CHAPTER_1_INTRODUCTORY CONCEPTS

INTRODUCTION

In today's world, the term *digital* has become part of our everyday vocabu-lary because of the dramatic way that digital circuits and digital techniques have become so widely used in almost all areas of life: computers, automa-tion, robots, medical science and technology, transportation, telecommuni-cations, 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 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.

A good example where conversion between analog and digital takes place is in the recording and playing of audio. Compact disks (CDs) have replaced cassette tapes because they provide a much better means for recording and

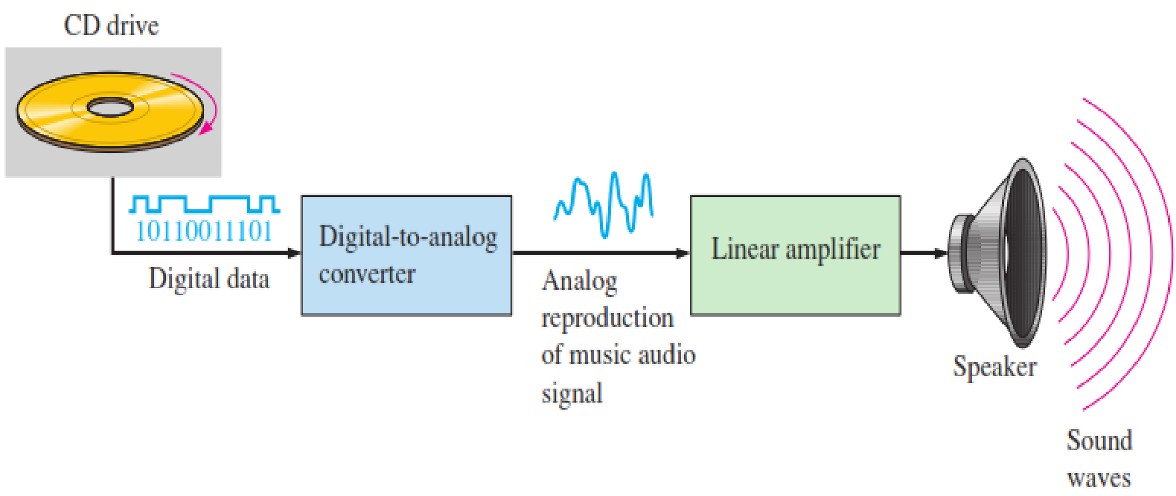


FIGURE 1-1 Basic block diagram of a CD player.

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.

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 trend in the last three decades show that THE FUTURE IS DIGITAL!

1-3 DIGITAL NUMBER SYSTEMS

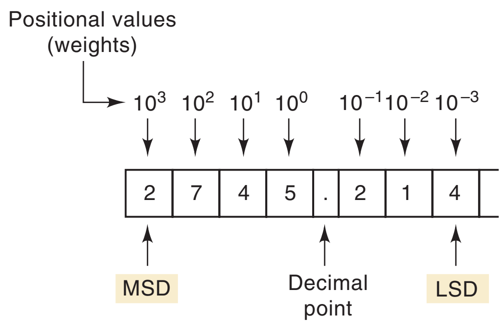
Many number systems are in use in digital technology. The most common are the decimal, binary, octal, and hexadecimal systems. The decimal system is clearly the most familiar to us because it is a tool that we use every day.

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)*.

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



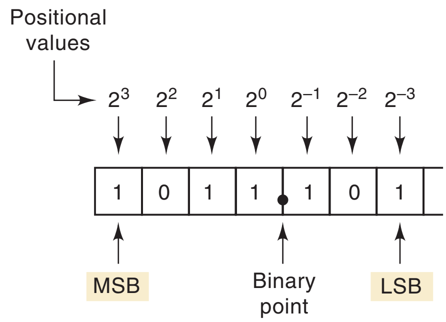
In general, any number is simply the sum of the products of each digit value and its positional value.

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

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.

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 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	$2^3 = 8$	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$	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
				LSB	

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

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

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

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).

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

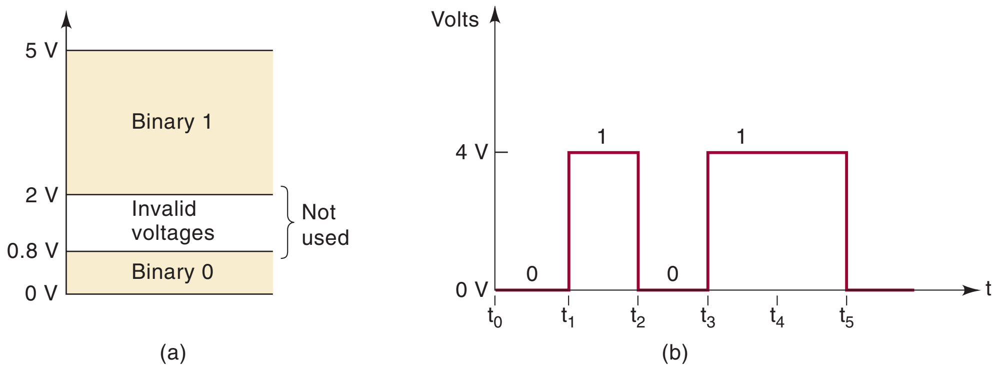


FIGURE 1-8 (a) Typical voltage assignments in digital system; (b) typical digital signal timing diagram.

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).

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.

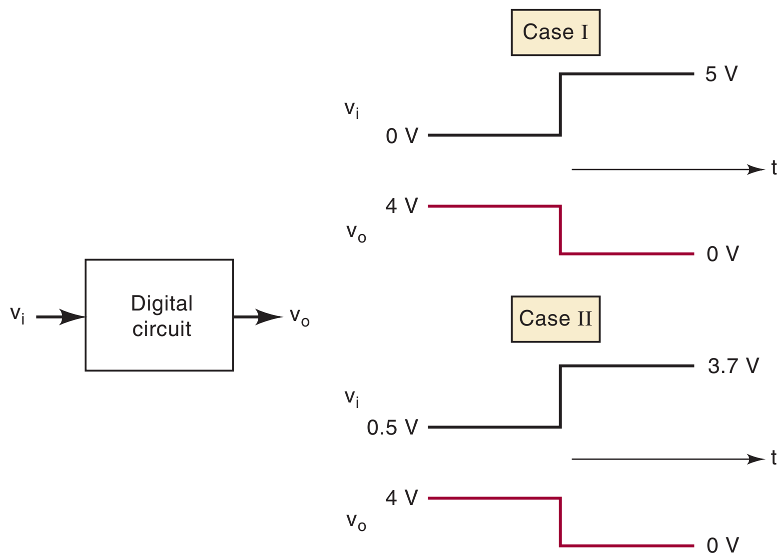


FIGURE 1-9 A digital circuit responds to an input's binary level (0 or 1) and not to its actual voltage.

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**.

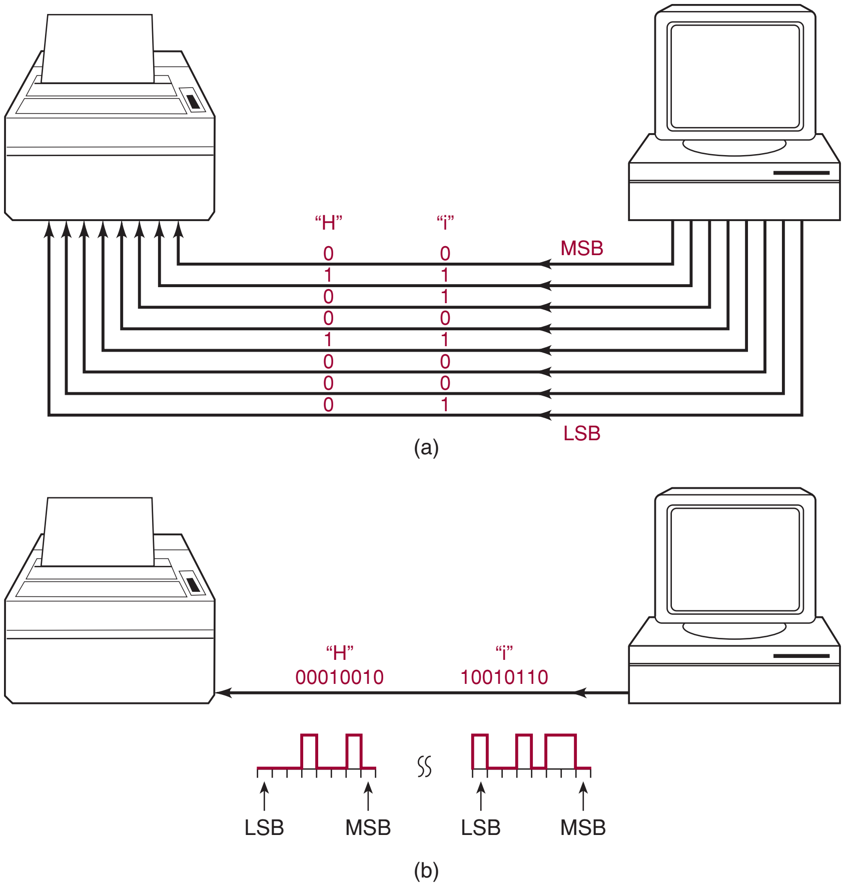


FIGURE 1-10 (a) Parallel transmission uses one connecting line per bit, and all bits are transmitted simultaneously; (b) serial transmission uses only one signal line, and the individual bits are transmitted serially (one at a time).

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.

1-7 MEMORY

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

In simplest terms, *a computer is a system of hardware that performs arithmetic operations, manipulates data (usually in binary form), and makes decisions.*

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

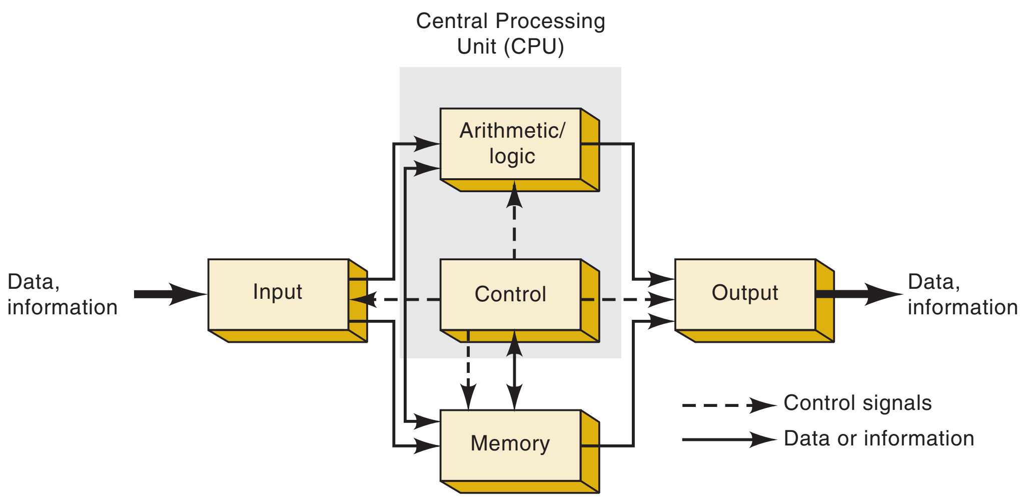


FIGURE 1-12 Functional diagram of a digital computer.

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).