Digital Systems
Principles and Applications
Tocci Widmer Moss
Eleventh Edition

Pearson New International Edition

# Pearson New International Edition

Digital Systems
Principles and Applications
Tocci Widmer Moss
Eleventh Edition

PEARSON

**Pearson Education Limited**
Edinburgh Gate
Harlow
Essex CM20 2JE
England and Associated Companies throughout the world

*Visit us on the World Wide Web at:* www.pearsoned.co.uk



PEARSON

ISBN 10: 1-292-02550-6
ISBN 13: 978-1-292-02550-6

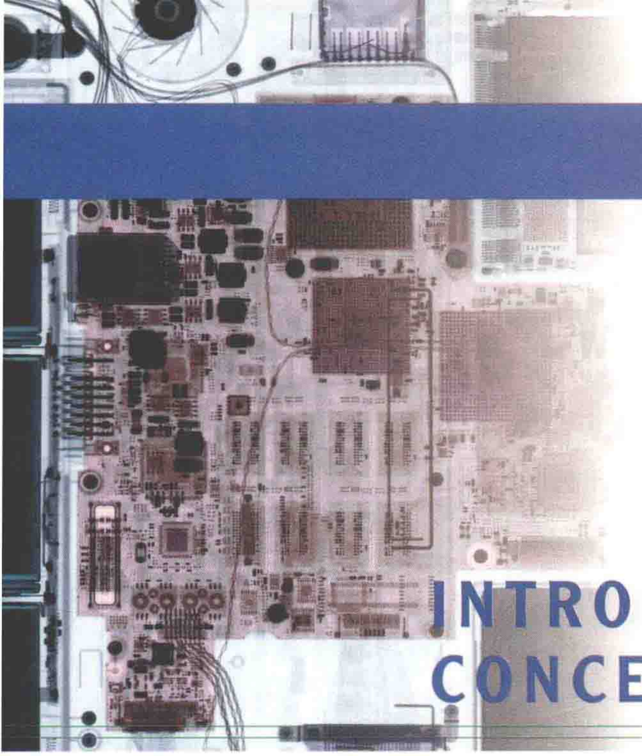
**British Library Cataloguing-in-Publication Data**
A catalogue record for this book is available from the British Library

Printed in the United States of America

# Table of Contents

# INTRODUCTORY CONCEPTS*

*The companion website to this chapter is http://www.pearsonhighered.com/tocci



# INTRODUCTORY CONCEPTS

## OUTLINE

## OBJECTIVES

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

- Distinguish between analog and digital representations.
- Describe how information can be represented using just two states (1s and 0s).
- Cite the advantages and drawbacks of digital techniques compared with analog.
- Describe the purpose of 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.

We introduce the underlying concepts through a device that has become familiar to nearly everyone: the cellular telephone. This amazing device is made up of many of the fundamental building blocks common to all *digital systems*. In order to break down the complexity of a cell phone, we will first discuss the evolution of telecommunications technology. Your familiarity with the past and present communications systems will help you to understand the role that each building block plays, learn the terms that define each block, the nature of the signals that connect the blocks, and prepare you to expand your horizons by seeing how these blocks can be used in other systems.

## 1 INTRODUCTION TO DIGITAL 1s AND 0s

It seems appropriate to begin by considering one of the largest electronic systems in the world: the world-wide telecommunications system. Today, a very large part of this system falls in the category of "digital systems." Amazingly enough, it all started out as a simple digital system that used only two states to represent information. This concept is fundamental and easier to understand by first studying early technology.

The telegraph system, depicted in Figure 1, was a simple electromechanical system that revolutionized communication. It consisted of a battery, a code key (normally open, momentary contact switch), a very long telegraph wire, and on the other end an electromagnetic "clacker." When the telegrapher pressed down on the key, it completed the circuit by connecting the positive battery terminal to the wire. The negative battery terminal was connected to a rod that was driven down in the ground. Current from the battery flowed through the telegraph wire to the electromagnetic coil at the receiving station and then back to a rod driven into the ground. Electric current flowing through the coil caused a magnetic field to attract a metal plate that made a "clack" noise. The plate stayed in this position until the code key was released (interrupting the circuit) and a spring returned the plate to its original position, making a different "click" noise. Notice the two states of the system: code key and clacker down; code key and clacker up.

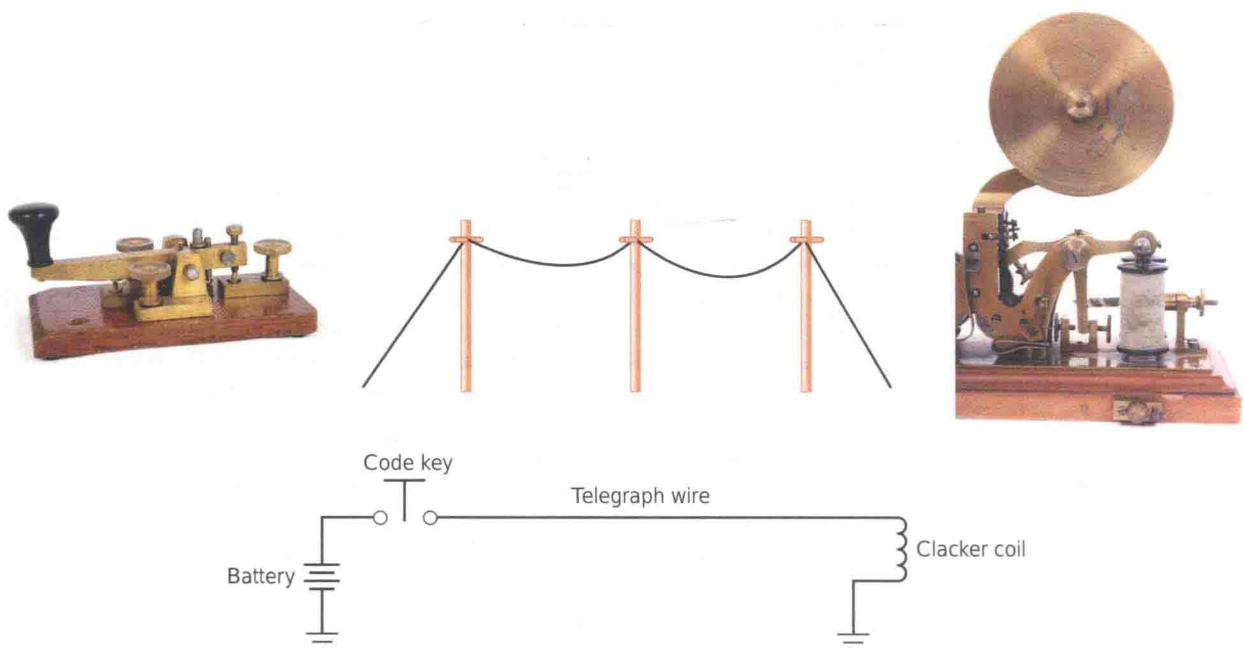



**FIGURE 1** A telegraph system.

The telegraph system used two distinct "symbols" to transmit any word or number: short and long electric pulses, which represent the dots and dashes of Morse code. As we will see, this describes a *digital representation* of

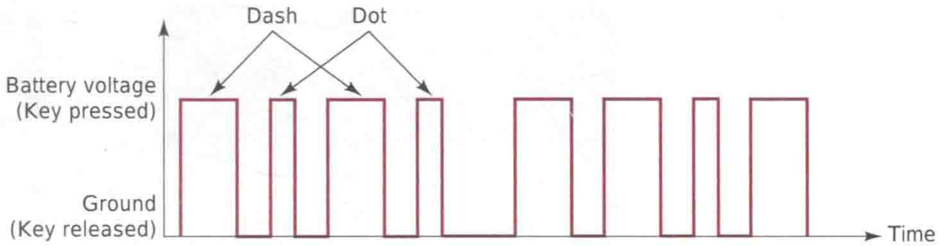



**FIGURE 2** Timing diagram of a telegraph line.

information. What did the information look like? Figure 2 shows a graph of the voltage pulses on the telegraph wire as the telegrapher presses and releases the code key (current flow through the wire could have been graphed as well and would be of the same waveshape as voltage). Notice the nature of the pulses. The electric signal is either on or off at all times. This relates to modern digital systems that use electrical signals to represent 1s and 0s. The information is **encoded** in the width (length of time) of each pulse and the sequence of pulses. Pulse waveforms like this are used extensively to describe the activity in digital systems. Since the *x* axis is time, these graphs are referred to as **timing diagrams**. A timing diagram shows which state (1 or 0) the system is in at any point in time, and it also shows the exact time when a change in state occurs.

Timing diagrams are used to describe the detailed operation of a digital system. The transitions between the low voltage level (when the code key is released) and high voltage level (when the code key is pressed) on this timing diagram are drawn as crisp, vertical lines. Certainly, in a primitive telegraph system, the waveforms were not this perfect due to things like contact arcing, long wires, and natural effects of electromagnetic coils. In fact, even in modern digital systems, transitions are not truly instantaneous (vertical lines). In many situations, however, the transition times are so short compared to the times between transitions that we can reasonably 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 using test instruments such as an oscilloscope, shown in Figure 3, we can compare the actual signals to the system's expected operation. A logic analyzer is another instrument that is able to display and analyze many concurrent digital signals as a timing diagram. Mastery of these instruments is an important part of testing and troubleshooting procedures used in digital systems.

**REVIEW QUESTIONS***

1. How many fundamental states are there in a digital system?
2. What do we call a graph that shows changes between two states (1s and 0s) with respect to time?

*Answers to review questions are found at the end of the chapter.

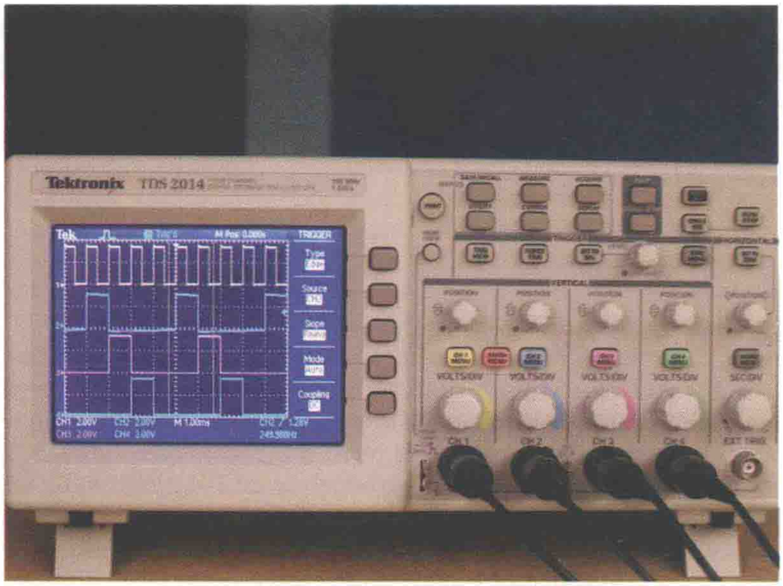



**FIGURE 3** An oscilloscope displaying a 4-trace timing diagram.

## 2 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. In 1875, Alexander Graham Bell figured out how to change his voice into a continuously variable electrical signal, send it through a wire, and change it back to sound energy at the other end. Today, the device that converts sound energy to an analog voltage signal is known as a microphone. Figure 4 shows what the analog voice signal looks like. The information is contained in the tones and inflections of this everchanging voice signal and is encoded by the spoken language of the speaker. Tones are measured by the **frequency** ($f$) which tells us how many cycles of the wave happen in a certain amount of time (cycles per second). The horizontal axis (time) gives us an indication of time for each cycle, known as the **period** ($T$) of the wave (seconds per cycle). The loudness is measured by the **amplitude** of the wave in units specified on the vertical axis (e.g., volts). Changes in amplitude represent

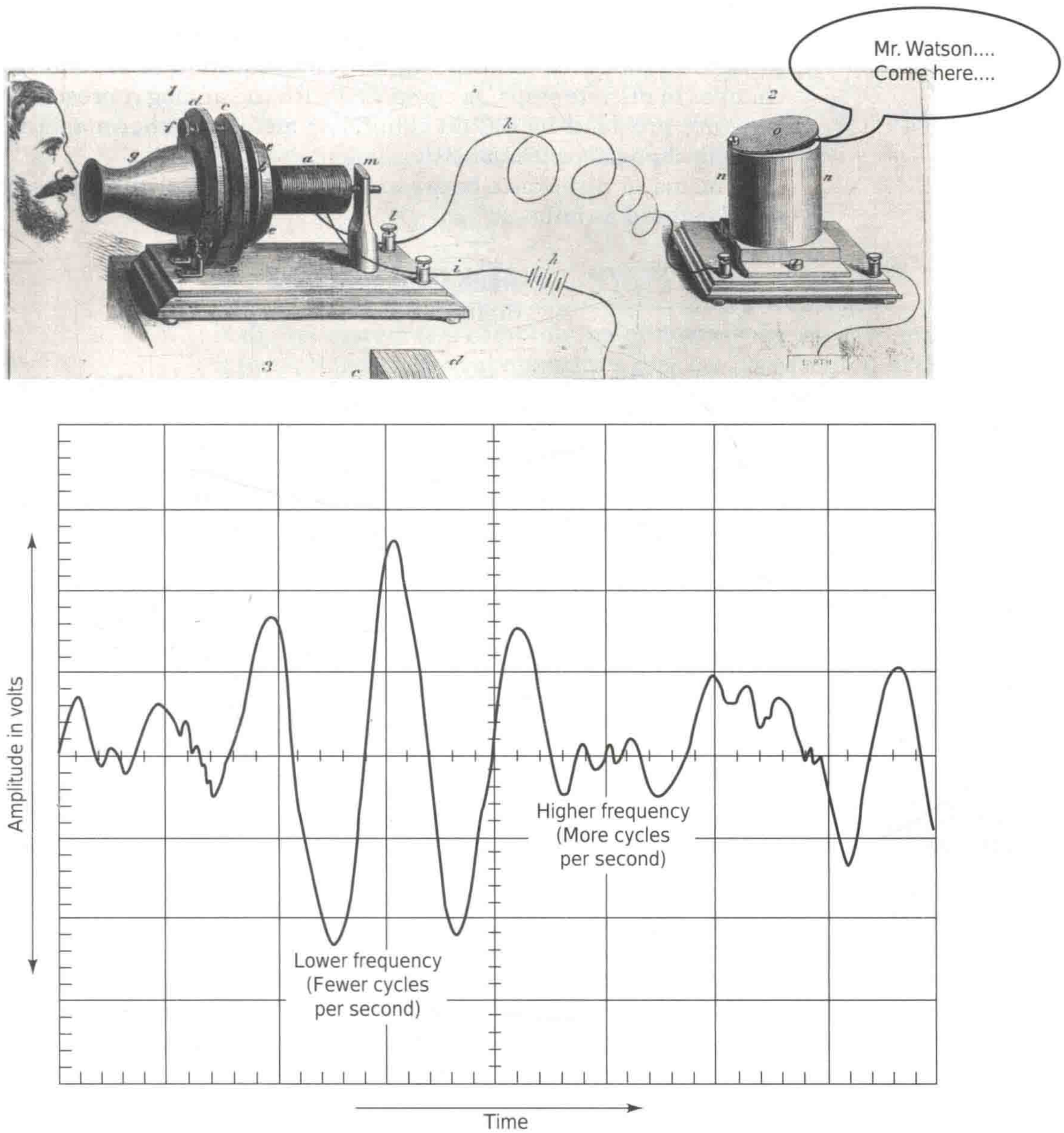



**FIGURE 4** An audio wave.

inflection or emphasis of certain sounds. In other words, higher amplitudes result in louder sounds and lower amplitudes result in quieter sounds.

No matter how they are represented, analog quantities have an important characteristic: *they can vary over a continuous range of values.* The automobile speed can have *any* value between zero and, say, 100 mph. Similarly, the temperature indicated by an analog thermometer can have any value from −20° to 120° Fahrenheit, and the analog voltage signal produced by a microphone can have any value between zero and its maximum positive or negative output.

## Digital Representations

In **digital representation** the quantities are represented not by continuously variable indicators but by symbols called *digits.* As an example, consider a digital indoor/outdoor thermometer. It has four digits and can measure changes of 0.1°. The actual temperature gradually increases from, say, 72.0 to 72.1 but the digital representation changes suddenly from 72.0 to 72.1. In other words, this digital representation of outdoor temperature changes in *discrete* steps, as compared with the analog representation of temperature provided by a fluid column or metal coil thermometer, where the 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.

The world around us is full of physical variables that are constantly changing. If we can measure these variables and represent them as a digital quantity, then we can record, arithmetically manipulate, or in some other way use these quantities to control things.

**EXAMPLE 1**

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

(a) Elevation using a ladder
(b) Elevation using a ramp
(c) Current flowing from an electrical outlet through a motor
(d) Height of a child measured by a yard stick ruler
(e) Height of a child measured by putting a mark on the wall
(f) Volume of sand in a bucket
(g) Volume of water in a bucket

**Solution**

(a) Digital
(b) Analog
(c) Analog
(d) Digital: measured to nearest 1/8 inch
(e) Analog
(f) Digital: can only increase/decrease by discrete grains of sand
(g) Analog: (unless you want to get to the nano technology level!)

**REVIEW QUESTIONS**

1. What were the two binary states of a telegraph system?
2. How was telegraph information encoded using these two states?
3. What property of an audio waveform affects loudness?
4. What property of an audio waveform affects the pitch of a tone?
5. Which method of representing quantities involves discrete steps?
6. Which method of representing quantities is continuously variable?

## 3 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 telecommunications 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.

### Mixed Systems: Digital and Analog

It is common to see both digital and analog techniques employed within the same system. This way the system is able to profit from the advantages of each. In these hybrid or mixed signal systems, one of the 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 today in most systems is to digitize the signals as early as possible and convert them back to analog as late as possible in the signal flow path of the system.

To look at systems that use both digital and analog techniques, let's revisit the evolution of the telephone. As we do so, we will discover that there are many ways to represent information in systems. Bell realized that to be useful, the telephones needed to be networked as shown in Figure 5. His solution was to put a hand-cranked electrical generator on each telephone. When a person turned the crank, it produced a voltage that would cause a bell to ring on every telephone connected to the network. Stopping the crank

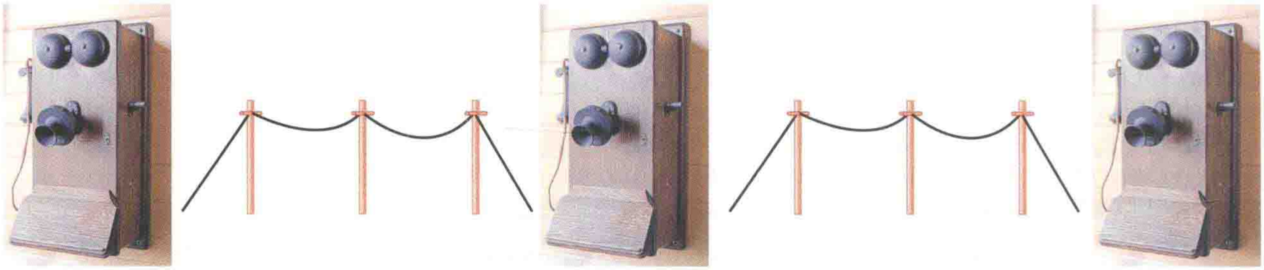


**FIGURE 5** A "party-line" phone network.

caused the bells to stop ringing. Each person on the network was assigned a unique code of long and short rings (like digital pulses). The calling party *encoded* a person's identification by the way he cranked his telephone. The receiving party mentally **decoded** the ring patterns to know when to complete the connection by picking up his telephone receiver. The signaling (rings) used digital representation, but voice communication over this connection was purely analog.

The rotary-dial telephone shown in Figure 6 came next and used a more sophisticated series of pulses, which represented the ten digits of the decimal number system. To dial a number, a person would stick his finger in a numbered hole, rotate the dial to the stop arm, and let it go. A spring returned the dial to its original position while turning a cam shaft that opened and closed switch contacts, producing pulses. A sequence of pulses represented each number on the dial. For example, nine pulses represented the number 9, two pulses represented the number 2, and ten pulses represented the number 0. Electromechanical switching mechanisms interpreted (decoded) the pulses and made the connection to wires that went to the correct telephone on the network and caused it to ring until someone answered. Notice that in these systems a different type of digital code was used. The encoding and decoding were done by electromechanical machines to automatically make a connection for analog communication.

**FIGURE 6** A rotary-dial telephone.

Touch-tone telephones came next. A different complex audible signal made up by combining two different sinusoidal frequencies represented each digit of a phone number. These familiar touch-tone sounds are referred to as Dual Tone, Multiple Frequency (DTMF). Electronic circuits were able to recognize each "touch tone," translate the tones into a sequence of digits, and make the right connections to cause a single phone to ring. Notice that in this example, digital switching information is sent using analog tone signals but each tone is made up of two distinct frequencies. Analog and digital representations of information have always worked together in electronic communication.

**THE CELL PHONE** Consider the cell phone in Figure 7 or pick up your own phone and marvel at what it does. Perhaps right now it seems impossible that you could understand how such a complex system operates. Inside a cell phone are some very sophisticated electronics, most of which are covered by the metal shielding on the circuit board. All complex systems (e.g., laptops, HDTV, and automotive controls) are made up of the same basic building blocks. By learning the basic building blocks and using the technology available today, you can design and miniaturize digital systems like the one shown in this cell phone.

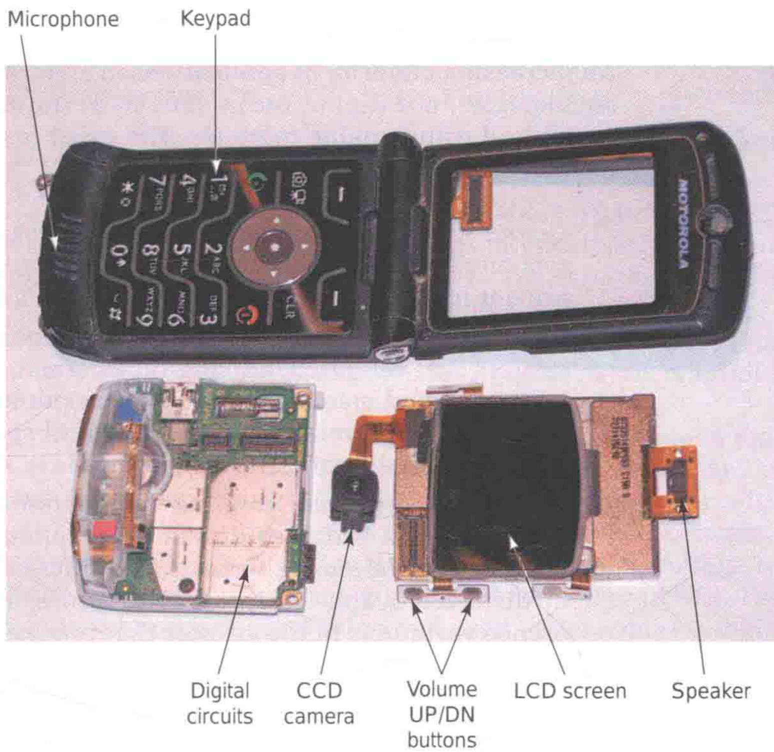



**FIGURE 7** A cell phone disassembled.

The cell phone is a mixed signal system, meaning that it has digital and analog components and uses both types of signals. Your voice is picked up by an analog microphone, but is soon converted to a digital signal. The digital audio signal and lots of other digital information such as phone numbers, global position coordinates, text messages, and so on, are combined with a very high frequency radio wave and sent to a cell tower. Your phone also receives an analog radio signal, separates the digital information, converts the digital audio signal back to analog, and applies it to your speaker.

The keypad is the most obvious input to a cell phone. Each key is in one of two positions or states: pressed or not pressed. A system with only two states is a binary system. Of course, each key must be represented in a unique way to the digital system so the values (numbers on the keys) can be easily distinguished from one another. The **binary number system** uses groups of **binary digits** or **bits** (1s and 0s) to represent decimal numbers in a digital system. We will begin our study of binary numbers later in this chapter. How does a cell phone translate a specific button press to a unique binary code? The *encoding process* for keypads is not covered in this chapter.

The phone in Figure 7 also has a switch that recognizes whether the phone is flipped open (1) or is closed (0). This open/closed sensor also is used to determine when to turn on the backlight and when to end a call. Digital systems are full of sensors and switches like this that provide information about what is happening in the system. Logical decisions are made using the information from these inputs. For instance, the volume buttons increase or decrease the sound level if the phone is open, but the volume setting is not affected if you press them when the phone is closed. The condition of one sensor affects the role of other inputs to the system. The point is that resulting actions of the digital system depend on combinations of the inputs, with each input device being in one of two possible states.

## 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. *Operations 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.**