1.4 FUNDAMENTAL STEPS IN DIGITAL IMAGE PROCESSING

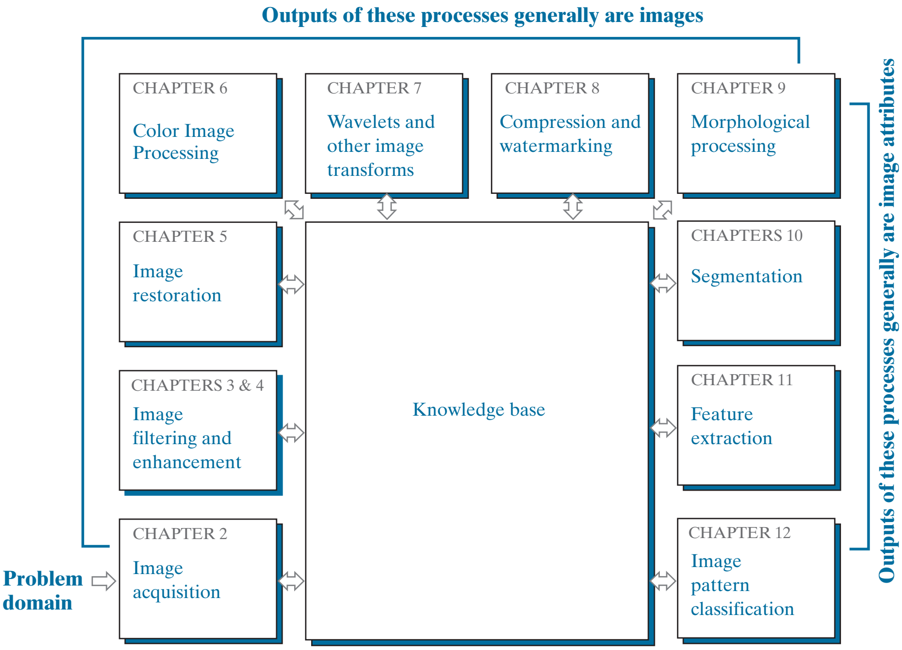
It is helpful to divide the material covered in the following chapters into the two broad categories defined in Section 1.1: methods whose input and output are images, and methods whose inputs may be images, but whose outputs are attributes extracted from those images. This organization is summarized 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

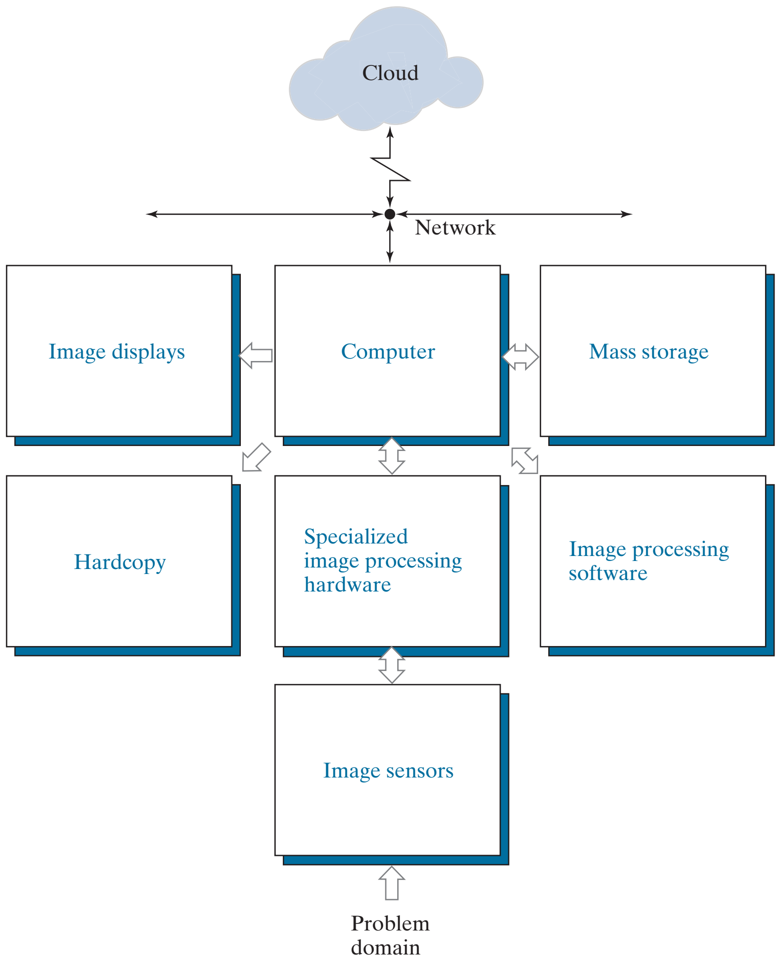


FIGURE 1.24 Components of a general-purpose image processing system.

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*.

intuitive. Conceptually, until we arrive at Chapter 10, it is helpful to think of edges as intensity discontinuities, and of boundaries as closed paths.

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

(a) $D(p,q) \geq 0 \quad (D(p,q) = 0 \text{ iff } p = q)$,
(b) $D(p,q) = D(q,p)$, and
(c) $D(p,s) \leq D(p,q) + D(q,s)$.

The *Euclidean distance* between p and q is defined as

$$D_e(p,q) = \left[(x-u)^2 + (y-v)^2\right]^{\frac{1}{2}} \tag{2-19}$$

For this distance measure, 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 D_4 *distance*, (called the *city-block distance*) between p and q is defined as

$$D_4(p,q) = |x-u| + |y-v| \tag{2-20}$$

In this case, 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:

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

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

$$D_8(p,q) = \max(|x-u|, |y-v|) \tag{2-21}$$

In this case, 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:

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

The pixels with $D_8 = 1$ are the 8-neighbors of the pixel at (x, y).

Since digital image processing has very wide applications and almost all of the technical fields are impacted by DIP, we will just discuss some of the major applications of DIP.

Digital image processing has a broad spectrum of applications, such as

- Remote sensing via satellites and other spacecrafts
- Image transmission and storage for business applicationsMedical processing,
- RADAR (Radio Detection and Ranging)
- SONAR(Sound Navigation and Ranging) and
- Acoustic image processing (The study of underwater sound is known as underwater acoustics or hydro acoustics.)
- Robotics and automated inspection of industrial

parts. Images acquired by satellites are useful in tracking of

- Earth resources;
- Geographical mapping;
- Prediction of agricultural crops,
- Urban growth and weather monitoring
- Flood and fire control and many other environmental

applications. Space image applications include:

- Recognition and analysis of objects contained in images obtained from deep space-probe missions.
- Image transmission and storage applications occur in broadcast television
- Teleconferencing
- Transmission of facsimile images(Printed documents and graphics) for office automation

Communication over computer networks

- Closed-circuit television based security monitoring systems and
- In military

communications. Medical applications:

- Processing of chest X- rays
- Cineangiograms
- Projection images of transaxial tomography and
- Medical images that occur in radiology nuclear magnetic resonance (NMR)