DIGITAL SIGNAL PROCESSING

A HANDS-ON APPROACH

Charles Schuler
Mahesh Chugani

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To
my brother, Rajesh Chugani,
and
my Doctoral Thesis Advisor, Prof. Michael Savic,
for showing me that miracles are possible.

Mahesh Chugani

To my wife Elaine who has always nurtured my dreams and ambitions.

Charles Schuler

About the Authors

Mahesh Chugani received his M.S. and Ph.D. degrees from Rensselaer Polytechnic Institute (RPI) in 1990 and 1996 respectively. Mahesh also obtained the Bachelor of Engineering (Electronics and Telecommunications) degree from the College of Engineering, Pune, India, in 1987, and a Diploma in Electronics and Radio Engineering from the Cusrow Wadia Institute of Technology, Pune, India, in 1984. He has published several papers, coauthored the book *LabVIEW Signal Processing,* and won numerous awards, amongst them the Charles M. Close Doctoral Research Prize at RPI in 1996, the Whitaker Award at the 20th Annual Bioengineering Conference in March 1994, and the RPI Presidents International Service Award in 1993.

Mahesh is currently Director of Support and Training at Momentum Data Systems (MDS) where he has gained experience on a number of projects covering a variety of digital signal processors and DSP software. Prior to joining MDS in February 2001, he was a DSP software engineer in the DSP Measurements group at National Instruments for about four and a half years. He is a member of the *IEEE* and *Eta Kappa Nu.* He also serves as a reviewer for the *IEEE Potentials* magazine.

Mahesh's books emphasize a hands-on and intuitive approach to DSP and provide the reader with signal processing software with which to experiment. Apart from digital signal processing, his other interests include learning languages, traveling, ballroom dancing, and playing the piano.

Charles Schuler received his Ed.D. from the College of Engineering of Texas A& M University in 1966 where he was an N.D.E.A. fellow. Charles received his B.S. from California University of Pa. in 1963. He has published many articles and seven textbooks in electricity and electronics, almost as many laboratory manuals, and another book which deals with ISO 9000. He taught electronics technology and electrical engineering technology at the university level for 33 years. He also has served as a consultant in the areas of electronic product design and ISO 9000.

Charles is currently a full-time writer and is also the editor of a popular series of electronics books published by Glencoe, McGraw-Hill.

He lives in Naples, Florida with his wife Elaine and his other interests include swimming, cycling, and photography.

List of Hands-on Activities

Preface

This book is intended for students in 2-year and 4-year electrical and electronic technology programs. It is also useful for engineers and scientists who did not take digital signal processing (DSP) courses during their formal education but are now curious about what this amazing and rapidly growing technology is all about. Finally, it is an excellent tool for industry practitioners who need to learn about applied DSP.

Digital signal processing can be explained using mostly mathematics. This can be a reasonable approach because that's what it is based on. However, technicians and practicing engineers usually need a more intuitive sense of what's going on. Equations alone rarely provide this. This book does not forsake mathematics—it does relegate math to a supportive role. The mathematics used in this book is mostly algebra. Examples and software simulations make the math concepts interesting and easy to understand.

One might wonder what is missing in the modest mathematics presented in this book. The fact is that DSP chips work their magic with three basic operations: addition, subtraction, and multiplication. The answer to the question is that *nothing important is missing* for those who need a practical understanding.

This book is very practical. It's a hands-on book written by hands-on authors for a hands-on audience. It will appeal to that large group of people that do not plan to uncover fundamental breakthroughs in signal processing but need to understand it well enough so that they can intelligently apply it, and also to those who will be troubleshooting modern electronic systems. The odds are that DSP technology will soon be a part of many, if not most, modern electronic systems.

This book presents critical ideas and then immediately applies them via software simulations and examples. This approach is extremely effective because it boxes up theories, before they begin to blur, and provides the reader with activities that clearly illustrate core concepts. Learning theory suggests that reading alone is a passive activity and that most readers retain only a small percentage of what they read. The activities (entitled *Hands-on*) in this book will significantly increase understanding and aid retention. The authors recommend that the reader use all, or most, of the hands-on sections.

The software suite supplied with this book (on the CD-ROM) contains five programs that support the hands-on activities. Three of these were specially prepared for beginners just learning DSP and two are demonstration versions of professional software used by DSP designers. In total, the suite exposes the reader to the most important ideas in this vital field and also allows a wide range of experimentation with those ideas. The what-if potential of computer software is an awesome advantage that today's learner has over those of the past. In the past, solving equations with changing variables might eventually lead to an understanding of the important factors and the relationships. Minutes or hours were often required for several iterations. Now, seconds are required. Computers have changed the way we learn and, more fundamentally, the way we live!

The authors hope that you enjoy learning about DSP and that this book will get you where you want and need to be with high efficiency. That's why and how we wrote it.

Charles Schuler
Mahesh Chugani

Acknowledgments

The authors extend their most sincere thanks to Momentum Data Systems for providing demonstration versions of their popular QEDesign 1000 filter design software and DSPworks signal generation and analysis software. Many of the hands-on activities in this book make use of QEDesign 1000 or DSPworks to illustrate important digital signal processing concepts. These applications are invaluable for insightful hands-on experimentation which provides an enriched "learn-by-doing" environment.

We are also extremely thankful to Analog Devices, Motorola, and Texas Instruments for permission to include information about some of their latest digital signal processors. These state-of-the-art processors are widely used in numerous electronics products.

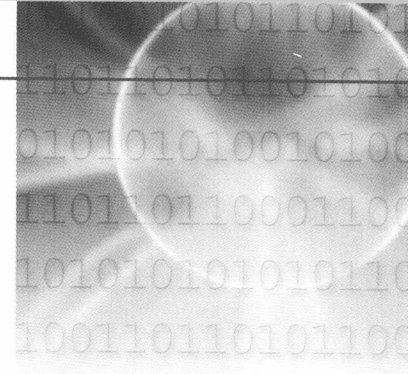
Many of the figures in this book were created using LabVIEW, a graphical programming environment developed by National Instruments. LabVIEW's signal processing and graphical capabilities, ease-of-use, and flexibility are well known in the DSP community.

Very special thanks go to our reviewers, for their painstaking efforts in reading the original manuscript and for their insightful comments and suggestions which greatly contributed to readability and accuracy.

We also thank the editors in the Higher Education division of McGraw-Hill. They provided meticulous attention to detail and significantly improved clarity and consistency.

Our professors, colleagues, and fellow engineers and technicians from whom we have learned so much also deserve acknowledgment. They are at the forefront of technology and have graciously shared their knowledge and experience.

And to our families and friends, we extend our deepest thanks for their support and encouragement during the periods of research, writing and rewriting and for the joy and happiness they bring at all times.



Getting Started with the Software

The CD-ROM included with this book contains the software required for performing the hands-on activities. This text can be used without performing the hands-on activities. However, most readers who perform them will find them to be of immense value. The activities have been carefully designed to provide a deeper insight into the important concepts. They are straightforward and appear in context to support significant ideas just after they are presented. Experimentation will allow many readers to answer their own questions and even to go beyond what has been presented. Last but not least, the learn-by-doing approach will greatly enhance retention of the material.

The software on the CD-ROM includes programs that were created specifically for this book, as well as others that are commercially available and used by DSP engineers worldwide. Generally, signal fundamentals are supported by the specific programs and DSP design issues are addressed by the commercial programs. The progression from fundamentals to design has been carefully crafted and assumes very little prior knowledge.

The rest of this chapter provides detailed information on the contents of the CD-ROM, and for installing and using the software.

CDROM Contents

The CD-ROM supplied with this book contains five programs and several scripts that are used in the Hands-on activities. These programs and scripts are available in the following folders on the CD-ROM. (Click on `Explore the CD`)

DSPHSON
DSPworks
QED 1000
Scripts

1. DSPHSON An acronym derived from the name of this book. This folder contains three programs that were created specifically for learning key concepts with just the correct amount of information being presented at the appropriate time. The reader will find these programs fun, interesting, and easy-to-use.

   - *DSPHSON1.exe* models both analog and discrete **oscilloscopes** and is used to view time domain signals. It also introduces the concept of quantization (the analog to digital conversion process).
   - *DSPHSON2.exe* is a working audio **oscilloscope** and **spectrum analyzer** that uses the soundcard in your computer and displays either the waveform or its frequency content.
   - *DSPHSON3.exe* is a combination of a **function generator,** a **spectrum analyzer,** and a **filter designer.** You can generate square, triangular, sawtooth, rectified sine, or pulse waveforms, and view their frequency content. You can also design digital filters and view their magnitude and phase responses.

2. DSPWorks This folder contains the demo version of a commercially available software package used worldwide for a wide range of signal processing applications. Its rich library of functions also makes it a useful tool for learning about the basics of digital signal processing. This demo version is almost identical to the full version, but limits the number of samples of the generated waveforms to 600.
3. QED 1000 This folder contains the demo version of a commercial program used by digital filter designers. The demo version is almost identical to the full version but does not allow files to be saved.
4. Scripts Scripts are a sequence of commands that are stored in a file. The **Scripts** folder contains the DSPworks script files that you will be using with Chapters 6, 7, 8 and 9 of the text. When the scripts are run from within DSPworks, they create and save files in the same folder in which they are located. If run from the CD-ROM, you will get an "Unable to create file" error because the files that are created cannot be saved on the CD. To avoid this, you must first copy these script files to either a $3\frac{1}{2}$ inch floppy diskette in the **A** drive, or to the hard drive (usually the **C** or **D** drive) on your computer, as outlined in the instructions below:

    a. Copy the **Scripts** folder and all its contents from the CD-ROM either to a floppy diskette (**A** drive), or to your computer's hard drive (usually **C** or **D**).

       Note: If copying to a floppy, please make sure that the diskette is not write-protected. To ensure that the diskette can be written to, the write-protect tab should cover the opening.

    b. Launch DSPworks as instructed in section 2 above.
    c. Select **Play Script** from the **File** menu.
    d. A new window will open with a box to the left of the **Open** and **Cancel** buttons. What you do in this box will depend on where you copied the **Scripts** folder in step (a) above.

Installing and Using the Programs

Insert the CD supplied with this book into the CD-ROM of your computer. The user interface shown on the next page will automatically come up. Follow the instructions as specified in the user interface to install and use the programs.

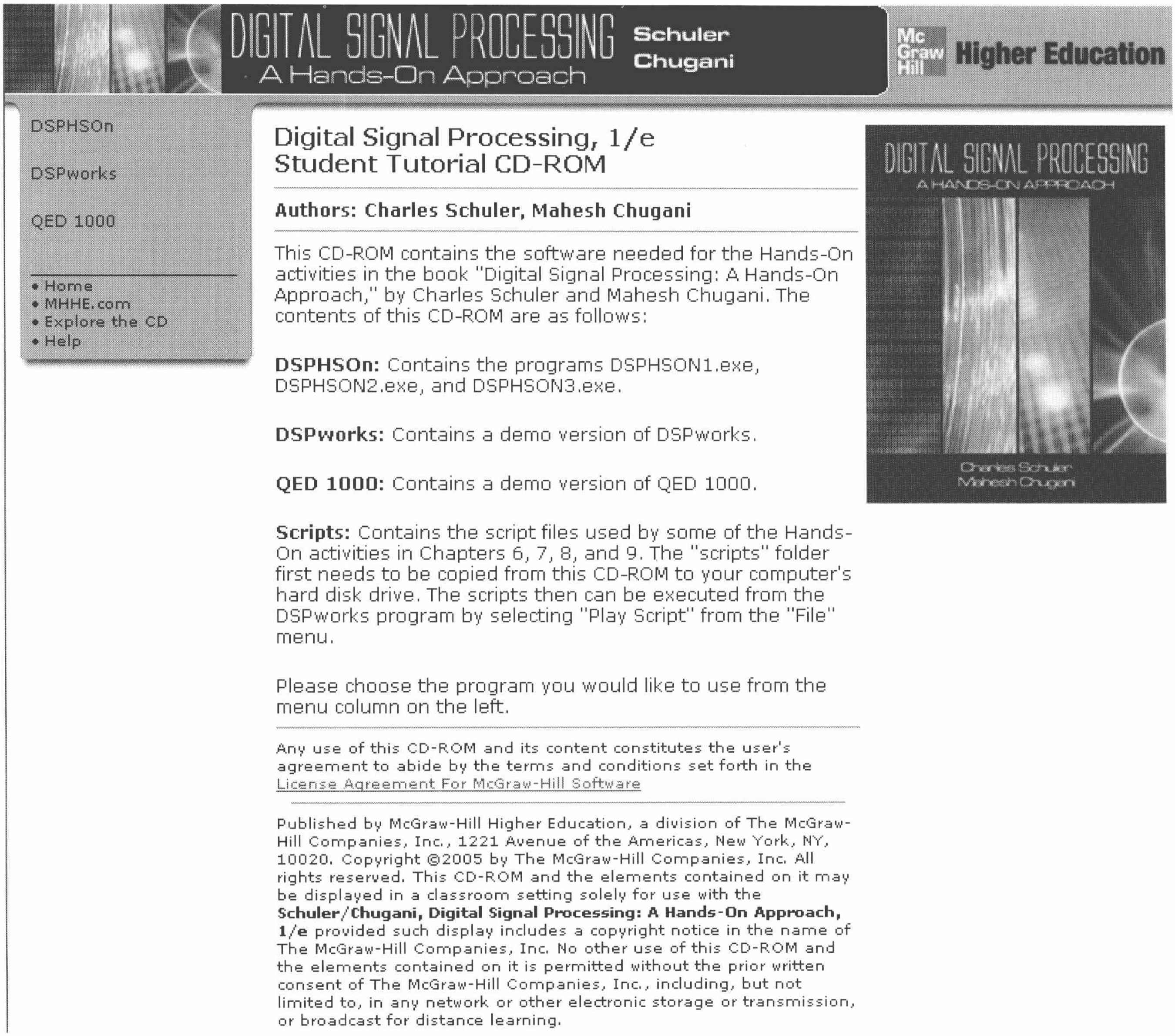
Floppy:

If you copied the **Scripts** folder to a $3\frac{1}{2}$ inch floppy, move the arrows and scroll towards the *bottom* of the box where the line containing [**-a-**] is displayed. Make sure the floppy is inserted in the drive. Use the left mouse button to double-click [**-a-**], and you will see the **Scripts** folder displayed in the box.

Hard Drive:

If you copied the **Scripts** folder to the hard drive, move the arrows and scroll towards the *top* of the box where the line containing [**..**] is displayed. Use the left mouse button to double-click [**..**] several times until you reach the top-level directory. (The full directory path name is displayed just above the box.)

When you reach the top-level directory, the line containing [**..**] will not be displayed any more. Now, double-click the appropriate drive letter (usually [**-c-**] or [**-d-**]) where you copied the **Scripts** folder and you should see the **Scripts** folder name displayed in



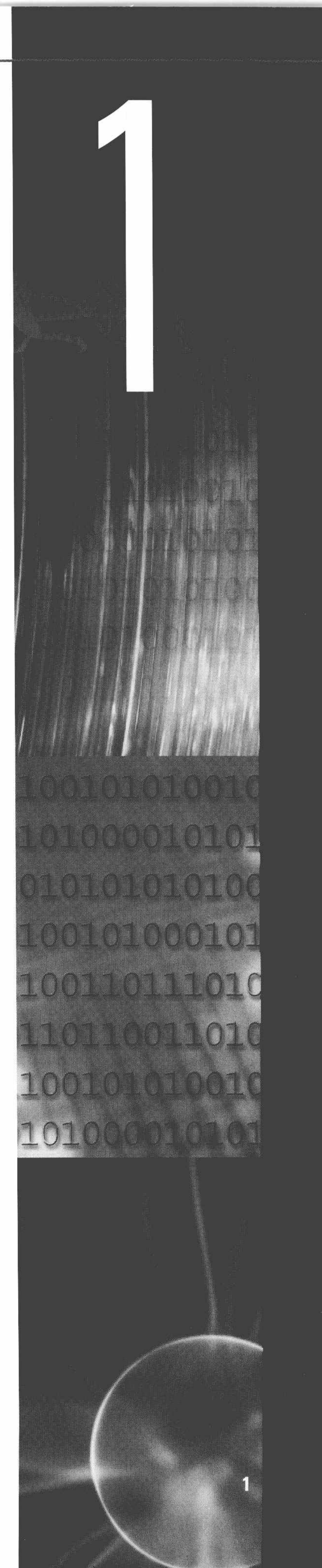
the box. You may need to use the arrow keys to scroll up or down to locate the **Scripts** folder.

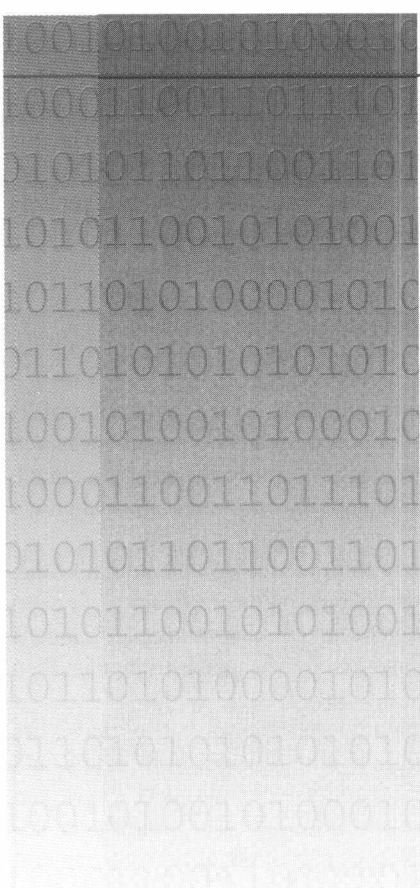
- **e.** Use the left mouse button to double-click the **Scripts** folder. **Chapter6, Chapter7, Chapter8,** and **Chapter9** are now displayed in the box.
- **f.** Use the left mouse button to double-click the appropriate chapter.
- **g.** Use the left mouse button to double-click the appropriate file (e.g., cdelay.scr). Or, highlight the file and click the **Open** button.
- **h.** DSPworks will now execute the script. Follow the rest of the instructions as given in the text.

Contents

chapter 1

Introduction to Digital Signal Processing





Objectives

In this chapter, you will

- Learn about different types of signals.
- Learn why transducers and sensors are necessary in electrical and electronics systems.
- Understand the differences between analog, discrete-time, and digital signals.
- Be introduced to several digital signal processing (DSP) applications.

What Is a Signal?

A dictionary definition of a *signal* is anything that serves to indicate, warn, direct, command, or the like, as a light, gesture, an act. A definition more specific to electronics is an electrical quantity or effect, as current, voltage, or electromagnetic waves, that can be varied in such a way as to convey information.

Information is the key concept. Signals are always presumed to represent or convey useful information. Electrical effects that do not convey useful information are termed *noise*. In fact, the major measure of signal quality is the signal-to-noise ratio. You have no doubt experienced poor signal-to-noise ratios, for example:

- Background hiss on an old recording.
- Snow on a television picture.
- Static pops and clicks on an amplitude modulation (AM) radio.
- Your companion's voice in competition with the roar of the crowd.

There will be more about noise and what DSP can do about it in Chapters 3 and 7.

Transducers and Sensors

Most signals do not originate in electrical form. In the world around us, signals can originate as pressure disturbances, temperature variations, mechanical displacement, or as changes in light intensity. It is often advantageous to convert signals to electric voltages or currents so that they may be more easily processed using electrical and electronic devices and, lately, digital computers.

A *transducer* is a device that converts a signal from one form of energy into another. For example, a thermistor is a transducer that converts heat energy into a change in resistance. Transducers that produce electrical signals for applications in the areas of *measurement* and *control* are known as sensors. Examples of sensors are solar cells that convert light energy into electric voltage and Hall effect semiconductors that convert magnetic fields into voltages. Microphones convert pressure variations into electric voltages but are usually *not* called sensors. The word *transducer* is a broader term that includes all energy transformers—even loudspeakers and motors. Figure 1.1 shows some of these devices.

Different Types of Electrical Signals

An electrical signal that does not change its amplitude with time, over the duration of its measurement, is called a direct current (DC) signal. For example, the signal measured across a battery is a DC signal. It might seem odd to classify battery voltage as a signal. Consider that sensors are often used in battery-powered equipment to alert users when it's time for a recharge.

The amplitudes of most signals that are encountered in practice do change with time. One can see what a signal "looks" like by plotting its amplitude on the vertical axis (y axis) versus time on the horizontal axis (x axis). If the shape of the corresponding plot happens to be a sine wave, then the signal is called a *sinusoidal* signal. If the shape is triangular, then the signal is called a *triangular* signal.

One of the most common signals encountered in nature is the sine wave. Sine waves are produced, for example, by musical instruments, people talking, seismic movements, and the motion of a pendulum. Many signals, including triangular waves and square waves, can be shown to be composed of a combination of sine waves. Thus, sine waves can be considered to be the building blocks of many other signals. We will see more of this in Chapter 4 entitled Periodic Functions and Fourier Synthesis.

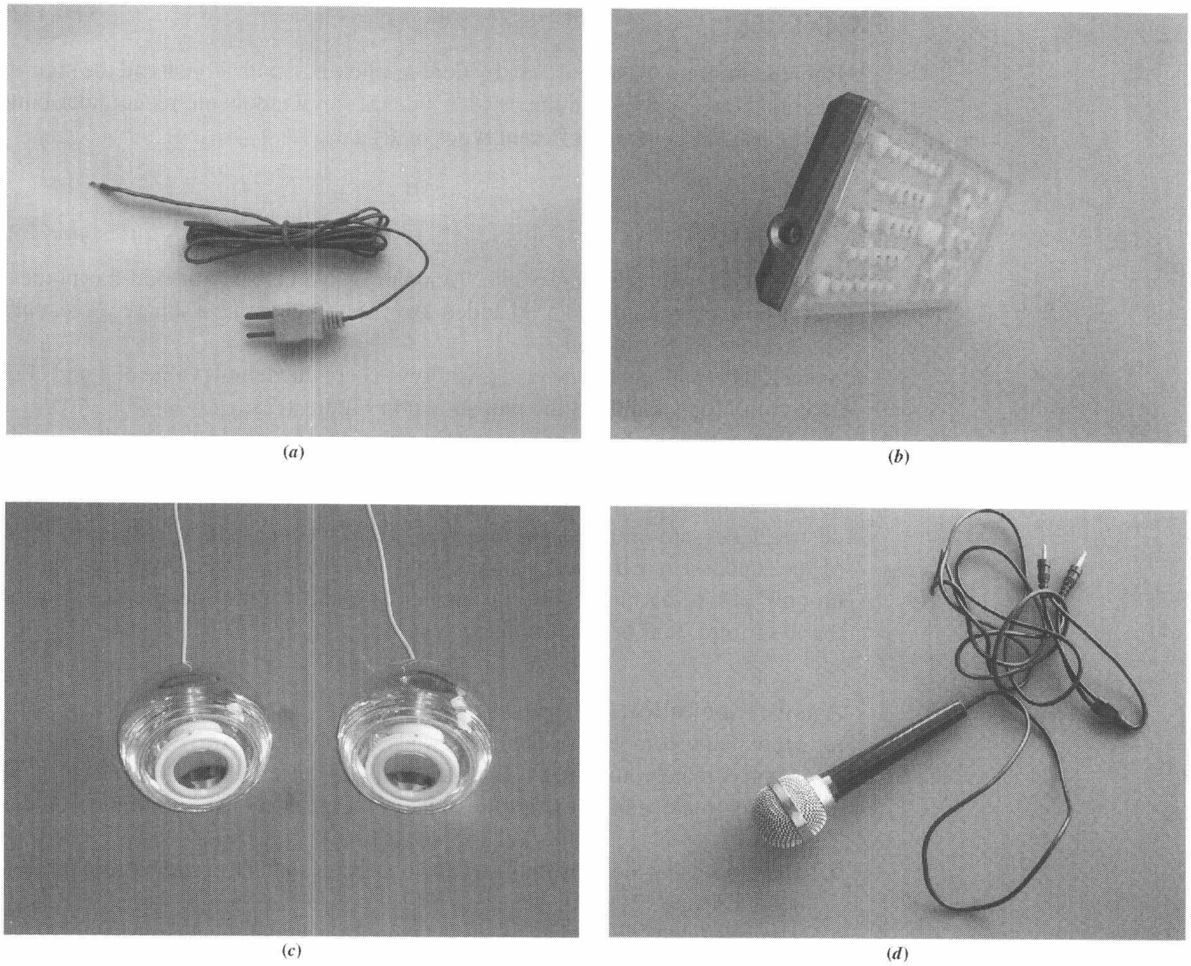


FIGURE 1.1 Transducers and sensors **(a)** Thermocouple **(b)** Infra-red sensor on remote control **(c)** Loudspeakers **(d)** Microphone.

In Hands-on 1.1, you can see for yourself the different types of signals that are commonly encountered in practice.

Hands-on 1.1

Common Electrical Signals

Purpose. To experiment with sine, square, triangle, and sawtooth waves.

Materials

Computer with Windows 95 (or later) and 800 · 600 (or better) color graphics.
Application program DSPHSON3.

Introduction. DSPHSON3 is a program that demonstrates

Synthesis of five common periodic waveforms
Filter design (more about this in Chapter 7)

For this particular hands-on, we will focus on the synthesis of five common periodic waveforms.

PROCEDURE

1. Run the program `DSPHSON3.exe` by double-clicking on its icon. Read the sign-on notice and click on `Continue`. In the `Select Operation` window are rectangular buttons that can be used to generate different types of signals.

SQUARE WAVE

2. Let us begin with a square wave. A square wave consists of odd harmonics of sine waves of various amplitudes all added together. To generate a square wave, click on the `Square Generator` button.

3. In the `Number of Odd Harmonics` window accept the default value of `3` and click on the `OK` button. You should get the plot shown in Figure 1.2a.

The program shows you a square wave that is generated by the summation of three sine waves. The lowest-frequency sine wave is known as the fundamental frequency or the *first harmonic*. Frequencies that are integer multiples of the fundamental frequency are known as *harmonics*. The harmonic with a frequency N times that of the fundamental frequency is known as the *Nth harmonic*. A square wave is made up only of odd harmonics. In this particular example, the square wave is made up of the first, third, and fifth harmonics.

Answer the following questions:

a. How many complete cycles, or periods, of the square wave are shown?

b. Approximately how many divisions is the duration of one cycle?

c. Approximately how many divisions is the peak-to-peak amplitude of the square wave?

d. How many oscillations (bumps) do you notice on the top and bottom portions of the square wave?

e. The *risetime* is defined as the time taken for a signal to go from 10 to 90 percent of its maximum value. It provides a measure of the rate at which the amplitude of a signal increases with time and is important in many control applications. How many divisions is the risetime of the signal in Figure 1.2a?

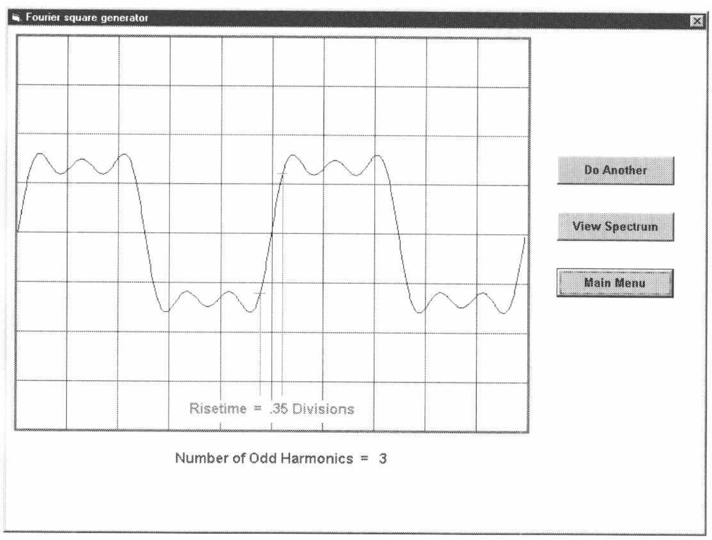


FIGURE 1.2a Square wave generated by the summation of three sine waves.