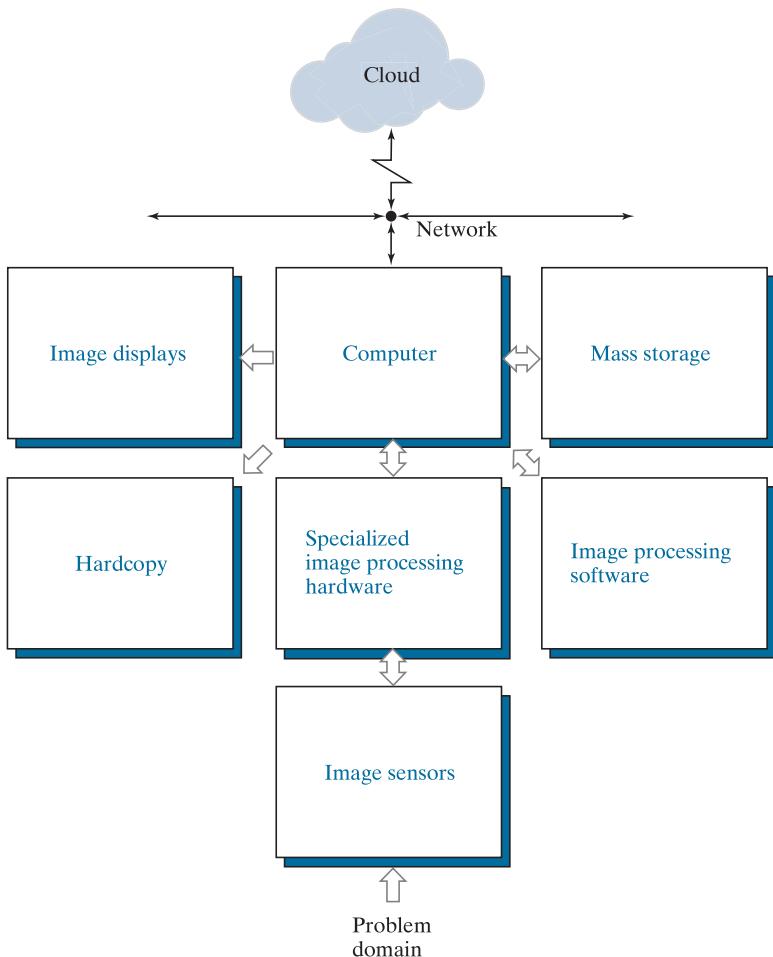
Specialized image processing hardware usually consists of the digitizer just mentioned, plus hardware that performs other primitive operations, such as an *arithmetic logic unit* (ALU), that performs arithmetic and logical operations in parallel on entire images. One example of how an ALU is used is in averaging images as quickly as they are digitized, for the purpose of noise reduction. This type of hardware sometimes is called a *front-end subsystem*, and its most distinguishing characteristic is speed. In other words, this unit performs functions that require fast data throughputs (e.g., digitizing and averaging video images at 30 frames/s) that the typical main computer cannot handle. One or more GPUs (see above) also are common in image processing systems that perform intensive matrix operations.

The *computer* in an image processing system is a general-purpose computer and can range from a PC to a supercomputer. In dedicated applications, sometimes custom computers are used to achieve a required level of performance, but our interest here is on general-purpose image processing systems. In these systems, almost any well-equipped PC-type machine is suitable for off-line image processing tasks.

Software for image processing consists of specialized modules that perform specific tasks. A well-designed package also includes the capability for the user to write code that, as a minimum, utilizes the specialized modules. More sophisticated

FIGURE 1.24

Components of a general-purpose image processing system.



software packages allow the integration of those modules and general-purpose software commands from at least one computer language. Commercially available image processing software, such as the well-known MATLAB® Image Processing Toolbox, is also common in a well-equipped image processing system.

Mass storage is a must in image processing applications. An image of size 1024×1024 pixels, in which the intensity of each pixel is an 8-bit quantity, requires one megabyte of storage space if the image is not compressed. When dealing with image databases that contain thousands, or even millions, of images, providing adequate storage in an image processing system can be a challenge. Digital storage for image processing applications falls into three principal categories: (1) short-term storage for use during processing; (2) on-line storage for relatively fast recall; and (3) archival storage, characterized by infrequent access. Storage is measured in bytes (eight bits), Kbytes (10^3 bytes), Mbytes (10^6 bytes), Gbytes (10^9 bytes), and Tbytes (10^{12} bytes).

One method of providing short-term storage is computer memory. Another is by specialized boards, called *frame buffers*, that store one or more images and can be 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 in Fig. 1.24. On-line storage generally takes the form of magnetic disks or optical-media storage. The key factor characterizing on-line storage is frequent access to the stored data. Finally, archival storage is characterized by massive storage requirements but infrequent need for access. Magnetic tapes and optical disks housed in “jukeboxes” are the usual media for archival applications.

Image displays in use today are 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. Seldom are there requirements for image display applications that cannot be met by display cards and GPUs available commercially as part of the computer system. In some cases, it is necessary to have stereo displays, and these are implemented in the form of headgear containing two small displays embedded in goggles worn by the user.

Hardcopy devices for recording images include laser printers, film cameras, heat-sensitive devices, ink-jet units, and digital units, such as optical and CD-ROM disks. Film provides the highest possible resolution, but paper is the obvious medium of choice for written material. For presentations, images are displayed on film transparencies or in a digital medium if image projection equipment is used. The latter approach is gaining acceptance as the standard for image presentations.

Networking and *cloud* communication are 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.

Summary, References, and Further Reading

The main purpose of the material presented in this chapter is to provide a sense of perspective about the origins of digital image processing and, more important, about current and future areas of application of this technology. Although the coverage of these topics in this chapter was necessarily incomplete due to space limitations, it should have left you with a clear impression of the breadth and practical scope of digital image processing. As we proceed in the following chapters with the development of image processing theory and applications, numerous examples are provided to keep a clear focus on the utility and promise of these techniques. Upon concluding the study of the final chapter, a reader of this book will have arrived at a level of understanding that is the foundation for most of the work currently underway in this field.

In past editions, we have provided a long list of journals and books to give readers an idea of the breadth of the image processing literature, and where this literature is reported. The list has been updated, and it has become so extensive that it is more practical to include it in the book website: www.ImageProcessingPlace.com, in the section entitled *Publications*.