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PREFACE

First of all, this volume is intended to be a companion book to my previous work, *Arithmetic Operations in Digital Computers*, which was published by D. Van Nostrand Company in 1955. In that book the emphasis was on arithmetic in a computer and on "logical" design and organization, the engineering aspects being mentioned only briefly. The present book is intended to supply engineers with the information needed to reduce the ideas about arithmetic and logic to a working machine.

In recent years the intense and widespread interest in digital computers has resulted in great advances in the development of improved computer components and circuits. For the most part, these advances have been obtained through the generation of new ideas rather than by refinements in the designs of the original units. Since these ideas, if published at all, tend to become widely scattered in various technical journals or proceedings of conferences, it has become increasingly difficult for an engineer, particularly a newcomer to the field, to learn the state of the art in any phase of the subject which he has not been following closely. Accordingly, a major purpose of this volume is to collect the ideas related to digital techniques and to organize them in a coherent and unified manner. A certain amount of original material has been included, but as evidenced by the bibliography, most of the information has come from other sources. The intention has been to provide a ready source of reference material for the practicing engineer and to provide a means for the newcomer to "get on board."

Although this book follows the first one in time, considerable care has been exercised to write it in a manner such that the reader will not be required to have a knowledge of the information contained in the first one. In a few instances it has been found that for a sensible explanation of the component or circuit in question it was almost mandatory that the reader have at least a basic understanding of the principles of logical functions and mechanized arithmetic. For this reason a few items such as Boolean notation and brief discussions of counters and adders have been repeated in this text, but the duplication of information has been held to a minimum.

On the other hand, in order to be able to concentrate on concepts that are directly related to digital techniques, the presentations are made with the assumption that the reader is reasonably familiar with electrical and electronic fundamentals. Actually, a rather comprehensive knowledge of physics would be required for a thorough understanding of all components that have been devised for digital computers. Examples that might be cited to illustrate this point include the theory of the solid state for transistors, theory of magnetic phenomena for magnetic cores, secondary emission phenomena for certain storage tubes, gas-discharge phenomena for certain counter tubes, and superconductivity and other low-temperature phenomena for cryotrons. However, it is possible to obtain an appreciation of the digital aspects of the subject without this extensive knowledge. In the explanations of the various components and circuits the aim has been to present enough background material for a person who is moderately well versed in electrical and electronic fundamentals to be able to understand the subject without having the text unduly diluted with topics that are not closely related to digital techniques.

The aim of concentrating on digital concepts has had an influence in the character of the text in that much of the information presented is of a qualitative nature rather than quantitative. Of course, when an engineer is actually engaged in choosing the design parameters to be used in a working machine, it is necessary to make a quantitative analysis of the components and circuits. Although design formulas are presented in some instances (diode switching circuits, for example) where the digital aspects of the subject have an outstanding influence on the design, it has been found that for the most part the design procedures are the same as used in many other branches of electrical and electronic engineering, and these procedures have been adequately covered in other text books.

Another reason for concentrating on digital concepts rather than detailed design techniques is that, in spite of the applicability of the principles of well-known design procedures, many of the components and circuits are sufficiently complex to render the procedures ineffective unless the interrelationships among a large and generally impractical number of parameters are found. The nonlinear characteristics of most computer components, the parameter variations which must be expected, the conflicting requirements of speed, reliability and cost, and numerous other factors often cause the bulk of the design procedure to consist of empirical studies on the work bench. The flip-flop, which is a basic circuit in many computers, is an example that provides a good illustration of the situation with regard to the design of digital circuits. Several technical papers on the subject of flip-flop design have appeared in the literature

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(see especially the Bibliography for Chapter 3), but it is still not possible to insert the desired conditions in a few well-selected formulas and "turn the crank" to obtain the design in the sense that this is possible in some other areas of engineering. The situation is complicated by the fact that there are so many different variations in the flip-flop circuit even when consideration is restricted to circuits employing vacuum tubes as the basic component.

Perhaps the most compelling reason for emphasizing concepts rather than design details is in the fact that the computer art is advancing so rapidly that design details almost literally become obsolete in the time consumed in publishing a book. So far, more progress has been achieved by developing new components and circuits than by "designing the last drop" out of an existing configuration. For example, if the book had been written as recently as two years ago, the subject of electrostatic tubes would surely have had the dominant position in the area of digital storage; but now attention is centered on magnetic cores. Also, the flip-flop mentioned in the preceding paragraph is being supplanted by transistors, magnetic cores, and cryotrons in a wide assortment of configurations.

It will probably become apparent to most readers that many of the topics included in this book represent components and circuits which have never seen service in a working computer or which have been used at most in one or two experimental machines. The fact that a certain component or circuit has been selected for presentation does not necessarily imply that it is deemed to be attractive in comparison with alternative methods of accomplishing the same function. In some cases the item was selected for inclusion because of its historical interest in the development of computers or because it represents an approach which has often been suggested but which contains some drawback that may not be apparent. Of course, in most cases the basis for selection was its proven or potential advantages, and in all cases there has been an effort to make some comment that will allow the reader to view the item in the proper perspective with respect to its practical usefulness.

I wish to express my appreciation to the International Business Machines Corporation for permission to use the library at their Engineering Laboratory in Poughkeepsie, New York. In particular, I wish to thank Dr. Wayne A. Kalenich, Head Librarian, and the members of his staff for the many courtesies extended to me, and I further wish to commend them for the excellent library that they have assembled on the subject of digital computers.

R. K. R.

CONTENTS

Chapter 1

HISTORY AND INTRODUCTION

For many years the electronics industry was devoted almost entirely to the subject of communication or the transmission of information from one place to another. Besides wire and radio communication the industry included sound recording, hearing aids, television, and other information handling systems. In each of these applications the principal objective of the various pieces of equipment is to reproduce the input signal as accurately as possible at the output device. In other words, it is desired that the output signal be a linear function of the input signal; any deviation from linearity is called distortion and is highly undesirable.

More recently the concept of information "processing" has been developed, and the devices used to process the information are known as computers. The nature and usefulness of the information, however, are not at all the same in computer applications as where the information is in the form of voice sounds, music, or pictures. In computers the term "data" would probably more aptly describe the input information. Broadly speaking, the data can come from one or more of at least three different types of sources. In one source type the data are generated as the result of physical measurements on quantities such as position, velocity, acceleration, pressure, temperature, voltage, resistance, charge, current, or time. It is often desired that data from these sources be supplied to the computer directly from the measuring instruments, although in many applications it is appropriate to transcribe the data manually or to employ a recorder of some sort to store the items until the computer is ready to process them. A second source of data is the alphabetical and numerical information encountered in statistical and accounting work. Examples of data in this category would include names, addresses, part numbers, dates, prices, quantities sold, interest rates, and many others. The third major source of data is the numbers involved in the solution of mathematical problems. In some instances the numbers may bear some relationship to the first two data sources that were mentioned, but in other instances, where the mathematics of the problem is of prime importance, the numbers may have no physical significance whatsoever. Regardless of the source of the information, the purpose of the computer is to manipulate the data in a manner such that the output signal is some nonlinear function, usually a very complex function, of the input data. In accordance with the application to which the computer is being applied the output may then be used for such things as controlling machines, creating documents and records, and indicating the solution to a mathematical problem.

In view of the considerable differences in the nature of information transmission and data processing, it should not be surprising that the circuits which have been developed for computers bear little resemblance to the oscillators, amplifiers, modulators, detectors, etc. that are commonplace in applications where the output signal should be a faithful reproduction of the input signal. As is now generally well known, there are two basic types of computers—*analog computers* and *digital computers*. In an electronic analog computer there is a direct correspondence or an "analogy" between the quantities undergoing calculations and certain electrical quantities, mostly voltages, existing at various points in the computer. In a digital computer the items of data are represented by coded combinations of signals in which each signal may exist in one of a finite number (usually only two) of discrete conditions. The circuits of analog and digital computers are quite different from each other, and as the title of this book suggests, its subject matter will be limited to circuits found in computers of the digital type.

The components, on the other hand, that can be used in the design of a digital computer can be exactly the same components which were developed for information transmission applications. In fact, the first few electronic digital computers built were made almost entirely with tubes, resistors, capacitors, and other items that were standard in the communications field.

Although it would still be within reason to consider designing a computer entirely around components intended for communications purposes, it would probably be found that the resulting machine would have two important shortcomings. For one thing the very large number of components needed in a computer of respectable capabilities introduces component reliability requirements that are not often encountered in radios and other devices where the total number of components is relatively small. The other shortcoming would be in the cost of the computer. When a component is developed for one application, it can hardly be expected to be optimum for a widely differing application. In the case of digital computers some functions, such as the AND function, bit storage, and others that are discussed in later chapters, are performed at a great multitude of points in the machine. In view of this situation, a considerable cost saving can be obtained through the development of components intended for specific functions. Also, because of the very large number of individual operations required for a computer, factors such as size, weight, and power consumption are particularly important in the development of computer components. Still another factor of considerable importance is speed of operation. Here, it must be conceded, some communications systems employ very high frequencies, and so it happens to be possible to achieve very high computer speeds with certain of the communications components.

Brief History of Digital Computer Components and Circuits. If mechanical machines are considered, the history of digital computer components extends back some three hundred years to the origins of the adding machine concept. However, since practically all present-day computers are electronic in nature (although a few electromechanical machines are in use) and since the remainder of this text is concerned almost exclusively with electronic components and circuits, the history presented here will be limited to the origins of the inventions and ideas that pertain to the electronic aspects of the subject. As might be expected, the origins of components and circuits for electronic digital computers is very much more recent by comparison.

The very first electronic circuit that pertains specifically to digital computers seems to have been the flip-flop, which was described by W. H. Eccles and F. W. Jordan in a 1919 issue of *Radio Review*. At that time they called their circuit a "trigger relay," and the term *Eccles-Jordan trigger* is still used occasionally in referring to this type of circuit. The flip-flop contains two triodes, the anode output of each triode being fed to the grid input of the other in such a manner that the circuit is capable of existing in either one of two stable states. This circuit as well as most of the other circuits and components mentioned in this chapter is discussed in considerable detail in subsequent chapters. In spite of the early appearance of the flip-flop, the concept of electronic computers was apparently nonexistent in 1919 and for some years thereafter.

The next circuit to appear is mentioned here mainly to illustrate the gap between the first and second known references on the subject. In the *Proceedings of the Royal Society* of 1931 and 1932, C. E. Wynn-Williams published descriptions of some counter circuits employing thyratrons. The functioning of these circuits is based on the fact that the anode voltage necessary to initiate a current in a gas thyratron is greater than the voltage necessary to maintain the current once it is initiated, and a circuit containing a thyratron can thereby be made to exist in one of two stable states. By suitable interconnections between a set of such circuits it is possible to cause them to change states in a prescribed sequence in response to input pulses. The function is therefore that of a counter. Subsequent literature, particularly patent literature, indicates that a great amount of effort has been applied to thyratron counters. Although counters of this type are of interest in special applications, their use in computers has not been extensive because the deionization requirements in the tubes impose severe speed limitations.

The next published literature on electronic digital computer subjects consists of a few scattered references appearing in the late 1930's. The subject matter was still limited to the use of bistable circuits of the flip-flop or thyratron type for counting functions. Incidentally, at this time the outstanding application of counters seemed to be in the counting of impulses created by particles from radioactive elements as the particles entered a suitable detecting instrument such as a Geiger-Müller tube. Note that a Geiger-Müller "counter" tube is not a counter in the sense used in the computer field; it is only the device which converts the energy from the particle into a pulse that is counted. It is believed that during this same period certain business machine manufacturers were working on electronic counters to replace the mechanical and electromechanical counters used in business machines of the day, but no published literature on this phase of the subject is known. In the 1930's the concept of an electronic digital computer as it is now understood was still in the most primitive stages of development.

The real start of modern electronic digital computer development seems to have taken place in government projects during World War II. However, because of military secrecy restrictions nothing was published at the time. The only electronic machine of this period to come to light was the ENIAC, which was developed at the Moore School of Engineering, University of Pennsylvania, for the Ordnance Department of the United States Army and which was described publicly for the first time in a 1946 issue of *Mathematical Tables and Other Aids to Computation*. A large portion of the ENIAC arithmetic unit and data-storage circuits was based on counters that were in turn based on the Eccles-Jordan flip-flop. Various special-purpose vacuum-tube circuits were developed for the control portion of the computer, but the concept of general-purpose logical circuits that could be assembled in building-block fashion appears not to have been developed. No electronic components specifically intended for digital applications were available at this time; in

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fact, the following statement is found in one of the papers describing the machine: "War circumstances made it imperative to construct the ENIAC out of conventional electronic circuits and elements with a minimum of redesign."

The extensive military effort on radar development that took place during World War II was another important source of techniques that are useful for electronic digital computers. Prior to the advent of radar the design procedures used for electronic devices were largely in terms of making a Fourier analysis of the signals and of describing the response of the various circuits and components in terms of the response to the sine waves obtained in the Fourier analysis. In radar a knowledge of the sine wave composition of certain of the signals is still valuable for parts of the problem, but in large sections of the equipment the circuits and design procedures fall into a category generally known as "pulse techniques." When the signals are in the form of pulses and particularly when the pulses occur at nonuniformly spaced intervals, it is usually preferable to disregard the sine wave composition of the signals and to consider the response of the circuits to the individual excursions of the signal voltage swing. In general the circuits are approximately linear over limited regions of the signal swing, but because of diode action, grid cut-off, and other properties of the components, there are sharp discontinuities in the response when the entire range is considered. The usual design procedure involves determining the circuit equations for each individual region of linearity and adjusting the circuit parameters so that the desired response is approximated as closely as possible in each region. Of course, the desired response is in general not the same in each region, and with most pulse circuits the desired objective is achieved through the discontinuities in the properties of the circuit components. Because radar signals are of the pulse type, the cathode followers, frequency dividers, sawtooth generators, blocking oscillators, etc., that are discussed in texts on radar provide a much better introduction to computer circuits, which also employ pulses, than do communications circuits of the type mentioned previously. Incidentally, pulse techniques are also widely used in television and other applications, but since the similarity between computer circuits and either radar or television circuits is not really close when the details are considered, the subject will not be pursued further.

Storage Devices. After about 1946, when the possibilities of large-scale general-purpose electronic digital computers were brought to the attention of more people, the research and development activity on the subject increased very rapidly. With regard to the electronic part of the machines (in contrast to the input-output mechanisms) one of the first shortcomings of available components to be recognized was the very large expense, size, and power consumption involved in providing for the large digital storage capacity that was needed when complex problems were to be solved by the computer. To meet the need of improved storage, three new devices appeared on the scene very quickly. These three devices were delay lines, magnetic drums, and electrostatic storage tubes. Because so many people participatd in the developement of the various components it is difficult to assign credit to the specific originators, although a person familiar with all of the pertinent patent literature and interference proceedings might have some authoritative information on the subject. However, certain groups or organizations were definitely more prominent than others in the early development of these three storage mechanisms.

Several different forms of delay lines for large-capacity storage have been invented, and at least three have been used commercially in digital computers—lumped-constant delay lines, mercury lines for ultrasonic vibrations, and magnetostrictive delay lines. The mercury lines were the first of these to receive extensive application in digital computers, and the EDSAC computer appears to have been the first machine to employ storage of this type. This computer was built by a group under the direction of Prof. M. V. Wilkes at Cambridge University in England. Descriptions of this machine were published in British journals in 1948. However, other computers employing delay-line storage were under construction during this same period, and a summer conference at the Moore School of Engineering in 1946 seems to have been the first public appearance of the idea of using delay lines for the storage of digital data. Even this point was not the true beginning of the subject, because delay lines had been used in radar applications several years previously.

Engineering Research Associates, Inc., which is now a part of Sperry Rand Corporation, is generally credited with the bulk of the early development of magnetic drums although the first machines built by this company were never described publicly.

In electrostatic storage the information is retained through the medium of a pattern of stored charge on an insulating surface. At least four different forms of the storage tubes were developed to the state of perfection where they could be (and were) used in digital computers. These four are known as the Williams tube, the Selectron, the holding-gun tube, and the barrier-grid tube. In the Williams tube scheme of electrostatic storage it was possible to employ cathode ray tubes of the type which had already been developed for television and oscilloscope applications. This form of storage was adopted in several different computer designs, whereas each of the other types of electrostatic storage appeared in only one or two machines. The name, incidentally, is derived from Professor F. C. Williams, who worked with others at the University of Manchester in England, where an experimental storage device of this type is reported to have been completed in about March of 1948. However, other groups are known to have been working on the same type of storage mechanism at approximately the same time. A description of the Selectron tube was published in 1947 in *Mathematical Tables and Other Aids to Computation.* Electrostatic storage has an outstanding advantage in comparison with either delay lines or magnetic drums in that it is never necessary to wait for the desired bit or bit position to appear at the reading and writing circuits. Instead, it is possible to select any location by electronic means in the period of a few microseconds. However, coincident-current magnetic core storage, which appeared somewhat later, also has this feature plus some other advantages. Accordingly, by about 1955 the interest in electrostatic storage had diminished almost to the vanishing point.

The idea of using magnetic cores for storage seems to have originated at Harvard University. The concept developed at Harvard involved shifting the bits from one core to the next, and in this way it was possible to simulate a delay line. Although a computer employing this form of storage was built at Harvard, the use of magnetic shift registers for large-capacity storage did not become widespread, because it was still necessary to wait for the appearance of the desired bit or bit position at the reading and writing circuits. Also, the cost of storage when the cores are used in shifting circuits is not competitive with other arrangements. Core storage became much more attractive when the coincident-current scheme was developed for selecting any core out of a large array with equal facility. This idea appears to have been developed at the Massachusetts Institute of Technology, and the first published reference on the subject was a paper by J. W. Forrester in the January 1951 issue of the *Journal of Applied Physics.* MIT was also active in applying this storage method to a computer, and early in 1953 the MIT group obtained successful operation of a machine known as the Memory Test Computer, which employed ferrite cores in a coincident-current array.

Several other methods have been suggested for obtaining digital storage systems with large capacities and fast access speeds, but the only ones known to be surpassing the coincident-current magnetic core system are variations in the core access method. For special-purpose applications and for medium-sized and small computers not requiring fast access speeds it has been desirable to retain delay lines and magnetic drums for economic reasons.

More recently it has become apparent that there are many important applications of digital computers where a very large storage capacity (many millions of digits or alphabetical characters) is required but where an access time that is an appreciable fraction of a second can be tolerated. Magnetic drums can be used for this purpose, although a rather large number of them is required. Much effort has been devoted to the task of finding a more suitable combination of magnetic surface geometry and means for positioning the reading and writing head at different points on the surface. Several schemes have been devised to meet the need; they include belts, discs, and strips of tape, together with a variety of mechanical mechanisms for positioning the heads. Photographic film in several different forms has also been studied. However, the search for storage mechanisms with very large capacity and moderately rapid access to randomly chosen addresses has not as yet uncovered any storage mechanisms that differ from the previously known ones in the basic principles of operation.

Arithmetic and Control Circuits. The arithmetic and control circuits of the early computers employed conventional vacuum tubes in a variety of different types of circuits. As discussed in more detail in a later chapter, groups of engineers in different organizations and at different locations each seemed to develop their own set of circuits, and marked differences occur among the sets. Regardless of the type of circuits it was always found that the total number of tubes required for a computer of any appreciable capabilities was much greater than desired. The large number of tubes created the obvious objection of high cost, but also the power required to operate the tubes, particularly for the heaters, caused the total power consumption to be objectionably great for the arithmetic and control circuits alone. Even the smaller machines required several kilowatts, and in the larger machines the power consumption exceeded 100 kilowatts. In addition to the cost of the tubes themselves the large power consumption created large costs for the power supply, for installing the power lines to the building housing the computer, for the power itself, and for the air conditioners needed to remove the heat from the building. Because of the objections to vacuum tubes, the search for a replacement component has been intensive.

An interesting sidelight in the history of computer components is that for a period of a few years even the technical suitability of vacuum tubes was in doubt. In many digital circuits one or more of the tubes may be held in the cut-off condition for long periods of time. It was found that the cathodes of tubes in this type of service tended to loose their thermionic emission characteristics quite rapidly. Investigation disclosed that a high-resistance "interface" layer developed between the nickel sleeve and the oxide coating of the cathode. For some reason the continuous or frequent drawing of current from the cathode prevents the formation of the interface, and since most circuits designed for communications purposes are not held in the cut-off condition for any appreciable length of time, the phenomenon had not been encountered before. The problem was studied extensively, and several technical papers on the subject appeared during a period centering on about 1950. It is not certain that a thoroughly satisfactory explanation of the phenomenon was ever produced, but it was found that the problem could be avoided by carefully eliminating impurities in the tube structure. Although several impurities have an effect, it is particularly important that the nickel cathode sleeve be free of silicon.

When manufacturing a vacuum tube containing an oxide-coated cathode, it is necessary to "activate" the cathode before the high-emission characteristics of oxide cathodes are obtained. It is found, again without a thoroughly satisfactory explanation being available, that a certain amount of impurities is desirable in that an activated cathode can be obtained more quickly and in that higher ultimate emissions are usually possible. For this reason vacuum tube manufacturers normally preferred to have a certain amount of impurities present; also, the elimination of impurities generally involves added expense. In the technical data sheets prepared by tube manufacturers it will be noticed that some tube types are specifically intended for digital computer service. One of the major differences between these types and the conventional types is in the fact that the computer tubes have closely limited impurities and can therefore be operated in the cut-off condition for long periods of time.

The introduction of the germanium diode was an important step in the reduction of the number of vacuum tubes required in the arithmetic and control portions of a computer. Semiconductor diodes had been known ever since the days of the "crystal detector" radio sets and had been used extensively in radar receivers and other applications in World War II. However, diodes of the quality needed for digital computer service did not appear until a few years later. Also, in spite of the simplicity of the diode AND and OR circuits as described in the next chapter, these circuits did not seem to be among the first inventions related to digital computers. The first published reference on the subject was a paper by C. H. Page in the September 1948 issue of *Electronics*. During the next two years or so the possibility of reducing the number of thermionic heaters by replacing many of the vacuum tubes with semiconductor diodes became widely appreciated. Almost all sets of arithmetic and control circuits designed after this period included a large proportion of diodes.

The announcement of the transistor in 1948 was met with enthusiasm by the computer industry because of the obvious potentialities with regard to reduced power consumption and also with regard to smaller size, reduced weight, and other factors. Many projects were initiated in educational, industrial, and government organizations to investigate the transistor and to develop digital computer circuits with the transistor as the basic element. Many of the results of this work are described later in the chapters on transistor systems of circuit logic. Unfortunately, the initial expectations with regard to availability, uniformity, reliability, stability, and cost were very slow to materialize. Also, when digital computer circuits are considered in detail it is found that some transistor characteristics (collector cut-off current, for example) are not of the form that would be desired for convenient circuit design. By 1955 a few small experimental computers employing transistors had been built, and by the middle of 1957 at least three companies had announced commercial versions of computers employing transistors. However, actual deliveries had not yet begun.

Although the magnetic core shifting circuits that originated at Harvard University did not become widely accepted as a large-capacity storage medium, they did become the basis for several different sets of arithmetic and control circuits that are described in the chapter on magnetic core systems of circuit logic. The idea of using magnetic cores in circuits of this category appeared as early as 1950 in a Ph.D. thesis by M. K. Haynes at the University of Illinois, but the first published literature on the subject did not appear until 1953. After this approximate date the development activity on magnetic core circuits increased rapidly in a number of laboratories. The first digital computer employing core circuits in the arithmetic and control section was, so far as is known, a machine built by Sperry Rand for the United States Air Force. This computer was described briefly in the July 1956 issue of *Electronics*.

Input-Output Devices. The early digital computers relied heavily on existing devices for entering the data into the arithmetic and control portion of the computer and for recording the computed results. These devices were obtained both from the communications industry and the business-machines industry. The communications industry supplied teleprinters and equipment for handling punched paper tape. The business-machines industry supplied line-at-a-time printers and equipment for handling punched cards. Also, solenoid-actuated electric typewriters of various designs were soon adapted to computer service. All of these devices are still of basic importance in computer applications, although, as might be expected, the more recent models are greatly improved in comparison with the ones available originally. In particular, the speeds of operation are much greater, and the interconnections between the

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