ANALYSIS AND DESIGN OF DIGITAL CIRCUITS AND COMPUTER SYSTEMS

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Preface

This introductory book's objective is to provide the reader with the basic ideas and tools needed to analyze and design digital circuits and computer systems. Since this is a text for use in a basic course, the fundamental ideas of switching circuits and their design is stressed. However, it is felt that, after completing such a first course, the student should have an understanding of a complete digital computer or a computer system. Therefore, such things as elementary computer organization and machine language are discussed. This latter discussion is by no means exhaustive since it would not be appropriate for an elementary course taken by all students. However, sufficient detail is included to give the reader an understanding of how a computer or computer system operates.

The discussion of such things as number systems, chage of radix, and elementary binary arithmetic are made very detailed. This is done so that, if desired, this material need not be covered in class but may just be assigned for home reading.

It is assumed that the readers of this book have studied some very elementary circuit material. However, they need not have any other prerequisites.

The block diagram approach can be used to discuss switching circuits and computers. However, this does not provide a full understanding of computer operation. Consequently, the electronic circuit aspects of switching circuits are discussed in Chapter Five. In addition to basic ideas, computation of such things as switching levels and noise immunity are also considered there. The block diagram approach is used in most of the remainder of the text so that the discussions of Chapter Five can be omitted or deferred.

Chapter Five assumes that the student is familiar with the basic ideas of semiconductor devices. If this is not the case, then the material presented in the Appendix will provide him with the necessary background.

The first chapter is an introductory one which is designed to provide the student with a brief picture of digital device usage.

In Chapter Two we consider number systems and simple binary arithmetic operations.

The elementary ideas of logic and basic gates are discussed in Chapter Three.

In Chapter Four, minimization techniques for combinational circuits are studied. The topics covered include basic ideas of switching algebra, minimization using maps, prime implicants, the Quine-McCluskey method, minimization of multiple output networks, and use of decimal notation in prime implicant tables.

We have discussed logic gates and the mathematical means of minimizing them. Now, in the fifth chapter, we consider the circuits from the viewpoint of an Electrical Engineer. We start with a discussion of logic circuits. First, the idea of logic families is presented and the various criteria for their choice are considered. Next, all the commonly used transistor logic families are discussed. Following this, we consider the MOS logic families. Finally, all the logic families are compared. Again, these devices are studied from the viewpoint of the Electrical Engineer.

In the sixth chapter, we start with a general discussion of sequential circuits. Next we discuss the various flip-flops. Synchronization and triggering are considered in detail. The basic tools needed to analyze synchronous circuits are discussed followed by a discussion of registers. A detailed discussion of the design of synchronous sequential circuits is presented. Counters are considered here. The basic ideas of asynchronous sequential circuit are discussed, and the problem of hazards and races are considered. The design of asynchronous sequential circuits is then presented.

After developing the basic tools, some of the components of the digital computer are discussed. In Chapter Seven we consider memories. Random access memories are considered in great detail. This discussion includes core, film, transistor and MOS memories. Next, auxiliary memories are discussed. Finally, read only memories and decoders are studied.

In Chapter Eight, the ideas of binary codes are discussed. First we consider BCD codes, then alphanumeric codes. Next, reflected codes are considered. Finally we study error detecting and correcting codes.

In Chapter Nine, binary arithmetic is discussed. We start with a consideration of modular arithmetic. Next, complementary arithmetic is studied. Floating point arithmetic is discussed. Precision and accuracy are considered in detail.

Computer arithmetic is presented in Chapter Ten. The actual computer implementation of addition, subtraction, multiplication and division are presented. BCD conversion is also considered here. Circuits which implement these operations are explained. The chapter concludes with a complete discussion of the accumulator.

In Chapter Eleven the complete digital computer is considered. We start with a general discussion of the components of a computer. This is followed by a consideration of information storage and transmission. The complete computer is then discussed. A simple machine language is developed and simple programs are written. The object here is not to teach programming but to relate the machine language to the actual operation of the computer. Assembler and higher level languages are then discussed, again, not to teach programming, but to provide a basic understanding of what these are.

In the twelfth chapter, we consider some digital circuits. There is no attempt at completeness here. The purpose of the chapter is to provide some basic ideas and to discuss the elements of computer interfacing. Operational amplifiers are discussed. Next, comparators and sample and hold circuits are presented. These are then used in a discussion of digital to analog and analog to digital conversion. Astable and monostable multivibrators are next considered. The use of thse components in fabricating computer interfacing is next discussed.

The Appendix discusses the basic ideas of semiconductor devices. This is done so that the reader who has not been exposed to this material previously can understand the electronic circuits. This Appendix contains a brief discussion of semiconductor physics, the p-n junction diode, the transistor, the field effect transistor, switching in semiconductor devices and integrated circuits. All necessary background material is provided in this appendix.

Many varied problems are given at the end of each chapter.

The author would like to express his gratitude to his colleagues Prof. Alfred C. Gilmore, Jr. and Otto C. Boelens for the numerous and lengthy discussions held with him during the writing of the book. They provided much help and inspiration. The author would also like to thank his colleagues Profs. Preston R. Clement, Emil C. Neu, and Gerald J.Herskowitz for their helpful comments.

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Paul M. Chirlian

Contents

4 COMBINATIONAL LOGIC-SWITCHING ALGEBRA 65

5 COMBINATIONAL LOGIC CIRCUITS 143

6 SEQUENTIAL CIRCUITS 197

7 MEMORIES 289

1 Introduction

This book will discuss digital systems emphasizing the details of the analysis and design of the elements of these systems. Although emphasis will be placed on the digital computer, other digital systems will also be treated.

Digital systems are often studied by considering them to be made up of blocks which perform logical operations. In addition to this block diagram approach, we shall also discuss the electronic circuits within the blocks.

In this first chapter, we shall discuss some general ideas of digital systems.

1.1 A GENERAL DISCUSSION OF DIGITAL DEVICES

The digital computer can perform many operations. It can, in seconds, solve equations which could take years to calculate by hand An entire industrial process can be controlled by a digital computer. For instance, special sensors could determine the temperature, pressure, acidity, etc., in a chemical process. In an appropriate form, this information is then supplied to a digital computer. Calculations on this data are then performed. As a result of these calculations, electrical signals, which control the process, are generated. For instance, in response to these signals, heaters could be truned on or off, or additional chemicals added.

When a radar signal is reflected from a distant planet (or object) it is often very weak and obscured by noise. Ordinary techniques cannot be used to detect this signal. However, a digital computer can process it and make the radar signal detectable. Computers can also be used to monitor a hospital recovery room. We have only considered several of the host of tasks that can be performed by a digital computer. In order to perform such complex operations, the digital computer must contain very many circuits. In fact, each computer is made up of the interconnection of thousands of relatively simple circuits. Thus, we must study the individual circuits before considering how they are interconnected to form a complete computer.

Integrated circuit techniques can be used to produce simple digital computers which are small in size. Such computers, called *microprocessors*, are used to perform many tasks. For instance, a microprocessor in an oscilloscope can be used to obtain a reading of the true rms value of a signal. Actually, microprocessors can be used for many of the previously discussed control tasks.

The earliest digital computers used relays as their fundamental elements. Note that a relay is simply a switch controlled by an electromagnet. These switches were either on or off(i.e.,either open or closed). Present digital computers have replaced the relays with electronic devices. However, these still act as controlled switches which are either on or off. In the next section we shall discuss how these on or off conditions give rise to a signal which has two levels that are called *zero* and *one*.

In a digital system, all signals are made up of combinations of such zeros and ones. In contrast, in an *analog* system, the signals can vary continuously. For instance, if the number 1.23 is computed by an analog computer, then 1.23 volts might actually appear at the output. In a digital computer, the number 1.23 would be represented by a sequence of zeros and ones. In addition, the output of an analog system can vary continuously while that of a digital one can only vary in discrete steps. The digital system seems more complex and, indeed, it often is. However, it has many advantages. A digital system can be extremely accurate. Many systems can provide greater than 16 place accuracy. Such accuracy is impossible with an analog system, where the limit of precision is usually 3 or 4 significant figures. In addition, analog systems often change their characteristics with time, temperature, etc. (or drift) while digital systems do not. Digital systems can often be more flexible. Thus, in spite of their complexity, digital computers are very widely used for a great variety of operations. In fact, digital systems have replaced analog systems in very many operations. One reason for this is that the use of integrated circuits now allows the extremely large circuits needed for digital computers to be reliably built in small volumes at relatively low costs.

All very large computers, small desk calculators, and most intermediate size computers are digital in nature. Analog computers are still built, but today, most of them are special purpose in nature. In addition, digital systems are now used in areas which were once the province of analog systems. Let us consider some of these. The ordinary voltmeter is an analog device. The accuracy of such instruments is, at best, 1 percent of the *full* scale value. (Thus, they tend to be inaccurate at low scale readings.) On the other hand, digital voltmeters are built which are capable of a fraction of a percent accuracy over almost their entire range. (We shall discuss such voltmeters in Chapter 12.) Digital voltmeters also have the advantage that the voltage is presented as an easily read number(i.e., 346.2 volts appears as the numbers, 346.2). Thus, it is easy to read and no interpolation is required. Another example of a digital device replacing an analog one is the electric filter, which selects one signal and rejects all others. Usually, this is an analog system. (Such filters are used to tune a radio to one station while rejecting the others.) However, in many complex applications, simple digital computers are programmed to perform the mathematical operation of filtering. In thse and other applications, analog systems are being replaced by digital ones. Of course, because of their relative simplicity, there are many circumstances where analog systems will continue to be used. However, digital systems are becoming more and more important.

Often, we must work with both analog and digital systems in a single device. For intance, in a digital voltmeter, the input signal, the voltage, is a continuous signal. It must be converted to a digital representation. Similarly, in a digital filter, the input signal is continuous. It must be converted to a digital representation, which is processed digitally, and then converted back to a continuous signal. Devices called analog to digital converters and digital to analog converters are used for such purposes. We shall discuss these in Chapter 12. (At times, the combination of a digital and an analog system is called a *hybrid system*.)

1.2 SOME FUNDAMENTALS OF COMPUTERS

Digital computers always manipulate numbers. For instance, if a nonlinear differential equation is to be solved, then the computer is programmed to implement an appropriate numerical analysis procedure. The program instructs the computer to perform many arithmetic operations (addition, subtraction, multiplication, and division)on a set of input data(i.e., numbers). These operations result in the solution. Similarly, if a digital computer is used as a digital filter, a sequence of numbers, obtained from an analog to digital converter is supplied to the computer. The appropriate arithmetic operations are then performed. These result in a sequence of numbers proportional to the output signal. Digital to analog conversion constructs an analog signal from this sequence. The operations performed by the computer are governed by a series of instructions called a *program*, which is supplied by the user. Although the basic operations of the computer are arithmetic in nature, these can be combined to approximate other mathematical operations such as differentiation and integration.

A computer consists of several basic parts. There is a *control unit* which receives the instructions of the program and directs the appropriate computer operations. The *central processor unit* performs the operations of addition, subtraction, multiplication and division plus some additional operations. The *memory* is used to store both numbers and programs. There are also *input-output* devices such as card readers, teletypes and printers which are used by the human operators to supply the computer with the data and instructions and which conversely, are used by the computer to print out the calculated values.

All the data handled by the computer is in numeric form. At times, the computer performs non-numeric procedures such as the alphabetizing of a list of names. However, all such information is converted into numerical information using a suitable *code*.

Thus, the storage and manipulation of numbers is of fundamental importance in the study of digital computers. For this reason, we shall now study some fundamental ideas of number systems We all learned and used the *decimal number* system based on the ten digits 0,1,2,3,4,5,6,7,8, and 9. Such a number system probably developed because humans have ten fingers. Thus, ten was used for convenience. When mechanical adding machines and desk calculators were built, the decimal system was carried over to them easily since gears with ten or multiples of ten teeth were used. However, electronic devices have replaced almost all the mechanical ones, not only in large computers but also in simple adding machines and desk calculators. It is not desirable to use the decimal system in such electronic devices. We shall illustrate this discussion with the simple electronic circuit of Fig. 1-1a. The box represents an idealized electronic device; it could approximate a transistor. A plot of output voltage versus input voltage for this device is shown in Fig. 1-1b. Let us consider this characteristic.

If the input voltage v_1 is less than v_{1c}, then the output circuit of the device acts as an open circuit and $v_2=V_{CC}$. In this

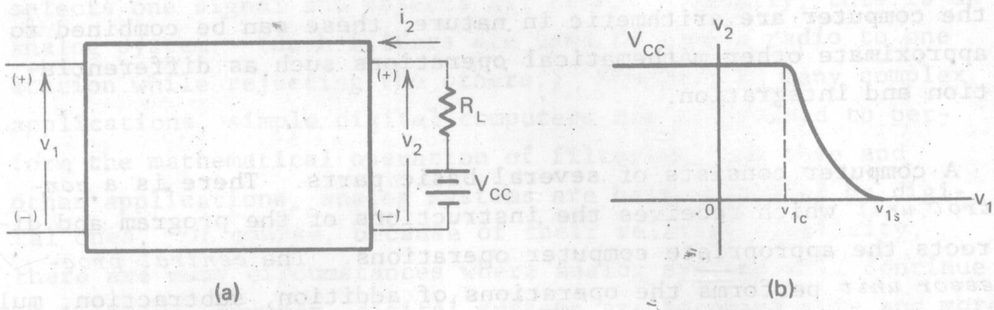

Figure 1-1. (a) An idealized electronic device; (b) the transfer characteristics of this circuit.

condition, the output current $i_2=0$ and the device is said to be *cut off*. If we want to be sure that the device is cut off, then we can make v_1 less than v_{1c}.

If v_1 is greater than v_{1s}, then the output circuit of the device acts as a short circuit and $v_2=0$. In this case, the device is said to be *saturated*. Again, if we want to be sure that the device is saturated, then we can make v_1 greater than v_{1s}.

The cut off and saturation values can be established easily and readily. These voltage levels are relatively far apart so that they can easily be distinguished. For instance, the saturation voltage may range between 0.5 and 0.1 volt while a cut off voltage could range between 9 and 10 volts. Note that the cut off values for each device need not be the same. They must only fall within some specified range. A similar statement can be made for the saturation values. Thus, the digital computer can be extremely reliable since a small shift in levels will still result in voltages which lie in their specified ranges and, thus, be interpreted correctly. Hence, there are two levels (ranges of levels) that are used. If the cut off and saturation levels represent numbers, then there are only two digits available. As before, these are called *zero* and *one*. This is called a *binary number system*. Thus, in digital computers, we work with arithmetic systems that use only the two digits zero and one. These are called *binary digits* and are often called *bits*. Note that this does *not* mean that the data cannot be entered in the usual decimal form. It is converted to the binary form within the computer. Thus, we are restricted to a *binary number system*.