DIGITAL ELECTRONICS
Theory, Applications, and Troubleshooting

BYRON W. PUTMAN

DIGITAL ELECTRONICS Theory, Applications, and Troubleshooting

DIGITAL ELECTRONICS
Theory, Applications, and Troubleshooting

BYRON W. PUTMAN
Computer Facilities and Communications
University of California, Berkeley
Formerly with the Heald Institute of Technology

PRENTICE-HALL, INC., Englewood Cliffs, N.J. 07632

Library of Congress Cataloging in Publication Data

Putman, Byron W., (date)
Digital electronics.

Includes index.
1. Digital electronics. I. Title.
TK7868.D5P88 1986 621.3819'58 85-9363
ISBN 0-13-212481-5

Editorial/production supervision
and interior design: *Theresa A. Soler*
Cover designer: *Lundgren Graphics, Ltd.*
Manufacturing buyer: *Gordon Osbourne*

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-212481-5 01

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*
Whitehall Books Limited, *Wellington, New Zealand*

FOREWORD

During my years as a student I searched for instructors who taught in an orderly and logical fashion material that was directly applicable to my work in the electronics industry. Byron Putman was my college instructor for my digital and microprocessor courses. In his classes we learned not just what makes circuits work, but more important, what may cause them *not* to work. He taught theory that I see reflected and used everyday in the "real world." It is much easier to learn when you are taught not to memorize how something works, but to understand how it actually functions.

Understanding and good theory enable the student to "think things through." When the student runs into a new circuit or device, it is not a cause for thinking "I've never seen this before" and stopping at that point. Instead, the thought is "I've seen something similar before. If I stop and analyze this, I should be able to figure out how it works." Unknown quantities do not become brick walls impeding any progress; they are paths, new means of traveling from one point to another.

When I edited the manuscript version of this work, I was continually pleased to see exactly what I had enjoyed in Byron's lectures and lab sessions shining through in this book: a concise presentation, a logical progression, a building of ideas—one leading to another, practical applications, and thought-provoking troubleshooting questions.

Byron is uniquely qualified to write a text on digital electronics. He has a decade of experience in the Santa Clara Valley (known to the outside world as "Silicon Valley") as a technician, design engineer, technical writer, and college instructor. He not only effectively communicates his technical knowledge in this book, but also an infectious enthusiasm for the subject of digital electronics as well.

My own regret that this book was unavailable while I was a student is compensated by the opportunity to commend it here to a new generation of electronic technology students.

Ellen L. Lawson
The Thomas Engineering Company

ACKNOWLEDGMENTS

I would like to thank the following people and companies for their direct and indirect efforts to assist me in the creation of this text:

Dr. Mark Hawkins and Dr. Gene Sealbach of Foothill College, two of the very best instructors that I have had the pleasure to know. Dr. Hawkins, a model of support and enthusiasm, helped me gain the confidence required for a project of this length. Dr. Sealback introduced me to the concept of an intuitive approach to abstract subjects.

Ellen L. Lawson, who edited the manuscript and provided creative input and support.

Texas Instruments, RCA, Intel, and Data I/O for providing specifications, block diagrams, and pinouts.

Mark Diamond and Hanania Bolcover, two of my most memorable students, for providing the motivation to write this book.

Professor Roy Kratzer of Foothill College. One of the first educational professionals to fully understand the changing role of electronic technicians in the computer service industry.

Jim, Mack, Sparky, and Christopher of the CFO Engineering Lab at UC Berkeley. Simply for sharing their vast pool of technical knowledge.

Roger Lanser of Lockhead Missile and Space. For his keen technical insight and for occasionally forcing me out from in front of my computer and into Yosemite.

Peter and Linda. Peter for his technical assistance and for the photographs in this text. And Linda for her steady stream of somewhat cynical, yet very applicable criticisms.

And my cat, Hemuior, for keeping me company during those endless hours of development and execution.

A special note of thanks to the following group of reviewers for their incisive critiques and much-appreciated feedback: Robert A. Ciuffetti, GTE Sylvania Technical School; James W. Nice, ITT Technical Institute, Portland; Robert D. Carpenter, Wake Technical College; John L. Keown, Southern Technical Institute; Richard Prestopmik, Fulton-Montgomery Community College; Ralph E. Folger, Jr., Hudson Valley Community College; and Neal D. Voke, Triton College.

PREFACE

People seek an electronics education at technical institutes, junior colleges, and four-year colleges for a wide variety of reasons. The common motivation of these students is the desire to enter the job market with a valuable and marketable skill. This is not a book on digital circuit design; the major objective of this text is to prepare these students to enter the "real" world of modern industrial electronics with a background that will enable them to be productive electronic test technicians and troubleshooters from their first day on the job.

This text is built around the analysis, application, and troubleshooting techniques of the most widely used commercial digital integrated circuits. Flip-flop applications are constructed with MSI flip-flops, not handfuls of simple gates. Counter applications employ MSI counter ICs, not cascaded flip-flops. I have often had the frustrating experience of working with rece graduates who knew how to construct any divide-by-N counter with discrete flip-flops, but had never been exposed to a simple 74LS90 MSI counter. Full understanding and appreciation of digital devices can be accomplished only in meaningful, realistic applications and troubleshooting simulations.

This text is written in a manner that appeals to the student's intuition and previous knowledge. It was designed to be used and read, not carried to and from class as a three-pound obligatory parcel; all device pinouts, timing diagrams, and complete circuits are strongly supported by detailed explanations. Advance reading assignments will prepare the students to derive the maximum benefit from lecture. When the student graduates and enters industry, the most important sources of information will be manufacturers' data books and applications notes. The technician who graduates without knowing how to read technical material will not prosper or grow. On the contrary, that technician will be dependent on others for new and accurate information.

This text assumes that the reader has a solid background in basic electronics and transistor theory. The last chapter, which introduces data conversion techniques, also requires an elementary knowledge of op-amp theory.

Chapter 1 introduces the concepts of digital electronics and the binary number system. Number theory is held to a bare minimum. The introduction to the hexadecimal number system is deferred until Chapter 12. No concept is be introduced until it can be applied immediately to the material at hand.

Chapters 2 and 3 introduce logic gates. Most texts present this material in one chapter. They rely on truth tables and rote memorization techniques. An alternative to memorization is the concept of dynamic input and unique output levels. The logic symbol of each gate is used to describe its operation; memorization submits to understanding. Positive-logic and negative-logic symbols of each gate are equally stressed; the logic symbol selected to represent a particular gate will be that symbol which best represents the gate's function within the context of the circuit. This technique is known as "self-documenting design." It results in exceptionally readable schematics for both the engineer and the technician.

Chapter 4 illustrates applications of simple gates. Concepts of Boolean algebra and circuit-reduction techniques are not stressed. Instead, a structured intuitive approach to solving simple logic problems is developed. Several circuits are then designed, inspected, and simple troubleshooting procedures are considered. The circuits developed in Chapter 4 lay the foundation for the survey of MSI devices in Chapter 7.

Chapter 5 introduces the TTL and CMOS logic families. There is no doubt that LS TTL is still the dominate logic family in the electronics industry, but as CMOS technology continues to increase in speed, it will displace TTL in many traditionally bipolar applications. In the near future, the 74HC00 series of high-speed CMOS SSI and MSI devices and logic-gate arrays will dominate the market. This text has a balanced presentation of devices from the 74LS00 TTL series and the 4000B standard CMOS series. Most of the applications in this text use TTL devices because static sensitive CMOS ICs may not survive the rigors of the typical college electronics laboratory.

Chapter 6 is entitled "Troubleshooting Logic Levels." In an electronics production facility, well over 50% of the faults lie in printed circuit board problems or incorrectly stuffed components. This chapter closely examines the elements of the PCB and techniques of isolating shorts and finding opens. The material developed in this chapter is used as the basis of troubleshooting techniques in the remainder of the text.

Chapter 7 is a survey of the most popular MSI combinational devices. The function table and pinout of each IC presented are examined in great detail. Well-supported and highly entertaining applications are illustrated that are designed to reinforce operation of the selected devices. The chapter-end questions test the student's understanding of each circuit by considering the cause and effects of various troubleshooting problems.

Chapters 8 and 9 introduce sequential devices. The idea of feedback is employed to develop the extremely important concept of memory. Timing diagrams are the major vehicle used to illustrate the operation of sequential devices. Each event in the timing diagrams is carefully discussed. Selected applications are used to reinforce the operation of simple sequential circuits. The one-shot, an extremely important device that is often ignored in digital texts, is discussed in great detail. Once again, the chapter problems and questions revolve around troubleshooting the applications illustrated within the chapter.

Chapter 10 is entitled "MSI Counters and Shift Registers." This chapter puts it all together; simple gates, MSI combinational devices, flip-flops, and one-shots are integrated with a wide variety of counters to create moderately complex circuits. These applications are well supported with text and detailed timing diagrams. This is an extremely critical chapter. The applications in this chapter require that the students understand not only each device, but also the function that it provides within the context of the circuit system. Interesting, entertaining, and challenging applications are the keys that transform the student into a technician.

Three-state devices are used in bus systems and bus systems are controlled by microprocessors. Traditionally, the pursuit of three-bus architecture is left to a microprocessor class. This is a conceptual mistake. The stage is now set to introduce the microprocessor as the master of the bus. The microprocessor is illustrated as a device whose major function is to perform memory-read and memory-write operations. The microprocessor is introduced as a natural extension of complex MSI devices. The concept of bus systems creates the need for three-state devices. Chapter 11 establishes the three-bus architecture of microprocessor systems and surveys the major three-state devices. The hexadecimal number system is also introduced to support the memory-mapping techniques in Chapter 12.

Because Chapter 11 introduced the read and write cycles of the microprocessor and three-state devices, complete memory systems can now be examined. Chapter 12 creates memory systems from static RAMs, dynamic RAMs, and ROMs. The techniques of memory decoding and memory mapping are studied in detail. The major specifications of RAMs are illustrated in timing diagrams. Familiar TTL components are used to create a row-and-column address multiplexing circuit for dynamic RAMs. There is absolutely no need to wait for a class on microprocessors to introduce memory systems. Students who enter a microprocessor class with a complete background in digital devices and memory systems can concentrate their efforts on understanding the software/hardware interaction of intelligent systems.

No digital text is complete without a chapter on data conversion techniques. Chapter 13 discusses the major types of DACs and A/Ds. Converters are developed using previously examined digital circuits and op amps. Reviews of the current summing op-amp and op-amp integrator are included in the chapter.

Byron W. Putman

CONTENTS

1

INTRODUCTION TO DIGITAL

1.1 ANALOG AND DIGITAL SIGNALS

When most people are asked to name a waveform they think of the sine wave. The sine wave is the fundamental waveform; all other waveforms are derived from various phase and frequency combinations of the sine wave. Another common waveform is the square wave. Let's take a moment to contrast these two waveforms (see Figure 1.1).

The amplitude of the sine wave is continuously changing. Following that line of thinking, we can say that the amplitude of any given sine wave has an infinite number of possible values. These values will exist between the positive and negative peaks. The sine wave is an *analog* signal. The term "analog" refers to a waveform whose amplitude changes in a continuous fashion.

The amplitude of a square wave consists of only two values, a high value and a low value. These amplitude changes occur discretely, that is, in steps. The square wave is called a *digital* waveform. This book is devoted to the study of electronic circuits whose outputs have only two possible values. The use of the term "digital" indicates that a numerical value can be associated with each level of the waveform. Our decimal number system is based on the fact that human beings have 10 fingers. In essence, a square wave has only two "fingers." It should seem logical that digital electronics supports a base 2 number system. The digits

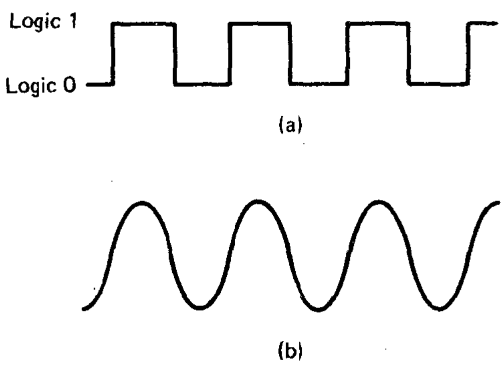

Figure 1.1 (a) Square wave; (b) sine wave.

in this system will be 0 and 1. The digit 0 will be assigned to the low part of the square wave and the digit 1 to the high part of the square wave.

The term "digital" is commonly used to describe a device that utilizes a numerical display. Watches, voltmeters, and almost any other device that one can imagine can be found with digital displays. Devices that use digital displays always contain digital electronic circuitry.

1.2 THE BINARY NUMBER SYSTEM

1.2.1 Number Bases and Counting

Because a square wave has two levels, digital electronics can be described by a base 2 number system. The base 2 system is called the *binary number system.* The base of a number system describes the number of unique digits in that system. In our decimal number system there are 10 unique digits, 0 through 9. In the binary number system there are two unique digits: 0 and 1.

All number systems, regardless of the base, function identically. We should take a moment and review the decimal number system. Most number systems operate with a *weighted code.* Weighted codes use place values. Refer to the following example.

What does the number 537 really represent?

$$\begin{matrix} 10^2 & 10^1 & 10^0 \\ 5 & 3 & 7 \end{matrix}$$

$$\begin{aligned} 10^0 \times 7 &= 7 \\ 10^1 \times 3 &= 30 \\ 10^2 \times 5 &= \underline{500} \\ & 537 \end{aligned}$$

Notice that the place value of the rightmost column is equal to the base raised to the 0 power. The next column's place value is equal to the base raised to the 1st power; the value of the last column is the base raised to the 2nd power. This process could continue indefinitely to represent a number of any size.

Consider the act of counting. We start with the first digit in the number system. This digit is always the number 0. Each time we increment the count, we will use the next digit in the system to represent the new, updated count. What happens when we run out of unique digits? When we use up all the digits in our number system, we must restart the counting procedure with the number zero. To assure that the objects we have already counted are not lost or forgotten, a *carry* will be generated. This carry will be added to the value in the next column.

Counting Table

	Comments:				*Decimal equivalent*
	2^3	2^2	2^1	2^0	
0000					0
+ 1					
0001				0 + 1 = 1	1
+ 1					
0010			0 + 1 = 1	1 + 1 = 0	2
+ 1					
0011				0 + 1 = 1	3
+ 1					
0100		0 + 1 = 1	1 + 1 = 0	1 + 1 = 0	4
+ 1					
0101				0 + 1 = 1	5
+ 1					
0110			0 + 1 = 1	1 + 1 = 0	6
+ 1					
0111				0 + 1 = 1	7
+ 1					
1000	0 + 1 = 1	1 + 1 = 0	1 + 1 = 0	1 + 1 = 0	8
+ 1					
1001				0 + 1 = 1	9
+ 1					
1010			0 + 1 = 1	1 + 1 = 0	10
+ 1					
1011				0 + 1 = 1	11
+ 1					
1100		0 + 1 = 1	1 + 1 = 0	1 + 1 = 0	12
+ 1					
1101				0 + 1 = 1	13
+ 1					
1110			0 + 1 = 1	1 + 1 = 0	14
+ 1					
1111				0 + 1 = 1	15

A decimal number is referred to as a *digit*. The term digit indicates one of the 10 fingers. A binary number is called a *bit*. The word "bit" is derived from the phase "*b*inary dig*it*." Notice the counting pattern. On every count the least significant bit toggles, 0 to 1 or 1 to 0. The next column toggles on every other count; the column after that, on every four counts. Finally, the most significant column toggles every eight counts. The fre-