DIGITAL ELECTRONICS: Fundamental Concepts And Applications

CHRISTOPHER E. STRANGIO

DIGITAL ELECTRONICS: Fundamental Concepts And Applications

CHRISTOPHER E. STRANGIO

Lecturer,
Lowell Institute School,
Massachusetts Institute of Technology

PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey 07632*

Library of Congress Cataloging in Publication Data
Strangio, Christopher E
Digital electronics.

Includes index.
1. Digital electronics. I. Title.
TK7868.D5S77 621.3815 79-23183
ISBN 0-13-212100-X

Editorial production supervision
and interior design by: James M. Chege

Page layout by: Rita K. Schwartz

Manufacturing buyer: Gordon Osbourne

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall of Canada, Ltd., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

Library of Congress Cataloging in Publication Data
Strangio, Christopher E
Digital electronics.

Includes index.
1. Digital electronics. I. Title.
TK7868.D5S77 621.3815 79-23183
ISBN 0-13-212100-X

Editorial production supervision
and interior design by: JAMES M. CHEGE

Page layout by: RITA K. SCHWARTZ

Manufacturing buyer: GORDON OSBOURNE

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

PRENTICE-HALL INTERNATIONAL, INC., *London*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*
PRENTICE-HALL OF CANADA, LTD., *Toronto*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*
PRENTICE-HALL OF SOUTHEAST ASIA PTE. LTD., *Singapore*
WHITEHALL BOOKS LIMITED, *Wellington, New Zealand*

PREFACE

A *signal* is a means used to convey information from one point to another. It may be embodied as a visual, audible, electrical, or other variation that can be transmitted in an appropriate medium through space. Traditional electrical signals have been analog in nature, in which case an informational quantity, such as temperature, is proportionally related to an electrical parameter, such as voltage. *Analog signals* smoothly span a continuous range of voltage (or current), and are restricted only in the absolute limits of the range. In contrast, a *digital signal* is a numerically coded representation of an informational quantity, and is confined to a small number of discrete levels of voltage (or current). The majority of digital signals are binary coded, thereby limited to exactly two discrete voltage (or current) levels, and appear as a sequence of 'on'-'off' conditions (high or low voltages) on an electrical conductor. *Digital Electronics* concerns the generation, processing, and storage of digital signals, and establishes a framework for the analysis, design, and construction of digital systems.

The intent of this book is to convey the principle concepts of digital electronics, and offer a thoughtful, practical approach to digital circuit analysis and design. Digital computers comprise one specific branch of the digital systems tree, and are also discussed. Since this book is more particularly focused on the hardware issues, computers are introduced from this vantage point. As prerequisites, students should have had only a basic course in algebra, and some background in simple electrical circuits as might be found in an electric shop course or in introductory physics. Semiconductor circuit analysis is not involved. The expected audience is upper level technical school students, and college undergraduates specializing in any of the branches of engineering and science.

A teacher's greatest responsibility is to cultivate the student's ability to think. That philosophy is the theme of this book. Rather than present a catalog of techniques, a fewer number of carefully selected techniques are examined in detail, and applied to typical analysis or design problems. Answers to "Why?" and "How?" are deemed as important as those for "How to . . . ?" Above all, it is important that the student be equipped to assimilate new developments as advancing technology produces them. In this, the ability to think clearly about digital concepts is invaluable, and is strongly emphasized in the presentation.

Chapter One introduces the student to the essential concepts in digital electronics, and tries to establish a framework of thinking that will facilitate comprehension of the topics to follow. Although relays are used very rarely in modern digital systems, their basic simplicity is relied on here to permit a clear, understandable description of logic functions without forcing the student to understand semiconductor circuits, and without using the unconvincing "black box" approach to describe logic functions.

Chapter Two addresses Boolean algebra from the switching logic viewpoint introduced in Chapter One, and develops a useful set of Boolean properties. Some educators feel that the usefulness of Boolean algebra and Karnaugh map techniques is minimal at the present and will decline in the future. In this text, it is felt that the *method of thinking* developed in a study of Boolean algebra and related mathematical techniques is crucially important in perceiving efficient digital systems and in evolving simple minimal hardware solutions to design problems, even though certain specific techniques may not themselves be used frequently.

Combinational logic is the basis of all further chapters in this book, and is introduced in Chapter Three. A realistic, practical approach is integrated with the Boolean algebra concepts of Chapter Two to validate by use those symbolic techniques that have been presented. Karnaugh maps build further on the mathematical framework started with Boolean algebra, and are substantiated by application to problems with solutions that are not obvious.

In Chapter Four, binary digital computation is explained emphasizing the natural relationship between decimal arithmetic and binary arithmetic. The number circle is introduced as an adaptation of the number line, thereby accounting for the limited numerical capacity of all digital hardware. Octal and hexadecimal codes are explained to benefit those students intending subsequent study in the area of digital computers and microprocessors.

As the first formal presentation of memory elements, the flip-flop is carefully described in Chapter Five, using as the chief subject a latch. Building around the latch clocked flip-flops, monostables, and astables are described. Most importantly, the sections on applications bring together the key ideas behind flip-flops. The concept of a digital "module," such as a shift register or counter, becomes apparent, and their use as subsystems in an integrated digital system is explained.

In Chapter Six, a detailed examination of counters offers the first opportunity to examine the intricacies of timing and synchronization in digital circuits. The race problem encountered in decoding output states of a ripple counter motivates the synchronous counter. Generalizing the natural binary count sequence to an arbitrarily permuted one, programmed counters ease the student into the concept of a sequential circuit—a difficult topic thoroughly covered in the following chapter. Special purpose counters for timing and clock generation demonstrate how counters can be used for purposes other than just counting.

One of the most intriguing subjects in this book concerns sequential circuits, and is covered in Chapter Seven. The operation of a sequential circuit is not obvious from the logic diagram, but slowly unfolds as succeeding stages of analysis progress. The lack of obviousness in a sequential circuit's operation gives the designer the feeling that some primitive form of life has been created, and drives the curiousity to understand. Asynchronous sequential circuits are presented first primarily because they were historically developed first. The natural process of evolution in engineering design is taken advantage of by solving the race/hazard problem in asynchronous circuits with synchronous circuit design. Since the process of synchronous circuit analysis is virtually identical to that of asynchronous circuits, time is saved in presenting synchronous circuits, and the concepts of asynchronous circuits are reinforced.

Digital circuit fault analysis is discussed in Chapter Eight, and is a subject that has been, surprisingly, ignored in many texts. Experience has shown that students interested in other than a strictly theoretical knowledge of digital electronics, want and need an understanding of how a digital circuit can malfunction. Some basic concepts are presented that explain the effect of various circuit faults, and propose corrective actions.

As the cost of digital integrated circuits continues to fall, many electronic systems once relying exclusively on analog circuitry will be supplemented or replaced by digital circuitry. That transition, however, does not change the analog nature of many real-world signals. Consequently, the use of analog-digital conversion circuits to make actual signals amenable to digital processing must increase. Chapter Nine is one of the most important in preparing students for the future, as indicated by present trends. The principles of digital-to-analog and analog-to-digital conversion are presented, followed by detailed examples that illustrate some important applications.

Chapter Ten very carefully introduces the student to the concept of programmed logic. The idea of a computer is developed from the digital electronics basics presented in Chapters One through Seven, and is motivated by the need for complex and flexible digital processing. Simple program examples illustrate how the basic components of the computer's CPU interact to provide a functional processing unit. Algorithms are described, and some practical program examples demonstrate the usefulness of computers. Microprocessors are described as a specialized subset of the general purpose digital computer. The factors that have influenced microprocessor development are emphasized.

An appendix is provided with the company names and addresses of most of the major semiconductor manufacturers. This will assist those interested in obtaining data books and applications manuals on the latest technological innovations and logic families.

Several individuals have made invaluable contributions to this book, and have my deepest gratitude. I am particularly indebted to Rick Bahr and Eliot Moss for their consistent and devoted effort in technically reviewing the entire manuscript. These are two rare and talented engineer/scientists who have the unique combination of technical expertise and supurb command of the English language. In his reviewing the manuscript, Professor Tsute Yang of Villanova University has provided some fundamental suggestions that have greatly enhanced the pedagogical value of this book. For these suggestions, and for his time and patience, I am very grateful. My thanks also go to Ken Wacks for his review and comments in the final stages of this project.

CHRISTOPHER E. STRANGIO

Cambridge, Massachusetts

CONTENTS

1 LOGIC CONCEPTS

1.1 INTRODUCTION

1.1.1 Prelude

People make simple decisions every day. When to arise in the morning, when to eat, and whether to take an umbrella to work are thoughts that cross our minds frequently. Whenever decisions like this are made, one or more different factors must be accounted for, such as the time of day or the condition of the weather, before action is taken. Perhaps a number of conditions must exist to justify a decision, or perhaps a single condition might result in several decisions. Our upbringing has trained us to respond in particular ways to conditions of our environment, and we can do this now without conscious thought. Sometimes complex decisions must be made, such as in selecting an occupation or choosing a place to live. Such complex decisions involve many factors and must be carefully considered before a course of action is selected. In making important decisions that may have a permanent effect on our lives, we rely much less on our childhood training, and instead try to anticipate and understand the results a decision may bring. Our attempt to understand the effect of a decision requires that we analyze the situation and draw some kind of logical conclusion from the information available to us. Common to both simple and complex decisions is the act of drawing on an available body of knowledge, deliberating alternative courses of action, and finally selecting a course of action that will achieve a desired result.

As mankind has come to rely increasingly on machines to do work, certain elementary decision operations have become mechanized. A decision machine will accept inputs from human beings or other machines and respond according to a predetermined plan that is specified by the machine's design. A simple combination lock is an example of a decision machine. Appropriately turning the dial to the proper settings provides input information that results in the opening of a lock. If a setting is incorrect, the machine's design prevents the lock from opening. In the sense that the combination lock permits or prevents action based on input information, it is a decision machine.

Electrical circuits may also be used to mechanize decision operations. In an electrical circuit, though, the condition of switches, sensors, or other components modifies the flow of current in the circuit. Decision circuits in which only a limited number of fixed current or voltage values are possible, determined by the setting of switches or the condition of other components, are referred to as ***logic circuits***. The simple two-switch hall light is an example of an elementary logic circuit. In the same sense that we account for various factors when we make a decision, a logic circuit responds to the condition of switches or other components to cause a specified current or voltage in the circuit.

Our basic aim is to study logic circuits. In doing so, we will gain an understanding of their operation and be able to apply our knowledge to the practical solution of real problems. Many examples will be encountered to illustrate the principles and to reinforce important concepts in logic circuit analysis. We will see how simple electrical and electronic circuits can make decisions for us to provide services that would otherwise be difficult or impossible to obtain.

1.1.2 Historical Background

Logic circuits had their beginning well over one hundred years ago with the development of the railway signal interlock system in 1855. The increasing volume of rail traffic at this time required rail lines to be shared by a number of different trains, placing a heavy burden on dispatchers in scheduling track usage. Railway signal interlock switches prevented the dispatcher from incorrectly issuing a "route clear" message for a track that was presently in use. This early system did not of itself initiate action, but simply prevented erroneous action by the dispatcher based on the rule that no two trains should run on the same track at the same time.

Although refinements and sophistication were made in railway signal and control equipment, the great revolution in logic circuitry began in 1879, when the first patent on an automatic telephone switching system was issued to Connolly, Connolly, and McTighe. Because of increased telephone usage that overtaxed the capability of human operators to make circuit connections for each call, automatic systems were developed. This was particularly true in urban areas, where the number of telephones and constant business activity required many daily telephone connections.

Perhaps as significant as the invention of the telephone itself was the installation of the first completely automatic telephone exchange at LaPorte, Indiana, in 1892. The heart of this system was the Strowger step-by-step switch, an electromechanical device in which a movable arm advances on the command of dial pulses to one of many switch contacts. This selection process would proceed as each digit was dialed, energizing at each level another step-by-step switch, until connection with the called party was achieved. The Strowger switch is still used today in many small exchanges.

Logic circuitry, such as might have been found in early automatic telephone switching equipment, was developed long before the invention of the transistor. This early circuitry was built with various complex forms of electrically controlled switches, of which the Strowger switch was one. The modern relay is a descendant of the original electrically controlled switches and is widely used in high-current switching networks, such as in elevator control circuits. It is important to note, though, that for almost fifty years, logic circuit design techniques relied almost exclusively on intuition and experience, with no mathematical tools available to analyze circuit operation. Thus, with the exception of the simplest circuits, it was not possible to know with certainty whether an optimum design had been achieved.

A great stride was made in 1938, when Shannon presented a means of symbolically analyzing the behavior of switching circuitry. Shannon's work was closely related to a system of symbolic logic developed by George Boole in 1854. Although it was Shannon who revived the seemingly forgotten work of Boole, it was Boole's symbolic algebra that has survived improvement and refinement to become known today as "Boolean algebra." Indeed, even with the introduction of the transistor in the late 1950's for use as a switching agent, the representation of the new "electronic" logic circuits with Boolean techniques was still perfectly valid. This is because the Boolean representation of a logical function is independent of the physical means by which that function is made operational. Thus, we might have a transistor logic circuit that is faster, cheaper, quieter, and cooler than its corresponding relay logic circuit, but both will be symbolically represented in the same way with Boolean algebra.

1.1.3 Definition of Digital Systems

The word "information" can be defined in several ways. One definition that will be useful to us has "information" meaning "knowledge pertaining to something we wish to describe." For example, information about a particular radio receiver might indicate its frequency range, power requirements, and size. Information about the present environment might include temperature, humidity, ambient light, and air circulation. Electronic devices are almost exclusively used for *information processing*, as opposed to electrical devices, which are often used for energy conversion. Information processing means different things to different people; however, we will consider information processing to include the following operations:

1. ***Information translation.***
2. ***Information manipulation.***
3. ***Information storage.***

Traditional electronic devices, and historically the first, relied on ***analog information processing***. Specifically, a transducer would convert some quality of the environment, such as temperature, into an *analogous* corresponding voltage or current. This operation is the *translation* of environmental information into a proportional electrical quantity. The resulting electrical signal might then be converted to another electrical signal related in a well-defined way to the first. The new signal may, for instance, be an amplified version of the original signal. Operating on one electrical signal to produce another is information *manipulation* since the signal that is modified was initially made to correspond to information by use of the transducer. Finally, it may be necessary to store the resulting signal for future reference. To do so is information *storage*.