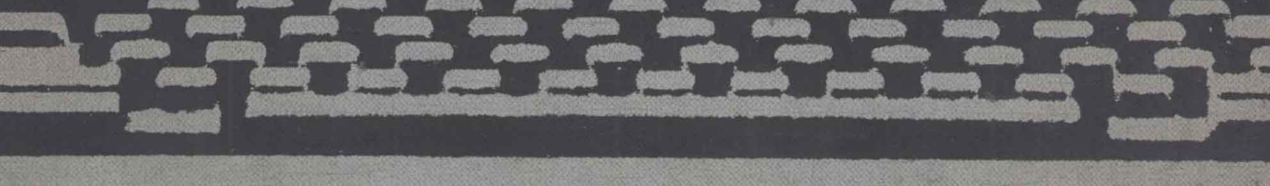
DIGITAL CIRCUITS AND MICRO-COMPUTERS



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PREFACE

Digital circuits have been important for many years, but their use dramatically accelerated in the 1960s with the development of integrated circuit technology. The circuits of this era were designed to implement the basic digital logic functions fundamental to all digital systems. These circuits, known as *random logic* circuits, are still used extensively and are of great importance. The most revolutionary recent development in integrated circuitry is the microprocessor, which performs the complex operations of a digital computer. The impact of this device on the field of electronics has been compared to that of the transistor in 1948.

The astonishing growth of integrated circuit technology has caused digital circuits to rival, in importance, the conventional analog circuits. In the foreseeable future, digital circuits will become of even greater importance. Thus there is a need for an elementary textbook which introduces fundamental digital circuit concepts, random logic design, microprocessors, and microcomputers. The primary purpose of this book is to fill this need in a manner that is easily understood by a beginning student with a background in high school algebra or its equivalent.

Before the microcomputer was in common use, random logic networks were required to be much more complex in many applications. Consequently, earlier textbooks on digital circuits presented elaborate design methods which are, in general, too difficult for the beginner. With the advent of the microcomputer, however, the emphasis on sophisticated circuitry is usually not necessary and the simpler design methods of this text are sufficient in most cases.

Chapter 1 presents a historical review of digital circuits and digital computers, including large-scale, mini, and microcomputers. Chapters 2, 3, 4, 8, and 10 contain the basic concepts of number systems, Boolean algebra, logic gates, codes, signed numbers, and complementary arithmetic. Chapters 5, 6, 7, and 9 are devoted to the design of random logic networks, such as combinational circuits, flip-flops, counters, and registers.

The final two chapters are devoted entirely to microprocessors and microcomputers. Chapter 11 deals with the architecture and hardware aspects of microcomputers. Chapter 12 concludes the book with microcomputer programming methods, known as software. An appendix for the Intel 8080 microprocessor is also included, as a supplement to Chapters 11 and 12.

To aid the reader in understanding the textual material, examples are liberally supplied and numerous exercises, with answers, are given at the end of virtually every section. Problems, some more difficult and some less difficult than the exercises, are also given at the end of every chapter.

There are many people who have provided invaluable assistance and advice concerning this book. We are indebted to our colleagues and our students for the form the book has taken and to Mrs. Marie Jines for the expert typing of the manuscript.

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1

INTRODUCTION

Digital computers have brought about a revolution in our everyday lives since their development in the 1940s. Consequently digital, or logic, circuits, of which computers and all other digital devices are examples, have become more important with each passing year. In the last quarter of the twentieth century digital circuits are becoming as important as the conventional analog circuits that have dominated electrical engineering since its beginnings. Many experts believe that before the end of this century, digital circuits will dominate the field.

Recent history has seen a number of revolutionary scientific developments: the automobile and airplane in the early 1900s, the radio in the 1920s, atomic power in the 1940s, television in the 1950s, and space travel and astronauts on the moon in the 1960s. Similarly, in its short history the digital computer has passed through a number of dramatic stages, beginning with the advent of vacuum tube computers in the 1940s, and continuing with the new generation of the 1950s, which used transistors, and the succeeding generation of the 1960s, employing integrated circuits. The 1970s is the age of the microprocessor–microcomputer, and this may well be the most revolutionary of all the computer eras. The microprocessor, a tiny integrated circuit containing hundreds of transistors on a single silicon chip, is the central data-processing unit at the heart of a microcomputer. Its development in the late 1960s and early 1970s is undoubtedly the most exciting technological event in electronics since the appearance of the transistor, in 1948.

The hardware of digital devices becomes increasingly sophisticated as vacuum tubes give way to transistors and transistors to integrated circuits and microprocessors; however, the basis for the hardware, the digital circuit theory, changes very little. A primary purpose of this book is to present the basic theory of digital circuits and the related theory of numbers and codes. We do this in Chapts. 2 through 10. Fortunately, the mathematics of digital circuitry is relatively simple, and our presentation assumes only a knowledge of elementary algebra.

The last two chapters are an introduction to microprocessors and microcomputers. Chapter 11 deals with the hardware of these devices, and Chap. 12 considers *software*, which is the programming of a sequence of detailed instructions for the computer to carry out.

1.1 Digital Circuits

Data, or information, takes many forms when it is stored, communicated, or processed. We may classify a set of data, or a signal, in two broad categories, *analog* and *digital*. An analog signal is usually a *smooth*, *continuously varying* one such as a column of mercury in a liquid thermometer. The height of the column varies continuously with temperature, and its value is *analogous* to the temperature.

An *analog device* is one that can manipulate, or *measure*, analog signals. The thermometer is one such device, and another example is a slide-rule, which measures a distance analogous to a number, and adds two distances which are analogous to two numbers being multiplied. Still another example is an analog electric circuit, such as a filter in a television set, which accepts a continuous wave signal of the desired frequency and blocks, or filters out, signals of other frequencies.

A digital signal is one that is by nature *discrete*, or *discontinuous*, such as a voltage that can only be either "high" or "low." Another example is the time of day as displayed by a digital clock, which indicates the time in whole minutes but does not indicate any fractional time between, say, 3:58 and 3:59.

A digital device is then one that processes digital signals. It may detect whether a signal is present or not, whether it is true or false, whether there is a punched hole in a card or not, etc. Examples are digital clocks (already mentioned), adding machines, and, of course, digital computers. Numerical values are represented by such devices as digits, which may be stored or displayed. We may say that the major difference between analog and digital devices is that the former *measures* and the latter *counts*. For instance, the digital counterpart of the analog slide rule (which measures) is the hand calculator, which displays digital answers.

In this book we will be interested in digital data that can change discretely from one to the other of two distinct states. We may characterize the two states in many ways, such as true or false, high or low, present or absent, etc., but we shall represent them abstractly by the digits 0 and 1. The digital devices we consider are digital circuits whose elements are so-called logic gates (which are themselves digital devices). The best known case of a digital circuit is, of course, a digital computer.

1.2 History of Digital Computers

Since humans learned to count they have probably been searching for devices to help in the process. One of the earliest such devices is the abacus, a mechanical calculator that has been used for 5000 years. It consists of a frame containing columns of beads strung on wires. The beads and their positions on the wires determine values of digits in a number. A person skilled in the use of an abacus can add, subtract, multiply, and divide with it faster than most mechanical calculators of today can perform these operations.

As far as digital devices go, the abacus had no competition until 1642, when the great French philosopher and mathematician Blaise Pascal (1623–1662) invented a mechanical calculator. Pascal's calculator, which may still be viewed in a French museum, had rotating gears and could be used to add and subtract decimal numbers.

Charles Babbage, an English mathematician and Cambridge professor, developed the idea of a mechanical digital computer in the 1830s. He designed and tried to build his device, which he called an "analytical engine," but because the engineers of Babbage's day could not meet the tight tolerances his plans called for, his machine was never completed (Fig. 1.1). However, Babbage's concepts can be found, with minor variations, in every digital computer built today.

In 1890 Herman Hollerith, a U.S. Census Bureau employee, conceived the idea of using holes punched in a card for the purpose of storing the census data to be processed by machines. Hollerith's ideas were used extensively with card-processing equipment for many years prior to the appearance of electronic computers. In the case of the latter machines, punched cards are, of course, a fundamental means of entering and extracting information.

In the late 1930s George Stibitz of the Bell Telephone Laboratories developed a computer using relays. His machine, called the Complex Calculator, was the first of several other relay computers developed during the 1940s and 1950s.

The first general-purpose computer was a relay machine called the Mark I, built by Howard Aiken of Harvard University in cooperation with the IBM Corporation. Aiken's computer, which became operational in 1944, used punched cards and could perform division in about 60 seconds.

The first-generation vacuum tube computers began with the Electronic Numerical Integrator and Computer, or ENIAC, developed by a team of engineers and mathematicians headed by J. P. Eckert, Jr. and J. W. Mauchly of the Moore School of Electrical Engineering of the University of Pennsylvania. The ENIAC, completed in 1946, contained over 18,000 tubes and was about 30,000 times faster than the relay Mark I computer.

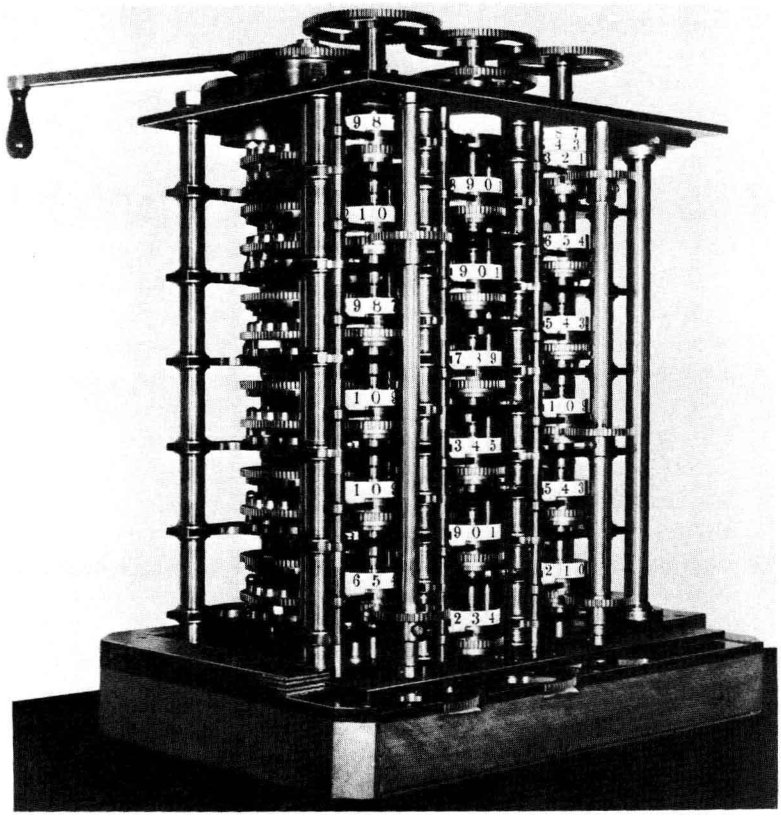

Figure 1.1 *Babbage's analytical engine (Courtesy, IBM)*

The most important computer advancement of the 1940s was perhaps the work of the American mathematician John von Neumann (1903–1957), who developed the idea of storing the computer program in the machine's memory. Earlier computers had used programs, but they were not stored in memory until the late 1940s, when von Neumann's idea was implemented. With stored program capabilities, the program may be changed at will without rewiring the computer; this, of course, is a great achievement in computer history.

We may divide computer history into roughly three generations, the first of which were the vacuum tube computers of the late 1940s and early 1950s. Some examples were the ERA 1101, built by Engineering Research Associates of St. Paul, Minnesota; the first UNIVAC (Universal Automatic Computer), built for the National Bureau of Standards by the Eckert–Mauchly Division of Remington Rand Corporation; the IBM 650; and the IBM 704.

The invention of the transistor in 1948 made possible the second generation of computers, in which transistors replaced vacuum tubes. These machines were smaller, faster, and much more reliable, the once common power and tube failures being things of the past. Some examples are the IBM 1401, the IBM 7090, and the Control Data Corporation's CDC 6600. As an example of the greatly increased speed and capabilities of the second-generation machines as compared to those of the first generation, we note that the CDC 6600 can perform more than 3 million instructions per second.

Around 1965 the production of third-generation computers began. These machines employ integrated circuits, which are miniature packages about the size of a typewriter letter containing hundreds of transistor circuits. As a consequence, third-generation computers are 100 times as fast as second-generation machines and are greatly reduced in size, with greater dependability. Examples are the IBM series of System 360 machines, General Electric's GE 600 series, RCA's Spectra 70 series, Burroughs Corporation's 5700, 6700, and 7700 machines, and IBM's System 370.

Minicomputers and microcomputers, which we discuss in the next section, are another new breed of computer that appeared in the late 1960s and early 1970s. They are integrated circuit computers and thus may be said to be of the third generation. However, they are radically different from their large ancestors and probably should be considered to be the fourth generation of computers.

1.3 Microcomputers

In the late 1960s and early 1970s the shrinkage in size of computers due to integrated circuit technology made it possible to have full-fledged computers that would fit on top of an office desk. The first of these computers, known as minicomputers, was the PDP 8, developed by Digital Electronics Corporation.

Minicomputers cannot perform the large tasks assigned to the big computers, such as the IBM 360 series, but they are faster and more powerful than many second-generation, and even third-generation, computers. To illustrate how far computer technology had come by this time, we might compare a minicomputer sitting on a desk with the ENIAC, mentioned in the previous section. The ENIAC had, as we have said, 18,000 vacuum tubes, it weighed 28 metric tons, and was the size of a six-room house; however, it did not have the capability or anything like the reliability of a typical minicomputer. The IBM Series/1 minicomputer (Fig. 1.2) is a good example.

Minicomputers, however, were just the beginning. The amazing decrease in size of the advanced integrated circuits, known as *large-scale integrated* (LSI) chips, started a new kind of computer revolution. The LSI chips were, in themselves, elementary computer components that served as subsystems for more complex computers. In particular, the basic ingredients of a computer, aside from the input–output devices (facilities for putting in and taking out data), are an arithmetic

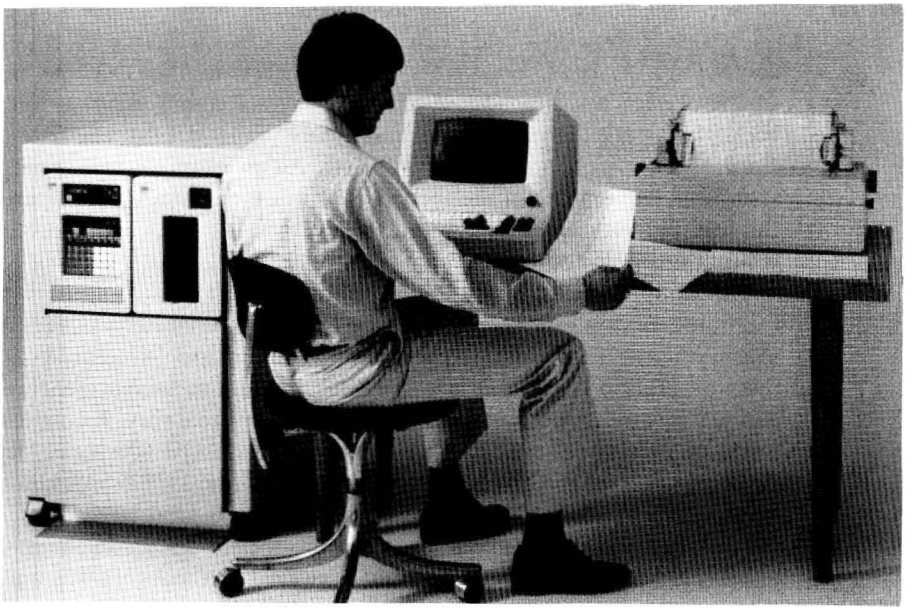

Figure 1.2 *The IBM Series/1 minicomputer (Courtesy, IBM)*

Figure 1.3 *The Intellec Series II microcomputer system (Courtesy, Intel Corp.)*