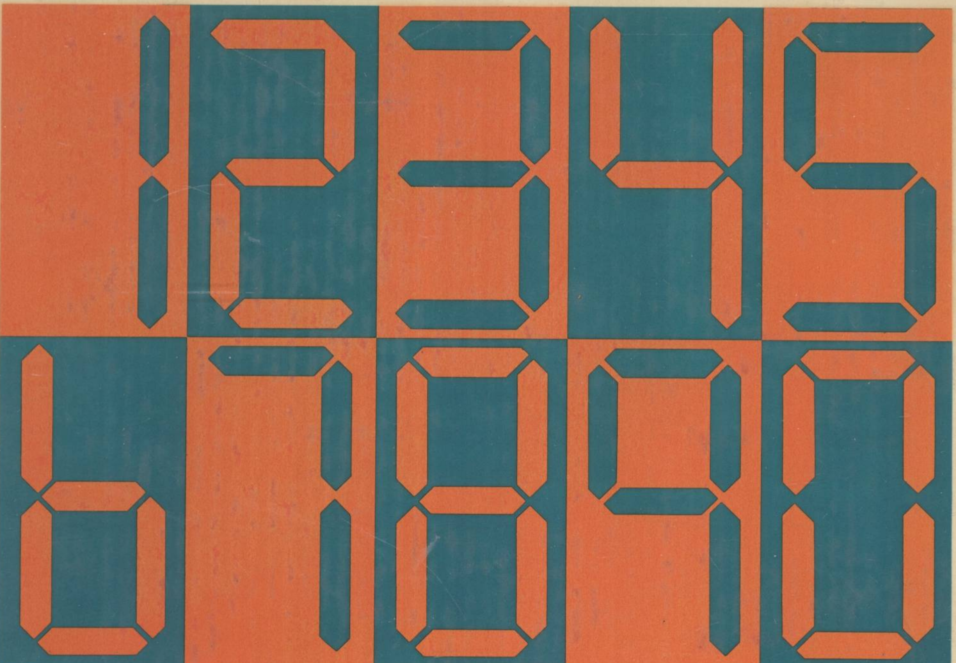
DIGITAL CIRCUITS



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PRENTICE-HALL, INC., Englewood Cliffs, NJ 07632

Library of Congress Cataloging-in-Publication Data

Muchow, Kenneth.
Digital circuits.

Includes index.
1. Electronic digital computers—Circuits.
2. Digital electronics. I. Zeppa, Anthony.
II. Deem, Bill R. III. Title.
TK7888.4.M83 1986 621.395 86-22602
ISBN 0-13-211996-X

Editorial/production supervision and
interior design: *Erica Orloff*
Cover design: *Wanda Lubelska Designs*
Manufacturing buyer: *Carol Bystrom*

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-211996-X 025

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*

PREFACE

Within the last decade there have been rapid technological advances in the computer field. The need for clear, comprehensive, and practical information on currently available digital devices has grown just as rapidly. The intent of this text is to close the gap between academic instruction and current industrial practices in digital electronics.

A thorough introduction to digital circuit concepts related to minicomputer and microcomputer applications is presented. Wherever possible, real off-the-shelf circuits are used in problems and examples.

This text is written for students in technical schools, community colleges, and universities and for electronics technicians currently employed in the field of digital computers.

Chapters 1, 2, 3, and 4 cover the basic concepts of number systems, arithmetic operations, Boolean algebra, and logic operations. Emphasis is on those concepts that are applied to practical examples. First-level logic circuits are discussed in Chapter 4.

Chapter 5 presents various logic gates emphasizing the TTL family. Hardware considerations begin with this chapter. The translation of concepts to real circuits is presented in Chapter 6. How to read and interpret logic circuits is presented in a special manner. Particular emphasis is given to communication by way of logic diagrams.

Because of the importance of understanding flip-flops, two entire chapters (7 and 8) are devoted to this topic. Latches, gated flip-flops, and master-slave flip-flops are discussed extensively so that the student will understand each of their characteristics.

Chapters 9 through 15 cover various MSI and LSI circuits. Chapter 9 is devoted to registers; Chapter 10 to encoders, decoders, and code converters; Chapter 11 to counters; Chapter 12 to timing; and Chapter 13 to arithmetic and logic units. Chapter 14 covers both MSI and LSI memory circuits. Chapter 15, titled "Interfacing," deals with the problems associated with interfacing circuits to minicomputer and microcomputer buses. Each topic or circuit is presented in a manner and to the depth that provide the student with the necessary insight to cope with the circuit in a real system.

To help the student master the subject matter, the text is illustrated with over 400 drawings, and many practical examples are worked out in detail. Numerous practical circuits using accepted (MIL SPEC) terminology and symbols are presented throughout the text.

We would like to express our appreciation to those companies who were very helpful in making available their application notes and circuits. Special thanks also go to the other members of the Electronics Department at San José City College and Evergreen Valley College who offered many valuable suggestions.

CONTENTS

1

SURVEY OF DIGITAL COMPUTERS

Computing devices were in use long before the advent of modern computers. The use of mechanical means to perform arithmetical calculations has always been one of man's goals. The first counting machine was probably the *counting board,* which consisted of several stiff wires or reeds on a wooden frame. Each wire had ten sliding beans—representing 0 to 9.

Perhaps the earliest known mechanical calculating device was the *abacus,* developed independently by both the Chinese and the Greeks over 4000 years ago. The abacus was the earliest known device that had the capability of denoting a *carry.* The abacus is still used today in China and Japan.

Around 1615, John Napier invented and published tables of logarithms. He devised ''Napiers Bones,'' which were numbered squares used in calculations. William Oughtred used Napier's logarithms in designing the first slide rule in 1621.

An important step in the development of ''computing'' machines took place in France in 1642: A 19-year-old inventor, Blaise Pascal, having tired of adding long columns of digits, designed and constructed an adding machine. Pascal's machine was composed of a series of gears, each with ten teeth to represent numbers 0 through 9. The gears were turned with a stylus, and when a 9 was reached, it automatically *carried* to the next gear. This same principle was still used in electromechanical calculators earlier this century.

In 1671, Baron Von Leibnitz constructed a machine called a *step reckoner.* Like Pascal's machine, it could add, but it could multiply as well. Twenty years later, Leibnitz improved his machine so that it could also divide and extract roots.

In 1725, Basile Bouchon, a Frenchman, invented punched paper tape for operating cloth-weaving machines. A roll of punched paper was moved past the needles so that only where a hole appeared was the needle allowed to pass through.

In 1801, another Frenchman, J. M. Jacquard, designed a system of binary coded cards for controlling looms. Both the punched paper tape and the punched cards are used today in modern computer systems.

In 1833, Charles Babbage invented a machine called the *analytical engine.* This machine was based on basic principles identical to those used in modern digital computers. Babbage was probably the first man to visualize a general-purpose computer complete with a programming scheme and memory units. He even made use of Jacquard's punched cards for input and output data. Unfortunately, Babbage's computer was never completed. The industry and technology of his time were not sufficiently advanced to produce the components with the necessary tolerances.

In 1854, George Boole, an English mathematician, published *An Investigation of the Laws of Thought on Which Are Founded the Mathematical Theories of Logic and Probabilities.* This work formed the basis of *logical algebra,* in which simple thought processes were represented mathematically. It is important to note here that Boole did not relate his algebra to mechanical or electrical devices.

In 1866, Dr. Herman Hollerith devised a method of recording data on punched cards. Because of the punched card, the 1890 census in America was completed in less than one-third the time required for the 1880 census. This system is sometimes referred to as the *unit record system* because data is stored as units on cards which can be used repeatedly.

C. E. Shannon, in 1938 at M.I.T., wrote a paper on how an electrical circuit consisting of switches and relays could be represented by mathematical expressions. The basic techniques developed by Shannon are required in the design of all types of switching circuits today.

Another American, Howard Aiken, designed the first general-purpose computer, the Mark I, a joint venture of Harvard University and IBM. This computer used electromagnetic relays and punched cards.

Among the leading contributors to modern computer technology were an electrical engineer, J. P. Eckert, Jr., and a physicist, J. W. Mauchley. In 1945 at the University of Pennsylvania, they completed the Electronic Numerical Integrator and Calculator (ENIAC). The ENIAC used vacuum tubes and was therefore the first all-electronic computer. It was wired to perform a specific sequence of calculations. If a different program was required, thousands of circuits had to be rewired because the computer was not able to *store* a program.

The ENIAC was a huge machine, weighing over 30 tons. It had 19,000 tubes and hundreds of thousands of resistors, capacitors, and inductors. It occupied 15,000 square feet of floor space and consumed almost 200 kilowatts of power. Nevertheless, it could perform 5000 additions per second. (Modern computers can perform millions of additions per second.)

In 1944, American Von Neumann began to develop the logical design of a computer capable of a stored program. The program could be changed at will—without the rewiring of the computer.

1.1 MODERN COMPUTERS

The first computers of the late 1940s and early 1950s used relays and vacuum tubes for their logic circuits. Power and tube failures were common. First-generation computers that were commercially available, such as the UNIVAC I, IBM 701, IBM 704, etc., used vacuum tubes. These computers were used essentially for single job operations.

With the advent of the transistor, second-generation computers were designed in the late 1950s. These were general-purpose computers—smaller, faster, and much more reliable. Integrated circuits (ICs) were used in the third-generation computers in the 1960s. Examples of third-generation computers are the IBM 360 series and the UNIVAC 1108.

Fourth-generation computers of the late 1960s to the 70s utilized solid-state medium-scale integration (MSI) and large-scale integration (LSI). Here, entire processing systems were fabricated on a single silicon chip.

One of the fastest and most powerful computers in use today is the CRAY-2. This computer is 40,000 to 50,000 times faster and its internal memory is 3000 to 6000 times greater than most personal computers. The CRAY-2 is capable of 1.2 billion operations per second, and it has an internal memory of 2 billion bytes. This machine is much faster than its predecessors due to the compact packaging of its components. Computer scientists expect to further increase the speed and the internal memory by the late 1980s.

1.2 ANALOG COMPUTERS

There are two general types of computers—analog and digital. An analog device is one whose operation is "analogous" to a mechanical or electrical quantity. It solves problems by using some mathematical model. For example, a mercury thermometer is an analog device: It compares the expansion of a column of mercury with the surrounding temperature.

Analog computers can be used in simulating the performance or characteristics of some future product. For example, the performance of a proposed new jet plane could be simulated by an analog computer long before actual construction begins. All of the design variables—such as wingspan, thrust, and other engineering data—could be fed into the computer, and the output would represent the performance characteristics. Any changes in input variables would immediately affect the output, thereby achieving the desired characteristics.

However, the accuracy of analog computers is limited. The reasons for this are the tolerance limitation of electronic components and our limited ability to read and interpret scales and graphs.

1.3 DIGITAL COMPUTERS

Digital computers operate on the numbers ONE and ZERO—the only digits in the binary number system. The computer can manipulate these digits at extremely high speeds and with great accuracy. High-speed computers can perform the addition cycle in less than 100 nanoseconds. Whereas accuracy in analog computers is limited, the limitation to accuracy in digital computers is the number of digits used. For example, if a number has 32 digits, the binary place accuracy obtainable is equal to 2^{32}.

1.4 WHAT A COMPUTER DOES

A digital computer is an electronic device that consists of input and output devices, arithmetic and control circuits, and a memory. Before the computer can do any work, a program of instructions must be supplied. These instructions are written by a programmer in a language that the computer "understands." This information can be put on punched cards, punched tape, or magnetic tape. A computer operator will sometimes sit at a console and simply type out the instructions. We therefore need to communicate with a computer through some appropriate input device.

The input data is then taken by the computer and translated or coded into some number code or machine language with which the computer can proceed to operate. After all the operations are completed, the coding process is "reversed" at the end, and machine language is translated back into a language we can understand.

Speed is an essential element of input and output devices, just as it is with the internal operation of computers. For example, some of these machines can "read" magnetic tape at a rate of hundreds of inches per second. Thirty thousand printed lines per minute can be reproduced by some output terminals.

Another characteristic of the digital computer is its ability to *store* information. The storage process involves taking the data received as input and "filing" it in a preselected location. This data may be retrieved when called upon, or it may be further processed and returned to storage at another location. The facility of storage is usually an electronic unit or device known as *memory*. The size of the memory may vary from a few thousand to many million binary digits.

Perhaps the biggest advantage of the computer is its ability to manipulate figures and symbols and to perform enormous quantities of arithmetic computations millions of times faster than any human—even one assisted by the slide rule, abacus, or adding machine. Calculations that would require months, and even years, can be done by the computer in a matter of seconds or minutes.

The arithmetic process is essentially one of addition or subtraction. Multiplication and division can be considered as rapid repetition of addition and subtraction, respectively. The arithmetic capacity of the computer is essential in many areas of modern technology. For example, the instantaneous computations involved in space flight make space travel a reality. Weather, census, insurance, etc., all require vast and rapid calculations of an enormous amount of data. The engineering designs of skyscrapers, bridges, and planes are made possible by the arithmetic capacity of the computer.

Another fundamental property of the computer is its ability to make a logical choice. The computer is capable of "comparing" two numbers and "knowing" whether they are equal or if one is greater or less than the other. The ability to compare and make logical choices allows the computer to select the next course of action. For example, suppose a program instructs the computer to add or otherwise calculate until a stated amount is reached and then stop. The computer will instantaneously compare the stated amount with the result of its calculations. When the two are identical, it will stop and go to the next instruction.

1.5 COMPUTERS AND MICROTECHNOLOGY

The number of components or devices per chip—a one-quarter inch square of silicon—has approximately doubled each year. It all started with one device per chip in the late 1950s, increasing to 32 devices by 1964. This was the era of SSI—small-scale integration. By 1969, 1000 components were being manufactured on a single chip, ushering in the era of MSI—medium-scale integration. In the early 1970s, microtechnology had advanced to a point where it was possible to have tens of thousands of devices and components per chip, called LSI—large-scale integration.

Chip designers and engineers perfected the VLSI—very large-scale integration—in the late 1970s and early 1980s. These chips contain hundreds of thousands of components. Currently, the industry is working on ULSI—ultra large-scale integration. These chips will contain millions of components and devices.

Some computer experts predict that by the end of the century, chips with one billion devices will be available. One of these chips would be able to do the work of one of today's large mainframes.

1.6 THE MICROPROCESSOR

During the late 1960s, a marriage took place between computer technology and LSI circuits. This resulted in 1969 in the development of the microprocessor. A microprocessor is actually a programmable integrated circuit. It is important to note that the microprocessor is not the entire computer, but contains logic elements necessary for manipulating data and performing various arithmetic and logic operations. In order to construct a complete functioning computer, the microprocessor must be augmented by several support elements such as memory, input/output devices, and other specialized functions. Computers-on-a-chip are currently available. They contain all the necessary circuits, including the processor, memory, and input/output circuits.

2

NUMBER SYSTEMS AND CODES

Numbers became important to man when he began to ask some basic questions: How much? How many? How far? How big? Number systems have developed as man's needs have increased. For example, certain tribes of aborigines in Australia used a system of numbers from 1 to 5. Since the needs of the aborigine were simple, he used a word meaning "plenty" for quantities greater than 5.

The early Romans, Greeks, and Egyptians used number systems in which symbols were used to represent numerical values. We are all familiar with Roman numerals where V means 5, C means 100, etc. The Egyptians used the symbol ∩ for 10. The symbol 𓍢 means 100. Zero was not a part of either of these systems. Furthermore, these systems were not "place value" systems; that is, the value for a given symbol never changed, regardless of its place or position in a given number. For example, in the Roman numeral IV, I means 1 and V means 5. When I appears before V, the number is 4 (5 − 1). For the numeral VI, I still has a value of 1, and V a value of 5; but the number has a value of 6 (5 + 1) because of the position of the numeral I. However, V always meant 5. It could never mean 50 or 500. The number 946 would be written as CMXLVI. Imagine performing mathematical operations of addition, subtraction, multiplication, and division with such a numbering system!

Our present number system was devised by Hindu mathematicians about 2000 years ago. Arabs began to use this system around 800 A.D. and introduced it to Euro-