DIGITAL COMPUTER FUNDAMENTALS

Fourth Edition

Thomas C. Bartee

DIGITAL COMPUTER FUNDAMENTALS

Fourth Edition

Thomas C. Bartee
Harvard University

McGraw-Hill Book Company

New York St. Louis San Francisco
Auckland Bogotá Düsseldorf
Johannesburg London Madrid
Mexico Montreal New Delhi
Panama Paris São Paulo Singapore
Sydney Tokyo Toronto

DIGITAL COMPUTER FUNDAMENTALS

1 2 3 4 5 6 7 8 9 0 DODO 7 8 3 2 1 0 9 8 7

This book was set in Helvetica Light by Ruttle, Shaw & Wetherill, Inc.
The editors were Peter D. Nalle and Matthew Cahill;
the designer was Jo Jones;
the production supervisor was Leroy A. Young.
New drawings were done by J & R Services, Inc.
R. R. Donnelley & Sons Company was printer and binder.

Library of Congress Cataloging in Publication Data

Bartee, Thomas C
Digital computer fundamentals.

Bibliography: p.
Includes index.
1. Electronic digital computers. I. Title.
QA76.5.B297 1977 001.6'4 76-43336
ISBN 0-07-003892-9

PREFACE

The purpose of this book is to present, as clearly as possible, the principles of modern digital computers. Many questions are included in a separate section of each chapter, and answers to selected odd-numbered questions are given at the end of the book.

This edition of the book includes major recent computer developments such as microprocessors, floppy disk memories, large-scale integrated circuits, and microprogramming. As a result, a considerable amount of the book has been rewritten, and consequently there are also many new questions. Further, I have received a number of suggestions and comments from users of the book and these have been used to improve the presentation and coverage.

Chapter 1 describes the uses of the computer in business, industry, and science, and it also presents a brief introduction to programming. Some historical material is also included, as are some basic concepts relating to computer usage.

Chapters 2 through 5 introduce some of the basic ideas and principles which are used in all digital computers and also in digital instruments, digital communications systems, digital control systems, and in fact in all digital devices. These chapters describe number systems, Boolean algebra, logic design, and the major digital circuit lines. The sections on counters and, in general, logic design using flip-flops have been expanded into a complete chapter. The material on digital circuits has been updated, and the major new circuit advances have been included.

Chapters 6, 7, and 8 treat arithmetic operations, memories, and input-output devices. The material on arithmetic operations first explains how arithmetic is performed in computers and then how arithmetic-logic units in computers are organized. The chapter on memories presents magnetic core and integrated circuit memories followed by drum, disk, tape, and other mass storage devices. The latest developments in this area, such as tape cartridges, floppy disks, dynamic integrated circuit memories, etc., are included here. The chapter on input and output describes the major input-output devices and also includes some material on analog-to-digital converters, digital-to-analog converters, terminals, modems, and acoustic couplers.

The final two chapters, 9 and 10, first discuss the control unit in modern computers, including a description of both conventional logic design of control circuitry and microprogramming for computer control. The overall organization of computers is then discussed, as are the major topics in computer architecture—addressing techniques, bus organization, interrupt servicing, etc. Existing computers are used as examples of the ideas presented. There is some emphasis on microcomputers and minicomputers, but the basic ideas in large systems, such as multiprocessors, pipeline computers, multiprogramming, etc., are also discussed.

The book is arranged so that the material on electronic circuits can be skipped over. There are several reasons for this. In some schools, circuits are covered in a separate course. Other schools wish to treat circuit material lightly, since an understanding of circuit details is not essential to comprehending the functions performed by the circuits. Also, the widespread use of integrated circuits makes it possible to study the operation of a computer from a module, or block, viewpoint, as in Chapters 3 and 4, so that computer operation can be understood by considering flip-flops and gates from a functional, or operational, viewpoint.

The block diagram symbols in this book are those which have been adopted by the American National Standards Institute and also as Military Standards.

I have had considerable help and advice during the preparation of the various editions of this book. The first edition was written at MIT Lincoln Laboratory, and I will always be indebted to MIT and the laboratory members for the considerable support provided me.

Many friends and users of the book have contributed to later editions. I regret that I cannot name them all. Certainly Professors Glen Goff, W. W. Peterson, Robert Carroll, Irving Reed, and Irwin Lebow should be singled out. I must also thank the teaching assistants in my courses for their many suggestions.

Ms. E. M. Vadeboncoeur prepared the manuscript for this edition, and I am permanently indebted to her for her work on both this and prior editions.

Thomas C. Bartee

CONTENTS

1 COMPUTER OPERATION

The computer industry continues to be the fastest-growing major industry. The sales of large computers increase every year, and the size of the overall computer industry has been further supplemented by the booming minicomputer market and the introduction of microcomputers to the market.

Minicomputers and microcomputers make possible exciting new application areas for computers because of their low cost, reliability, small size, and low weight. These small computers are able to calculate at a rate of hundreds of thousands to millions of operations per second and offer computing power which was available in only the larger computers as recently as 10 years ago. The places where small computers can be used appear endless: such areas as process control; medical monitoring; production testing; scientific instrument recording; store checkout systems; and automobile test and evaluation systems were among the first to appear.

Well over a million people now work in the computer industry, and this does not include the millions who work with computers indirectly, such as bank clerks who put all their transactions into computers, airline and motel employees who work with computers to make reservations, and machinists who use computer-controlled power tools.

In fact, computers now route our long-distance telephone calls, process and issue the checks in our banks, schedule our planes and trains, make our weather forecasts, predict and process our elections, and figure in so many things that entire books will be (and have been) written just documenting the types of applications.

Computers now use the major share of the electronics components being manufactured, and this share will continue to rise. The need for computer personnel in all areas continues pressing: over a quarter of a million new programmers are needed each year; the federal government's Department of Labor continues to maintain business machine service personnel and electronic computer operating personnel in first and second place in a list of five "fastest-growing employment areas."

1 • 1 CALCULATORS AND COMPUTERS

From the time individuals first started using arithmetic, they have been inventing devices to aid in handling numbers. One of the earliest and most ingenious examples of an aid to computation is the abacus. This primitive (4000 to 3000 B.C.) predecessor of modern computers consists of a rectangular frame carrying several parallel wires. Each wire supports a number of beads which are free to slide along the length of the wire. The Romans called these beads *calculi*, the plural of *calculus*, meaning pebble. This Latin root gave rise to our word "calculate." By manipulating the beads, a skillful operator can add, subtract, multiply, and divide with amazing speed. In a contest between a Japanese proponent of this ancient invention and the trained operator of a modern manually operated calculating machine, the abacus won easily. Science will have the last word, however, for the computers described in this book perform operations several million times faster than the best of the abacus experts.

Calculating machines, including such familiar devices as adding machines, desk calculators, and cash registers, were invented more recently. The first successful mechanical calculator was constructed by Blaise Pascal in the seventeenth century. It was completed in 1642, and authentic models are still in existence. The primary conception which this machine introduced was the mechanization of the carry. The machine consists of a series of numbered wheels, or dials, each numbered from 0 to 9 and arranged to be read from left to right. When one of the dials passes from 9 to 0, a ratchet causes the wheel on its left to be moved one unit forward. The machine adds and subtracts directly, but multiplication and division are accomplished by repeated additions and subtractions.

In 1671, Leibniz constructed a calculating machine which could not only add and subtract but also multiply. Addition and subtraction were accomplished in the same manner as in Pascal's machine, but additional gears were included which enabled the machine to multiply directly.

Leibniz commented that although the device was not completely automatic, the slight effort involved in using it was certainly preferable to the tedious and often erroneous procedures required in manual arithmetic. The calculator designed by Leibniz was the model for most later machines and embodied almost all the principles now used in the design of calculators.

As business techniques and science progressed, the need for the mechanization of simple arithmetic operations increased. The amount of arithmetic done by business concerns increased vastly and became far more complex, and bookkeepers increased in number, as did all types of white-collar workers. The paper work required to manage government functions efficiently also reached staggering proportions. For instance, it took so long to process the data gathered during the United States government census that the information was not available in a convenient summary form until after it had lost its timeliness. The problems of the Bureau of the Census are so acute that it became the developer of the punched card, using punched cards for its tabulating as early as the 1890s.†

In the fields of science and engineering, many problems were being reduced to mathematical expressions which were so complex that it took a prohibitive amount of time to perform the arithmetic necessary to evaluate them for the various sets of parameters. For example, when the mathematical formulas describing the flight of an artillery shell along a ballistics trajectory were first known with considerable accuracy, the solution of these formulas (involving many different gun-elevation angles, distances, etc.) required the services of a large staff of human computers for long periods of time. Further, the tables had to be recalculated for new types of shells and weapons. This often introduced a lag from the time weapons became available until they could be accurately used.

Fortunately, the calculator was progressing also. Improvements in design and construction increased the speed and the number and variety of operations which could be performed by these devices, and at the same time improved manufacturing techniques made them more readily available. In early models, hand cranks were replaced by electric motors, and the speed of calculation was increased. Numerous aids to the operator were also introduced, thus increasing the speed of computation and decreasing the chances of error. Various types of desk calculating machines were common, and most business arithmetic was performed by these devices.

The final step in calculator development came with the introduction of electronic calculators. The speed of these devices is electronic—not mechanical—and in the larger models, there are even small electronic memories or sometimes tape strips or metal cards which can store short "programs" containing instructions to the calculator. The calculator can then perform these short programs at electronic speeds at the will of the operator.

The fact remains that the data (generally numbers) operated on must be inserted by the human operating the calculator. The remarkable functions provided by electronic calculators greatly help but do not remove the need for computers.

For instance, many computers operate on large files of data which are stored in computer memory devices, such as magnetic tape or disks. These data would occupy many filing cabinets and it would take human operators long periods of time to find items in these files. The computer, however, can search these files, often in fractions of a second but occasionally in seconds, and find and update records automatically. For instance, the larger banking computers contain millions of records relating to customers' accounts. All transactions made in the branches of a large bank must be recorded and the

† Herman Hollerith, who developed the punched card for the Census Bureau, later formed his own company, which still later was incorporated into IBM.

appropriate records updated at the end of each day. The computer can accomplish this automatically, and banks and insurance companies are large users of computers as are businesses which use computers to maintain their inventories, such as large grocery chains which use computers to order automatically, to bookkeep their operations, etc.

Computers are used to control production devices in industry, monitor the operation of industrial processes, and help set type for newspapers and books; they perform many functions automatically and often at speeds and with accuracy and precision not possible for humans.

For scientific applications, some calculations are extremely complicated and long, requiring hundreds of millions of calculations. The speed and lack of errors in computer calculations make computers ideal for performing these calculations. Often scientific calculation involves large amounts of test data (from satellites or nuclear experiments or from medical laboratories, for instance). These data must be analyzed using mathematical techniques which require many calculations. While such calculations could be performed on electronic calculators, the amount of human effort and time required would make the cost of such calculations prohibitive.

1 • 2 DIFFERENCES BETWEEN DESK CALCULATORS AND COMPUTERS

The basic difference between the automatic digital computer and the electromechanical and electronic calculator is that the computer performs *long* sequences of computations without human intervention and generally has a memory of some size. Also, the input data are generally read automatically. The computer can also make certain logical decisions and alter its future actions as a result of these decisions, sometimes changing the way it proceeds through the input data.

The sequence of instructions which tells the computer how to solve a particular problem is called a *program.* The program tells the machine what to do, step by step, including all decisions which are to be made. It is apparent from this that the computer does not plan for itself, but that all planning must be done in advance. The growth of the computer industry created the need for trained personnel who do nothing but prepare the programs, or sequences of instructions, which direct the computer. The preparation of the list of instructions to the computer is called *programming,* and the personnel who perform this function are called *programmers.*

1 • 3 ELECTRONIC DIGITAL COMPUTERS

The history of attempts to make machines which would perform long sequences of calculations automatically is fairly long. The best known early attempt was made in the nineteenth century by Charles Babbage, an English scientist and mathematician. Babbage attempted to mechanize sequences of calculations—eliminating the operator and designing a machine so that it would perform all the necessary operations in a predetermined sequence. The machine designed by Babbage used cardboard cards with holes punched in them to introduce both instructions and the necessary data (numbers) into the machine. The machine was to perform the instructions dictated by the cards automatically, not stopping until an entire sequence of instructions had been completed. The punched cards used to control the machine had already been used to control the operation of weaving machines. Surprisingly enough, Babbage obtained some money for his project from the English government and started construction. Although he was severely limited by the technology of his time and the machine was never completed, Babbage succeeded in establishing the basic principles upon which modern computers are constructed. There is even some speculation that if he had not run short of money, he might have constructed a successful machine. Although Babbage died without realizing his dream, he had established the fundamental concepts which were used to construct machines elaborated beyond even his expectations.

By the 1930s punched cards were in wide use in large businesses, and various types of punched-card-handling machines were available. In 1937 Howard Aiken, at Harvard, proposed to IBM that a machine could be constructed (using some of the parts and techniques from the punched-card machines) which would automatically sequence the operations and calculations performed. This machine used a combination of electromechanical devices, including many relays. The machine was in operation for some time, generating many tables of mathematical functions (particularly Bessel functions), and was used for trajectory calculations in World War II.

Aiken's machine was remarkable for its time, but limited in speed by its use of relays rather than electronic devices, and by its use of punched cards for sequencing the operations. In 1943, S. P. Eckert and J. W. Mauchly, of the Moore School of Engineering of the University of Pennsylvania, started the Eniac, which used electronic components (primarily vacuum tubes) and was therefore faster, but which also used switches and a wired plug board to implement the programming of operations. Later, Eckert and Mauchly built the Edvac, which had its program stored in the computer's memory, not depending on external sequencing. This was an important innovation, and a computer which stores its list of operations, or program, internally is called a *stored-program computer*. Actually, the Edsac, at the University of Manchester, started later but completed before Edvac, was the first operational stored-program computer.

A year or so later, John Von Neumann, at the Institute for Advanced Study in Princeton, started the IAS in conjunction with the Moore School of Engineering, and this machine incorporated most of the general concepts of parallel binary stored-program computers.

The Univac I was the first commercially available electronic digital computer and was designed by Eckert and Mauchly at their own company, which was later bought by Sperry Rand. The U.S. Bureau of the Census bought the first Univac. (Later Univac and half of Aiken's machine were placed in the

Smithsonian Institution, where they may now be seen.) IBM entered the competition with the IBM 701, a large machine, in 1953, and in 1954 with the IBM 650, a much smaller machine which was very successful. The IBM 701 was the forerunner of the 704–709–7094 series of IBM machines, the first "big winners" in the large-machine category

There were quite a few vacuum-tube electronic computers available and in use by the late 1950s, but at this time an important innovation in electronics appeared—the transistor. The replacement of large, expensive (hot) vacuum tubes with small, inexpensive, reliable, comparatively low heat-dissipating transistors led to what are called "second-generation computers," and the size and importance of the computer industry grew at amazing rates, while the costs of individual computers dropped substantially.

By 1965 a third generation of computers was introduced. (The IBM Corporation, in introducing their 360 series, used the term "third-generation" as a key phrase in their advertising, and it remains as a catch word in describing all machines of this era.) The machines of this period began making heavy use of *integrated circuits* in which many transistors and other components are fabricated and packaged together in a single small container. The low prices and high packing densities of these circuits plus lessons learned from prior machines led to some differences in computer-system design, and these machines proliferated and expanded the computer industry to its present multibillion-dollar size.

Fourth-generation machines are less easily distinguished from earlier generations. There are some striking and important differences, however: The manufacture of integrated circuits has become so advanced as to incorporate thousands of active components in volumes of a fraction of an inch, leading to what is called medium-scale integration (MSI) and large-scale integration (LSI). This has led to small-size, lower-cost, large-memory, ultrafast computers. Large computers have become increasingly complex; medium-sized computers now perform as large computers of the near past did; and there is a new breed of computers called microcomputers and minicomputers which are small and inexpensive, are manufactured by many different companies, and are proliferating at a surprising rate.

1•4 APPLICATION OF COMPUTERS TO PROBLEMS

Large office forces have for many years been employed in the accounting departments of business firms. The clerks employed by these businesses spend most of their time performing arithmetic computations and then entering their results into company books and on paychecks, invoices, order forms, etc. Most of the arithmetic consists of repetitious sequences of simple calculations which the clerks perform over and over on different sets of figures. Few decisions are required, rules having usually been defined covering almost all problems which might arise.

A typical task in a payroll office is the processing of paychecks for com-