ESSENTIAL ELECTRONICS

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John Wiley & Sons
New York Chichester Brisbane Toronto Singapore

Library of Congress Cataloging in Publication Data:

Stubbins, Warren Fenton.
Essential electronics.

Bibliography: p. 493
Includes index.
1. Electronics. I. Title.
TK7816.S74 1986 621.381 85-9447
ISBN 0-471-88604-1

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

PREFACE

Electronics pervades every aspect of modern life. Its importance increases with each advance in technology and with the drive to computerize human tasks and industrial processes. This textbook presents the fundamental concepts on which modern electronics is based and on which the technology will advance. It is written for science and engineering students, and its material was developed in courses we taught over several years.

The nature of electronics is changing rapidly as integrated circuits of unbelievable complexity and capability are developed both in the digital and analog realms and in the marriage between them. But the principles that form the bases of the electronic revolution are the elementary principles of physics and electrical engineering. The aim of this book is to put these basic concepts in perspective and to relate them to the student's desire to understand and apply electronics. We have found that this is the best way to introduce this interesting and challenging subject.

Only a few of the students who were taught the material in this book had earlier experience or instruction in electronics (often consisting of no more than the dc circuits and electricity offered in an introductory physics course), but all were able to learn the material and to do the exercises. The text does not presuppose a more extensive background. The participation of students in the exercises, however, is an essential step in their learning electronics and in making the knowledge useful to them.

The material in the book may be divided into four parts. The first six chapters deal exclusively with digital electronic concepts. In combination with the first 14 laboratory exercises in Appendix B, they may be used as a self-contained text for a course limited to digital electronics. The principles of digital electronics can be taught without exploring or learning the electrical nature of the digital gates because the flow of digital signals is the focus of the work. In the second portion of the text begins the work in analog electronics, in which we must examine the nature of electrical signals rather than the on-off nature of digital signals. Chapters 7 to 10 and Chapter 14 provide the basis for analog electronics. Chapters 11, 12, and 13, which deal with analog electronics and its union with digital electronics, constitute the third portion of the text. The fourth portion includes Appendix A, which discusses computer arithmetic, and Appendix B, the laboratory exercises.

Chapter 1 introduces the basic logic gates and establishes the Boolean algebraic nature of digital signals. Chapter 2 develops Boolean algebra appropriate to the application of logic gates and gives several techniques for simplifying logic-gate circuits. Combinational digital electronics is the subject of Chapter 3, in which combinations of digital gates provide various logic functions. Sequential digital circuits are the subject of Chapter 4, and Boolean algebra is applied to achieve specific sequential patterns. Chapter 5 addresses digital memory elements in various forms. The strictly digital portion of the text concludes in Chapter 6 with an examination of how the digital elements may be brought together to form an elementary microprocessor, in which a simple algorithm is used to solve an arithmetic problem.

In Chapter 7, elementary electrical circuit theory explores dc and ac properties of the circuit elements—resistor, capacitor, and inductance—and their behavior under transient and sine wave signals. This chapter also presents Thevenin's theorem, the rotational operator, and electrical resonance. Chapter 8, which discusses solid-state electronic devices, presents an elementary account of the physics of semiconductors and develops the properties of the *pn* junction. Chapter 8 includes a description and the characteristics of bipolar-junction transistors, field-effect transistors, and metal-oxide-semiconductor field-effect transistors. Chapter 9 examines the nature of electronic amplifiers and the role that feedback plays in changing the amplifying properties. In Chapter 10 a transistor amplifier, the common-emitter amplifier, is used as a design example in preparation for describing the transistor nature of TTL (Transistor-Transistor-Logic) gates. Other material in this chapter pertains to registers and memory elements and their operation. Chapter 14 discusses the power supply, a necessary part of every electronic device, which furnishes regulated voltages to operate the digital and analog electronic elements.

Chapter 11, on the subject of operational amplifiers, explores analog electronics. The emphasis on operational amplifiers reflects our opinion that many analog electronic applications and problems can be satisfied by operational amplifiers and that the use of these elements is the simplest approach for an inexperienced user of electronics. The chapter covers the properties, the limitations, and the arithmetic use of operational amplifiers. Chapter 12 brings analog and digital electronics together and shows how they unite in instrumentation, control, and measuring circuits as analog-to-digital converters and digital-to-analog converters. This chapter also examines the forms of several conversion techniques. Chapter 13 discusses imaginative uses of electronics and suggests further possibilities to the student.

Appendix A concerns the conversions to and from binary, octal, decimal, binary-coded-decimal, and hexadecimal number systems, and gives two algorithms. One shows how division may be performed only by iterative multiplication and addition by a computer to produce the quotient in a fraction of the time required for conventional long division of large numbers. The other is a square root algorithm.

Appendix B is a set of 30 laboratory exercises that illustrate the electronic principles in the text and prepare the student for independent ventures in the applications of electronics. Exercise 1 to 14 are digital exercises, which parallel the presentation of digital electronics in the first portion of the text. The next 11 exercises develop an understanding of analog electronics and the properties of operational amplifiers. Finally, 5 exercises illustrate unusual electronic possibilities and applications to measurements.

These exercises have evolved over several years with the help of student response. Each exercise contains the background and rationale for the exercise and raises points that relate the exercise to the material in the text.

Throughout the chapter discussions, rather than examining particular digital or analog electronic elements, we have restricted the presentation to the concept that the element satisfies. Thus, for example, the property of an AND-gate presented in the text is common to all electronic elements called AND-gates. Only in the exercises do we identify specific elements; there we use the simplest, most reliable, most useful elements, and perhaps the ones whose limitations may be uncovered most easily. From a practical standpoint we discuss in the text and illustrate in the exercises many of the difficulties that may arise when electronic elements are placed together to solve a logic, control, or measurement function.

The instructor's manual contains answers to the chapter questions and to the queries in the exercises and supplies additional technical details about the electronic elements used in the exercises. The manual also lists the instruments required for the laboratory exercises and includes suggestions for using the text and the exercises.

It is my pleasure to acknowledge the encouragement of Ernst Franke and many other colleagues and students and the very competent assistance of Patricia King and Karen Feinberg in the preparation of the text.

Warren Fenton Stubbins

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INTRODUCTION

The nature of electrical signals in electronic circuits readily enables the technology to be divided into classes. One of the classes is *analog* electronics; another is *digital* electronics. Both analog and digital electronics use similar electronic elements, but the manner of use is different, and the technologies appear to be quite distinct. For this reason we shall study them separately until we bring them together as they invariably unite in instrumentation and applications.

Analog electronics pertains to those systems in which the electrical voltage and electrical current are analogous to physical quantities and vary continuously. Electronic circuits that reproduce music must have voltages and currents that are proportional to the sound. A high fidelity amplifying system attempts to keep the analogy as true as possible. Analog electronic circuits are carefully designed to make the electrical voltages and currents follow the input signal. If an input signal doubles in amplitude, the output voltage or current also should double; this is possible because the circuit elements are made to operate within limits that preserve the linearity.

An electrical voltage that is proportional to temperature and changes smoothly as the temperature changes is an analog of temperature. If the temperature range is divided into small increments, however, and a numerical assignment is made to each increment, then the temperature may be indicated by a digital display. As the temperature (voltage) changes smoothly, a decision must be made by an electronic system as to the numerical value to be displayed as the temperature. The circuit making the decision is called an *analog-to-digital converter*, ADC. The inverse process is accomplished by a *digital-to-analog converter*, DAC.

Digital electronic circuits do not require the linearity of analog circuits. Digital circuits act as electronic switches and switch from one state to another. The output state, on or off, is the only signal condition to be examined. In digital circuits the output state is determined by the input signals in as direct a manner as the output voltage of an analog circuit is related to the input signal. In digital circuits the relation between input and output states are expressed as logic equations; the elements of digital electronics are called logic gates. Logic gates switch between states, on or off, very quickly so that they may operate at many megahertz in computers and other applications.

As technical developments continue to provide new and amazing integrated circuits, as they have since the 1960s, both analog and digital systems will be more capable. The designers of electronic systems using integrated circuits will have unlimited possibilities for innovation.

The topics that follow present the foundations of modern electronics. The technology can be comprehended only by emphases on basic electrical and electronic principles. We believe that by learning the basics the student can decipher modern electronics. The topics and the organization of the text were chosen for this purpose.

CHAPTER

1

BASICS OF DIGITAL ELECTRONICS

The approach to digital electronics is straightforward. The details of the involved electronic processes in the transistors and other circuit elements can be put aside, and the character of digital electronics can be revealed by the flow of the electrical signal alone. Taking this simplified approach, we can guide our efforts and illustrate digital technology with binary logic, which considers only two states: on and off.

We can approach the subject by this simplified route because the design of the electronic components and their combination as integrated circuits are the technological miracle of our time. We can compare our approach to digital electronics with that of a machine designer who carefully chooses among the available gears those that will meet his requirements, but does not concern himself with the design of the teeth on the gears. This approach is possible because of the invention of integrated circuits (IC) in 1958, their combination into the more complex medium-scale integrated circuits (MSIC), the still more complex large-scale integrated circuits (LSIC) in the 1970s; finally, the recent very large-scale integrated circuits (VLSIC) has brought this possibility to us.

To prepare ourselves to understand and use integrated circuits, we examine the three basic electronic elements with which all digital circuits are made and the binary logic they follow.

BINARY LOGIC

Binary logic is applied to the study of the state of a system in which the electrical signal is either present or absent. The presence of a signal is designated by 1 and the absence by 0, or by *high* and *low* or *on* and *off*, respectively.

In the actual digital circuits the condition 1 means the presence of a reasonable voltage, for example, 3 to 5 volts (V), while 0 represents a much smaller voltage, for example 0 to 0.5 V. The difference between 1 and 0 must be sufficient to allow no mistake in recognizing the state of the element, that is, 1 or 0. Such a relationship is called positive logic, in which the high voltage is associated with the 1. (Negative logic associates the 1 with the low voltage.) We will use positive logic throughout this work.

The voltages required in systems using integrated circuits are typically ± 12 and $+5$ V, but specific elements may require other voltages. Higher voltages are not generally required except perhaps for output devices. It is extremely important to stay within the rated voltages. For example, a slight overvoltage, such as 5.25 V for 5.0 V ICs, may be acceptable, but greater voltages may degrade the integrated circuits.

To say that an electronic element is in state 1 means that its *output* is near 5.0 V; in state 0, that its *output* is near the zero volt level. These two states are the only ones possible. Later we will consider an element that can be electrically disconnected so that its state is not involved in the binary logic. The element that can be electrically connected or electrically disconnected is called a tristate device: on, off, or electrically disconnected.

All digital circuits, from simple combinations of binary logic circuits to the most sophisticated computers, digital signal processing systems, and artificial intelligence devices are built of three basic binary elements. The three perform the equivalent of multiplication, addition, or negation (inversion). The flow of these voltage states through the binary logic elements constitutes the electronic process in computers and other digital systems.

Our purpose is to understand these three basic binary elements and to learn how they may be combined to serve any control, computational, decision, or other process we wish to implement.

ELECTRICAL EQUIVALENT

Although integrated circuits may contain many electrical circuit components, such as resistors, capacitors, diodes, and transistors, the circuit with binary logic is exactly equivalent to a simple electrical circuit composed of a fixed resistor and a variable resistor in series with the supply voltage across them. The output voltage is taken across the variable resistor. Figure 1-1 shows this simple arrangement.

We designate the fixed resistor by R_L because it is typically called the load resistor. By external control the variable resistor R may have its resistance changed to a value many times greater than R_L or to a value many times smaller than the