DIGITAL COMPUTER PRINCIPLES

by

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PREFACE

This book is for the beginner. No previous acquaintance with computers, electronics or mathematics is necessary.

The material is organized so the intelligent layman can approach the complexity of digital computers in short, easy steps. However, the book is not for the casually curious or the coffee-break readers. The reader must have sufficient interest to be willing to digest many new ideas which are not similar to common experience.

There are already many excellent books and magazine articles on this subject. Unfortunately, it is difficult for the beginner to read most of them. This text is intented to lessen the stretch toward these publications for the person having no related technical background.

The text was developed for a training course at The National Cash Register Company's Electronics Division, evolving gradually over a year or so, starting in 1956. Earlier Division courses tended to concentrate on specific topics or to be directed toward groups of individuals who had similar backgrounds. This new course was of more general interest for all who had a need to know something of computers, even though their backgrounds were widely different.

Many books proceed from a general description to the details. However, in this book I have chosen to start with the details and synthesize a general system. The former approach is perhaps the better when one is considering a familiar topic, like an automobile. The author can begin with a description of the exterior of an automobile and gradually work into the engine and transmission, explaining what the various parts do. The approach is reasonable because the minor assemblies are made from familiar parts like wheels, gears, nuts and bolts.

However, when the basic building blocks are themselves new and strange, this method is questionable. It is not very helpful in explaining a flabajab to state that it is made up of thingamabobs and jimacoils interconnected so as to wigglewaff properly. In learning the subject myself and later presenting it to the class, I found it preferable first to develop each of the minor points which must later be combined into new concepts. The method has been put to the test and has stood up well.

More emphasis has been placed upon symbolic logic than any other subject. Some chapters in that section, in particular the chart methods for simplifying Boolean expressions, may not be of interest to many readers and can be skipped without impairing their understanding of later material. However, the distinguishing characteristic of digital computers compared to most other products is the extent to which their behavior must be described in a very rigorous logical manner. Since these basic ideas will be completely novel to most readers, the logical topics have been treated more extensively.

Throughout the text, the emphasis is on principles. They are illustrated with examples of circuits, devices and systems. Naturally, the examples have been selected from among those with which I am familiar. No implication is intended that these methods are better than alternate methods, or have been widely marketed, or are especially significant in any other way. They are merely convenient to illustrate the points being discussed.

Because the book grew out of our own Division need, many of the examples have been selected from our own experience. However, the book samples the techniques used throughout the industry, including a great number not of current interest to this company. For example, the abstract symbols for logical circuits, employed as a convenience in this text, are not widely used at the Electronics Division, nor do we have much interest in electronic tube or relay logic, Williams tubes and various other topics. Concepts developed independently by NCR include the flow diagram approach to design, the mechanizing of this concept with a control core matrix, the magnetic rod, the experimental magnetic printer, the transistorized "exclusive-or" circuit, and the system of core logic discussed near the end of the book.

The text is concerned primarily with the nature of things rather than their significance. The manner in which a device operates becomes a fact of history and does not alter, although it may be replaced by other models. On the other hand, the importance of a technique or device can change radically in a very short time. A new development in research may make the whole concept obsolete. A reduction of manufacturing cost may suddenly change an idle notion to a best-selling unit. Therefore, I have stayed away, for the most part, from interpretation, concentrating instead on the factual situation.

The number of people to whom I am indebted for assistance is almost legion. Many staff members explained technical points to me, and class members influenced the material by their questions and suggestions. Also, several Division executives have energetically supported the publication endeavor. And, of course, without the publications of other authors I could never have grasped the subject. It is my hope that this book will aid in the indoctrination of new students of the digital art, so that these other publications may enjoy an even wider readership.

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INTRODUCTION

On an isolated concrete pad, a slender rocket stands erect, pointed toward the blackened sky. A sudden, surging brilliance engulfs its base and giant engines lift it screaming into the upper atmosphere and the void beyond. In systematic procession, the earlier stages drop away until only the final stage and its satellite continue to accelerate. At a precise moment the final stage blasts loose, and the satellite begins its lonely, unending circling of the Earth.

On the ground men cluster around cabinets of electronic circuitry. Several moments pass tensely, and then from the computer comes the answer for which they have been waiting. The satellite is successfully in orbit, following the path described by the printed figures.

Under the Artic icecap a submarine moves silently. For days it has been beneath the surface of the sea without conventional navigational aid. Ahead of it lies a long, arduous journey before once again it can surface upon open water. Within the submarine, small changes of voltage and current proceed from circuit to circuit at incredible rates, rearranging, questioning, calculating. The navigator interprets his instruments and records the exact position of the vessel in the ship's log.

In a large department store a boy delivers several spools of paper tape to the data processing center. The spools contain the record of sales of the shoe department. In the processing center, information on the spools is converted to electronic impulses and fed into attractive cabinets. More spools arrive from the other departments, and soon the departmental sales have been totaled, records of individual sales persons reported, inventories corrected, short-supply items reordered, and the trend of sales interpreted for management.

These examples are instances of digital data processing and computing, a relatively young but enormously important portion of the electronic industry. With its related field of analog computation, digital processing permits the extremely rapid calculating and control which is an absolute essential for many scientific, military, and business applications, and is a great convenience for a host of others.

This book is an introduction to some of the aspects of digital processing. While relating to the digital field generally, the book is confined to the general-purpose computer. The selection of the general-purpose computer was made because it can operate upon an arithmetic problem in much the same way that humans ordinarily solve arithmetic (although this is not the only way it can solve problems). Therefore, the reader can concentrate on how the computer operates without concerning himself with mathematical techniques with which he may be unfamiliar.

A general-purpose computer is not the only type of computer manufactured. There are a great number of special-purpose computers which have important applications. These special-purpose machines are intended to be most efficient for particular data-processing tasks (with due allowance for the cost which can be justified and the engineering techniques known at the time of design). They may not be capable of other tasks. On the other hand, a general-purpose computer is capable of performing any type of calculation whatsoever, with some sacrifice of efficiency or speed on certain types of problems. A knowledge of it is helpful in understanding other digital systems.

The discussion begins, after a short explanation of basic digital notions, with the nature of the computing task, proceeds next to methods of precise description, then to elementary electronic parts and circuits, subportions of a computer, a complete machine system, operation by a human operator, machine errors, and some present trends in development. It is shown in the examination of the computing task that certain options are available to the designer in regard to the particular mathematical methods to be employed by the computer. The section on symbolic logic explains methods for describing electronic circuits, and the activity they are to perform, without confusion of meaning. It also shows some techniques for simplifying such descriptions mathematically, thereby permitting a complex machine to be designed systematically and efficiently.

The various sections on electronics discuss the essential internal functions of a computer, its over-all operation as a unit, and the manner in which it communicates with its exterior world. The examples of electronic devices and system concepts, although being only a sampling from among the many which exist, are reasonably representative of those employed in completed machines or considered in experimental projects, and illustrate that there is ordinarily more than one way to accomplish a desired result. Similarly in the discussion of the preparation of instructions, examples are given for different types of computers. Codes and processes for reducing the opportunity for undetected machine error are described briefly, as are some of the trends and additional technical developments which are of considerable interest within the computer industry.

DIGITAL VERSUS ANALOG

A digital processor is distinguished from its analog counterpart by the manner in which it represents numbers with its electrical currents and voltages. In the digital processor a number is represented by a coded pattern of electrical pulses[1] somewhat like Morse Code. In some machines, as explained later in detail, each of the decimal numerals in the number has its own characteristic pattern. In others, the identity of the decimal digits is lost within the pattern for the complete number. In an analog computer, this pattern feature is missing. Instead, a number is represented by a certain amount of voltage or current. The larger the number, the larger the current or voltage. Therefore, to determine the value of a number in a computer, one would inspect the pattern in a digital computer, but one would measure the quantity of current or voltage in an analog computer.

Both types of computers are of great importance in modern technology, and each has its relative advantages over the other when considered for certain tasks. Although a few brief paragraphs cannot do justice to a discussion of the relative merits, an understanding of the following points will give the newcomer to the computer field some idea of these advantages.

The analog computer, by virtue of its characteristic feature of operating upon currents which vary with the size of the number,[2] quite naturally

[1] More accurately, the pattern consists of pulses while the number is being transmitted from one place to another within the machine. When stationary, the pulses are replaced by an equivalent pattern of electrical currents or other physical phenomena. Various ways of mechanizing these patterns form an important part of this book.

[2] To avoid monotony, the word "current" or "voltage" will sometimes be used alone when actually both are suitable. The distinction is of no importance in many of the discussions which do not involve technical considerations.

falls heir to many of those problems in which the quantities to be computed occur originally as currents rather than as numbers. For example, a radar antenna may indicate the direction in which it is pointing toward a target by supplying a voltage which becomes larger as the angle of turn becomes larger. A temperature measuring device may increase its voltage output as the temperature rises. Although these two quantities—angle and temperature—are ordinarily written down in numbers for human calculations, since they are first measured in analog quantities, they are ideally suited to analog computation.

On the other hand, many numerical problems, especially those which occur routinely in business transactions, involve quantities which initially appear as numbers. Examples are prices, quantities, and hours worked. For these numbers to be processed in analog fashion, it would be necessary for them to be represented by analog quantities. However, it is an advantage to have a method of calculating which has no opportunity to alter the exact value of the numbers. Just as a message can be encoded into different symbols and later decoded without introducing a change in the words or numbers, so also can numbers be encoded into digital computer patterns with no reduction of accuracy.

If these numbers were to be represented by voltage magnitudes, instead of voltage patterns, the magnitudes might not be exactly correct because of small errors introduced by even the most accurate parts available. Calculations would then compound the inaccuracies. The accuracy of an analog computer is limited by the precision with which it can control the voltages and currents. At present, that limit is approximately one part in one thousand, or 0.1 percent. Even at considerable expense, one could not achieve much greater precision unless some new concept of measurement or a new electronic part could be devised.

One advantage of digital computers, then, is a greater inherent accuracy with larger numbers. An important consequence of this fact is that it allows the processing of very large numbers which could not be adequately handled by analog machines. Because of the lack of precision with larger numbers, they would be rounded off, so that all the digits after the first few would be zeros. However, a digital processor treats each digit in a number, and each column in an addition problem, in the identical manner. Whatever circuitry can be built for one column can be reproduced for each of the other columns. More columns and more accuracy can be obtained by merely employing more parts of the same sort (or, as is shown in the text, by sharing the same part at different times). Thus, the national budget figures and other large numbers of this sort can be expressed accurately to the nearest penny.[3] Since the greater accuracy is obtained by using more of the same kind of part, instead of by developing better parts, a computer for longer numbers can be assembled at only moderate additional expense beyond the minimum investment needed for a smaller machine which is otherwise the same.

Another advantage of the digital method is that it can represent alphabetic letters by patterns just as readily as it can numerals. This feature is especially important in business processing, which entails not only arithmetical calculations, but the rearrangement and listing of names, addresses, part numbers, and other combinations of letters and numerals. For these combinations, it is essential to have a method of preserving the identity of the individual symbols throughout the processing. As will be seen, the patterns for letters and the patterns for numerals can be handled easily together in the same circuits.

Many devices exist for converting either analog or digital values to the other form, and also many processing systems employ both techniques in combination. In designing such systems, the subportions are selected so that their various contributions lead to the best total system. It often happens that the device or technique which would be best for one particular task alone is not the best when combined with others into a larger system. For example, although digital computation is inherently more accurate than analog, and though analog-to-digital converters can change the one form to the other, it is not necessarily true that data which originates in analog form should be processed digitally. Approximations which occur during conversion may introduce enough error that the final solution is far less accurate than if achieved in analog fashion. Questions of this sort must be answered in terms of total system quality and compatibility, with cost always an important factor.

BASIC REQUIREMENTS FOR DIGITAL COMPUTERS

All digital computers have certain common characteristics, no matter how the machines vary in detail. In fact, some of their most basic properties are found in every device which aids in doing calculations, even though it has no ability to compute. These properties pertain to paper-and-pencil, a mechanical calculator, a slide rule, an abacus, an electronic computer, or other unit.

[3] This notion of accuracy, which applies to properly working machines, is completely distinct from the subject of errors which may result from some sort of machine failure.

One necessary property is the *ability to "store" numbers.* On paper, one can make marks to indicate numbers. These marks will remain "in storage" until erased or destroyed. They can be any shape the writer chooses provided he is consistent and remembers their meaning. Three different systems of numbers are commonly used without confusion, namely Arabic numerals, Roman numerals, and tallying by fives. In addition, the paper can be marked with letters to spell out the name of each number. Thus, one can write 12, XII, ~~IIII~~ ~~IIII~~ II, or twelve. It is evident that the particular method of marking can be chosen for its convenience.

In the common mechanical calculator, marking is by physical displacement. The pushing of buttons causes gears to move. The new positions of the gears then correspond to the buttons pushed and represent these numbers in storage. On a slide rule, storage occurs whenever the index or hairline is placed over a number. An abacus stores by position of the beads.

A second requirement is *access to the stored numbers.* A column of figures written in invisible ink is no aid to a person trying to balance his budget, even though a permanent change might have been made in the paper. To be of aid, the stored numbers must be available at the proper time to be entered into the arithmetic processes. Paper marks, gear positions, or other methods of storage must be capable of being "read" by a unit which can distinguish between the possible values.

A third requirement is the *ability to accept more numbers into storage after access to the others.* In the simplest calculation on paper, the answer is written merely by inspection of the problem. In more involved problems, the answer is discovered only after writing down many intermediate numbers, like partial sums and products. In both cases, much time may elapse before these additional marks are made. All the additional marks, including the answer, must be stored until used. If the paper becomes wet or the pencil runs out of lead, the paper-and-pencil system no longer is useful for calculation. Similarly, photographic paper, blueprint paper, and other materials capable of being marked by light may lose this ability during the developing cycle. Before development, the marks cannot be read, and after development no new marks can be added. Of course, these new marks must also be accessible.

Sufficient capacity for storage in terms of the intended application is a fourth requirement. A thick pad of paper can be considered to have nearly unlimited capacity. However, a slide rule can store only two numbers at a time, one under the index and one under the hairline.[4] Storing a third number requires that one of the others be dropped. This procedure corresponds to erasing a number from a tiny scrap of paper to make room for another. This restriction on storage space does not make the slide rule worthless compared to a pad of paper. Rather, it is used in a different manner.

For devices which are merely aids in calculation, these four attributes are sufficient. However, the difference between a pad of paper and a calculator is that the machine also does the arithmetic. An instruction to the machine (in the form of a pushed button) causes the answer to appear. A calculator, therefore, possesses a fifth attribute of being *able to perform at least one arithmetic operation unassisted.*

These five can be considered the basic requirements for a calculating device. In addition, there might be erasing or clearing ability to increase the capacity for temporary storage. And, of course, the calculator could not be used without a person or special equipment to write and read. In the computer industry, devices which read or write are usually called "input" or "output" units, rather than part of the basic calculation system. It will be shown later that digital computers employ such input-output devices to change from numbers or coded symbols to electrical values and back again. In addition, the computers contain different input-output circuits to move the electrical values from storage to the calculating circuits and back to storage. These latter are conventionally called "read-write" circuits.

IMPORTANCE OF BI-STABLE ELEMENTS

Just as numbers can be represented by specified marks or gear positions, so also can numbers be represented by increments of voltage in digital fashion, subject to a practical restriction. The amplitude of a voltage pulse can be calibrated in small steps, each level being equivalent to a certain number. Changes in amplitude then represent changes in the stored number.

Of course, if a specified voltage should be assigned to represent a certain number, it becomes imperative that the voltage remain unchanged so that it will not appear to be a different number. Confusion would immediately result if assigned voltages should vary during the computations.

With the use of electrical values, though, comes a problem which has

[4] Storage refers to the values specified, not to calibration marks.

no direct counterpart in paper-and-pencil or mechanical systems. Unfortunately, electrical values tend to change erratically and unpredictably unless regulated by additional equipment. Voltages can drift or fluctuate, leaving no clue to the original value. Even worse, there is no way of telling that a change has occurred.

As the details of computing circuits are explained, it will become apparent that extensive regulation is not an adequate means of ensuring stability for all the calibrated voltages. Regulation of the basic power supplies is routine practice, but regulation of each of the thousands of separate numerical values by more equipment becomes impossible. Thus, it is necessary to use electronic devices which can by themselves resist change.

Now, a mechanical gear can be made with any desired number of teeth, each allowing an increment of rotation and therefore each being able to represent a different numerical value. In calculators, ten-toothed gears are common, because each tooth can stand for one of the ten digits in the decimal system. When a gear has been turned to a certain position, it can be made to remain there as long as that digit must be stored. A gear of this nature can be said to have ten "stable states."

Electronic computers can also be built of elements which have ten stable states. However, ordinarily they are not. Among the known electronic devices and circuits which could apply to computers, there is a restricted choice, and only a few can be placed into ten stable states. The usual way to make a ten-state device is to assemble it from simpler parts. For instance, an electron tube can be built with ten separate conducting elements, so controlled that only one can conduct at a time. Each of these is assigned a number, so that the state of the tube is represented by the particular element which is conducting.

It happens, though, that no restriction is imposed by Nature as to the number of elements which can conduct at a given moment. If the tube were permitted to have all elements conducting at once, or any combination of them from none to ten, there would be 1024 possible combinations. Hence, the ten-element tube would have 1024 distinct states, all of which conceivably could be made stable. Therefore, it is apparent that if such a tube needs to represent only ten states, it does not require ten elements. Four elements are ample, because they yield sixteen combinations, giving the desired ten combinations with six to spare. These ten combinations of conducting and nonconducting elements are associated with ten of the distinct current patterns which were mentioned earlier.

This notion of combinations is extremely important in computer design and shifts the emphasis from the assembly to the separate elements. In the example of the tube above, the elements have only two states—conducting and nonconducting—and are quite stable because of the influence of additional circuit components. These elements are said to be "bi-stable."

A common example of a bi-stable unit (although not considered very reliable by computer standards) is the home light switch. It can be *on* or *off*, but cannot be *partly on* or *one-tenth on*. It will not spontaneously change its state and is reasonably unaffected by its environment. There are no tri-stable home light switches with some in-between condition. The three-way light switches are merely multiples of *on-off* switch contacts, having one *off* and three *on* positions. Dimming switches are assemblies containing resistive elements in addition to the switches.

Many different types of bi-stable elements exist, some being inherently stable and others achieving stability by virtue of their interconnections with other parts. As with the tube elements, they can be used in combination in a machine to achieve a far larger number of stable states than there are stable elements. Because of the economy which results from fewer parts to accomplish the same result, plus certain other important but less obvious considerations which favor this method of combinations, the circuitry in digital computers is almost exclusively designed around highly reliable bi-stable elements.

Having only two possible electrical states, bi-stable units individually can be made to represent only two numerical values. Thus, it develops that computers made of such elements do not use the decimal system. Instead, they are dependent upon a system of numbers composed of only two digits. Whereas the gear-type calculator can arrange ten different digits into all possible numbers, the computers discussed in this text can arrange only two digits to represent those same numbers.

A system employing only two digits is called a "binary" system, with any suitable marks being used for the digits. By convention, the first two marks of the decimal system, 0 and 1, are used for computer calculations. It will be shown in the next section that counting and arithmetic are performed by the same fundamental rules in both the decimal and binary systems.

MATHEMATICAL PROBLEMS

Calculations by computer fall into two major categories, business and scientific. In business problems, the calculations are almost entirely simple arithmetic. On the other hand, scientific problems sometimes consist of very sophisticated and complex notions. The subjects of mathematics and their forms of notation are so varied that special skills are required in each field.

Fortunately, most of the equations and functions of modern technology can be rearranged into more elementary form, so that they can be solved by simple arithmetic. An example is an equation with one or more terms having exponents, such as $a^2 + b^2 = c^2$, the well-known relationship for a right triangle. This equation can be rewritten as $a \times a + b \times b = c \times c$. Similar rearrangements apply to integration and other higher processes. With this freedom in rewriting, the solutions to complicated problems involve only simple arithmetic.

For this reason, most computers are confined internally to the elementary arithmetic operations. This restriction gives a flexibility for solving all types of problems while permitting design efficiency and economy.

Section I

METHODS OF COMPUTATION