ELECTRONIC CIRCUITS AND APPLICATIONS

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PREFACE

This book has been written for the person who wishes to learn the principles of modern electrical engineering and use those principles to make intelligent and practical use of electronic components, circuits, and instruments. Designed for students who have no previous background in circuit theory or electronics, the text provides a sufficiently broad and thorough exposure to practical electronics to permit the immediate application of electronic circuits and instruments to laboratory and research work. Because these applications involve increasingly sophisticated concepts in signal processing, we have included practical introductions to network theory, linear system theory, modulation and detection, noise, guarding and shielding, and analog and digital instrumentation. Thus, this book can be used either as a textbook for an introductory first course in electrical engineering, as a textbook for a one-semester or two-semester "Electronics for Scientists and Engineers" survey course or as a self-study primer for the professional scientist or engineer who needs additional background in the theory and practice of electronics.

The development of integrated circuits during the last decade has led to many important changes in electronic-circuit technology. A scientist or engineer can now work with inexpensive, flexible, integrated-circuit function modules to design and build surprisingly sophisticated circuits without first having to master all of the intricacies and subtleties of the transistor. Furthermore, the manufacturers of commercial equipment have used these same modules to build sophisticated signal-processing circuits into successively lower-cost packages, making available to the user of electronics a wealth and diversity of commercial electronic instruments that were unheard of a decade ago.

This textbook evolved from a one-semester introductory electronics course taught by the authors at the Massachusetts Institute of Technology. The students in this course (and there have been more than a thousand since the course became organized in its present format) come from all fields—physics, biology, chemistry, mechanical, civil, chemical, and aeronautical engineering—and range from freshmen to graduate students, including several medical and law students. The course is used by many freshmen as a precursor to the MIT Electrical Engineering Core program.

In order to prepare this diverse audience for dealing with modern integrated circuit electronics, we have developed a pedagogical approach that differs in several ways from the approaches found in other introductory texts. We stress the close intermingling of:

(*1*) theoretical results based on ideal elements;
(*2*) facts about real devices, and practical circuit models that represent the devices; and
(*3*) applications that exploit both the devices and the key theoretical concepts.

Network theory is treated as a learnable skill instead of a mathematical discipline. The student is encouraged to learn how to put network theory to work with the aid of text examples and carefully graded exercises and problems based on actual applications. Design problems, which represent challenging applications of the text material, are identified by boldface problem numbers. Equivalent circuit concepts are heavily emphasized in both purely resistive and single-time-constant networks. The operational amplifier (Chapter 5) is the first active element introduced because it is simpler to understand and apply than the transistor and because it has largely replaced the transistor as the basic building block of analog circuits. Diodes and transistors (including both bipolar and field-effect transistors) are then introduced in a context that stresses those circuit applications that cannot be performed by op-amps alone. In the process, of course, the student encounters many of the circuit configurations that are employed in op-amps. Thus the student is "bootstrapped" to an understanding of op-amp characteristics and limitations in two steps; first, with the op-amp itself treated as an ideal element, and, second, with the op-amp reappearing as a complex circuit containing transistors and diodes.

With the exception of step responses in single-time-constant circuits (which is introduced in Chapter 6 to permit the early discussion of many important applications examples), the subject of ac circuits is postponed until after op-amps, transistors, and diodes have been fully discussed on a dc or quasi-static basis. During the presentation of small-signal models (Chapter 11), it becomes apparent that techniques are needed for dealing with circuits containing more than one energy storage element, and for dealing with time-varying wave-forms of more complexity than a step function. The discussion of amplifier frequency response thus becomes the vehicle for a three-chapter introduction to linear system theory, including complex impedance and s-plane techniques at a level that requires no advanced mathematics. Superposition in both the time and frequency domain is then discussed, the latter leading into the concept of a frequency spectrum. The spectrum concept is immediately applied in the discussion of modulation (Chapter 15), and is also exploited in the later chapters on noise and instrumentation applications. The material on digital signals and circuits (Chapter 16) includes a review of logic families, gates, flip-flops, and their applications to counters, shift registers, and combinational logic problems. Chapters 17 and 18 contain information on noise and instrumentation of a kind not usually encountered in elementary texts, including shielding and guarding, device noise, analog signal processing, analog-to-digital conversion, sampled data, and digital signal processing. This material has become essential for the modern user of electronics, particularly in the age of the minicomputer, and is now made accessible to beginning students.

The prerequisite background for this textbook has been kept to a minimum: elementary calculus and the equivalent of high-school physics. The course at MIT includes a modest laboratory program to supplement lecture and recitation classes, and makes extensive use of lecture demonstrations. The laboratory program, suggested course outlines, and sample lecture demonstrations are described in the *Teacher's Manual*.

The preparation of a book of this size has drawn on the contributions of many people. The concept of teaching network theory and electronics as a single unified subject derives from Professor Campbell Searle, who taught the introductory electronics course when one of us (S.D.S.) was a first-year physics graduate student trying to learn electronics. In addition, Professor Searle has provided invaluable constructive criticism throughout the writing of this text. Several members of the MIT faculty and nearly 40 graduate teaching assistants have participated in the teaching of this material over the past five years, many of whom have made important contributions through their suggestions and examples. Among these, we especially wish to thank O. R. Mitchell, Irvin Englander, George Lewis, Ernest Vincent, David James, Kenway Wong, Gim Hom, Tom Davis, James Kirtley, and Robert Donaghey. The chairman of the MIT Department of Electrical Engineering, Professor Louis D. Smullin, has provided support and encouragement during this project, as have many colleagues throughout the department. To Mrs. Thalia P. Stone, who prepared the original manuscript and nurtured it through several revisions, our thanks for her skill and good humor throughout a long job. Mr. Max Byer was particularly helpful in the production of preliminary editions for student use at MIT. To the legion of students who prodded us to do it over until we did it right, our thanks for their encouragement and witheringly honest criticism. Finally, to our wives, Alice Senturia and Mary Ann Wedlock, goes that special kind of thanks reserved for those who understand when no one else does.

We have tried to make this an accurate and useful book. To the extent that we have succeeded, we owe a great deal to the people listed above and to others. Any errors and flaws that remain are our own, and for them we take full responsibility.

Cambridge, Massachusetts
August 1974

Stephen D. Senturia
Bruce D. Wedlock

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CHAPTER ONE

PROLOGUE

1.0 SCOPE AND GOALS

To say that we live in an age of electronics is an understatement. From the omnipresent transistor radio to the equally omnipresent digital computer, we encounter electronic devices and systems on a daily basis. In every aspect of our increasingly technological society—whether it be science, engineering, medicine, music, maintenance, or even espionage—the role of electronics is large, and it is growing.

The primary goal of this textbook is to provide a broad introduction to the concepts and uses of modern electronics. We shall discuss the language, the ideas, and the techniques of this field with reference to a variety of applications. These applications have been chosen primarily to suit the needs of persons in scientific and engineering fields who must learn to *use* electronics in intelligent and creative ways. Thus, although we will begin with the most fundamental aspects of electrical networks, our ultimate purpose is to teach the student to understand and to synthesize interconnections of electrical and electronic components into systems that perform useful and interesting tasks.

In general, all of the tasks with which we shall be concerned can be classified as "signal-processing" tasks. Let us explore the meaning of this term.

1.1 SIGNAL PROCESSING

1.1.1 What Is a Signal?

A *signal* is any physical variable whose magnitude or variation with time contains *information*. This information might involve speech and music, as in radio broadcasting, a physical quantity such as the temperature of the air in a room, or numerical data, such as the record of stock market transactions. The physical variables that can carry information in an electrical system are voltage and current.[1] When we speak of "signals" in this book, therefore, we refer implicitly to voltages or currents. However, most of the concepts we discuss can be applied directly to systems with different information-carrying variables. Thus, the behavior of a mechanical system (in which force and velocity are the variables) or a hydraulic system (in which pressure and flow rate are the variables) can often be *modeled* or represented by an equivalent electrical system. An understanding of the behavior of electrical systems, therefore, provides a basis for understanding a much broader range of phenomena.

1.1.2 Analog and Digital Signals

A signal can carry information in two different forms. In an *analog signal* the continuous variation of the voltage or current with time carries the information. An example, in Fig. 1.1, is the voltage produced by a thermocouple pair when the two junctions are at different temperatures.[2] As the temperature difference between the two junctions varies, the magnitude of the voltage across the thermocouple pair also varies. The voltage thus provides an analog representation of the temperature difference.

The other kind of signal is a *digital signal.* A digital signal is one that can take on values within two *discrete* ranges. Such signals are used to represent ON–OFF or YES–NO information. An ordinary household thermostat delivers a digital signal to control the furnace. When the room temperature drops below a preset value, the thermostat switch closes turning ON the furnace. Once the room temperature rises high enough, the switch opens turning

[1] Readers totally unfamiliar with these terms may wish to look ahead briefly to Section 2.1 of the following chapter.

[2] A thermocouple is a junction between dissimilar metals, such as copper and constantan. The voltage generated by a pair of thermocouples is used to measure the temperature difference between the two junctions.

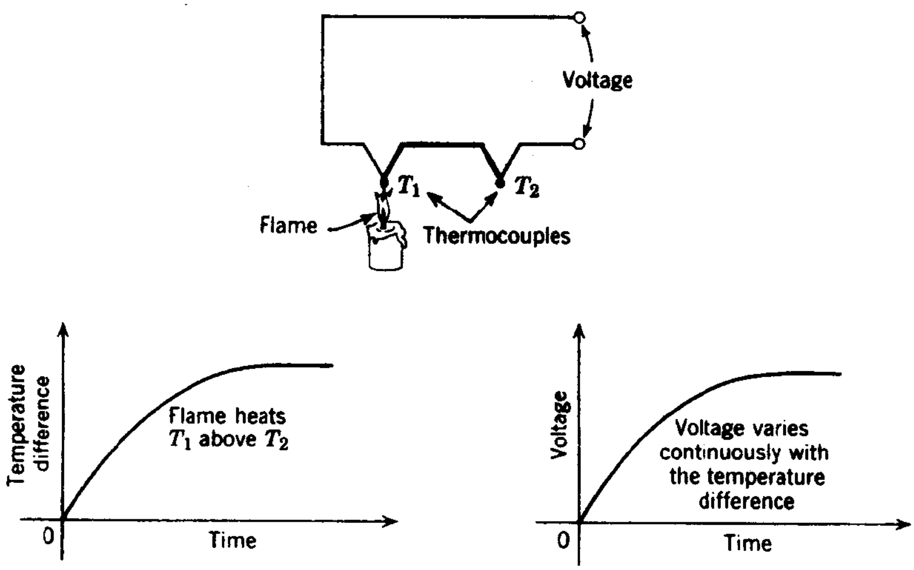

Figure 1.1
An example of an analog signal. One thermocouple is heated above the temperature of the other, giving rise to an analog output voltage.

OFF the furnace. The current through the switch provides a digital representation of the temperature variation: ON equals "too cold" while OFF equals "not too cold."

1.1.3 Signal-Processing Systems

A *signal-processing system* is an interconnection of components and devices that can accept an input signal or a group of input signals, operate on the signals in some fashion either to extract or improve the quality of the information, and present the information as an output in the proper form at the proper time.

Figure 1.2 illustrates the components in such a system. The central circles represent the two types of signal processing (digital and analog), while the block between the two signal-processing blocks represents the conversion of an analog signal to equivalent digital form (*A/D* = *A*nalog-to-*D*igital) and the reverse conversion of a digital signal to the corresponding analog form (*D/A* = *D*igital-to-*A*nalog). The remaining blocks involve inputs and outputs—getting signals into and out of the processing system.

Many electrical signals derived from physical systems are obtained from devices called *transducers*. We have already encountered an example of

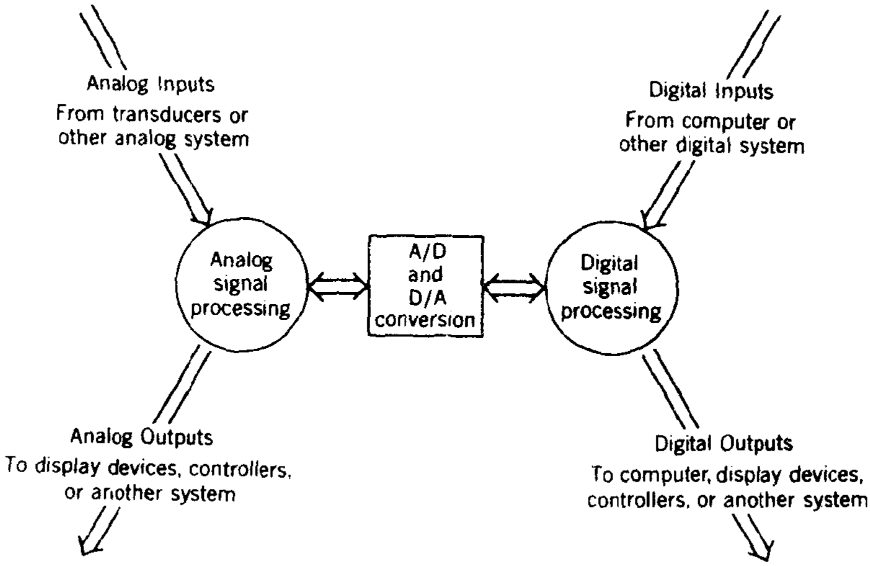

Figure 1.2
Components of a signal-processing system.

an analog transducer, the thermocouple pair. It converts temperature difference (the physical variable) to a voltage (the electrical variable). Generally, a transducer is a device that converts a physical or mechanical variable to an equivalent voltage or current signal. Unlike the thermocouple example, however, most transducers require some form of electrical excitation to operate.

The output from a system can be in many forms, depending on the use to be made of the information contained in the input signals. One can seek to display the information, either in analog form (using a meter, for example, in which the needle position indicates the size of the variable of interest) or in digital form (using a set of digital display elements that are lit up with a number corresponding to the variable of interest). Other possibilities are to convert the output to sound energy (with a loudspeaker), or to use the output as an input signal to another system, or to use the output as a control signal to initiate some action. The examples presented in Section 1.2 below illustrate some of these cases.

1.2 ILLUSTRATIVE SYSTEMS

1.2.1 A Communications System

The first system we shall illustrate is the *communications system.* The input can be either speech, music, or data that is produced at one location and transmitted efficiently over long distances, permitting faithful recovery of the original input. The example chosen, the familiar AM broadcast system is shown schematically in Fig. 1.3.

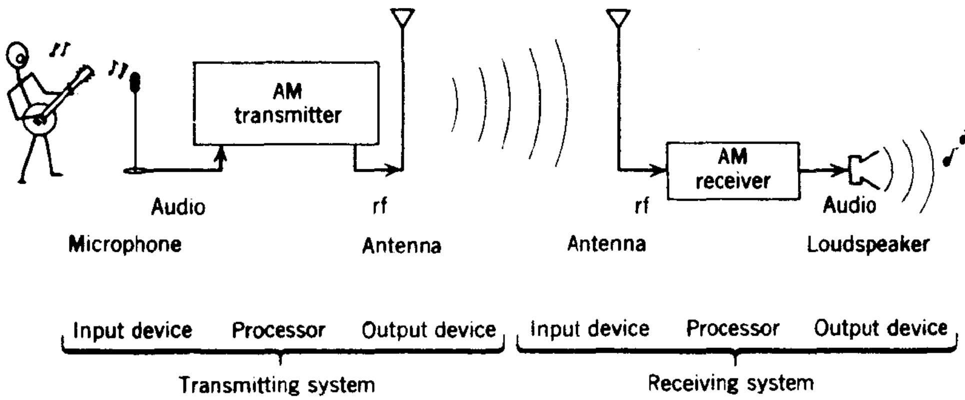

Figure 1.3
An AM broadcast communication system.

The letters *AM* stand for *A*mplitude *M*odulation. They mean that the amplitude or magnitude of a radio frequency (rf) signal is caused to vary according to the magnitude of a lower-frequency signal (audio, corresponding to audible frequencies). The function of the transmitter in an AM broadcast system is to accept the input signal from an input device (microphone), use this signal to control the amplitude of a radio frequency signal (each broadcast station is assigned its own radio frequency), and drive the output device (the antenna) with a radio frequency current to produce electromagnetic waves radiating into space. The receiving system consists of an input device (the antenna), a processor (the receiver), and an output device (the loudspeaker). The functions of the receiver are to amplify or increase the strength of the relatively weak signal obtained from the antenna, to filter or select the desired radio frequency signal from the signals of all other broadcast stations, to recover the audio signal from the amplitude variations of the radio frequency signal, and to drive a loudspeaker with this audio signal.

1.2.2 A Measurement System

A second system is a *measurement system*. The purpose of this system is to acquire information from suitable transducers about the behavior of some physical system and to display this information to the observer. An example of such a system, a digital thermocouple thermometer, is shown in Fig. 1.4.

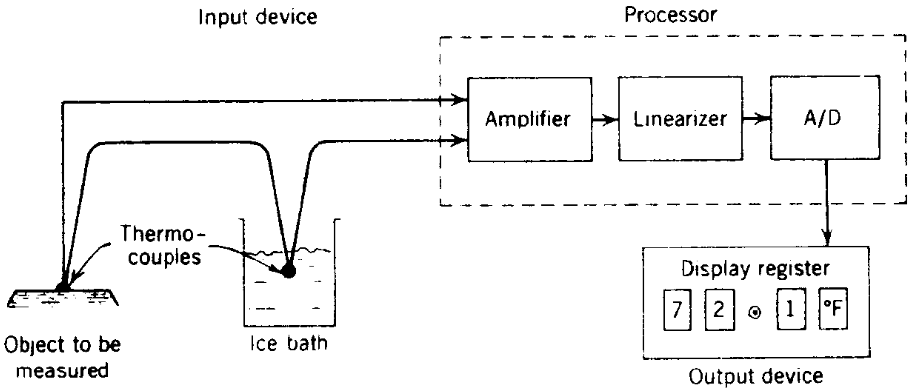

Figure 1.4
Block diagram of a digital thermometer.

The pair of thermocouple junctions, one attached to the object whose temperature is to be measured, the other submerged in an ice bath (to establish a stable reference point), presents to the processor a voltage that depends on the temperature difference between the object to be measured and the ice bath. Because the thermocouple voltage is never exactly proportional to the temperature difference, a small correction must be applied to the thermocouple voltage to produce an analog voltage that is exactly proportional to the temperature. This correction is the role of the linearizer. The analog voltage from the thermocouple is first amplified (i.e., made larger) then linearized, and then converted to digital form. Finally, it is displayed in a digital display register as the output of the thermometer.

Although a major goal of the communications system is to transmit a faithful reproduction of the source signal, a major goal of the measurement system is to produce numerically accurate data. In a measurement system, therefore, one expects to be concerned with locating and removing any small errors that might be added to the signal at each step of the processing sequence.

1.2.3 A Feedback Control System

The third system is the *feedback control system*, in which information about the behavior of the output modifies the signals driving the system. In Fig. 1.5 a thermostat is used to control the temperature of a room. In this case, the thermostat contains the input device for determining the room temperature (normally a bimetallic strip that bends as its temperature is varied), a mechanism for setting the desired temperature (the set point dial), and mechanical switches, activated by the bimetallic strip, which control the furnace.

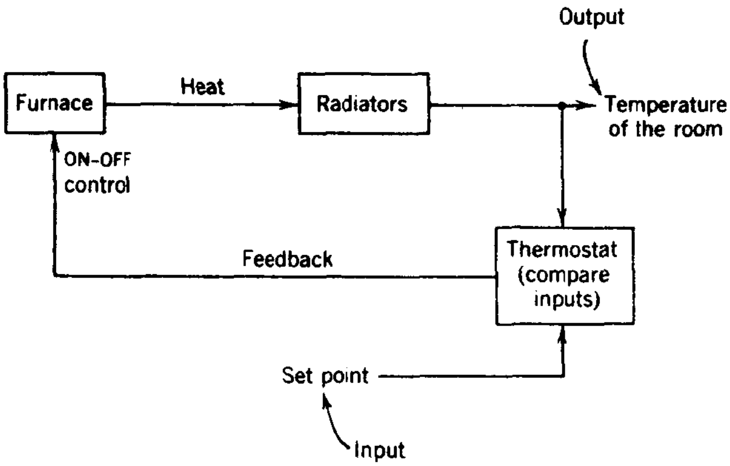

Figure 1.5
A feedback system.

This familiar example, which in fact includes *no* electrical components other than a switch, was chosen to emphasize the feedback concept. Suppose the feedback line were disconnected in Fig. 1.5. That is, suppose there were no mechanism for turning the furnace ON or OFF. The temperature of the room would either rise to some maximum (if the furnace were on all the time) or drop to some minimum (if the furnace were off all the time). Presuming that the maximum temperature is too hot for comfort while the minimum temperature is too cool, some "controller" is needed to turn the furnace ON and OFF. The "controller" might be a person who turns the heat ON when he feels cold and turns it OFF when he feels warm. Even at this level, the system (*including* the person) comprises a *feedback* control system, because information about the output (i.e., the temperature of the room) is used to modify one of the driving signals (the on-off switch on the furnace). The thermostat is simply a piece of hardware that performs automatically what the temperature-sensitive person would do; namely, it turns the furnace ON when the temperature drops below the point where the person set the thermostat, and turns it OFF otherwise.

There are many other feedback systems, including systems in which the processing of signals is done electronically. We shall encounter several electronic feedback systems later.

1.3 MODELING

As we proceed through the text, two somewhat different threads will be found running together. The first of these deals factually with the behavior of real devices, real circuits, and real systems. The second thread involves working with abstractions derived from the real devices, that is, with a somewhat idealized version of the real world. As we examine the basic laws of electrical networks and learn to use network theory to analyze the behavior of idealized circuits, we shall at the same time learn to use these idealized circuits to *model* or represent the behavior of real devices. As we examine what functions can be performed using idealized electronic devices, we shall at the same time ask which functions are needed for signal processing in the real world. Toward the end of the book, the two threads will get more tightly interwound as we face the limitations of real devices (e.g., the presence of noise) and discuss how these limitations impose constraints on the design of real systems. It will nevertheless help the student to be aware of this dual approach from the outset.

At each step of the development we shall encounter a conflict between accuracy and simplicity. If the model of a device is too simple, it will fail to portray essential device characteristics. If the model is too detailed, unnecessarily cumbersome calculations may obscure our understanding of the essential issues. As a result, the models we shall ultimately employ are compromises, accurate enough to represent the essential features of device and circuit performance, yet simple enough to permit rapid analysis and to enhance our understanding of system performance.

QUESTIONS

Q1.1 Describe a doorbell circuit as a communications signal-processing system. What is the information communicated? Identify the input device, the output device, and the processor. Are the signals analog or digital?

Q1.2 Describe an electric toaster that "pops up" the toast when finished as a feedback system.

Q1.3 How many different kinds of transducers can you think of?

Q1.4 How many different output devices can you think of?