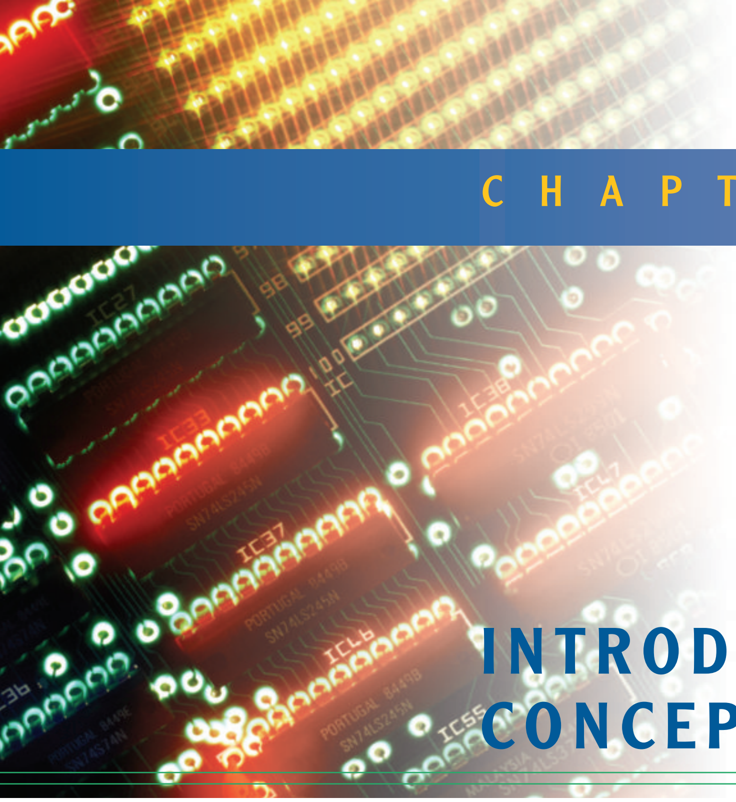


CHAPTER 1

INTRODUCTORY CONCEPTS

OUTLINE

OBJECTIVES

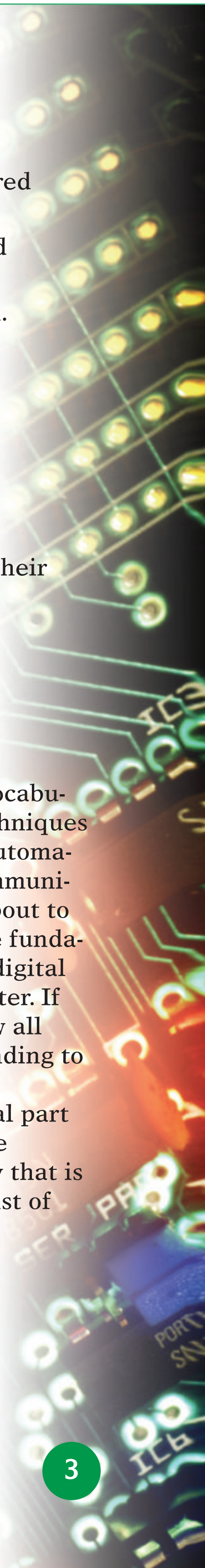
Upon completion of this chapter, you will be able to:

- Distinguish between analog and digital representations.
- Cite the advantages and drawbacks of digital techniques compared with analog.
- Understand the need for analog-to-digital converters (ADCs) and digital-to-analog converters (DACs).
- Recognize the basic characteristics of the binary number system.
- Convert a binary number to its decimal equivalent.
- Count in the binary number system.
- Identify typical digital signals.
- Identify a timing diagram.
- State the differences between parallel and serial transmission.
- Describe the property of memory.
- Describe the major parts of a digital computer and understand their functions.
- Distinguish among microcomputers, microprocessors, and microcontrollers.

INTRODUCTION

In today's world, the term *digital* has become part of our everyday vocabulary because of the dramatic way that digital circuits and digital techniques have become so widely used in almost all areas of life: computers, automation, robots, medical science and technology, transportation, telecommunications, entertainment, space exploration, and on and on. You are about to begin an exciting educational journey in which you will discover the fundamental principles, concepts, and operations that are common to all digital systems, from the simplest on/off switch to the most complex computer. If this book is successful, you should gain a deep understanding of how all digital systems work, and you should be able to apply this understanding to the analysis and troubleshooting of any digital system.

We start by introducing some underlying concepts that are a vital part of digital technology; these concepts will be expanded on as they are needed later in the book. We also introduce some of the terminology that is necessary when embarking on a new field of study, and add to this list of important terms in every chapter.



1-1 NUMERICAL REPRESENTATIONS

In science, technology, business, and, in fact, most other fields of endeavor, we are constantly dealing with *quantities.* Quantities are measured, monitored, recorded, manipulated arithmetically, observed, or in some other way utilized in most physical systems. It is important when dealing with various quantities that we be able to represent their values efficiently and accurately. There are basically two ways of representing the numerical value of quantities: **analog** and **digital**.

Analog Representations

In **analog representation** a quantity is represented by a continuously variable, proportional indicator. An example is an automobile speedometer from the classic muscle cars of the 1960s and 1970s. The deflection of the needle is proportional to the speed of the car and follows any changes that occur as the vehicle speeds up or slows down. On older cars, a flexible mechanical shaft connected the transmission to the speedometer on the dash board. It is interesting to note that on newer cars, the analog representation is usually preferred even though speed is now measured digitally.

Thermometers before the digital revolution used analog representation to measure temperature, and many are still in use today. Mercury thermometers use a column of mercury whose height is proportional to temperature. These devices are being phased out of the market because of environmental concerns, but nonetheless they are an excellent example of analog representation. Another example is an outdoor thermometer on which the position of the pointer rotates around a dial as a metal coil expands and contracts with temperature changes. The position of the pointer is proportional to the temperature. Regardless of how small the change in temperature, there will be a proportional change in the indication.

In these two examples the physical quantities (speed and temperature) are being coupled to an indicator by purely mechanical means. In electrical analog systems, the physical quantity that is being measured or processed is converted to a proportional voltage or current (electrical signal). This voltage or current is then used by the system for display, processing, or control purposes.

Sound is an example of a physical quantity that can be represented by an electrical analog signal. A microphone is a device that generates an output voltage that is proportional to the amplitude of the sound waves that strike it. Variations in the sound waves will produce variations in the microphone's output voltage. Tape recordings can then store sound waves by using the output voltage of the microphone to proportionally change the magnetic field on the tape.

Analog quantities such as those cited above have an important characteristic, no matter how they are represented: *they can vary over a continuous range of values.* The automobile speed can have *any* value between zero and, say, 100 mph. Similarly, the microphone output might have any value within a range of zero to 10 mV (e.g., 1 mV, 2.3724 mV, 9.9999 mV).

Digital Representations

In **digital representation** the quantities are represented not by continuously variable indicators but by symbols called *digits.* As an example, consider the digital clock, which provides the time of day in the form of decimal digits that represent hours and minutes (and sometimes seconds). As we know, the time of day changes continuously, but the digital clock reading does not change continuously; rather, it changes in steps of one per minute (or per second). In other words, this digital representation of the time of day changes in *discrete* steps, as compared with the representation of time provided by an analog ac line-powered wall clock, where the dial reading changes continuously.

The major difference between analog and digital quantities, then, can be simply stated as follows:

$$\text{analog} \equiv \text{continuous}$$
$$\text{digital} \equiv \text{discrete (step by step)}$$

Because of the discrete nature of digital representations, there is no ambiguity when reading the value of a digital quantity, whereas the value of an analog quantity is often open to interpretation. In practice, when we take a measurement of an analog quantity, we always "round" to a convenient level of precision. In other words, we digitize the quantity. The digital representation is the result of assigning a number of limited precision to a continuously variable quantity. For example, when you take your temperature with a mercury (analog) thermometer, the mercury column is usually between two graduation lines, but you would pick the nearest line and assign it a number of, say, 98.6°F.

EXAMPLE 1-1

Which of the following involve analog quantities and which involve digital quantities?

(a) Ten-position switch
(b) Current flowing from an electrical outlet
(c) Temperature of a room
(d) Sand grains on the beach
(e) Automobile fuel gauge

Solution

(a) Digital
(b) Analog
(c) Analog
(d) Digital, since the number of grains can be only certain discrete (integer) values and not every possible value over a continuous range
(e) Analog, if needle type; digital, if numerical readout or bar graph display

REVIEW QUESTION *

1. Concisely describe the major difference between analog and digital quantities.

1-2 DIGITAL AND ANALOG SYSTEMS

A **digital system** is a combination of devices designed to manipulate logical information or physical quantities that are represented in digital form; that is, the quantities can take on only discrete values. These devices are most

*Answers to review questions are found at the end of the chapter in which they occur.

often electronic, but they can also be mechanical, magnetic, or pneumatic. Some of the more familiar digital systems include digital computers and calculators, digital audio and video equipment, and the telephone system—the world's largest digital system.

An **analog system** contains devices that manipulate physical quantities that are represented in analog form. In an analog system, the quantities can vary over a continuous range of values. For example, the amplitude of the output signal to the speaker in a radio receiver can have any value between zero and its maximum limit. Other common analog systems are audio amplifiers, magnetic tape recording and playback equipment, and a simple light dimmer switch.

Advantages of Digital Techniques

An increasing majority of applications in electronics, as well as in most other technologies, use digital techniques to perform operations that were once performed using analog methods. The chief reasons for the shift to digital technology are:

1. *Digital systems are generally easier to design.* The circuits used in digital systems are *switching circuits,* where *exact* values of voltage or current are not important, only the range (HIGH or LOW) in which they fall.
2. *Information storage is easy.* This is accomplished by special devices and circuits that can latch onto digital information and hold it for as long as necessary, and mass storage techniques that can store billions of bits of information in a relatively small physical space. Analog storage capabilities are, by contrast, extremely limited.
3. *Accuracy and precision are easier to maintain throughout the system.* Once a signal is digitized, the information it contains does not deteriorate as it is processed. In analog systems, the voltage and current signals tend to be distorted by the effects of temperature, humidity, and component tolerance variations in the circuits that process the signal.
4. *Operation can be programmed.* It is fairly easy to design digital systems whose operation is controlled by a set of stored instructions called a *program.* Analog systems can also be *programmed,* but the variety and the complexity of the available operations are severely limited.
5. *Digital circuits are less affected by noise.* Spurious fluctuations in voltage (noise) are not as critical in digital systems because the exact value of a voltage is not important, as long as the noise is not large enough to prevent us from distinguishing a HIGH from a LOW.
6. *More digital circuitry can be fabricated on IC chips.* It is true that analog circuitry has also benefited from the tremendous development of IC technology, but its relative complexity and its use of devices that cannot be economically integrated (high-value capacitors, precision resistors, inductors, transformers) have prevented analog systems from achieving the same high degree of integration.

Limitations of Digital Techniques

There are really very few drawbacks when using digital techniques. The two biggest problems are:

The real world is analog.
Processing digitized signals takes time.

Most physical quantities are analog in nature, and these quantities are often the inputs and outputs that are being monitored, operated on, and controlled by a system. Some examples are temperature, pressure, position, velocity, liquid level, flow rate, and so on. We are in the habit of expressing these quantities *digitally,* such as when we say that the temperature is 64° (63.8° when we want to be more precise), but we are really making a digital approximation to an inherently analog quantity.

To take advantage of digital techniques when dealing with analog inputs and outputs, four steps must be followed:

1. Convert the physical variable to an electrical signal (analog).
2. Convert the electrical (analog) signal into digital form.
3. Process (operate on) the digital information.
4. Convert the digital outputs back to real-world analog form.

An entire book could be written about step 1 alone. There are many kinds of devices that convert various physical variables into electrical analog signals (sensors). These are used to measure things that are found in our "real" analog world. On your car alone, there are sensors for fluid level (gas tank), temperature (climate control and engine), velocity (speedometer), acceleration (airbag collision detection), pressure (oil, manifold), and flow rate (fuel), to name just a few.

To illustrate a typical system that uses this approach Figure 1-1 describes a precision temperature regulation system. A user pushes up or down buttons to set the desired temperature in 0.1° increments (digital representation). A temperature sensor in the heated space converts the measured temperature to a proportional voltage. This analog voltage is converted to a digital quantity by an **analog-to-digital converter (ADC)**. This value is then compared to the desired value and used to determine a digital value of how much heat is needed. The digital value is converted to an analog quantity (voltage) by a **digital-to-analog converter (DAC)**. This voltage is applied to a heating element, which will produce heat that is related to the voltage applied and will affect the temperature of the space.

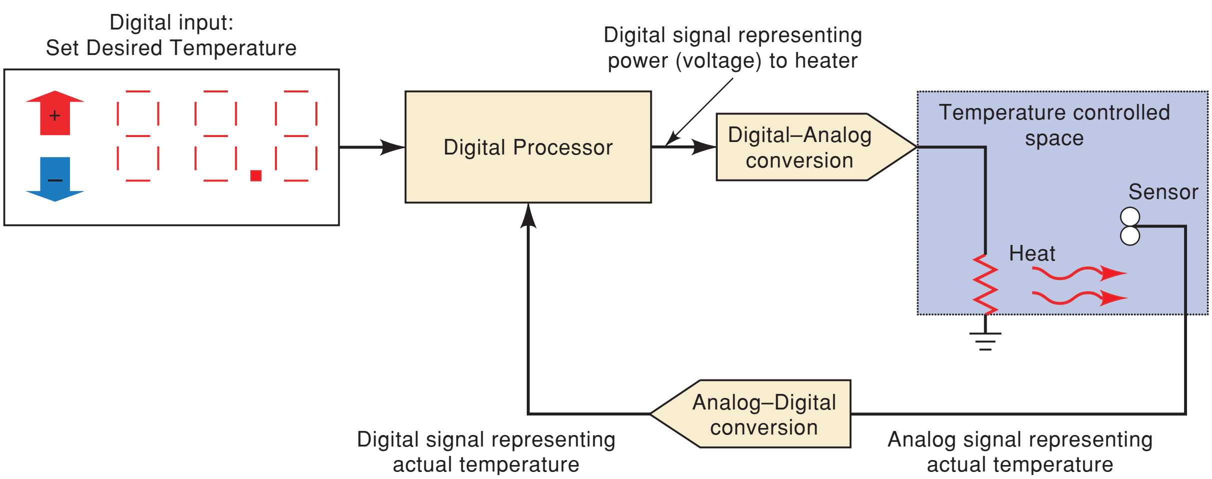
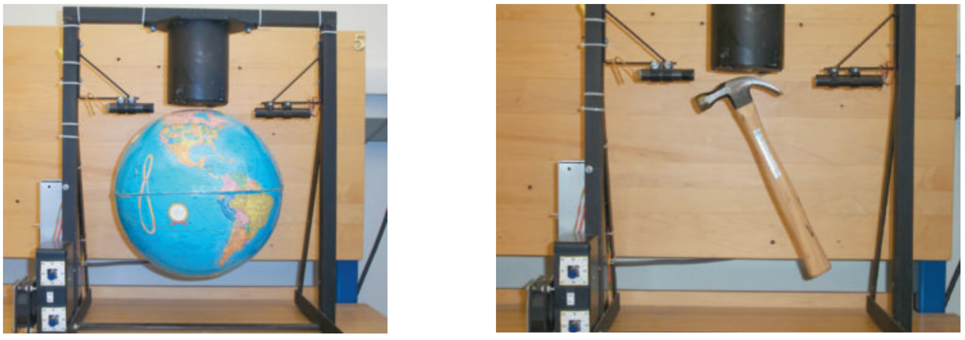


FIGURE 1-1 Block diagram of a precision digital temperature control system.

Another good example where conversion between analog and digital takes place is in the recording of audio. Compact disks (CDs) have replaced cassette tapes because they provide a much better means for recording and playing back music. The process works something like this: (1) sounds from instruments and human voices produce an analog voltage signal in a microphone; (2) this analog signal is converted to a digital format using an analog-to-digital conversion process; (3) the digital information is stored on the CD's surface; (4) during playback, the CD player takes the digital information from the CD surface and converts it into an analog signal that is then amplified and fed to a speaker, where it can be picked up by the human ear.

The second drawback to digital systems is that processing these digitized signals (lists of numbers) takes time. And we also need to convert between the analog and digital forms of information, which can add complexity and expense to a system. The more precise the numbers need to be, the longer it takes to process them. In many applications, these factors are outweighed by the numerous advantages of using digital techniques, and so the conversion between analog and digital quantities has become quite commonplace in the current technology.

There are situations, however, where use of analog techniques is simpler or more economical. For example, several years ago, a colleague (Tom Robertson) decided to create a control system demonstration for tour groups. He planned to suspend a metallic object in a magnetic field, as shown in Figure 1-2. An electromagnet was made by winding a coil of wire and controlling the amount of current through the coil. The position of the metal object was measured by passing an infrared light beam across the magnetic field. As the object drew closer to the magnetic coil, it began to block the light beam. By measuring small changes in the light level, the magnetic field could be controlled to keep the metal object hovering and stationary, with no strings attached. All attempts at using a microcomputer to measure these very small changes, run the control calculations, and drive the magnet proved to be too slow, even when using the fastest, most powerful PC available at the time. His final solution used just a couple of op-amps and a few dollars' worth of other components: a totally analog approach. Today we have access to processors fast enough and measurement techniques precise enough to accomplish this feat, but the simplest solution is still analog.



(a) (b)

FIGURE 1-2 A magnetic levitation system suspending: (a) a globe with a steel plate inserted and (b) a hammer.

It is common to see both digital and analog techniques employed within the same system to be able to profit from the advantages of each. In these *hybrid* systems, one of the most important parts of the design phase involves determining what parts of the system are to be analog and what parts are to be digital. The trend in most systems is to digitize the signal as early as possible and convert it back to analog as late as possible as the signals flow through the system.

The Future Is Digital

The advances in digital technology over the past three decades have been nothing short of phenomenal, and there is every reason to believe that more is coming. Think of the everyday items that have changed from analog format to digital in your lifetime. An indoor/outdoor wireless digital thermometer can be purchased for less then $10.00. Cars have gone from having very few electronic controls to being predominantly digitally controlled vehicles. Digital audio has moved us to the compact disk and MP3 player. Digital video brought the DVD. Digital home video and still cameras; digital recording with systems like TiVo; digital cellular phones; and digital imaging in x-ray, magnetic resonance imaging (MRI), and ultrasound systems in hospitals are just a few of the applications that have been taken over by the digital revolution. As soon as the infrastructure is in place, telephone and television systems will go digital. The growth rate in the digital realm continues to be staggering. Maybe your automobile is equipped with a system such as GM's On Star, which turns your dashboard into a hub for wireless communication, information, and navigation. You may already be using voice commands to send or retrieve e-mail, call for a traffic report, check on the car's maintenance needs, or just switch radio stations or CDs—all without taking your hands off the wheel or your eyes off the road. Cars can report their exact location in case of emergency or mechanical breakdown. In the coming years wireless communication will continue to expand coverage to provide connectivity wherever you are. Telephones will be able to receive, sort, and maybe respond to incoming calls like a well-trained secretary. The digital television revolution will provide not only higher definition of the picture, but also much more flexibility in programming. You will be able to select the programs that you want to view and load them into your television's memory, allowing you to pause or replay scenes at your convenience, very much like viewing a DVD today. As virtual reality continues to improve, you will be able to interact with the subject matter you are studying. This may not sound exciting when studying electronics, but imagine studying history from the standpoint of being a participant, or learning proper techniques for everything from athletics to surgery through simulations based on your actual performance.

Digital technology will continue its high-speed incursion into current areas of our lives as well as break new ground in ways we may never have considered. These applications (and many more) are based on the principles presented in this text. The software tools to develop complex systems are constantly being upgraded and are available to anyone over the Web. We will study the technical underpinnings necessary to communicate with any of these tools, and prepare you for a fascinating and rewarding career.

REVIEW QUESTIONS

1. What are the advantages of digital techniques over analog?
2. What is the chief limitation to the use of digital techniques?

1-3 DIGITAL NUMBER SYSTEMS

Many number systems are in use in digital technology. The most common are the decimal, binary, octal, and hexadecimal systems. The decimal system is clearly the most familiar to us because it is a tool that we use every day. Examining some of its characteristics will help us to understand the other systems better.

Decimal System

The **decimal system** is composed of *10* numerals or symbols. These 10 symbols are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9; using these symbols as *digits* of a number, we can express any quantity. The decimal system, also called the *base-10* system because it has 10 digits, has evolved naturally as a result of the fact that people have 10 fingers. In fact, the word *digit* is derived from the Latin word for "finger."

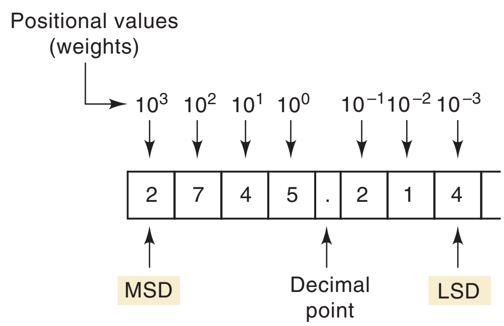
The decimal system is a *positional-value system* in which the value of a digit depends on its position. For example, consider the decimal number 453. We know that the digit 4 actually represents 4 *hundreds,* the 5 represents 5 *tens,* and the 3 represents 3 *units.* In essence, the 4 carries the most weight of the three digits; it is referred to as the *most significant digit (MSD)*. The 3 carries the least weight and is called the *least significant digit (LSD).*

Consider another example, 27.35. This number is actually equal to 2 tens plus 7 units plus 3 tenths plus 5 hundredths, or $2 \times 10 + 7 \times 1 + 3 \times 0.1 + 5 \times 0.01$. The decimal point is used to separate the integer and fractional parts of the number.

More rigorously, the various positions relative to the decimal point carry weights that can be expressed as powers of 10. This is illustrated in Figure 1-3, where the number 2745.214 is represented. The decimal point separates the positive powers of 10 from the negative powers. The number 2745.214 is thus equal to

$$(2 \times 10^{+3}) + (7 \times 10^{+2}) + (4 \times 10^{1}) + (5 \times 10^{0}) + (2 \times 10^{-1}) + (1 \times 10^{-2}) + (4 \times 10^{-3})$$

FIGURE 1-3 Decimal position values as powers of 10.



In general, any number is simply the sum of the products of each digit value and its positional value.

Decimal Counting

When counting in the decimal system, we start with 0 in the units position and take each symbol (digit) in progression until we reach 9. Then we add a 1 to the next higher position and start over with 0 in the first position (see

Figure 1-4). This process continues until the count of 99 is reached. Then we add a 1 to the third position and start over with 0s in the first two positions. The same pattern is followed continuously as high as we wish to count.

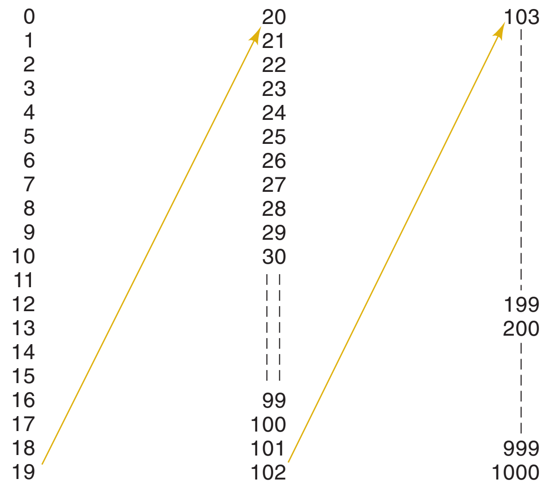


FIGURE 1-4 Decimal counting.

It is important to note that in decimal counting, the units position (LSD) changes upward with each step in the count, the tens position changes upward every 10 steps in the count, the hundreds position changes upward every 100 steps in the count, and so on.

Another characteristic of the decimal system is that using only two decimal places, we can count through $10^2 = 100$ different numbers (0 to 99).* With three places we can count through 1000 numbers (0 to 999), and so on. In general, with N places or digits, we can count through 10^N different numbers, starting with and including zero. The largest number will always be $10^N - 1$.

Binary System

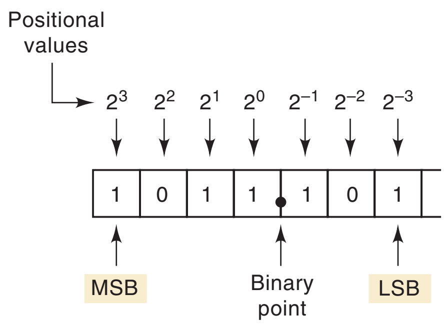
Unfortunately, the decimal number system does not lend itself to convenient implementation in digital systems. For example, it is very difficult to design electronic equipment so that it can work with 10 different voltage levels (each one representing one decimal character, 0 through 9). On the other hand, it is very easy to design simple, accurate electronic circuits that operate with only two voltage levels. For this reason, almost every digital system uses the binary (base-2) number system as the basic number system of its operations. Other number systems are often used to interpret or represent binary quantities for the convenience of the people who work with and use these digital systems.

In the **binary system** there are only two symbols or possible digit values, 0 and 1. Even so, this base-2 system can be used to represent any quantity that can be represented in decimal or other number systems. In general though, it will take a greater number of binary digits to express a given quantity.

All of the statements made earlier concerning the decimal system are equally applicable to the binary system. The binary system is also a positional-value system, wherein each binary digit has its own value or weight expressed as a power of 2. This is illustrated in Figure 1-5. Here, places to the left of the

*Zero is counted as a number.

FIGURE 1-5 Binary position values as powers of 2.



binary point (counterpart of the decimal point) are positive powers of 2, and places to the right are negative powers of 2. The number 1011.101 is shown represented in the figure. To find its equivalent in the decimal system, we simply take the sum of the products of each digit value (0 or 1) and its positional value:

$$\begin{aligned} 1011.101_2 &= (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (1 \times 2^0) \\ &\quad + (1 \times 2^{-1}) + (0 \times 2^{-2}) + (1 \times 2^{-3}) \\ &= 8 + 0 + 2 + 1 + 0.5 + 0 + 0.125 \\ &= 11.625_{10} \end{aligned}$$

Notice in the preceding operation that subscripts (2 and 10) were used to indicate the base in which the particular number is expressed. This convention is used to avoid confusion whenever more than one number system is being employed.

In the binary system, the term *binary digit* is often abbreviated to the term **bit**, which we will use from now on. Thus, in the number expressed in Figure 1-5 there are four bits to the left of the binary point, representing the integer part of the number, and three bits to the right of the binary point, representing the fractional part. The most significant bit (MSB) is the leftmost bit (largest weight). The least significant bit (LSB) is the rightmost bit (smallest weight). These are indicated in Figure 1-5. Here, the MSB has a weight of 2^3; the LSB has a weight of 2^{-3}.

Binary Counting

When we deal with binary numbers, we will usually be restricted to a specific number of bits. This restriction is based on the circuitry used to represent these binary numbers. Let's use four-bit binary numbers to illustrate the method for counting in binary.

The sequence (shown in Figure 1-6) begins with all bits at 0; this is called the *zero count*. For each successive count, the units (2^0) position *toggles*; that is, it changes from one binary value to the other. Each time the units bit changes from a 1 to a 0, the twos (2^1) position will toggle (change states). Each time the twos position changes from 1 to 0, the fours (2^2) position will toggle (change states). Likewise, each time the fours position goes from 1 to 0, the eights (2^3) position toggles. This same process would be continued for the higher-order bit positions if the binary number had more than four bits.

The binary counting sequence has an important characteristic, as shown in Figure 1-6. The units bit (LSB) changes either from 0 to 1 or 1 to 0 with *each* count. The second bit (twos position) stays at 0 for two counts, then at 1 for two counts, then at 0 for two counts, and so on. The third bit (fours position) stays at 0 for four counts, then at 1 for four counts, and so on. The fourth bit (eights position) stays at 0 for eight counts, then at 1 for eight counts. If we wanted to

FIGURE 1-6 Binary counting sequence.

Weights → $2^3 = 8$	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$ (LSB)	Decimal equivalent
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

count further, we would add more places, and this pattern would continue with 0s and 1s alternating in groups of 2^{N-1}. For example, using a fifth binary place, the fifth bit would alternate sixteen 0s, then sixteen 1s, and so on.

As we saw for the decimal system, it is also true for the binary system that by using N bits or places, we can go through 2^N counts. For example, with two bits we can go through $2^2 = 4$ counts (00_2 through 11_2); with four bits we can go through $2^4 = 16$ counts (0000_2 through 1111_2); and so on. The last count will always be all 1s and is equal to 2^N-1 in the decimal system. For example, using four bits, the last count is $1111_2 = 2^4-1 = 15_{10}$.

EXAMPLE 1-2

What is the largest number that can be represented using eight bits?

Solution

$2^N-1 = 2^8-1 = 255_{10} = 11111111_2$.

This has been a brief introduction of the binary number system and its relation to the decimal system. We will spend much more time on these two systems and several others in the next chapter.

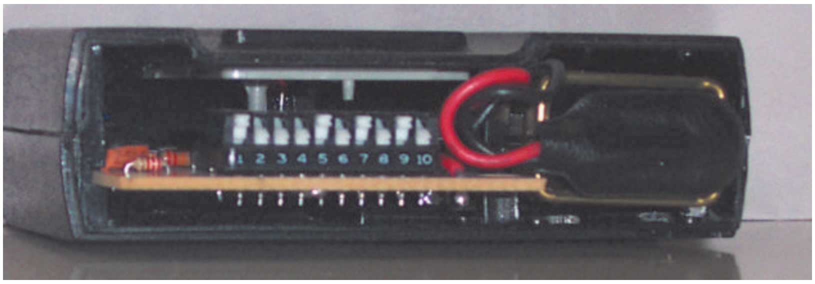
REVIEW QUESTIONS

1. What is the decimal equivalent of 1101011_2?
2. What is the next binary number following 10111_2 in the counting sequence?
3. What is the largest decimal value that can be represented using 12 bits?

1-4 REPRESENTING BINARY QUANTITIES

In digital systems, the information being processed is usually present in binary form. Binary quantities can be represented by any device that has only two operating states or possible conditions. For example, a switch has only two states: open or closed. We can arbitrarily let an open switch represent binary 0 and a closed switch represent binary 1. With this assignment we can now represent any binary number. Figure 1-7(a) shows a binary code number for a garage door opener. The small switches are set to form the binary number 1000101010. The door will open only if a matching pattern of bits is set in the receiver and the transmitter.

FIGURE 1-7 (a) Binary code settings for a garage door opener. (b) Digital audio on a CD.



(a)

(b)

Another example is shown in Figure 1-7(b), where binary numbers are stored on a CD. The inner surface (under a transparent plastic layer) is coated with a highly reflective aluminum layer. Holes are burned through this reflective coating to form "pits" that do not reflect light the same as the unburned areas. The areas where the pits are burned are considered "1" and the reflective areas are "0."

There are numerous other devices that have only two operating states or can be operated in two extreme conditions. Among these are: light bulb (bright or dark), diode (conducting or nonconducting), electromagnet (energized or deenergized), transistor (cut off or saturated), photocell (illuminated or dark), thermostat (open or closed), mechanical clutch (engaged or disengaged), and spot on a magnetic disk (magnetized or demagnetized).

In electronic digital systems, binary information is represented by voltages (or currents) that are present at the inputs and outputs of the various circuits. Typically, the binary 0 and 1 are represented by two nominal voltage levels. For example, zero volts (0 V) might represent binary 0, and +5 V might represent binary 1. In actuality, because of circuit variations, the 0 and 1 would be represented by voltage ranges. This is illustrated in Figure 1-8(a), where any voltage between 0 and 0.8 V represents a 0 and any voltage between 2 and 5 V represents a 1. All input and output signals will normally fall within one of these ranges, except during transitions from one level to another.

We can now see another significant difference between digital and analog systems. In digital systems, the exact value of a voltage *is not* important;

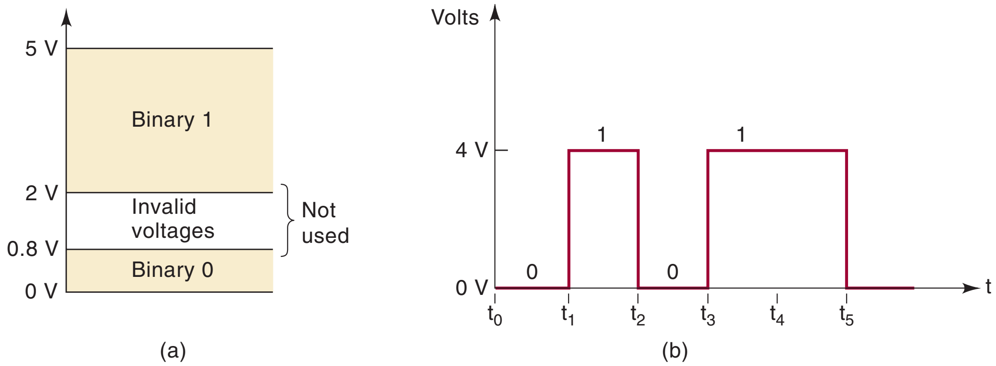


FIGURE 1-8 (a) Typical voltage assignments in digital system; (b) typical digital signal timing diagram.

for example, for the voltage assignments of Figure 1-8(a), a voltage of 3.6 V means the same as a voltage of 4.3 V. In analog systems, the exact value of a voltage *is* important. For instance, if the analog voltage is proportional to the temperature measured by a transducer, the 3.6 V would represent a different temperature than would 4.3 V. In other words, the voltage value carries significant information. This characteristic means that the design of accurate analog circuitry is generally more difficult than that of digital circuitry because of the way in which exact voltage values are affected by variations in component values, temperature, and noise (random voltage fluctuations).

Digital Signals and Timing Diagrams

Figure 1-8(b) shows a typical digital signal and how it varies over time. It is actually a graph of voltage versus time *(t)* and is called a **timing diagram**. The horizontal time scale is marked off at regular intervals beginning at t_0 and proceeding to t_1, t_2, and so on. For the example timing diagram shown here, the signal starts at 0 V (a binary 0) at time t_0 and remains there until time t_1. At t_1, the signal makes a rapid transition (jump) up to 4 V (a binary 1). At t_2, it jumps back down to 0 V. Similar transitions occur at t_3 and t_5. Note that the signal does not change at t_4 but stays at 4 V from t_3 to t_5.

The transitions on this timing diagram are drawn as vertical lines, and so they appear to be instantaneous, when in reality they are not. In many situations, however, the transition times are so short compared to the times between transitions that we can show them on the diagram as vertical lines. We will encounter situations later where it will be necessary to show the transitions more accurately on an expanded time scale.

Timing diagrams are used extensively to show how digital signals change with time, and especially to show the relationship between two or more digital signals in the same circuit or system. By displaying one or more digital signals on an *oscilloscope* or *logic analyzer*, we can compare the signals to their expected timing diagrams. This is a very important part of the testing and troubleshooting procedures used in digital systems.

1-5 DIGITAL CIRCUITS/LOGIC CIRCUITS

Digital circuits are designed to produce output voltages that fall within the prescribed 0 and 1 voltage ranges such as those defined in Figure 1-8. Likewise, digital circuits are designed to respond predictably to input voltages that are within the defined 0 and 1 ranges. What this means is that a digital circuit will respond in the same way to all input voltages that fall within the allowed 0 range; similarly, it will not distinguish between input voltages that lie within the allowed 1 range.

To illustrate, Figure 1-9 represents a typical digital circuit with input v_i and output v_o. The output is shown for two different input signal waveforms. Note that v_o is the same for both cases because the two input waveforms, while differing in their exact voltage levels, are at the same binary levels.

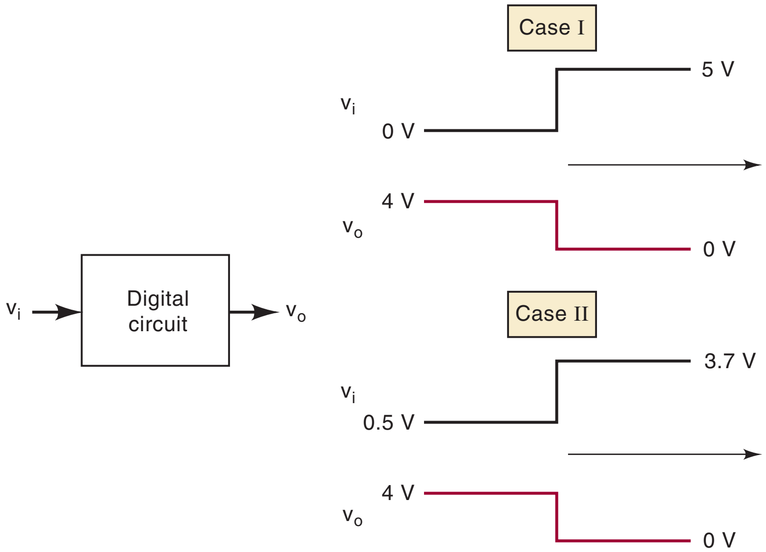


FIGURE 1-9 A digital circuit responds to an input's binary level (0 or 1) and not to its actual voltage.

Logic Circuits

The manner in which a digital circuit responds to an input is referred to as the circuit's *logic.* Each type of digital circuit obeys a certain set of logic rules. For this reason, digital circuits are also called **logic circuits**. We will use both terms interchangeably throughout the text. In Chapter 3, we will see more clearly what is meant by a circuit's "logic."

We will be studying all the types of logic circuits that are currently used in digital systems. Initially, our attention will be focused only on the logical operation that these circuits perform—that is, the relationship between the circuit inputs and outputs. We will defer any discussion of the internal circuit operation of these logic circuits until after we have developed an understanding of their logical operation.

Digital Integrated Circuits

Almost all of the digital circuits used in modern digital systems are integrated circuits (ICs). The wide variety of available logic ICs has made it possible to construct complex digital systems that are smaller and more reliable than their discrete-component counterparts.

Several integrated-circuit fabrication technologies are used to produce digital ICs, the most common being CMOS, TTL, NMOS, and ECL. Each differs in the type of circuitry used to provide the desired logic operation. For example, TTL (transistor-transistor logic) uses the bipolar transistor as its main circuit element, while CMOS (complementary metal-oxide-semiconductor) uses the enhancement-mode MOSFET as its principal circuit element. We will learn about the various IC technologies, their characteristics, and their relative advantages and disadvantages after we master the basic logic circuit types.

REVIEW QUESTIONS

1. *True or false:* The exact value of an input voltage is critical for a digital circuit.
2. Can a digital circuit produce the same output voltage for different input voltage values?
3. A digital circuit is also referred to as a ________ circuit.
4. A graph that shows how one or more digital signals change with time is called a ________.

1-6 PARALLEL AND SERIAL TRANSMISSION

One of the most common operations that occur in any digital system is the transmission of information from one place to another. The information can be transmitted over a distance as small as a fraction of an inch on the same circuit board, or over a distance of many miles when an operator at a computer terminal is communicating with a computer in another city. The information that is transmitted is in binary form and is generally represented as voltages at the outputs of a sending circuit that are connected to the inputs of a receiving circuit. Figure 1-10 illustrates the two basic methods for digital information transmission: **parallel** and **serial**.

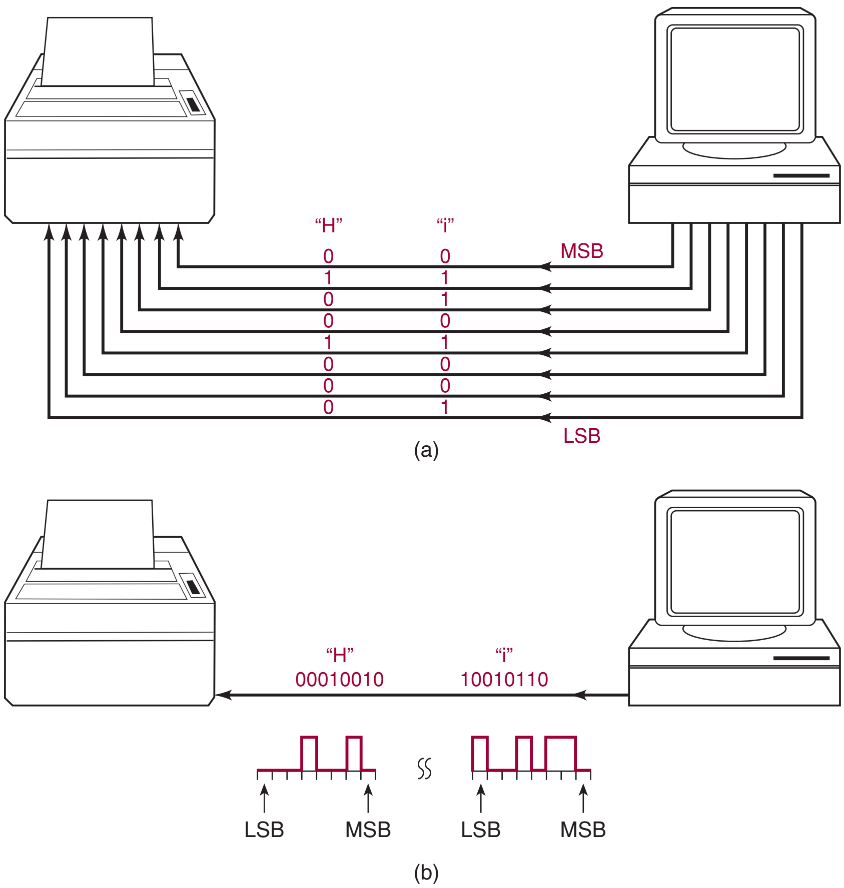


FIGURE 1-10 (a) Parallel transmission uses one connecting line per bit, and all bits are transmitted simultaneously; (b) serial transmission uses only one signal line, and the individual bits are transmitted serially (one at a time).

Figure 1-10(a) demonstrates parallel transmission of data from a computer to a printer using the parallel printer port (LPT1) of the computer. In this scenario, assume we are trying to print the word "Hi" on the printer. The binary code for "H" is 01001000 and the binary code for "i" is 01101001. Each character (the "H" and the "i") are made up of eight bits. Using parallel transmission, all eight bits are sent simultaneously over eight wires. The "H" is sent first, followed by the "i."

Figure 1-10(b) demonstrates serial transmission such as is employed when using a serial COM port on your computer to send data to a modem, or when using a USB (Universal Serial Bus) port to send data to a printer. Although the details of the data format and speed of transmission are quite different between a COM port and a USB port, the actual data are sent in the same way: one bit at a time over a single wire. The bits are shown in the diagram as though they were actually moving down the wire in the order shown. The least significant bit of "H" is sent first and the most significant bit of "i" is sent last. Of course, in reality, only one bit can be on the wire at any point in time and time is usually drawn on a graph starting at the left and advancing to the right. This produces a graph of logic bits versus time of the serial transmission called a timing diagram. Notice that in this presentation, the least significant bit is shown on the left because it was sent first.

The principal trade-off between parallel and serial representations is one of speed versus circuit simplicity. The transmission of binary data from one part of a digital system to another can be done more quickly using parallel representation because all the bits are transmitted simultaneously, while serial representation transmits one bit at a time. On the other hand, parallel requires more signal lines connected between the sender and the receiver of the binary data than does serial. In other words, parallel is faster, and serial requires fewer signal lines. This comparison between parallel and serial methods for representing binary information will be encountered many times in discussions throughout the text.

REVIEW QUESTION

1. Describe the relative advantages of parallel and serial transmission of binary data.

1-7 MEMORY

When an input signal is applied to most devices or circuits, the output somehow changes in response to the input, and when the input signal is removed, the output returns to its original state. These circuits do not exhibit the property of *memory* because their outputs revert back to normal. In digital circuitry certain types of devices and circuits do have memory. When an input is applied to such a circuit, the output will change its state, but it will remain in the new state even after the input is removed. This property of retaining its response to a momentary input is called **memory**. Figure 1-11 illustrates nonmemory and memory operations.

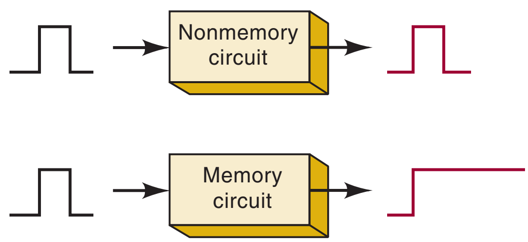


FIGURE 1-11 Comparison of nonmemory and memory operation.

Memory devices and circuits play an important role in digital systems because they provide a means for storing binary numbers either temporarily or permanently, with the ability to change the stored information at any time. As we shall see, the various memory elements include magnetic and optical types and those that utilize electronic latching circuits (called *latches* and *flip-flops*).

1-8 DIGITAL COMPUTERS

Digital techniques have found their way into innumerable areas of technology, but the area of automatic **digital computers** is by far the most notable and most extensive. Although digital computers affect some part of all of our lives, it is doubtful that many of us know exactly what a computer does. In simplest terms, *a computer is a system of hardware that performs arithmetic operations, manipulates data (usually in binary form), and makes decisions.*

For the most part, human beings can do whatever computers can do, but computers can do it with much greater speed and accuracy, in spite of the fact that computers perform all their calculations and operations one step at a time. For example, a human being can take a list of 10 numbers and find their sum all in one operation by listing the numbers one over the other and adding them column by column. A computer, on the other hand, can add numbers only two at a time, so that adding this same list of numbers will take nine actual addition steps. Of course, the fact that the computer requires only a few nanoseconds per step makes up for this apparent inefficiency.

A computer is faster and more accurate than people are, but unlike most of us, it must be given a complete set of instructions that tell it *exactly* what to do at each step of its operation. This set of instructions, called a **program**, is prepared by one or more persons for each job the computer is to do. Programs are placed in the computer's memory unit in binary-coded form, with each instruction having a unique code. The computer takes these instruction codes from memory *one at a time* and performs the operation called for by the code.

Major Parts of a Computer

There are several types of computer systems, but each can be broken down into the same functional units. Each unit performs specific functions, and all units function together to carry out the instructions given in the program. Figure 1-12 shows the five major functional parts of a digital computer and

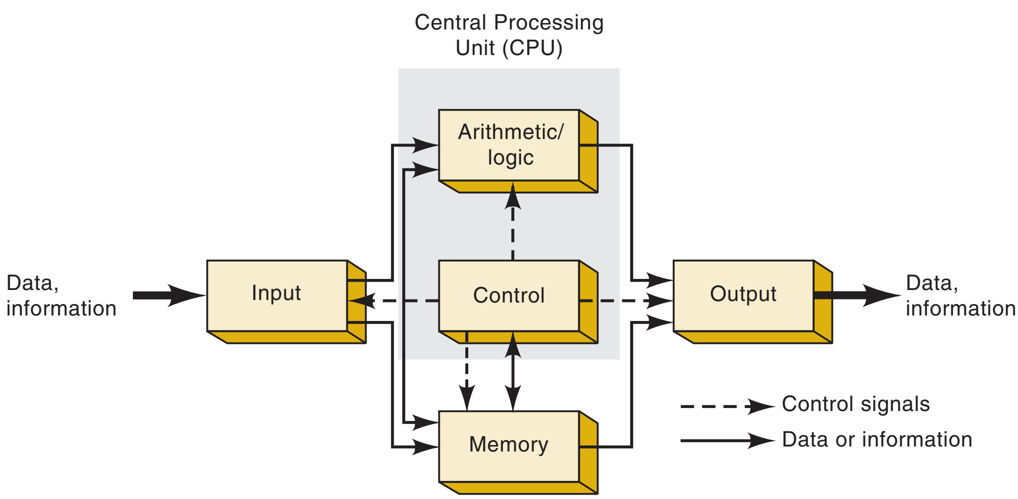


FIGURE 1-12 Functional diagram of a digital computer.

their interaction. The solid lines with arrows represent the flow of data and information. The dashed lines with arrows represent the flow of timing and control signals.

The major functions of each unit are:

1. **Input unit**. Through this unit, a complete set of instructions and data is fed into the computer system and into the memory unit, to be stored until needed. The information typically enters the input unit from a keyboard or a disk.
2. **Memory unit**. The memory stores the instructions and data received from the input unit. It stores the results of arithmetic operations received from the arithmetic unit. It also supplies information to the output unit.
3. **Control unit**. This unit takes instructions from the memory unit one at a time and interprets them. It then sends appropriate signals to all the other units to cause the specific instruction to be executed.
4. **Arithmetic/logic unit**. All arithmetic calculations and logical decisions are performed in this unit, which can then send results to the memory unit to be stored.
5. **Output unit**. This unit takes data from the memory unit and prints out, displays, or otherwise presents the information to the operator (or process, in the case of a process control computer).

Central Processing Unit (CPU)

As the diagram in Figure 1-12 shows, the control and arithmetic/logic units are often considered as one unit, called the **central processing unit (CPU)**. The CPU contains all of the circuitry for fetching and interpreting instructions and for controlling and performing the various operations called for by the instructions.

TYPES OF COMPUTERS All computers are made up of the basic units described above, but they can differ as to physical size, operating speed, memory capacity, and computational power, as well as other characteristics. Computer systems are configured in many and various ways today, with many common characteristics and distinguishing differences. Large computer systems that are permanently installed in multiple cabinets are used by corporations and universities for information technology support. Desktop personal computers are used in our homes and offices to run useful application programs that enhance our lives and provide communication with other computers. Portable computers are found in PDAs and specialized computers are found in video game systems. The most prevalent form of computers can be found performing dedicated routine tasks in appliances and systems all around us.

Today, all but the largest of these systems utilize technology that has evolved from the invention of the **microprocessor**. The microprocessor is essentially a central processing unit (CPU) in an integrated circuit that can be connected to the other blocks of a computer system. Computers that use a microprocessor as their CPU are usually referred to as **microcomputers**. The general-purpose microcomputers (e.g., PCs, PDAs, etc.) perform a variety of tasks in a wide range of applications depending on the software (programs) they are running. Contrast these with the dedicated computers that are doing things such as operating your car's engine, controlling your car's antilock braking system, or running your microwave oven. These computers cannot be programmed by the user, but simply perform their intended control task: they are referred to as **microcontrollers**. Since these microcontrollers are an integral part of a bigger system and serve a dedicated purpose, they also are called *embedded controllers*. Microcontrollers generally have all the elements of a complete computer (CPU, memory, and input/output ports), all contained on a single integrated circuit. You can find them embedded in your kitchen appliances, entertainment equipment, photocopiers, automatic teller machines, automated manufacturing equipment, medical instrumentation, and much, much more.

So you see, even people who don't own a PC or use one at work or school are using microcomputers every day because so many modern consumer electronic devices, appliances, office equipment, and much more are built around embedded microcontrollers. If you work, play, or go to school in this digital age, there's no escaping it: you'll use a microcomputer somewhere.

REVIEW QUESTIONS

1. Explain how a digital circuit that has memory differs from one that does not.
2. Name the five major functional units of a computer.
3. Which two units make up the CPU?
4. An IC chip that contains a CPU is called a _____.

SUMMARY

1. The two basic ways of representing the numerical value of physical quantities are analog (continuous) and digital (discrete).
2. Most quantities in the real world are analog, but digital techniques are generally superior to analog techniques, and most of the predicted advances will be in the digital realm.
3. The binary number system (0 and 1) is the basic system used in digital technology.
4. Digital or logic circuits operate on voltages that fall in prescribed ranges that represent either a binary 0 or a binary 1.
5. The two basic ways to transfer digital information are parallel—all bits simultaneously—and serial—one bit at a time.
6. The main parts of all computers are the input, control, memory, arithmetic/logic, and output units.
7. The combination of the arithmetic/logic unit and the control unit makes up the CPU (central processing unit).
8. A microcomputer usually has a CPU that is on a single chip called a *microprocessor.*
9. A microcontroller is a microcomputer especially designed for dedicated (not general-purpose) control applications.

IMPORTANT TERMS*

analog representation
digital representation
digital system
analog system
analog-to-digital converter (ADC)
digital-to-analog converter (DAC)
decimal system

*These terms can be found in **boldface** type in the chapter and are defined in the Glossary at the end of the book. This applies to all chapters.

binary system
bit
timing diagram
digital circuits/logic circuits
parallel transmission
serial transmission
memory
digital computer
program
input unit
memory unit
control unit
arithmetic/logic unit
output unit
central processing unit (CPU)
microprocessor
microcomputer
microcontroller

PROBLEMS

SECTION 1-2

1-1.* Which of the following are analog quantities, and which are digital?
 (a) Number of atoms in a sample of material
 (b) Altitude of an aircraft
 (c) Pressure in a bicycle tire
 (d) Current through a speaker
 (e) Timer setting on a microwave oven

1-2. Which of the following are analog quantities, and which are digital?
 (a) Width of a piece of lumber
 (b) The amount of time before the oven buzzer goes off
 (c) The time of day displayed on a quartz watch
 (d) Altitude above sea level measured on a staircase
 (e) Altitude above sea level measured on a ramp

SECTION 1-3

1-3.* Convert the following binary numbers to their equivalent decimal values.
 (a) 11001_2
 (b) 1001.1001_2
 (c) 10011011001.10110_2

1-4. Convert the following binary numbers to decimal.
 (a) 10011_2
 (b) 1100.0101
 (c) 10011100100.10010

1-5.* Using three bits, show the binary counting sequence from 000 to 111.

1-6. Using six bits, show the binary counting sequence from 000000 to 111111.

1-7.* What is the maximum number that we can count up to using 10 bits?

1-8. What is the maximum number that we can count up to using 14 bits?

1-9.* How many bits are needed to count up to a maximum of 511?

1-10. How many bits are needed to count up to a maximum of 63?

SECTION 1-4

1-11.* Draw the timing diagram for a digital signal that continuously alternates between 0.2 V (binary 0) for 2 ms and 4.4 V (binary 1) for 4 ms.

*Answers to problems marked with an asterisk can be found in the back of the text.

1-12. Draw the timing diagram for a signal that alternates between 0.3 V (binary 0) for 5 ms and 3.9 V (binary 1) for 2 ms.

SECTION 1-6

1-13.* Suppose that the decimal integer values from 0 to 15 are to be transmitted in binary.

(a) How many lines will be needed if parallel representation is used?

(b) How many will be needed if serial representation is used?

SECTIONS 1-7 AND 1-8

1-14. How is a microprocessor different from a microcomputer?

1-15. How is a microcontroller different from a microcomputer?

ANSWERS TO SECTION REVIEW QUESTIONS

SECTION 1-1

1. Analog quantities can take on *any* value over a continuous range; digital quantities can take on only *discrete* values.

SECTION 1-2

1. Easier to design; easier to store information; greater accuracy and precision; programmability; less affected by noise; higher degree of integration
2. Real-world physical quantities are analog. Digital processing takes time.

SECTION 1-3

1. 107_{10} 2. 11000_2 3. 4095_{10}

SECTION 1-5

1. False 2. Yes, provided that the two input voltages are within the same logic level range 3. Logic 4. Timing diagram

SECTION 1-6

1. Parallel is faster; serial requires only one signal line.

SECTION 1-8

1. One that has memory will have its output changed and *remain* changed in response to a momentary change in the input signal. 2. Input, output, memory, arithmetic/logic, control 3. Control and arithmetic/logic 4. Microprocessor