Digital Electronics

Principles, Devices and Applications

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In the loving memory of my father, Shri Sukhdev Raj Maini*, who has been a source of inspiration, courage and strength to me to face all challenges in life, and above all instilled in me the value of helping people to make this world a better place.*

Anil K. Maini

Contents

Preface

Digital electronics is essential to understanding the design and working of a wide range of applications, from consumer and industrial electronics to communications; from embedded systems, and computers to security and military equipment. As the devices used in these applications decrease in size and employ more complex technology, it is essential for engineers and students to fully understand both the fundamentals and also the implementation and application principles of digital electronics, devices and integrated circuits, thus enabling them to use the most appropriate and effective technique to suit their technical needs.

Digital Electronics: Principles, Devices and Applications is a comprehensive book covering, in one volume, both the fundamentals of digital electronics and the applications of digital devices and integrated circuits. It is different from similar books on the subject in more than one way. Each chapter in the book, whether it is related to operational fundamentals or applications, is amply illustrated with diagrams and design examples. In addition, the book covers several new topics, which are of relevance to any one having an interest in digital electronics and not covered in the books already in print on the subject. These include digital troubleshooting, digital instrumentation, programmable logic devices, microprocessors and microcontrollers. While the book covers in entirety what is required by undergraduate and graduate level students of engineering in electrical, electronics, computer science and information technology disciplines, it is intended to be a very useful reference book for professionals, R&D scientists and students at post graduate level.

The book is divided into sixteen chapters covering seven major topics. These are: *digital electronics fundamentals* (chapters 1 to 6), *combinational logic circuits* (chapters 7 and 8), *programmable logic devices* (chapter 9), *sequential logic circuits* (chapters 10 and 11), *data conversion devices and circuits* (chapter 12), *microprocessors, microcontrollers and microcomputers* (chapters 13 to 15) and *digital troubleshooting and instrumentation* (chapter 16). The contents of each of the sixteen chapters are briefly described in the following paragraphs.

The first six chapters deal with the fundamental topics of digital electronics. These include different number systems that can be used to represent data and binary codes used for representing numeric and alphanumeric data. Conversion from one number system to another and similarly conversion from one code to another is discussed at length in these chapters. Binary arithmetic, covering different methods of performing arithmetic operations on binary numbers is discussed next. Chapters four and five cover logic gates and logic families. The main topics covered in these two chapters are various logic gates and related devices, different logic families used to hardware implement digital integrated circuits, the interface between digital ICs belonging to different logic families and application information such as guidelines for using logic devices of different families. Boolean algebra and its various postulates and theorems and minimization techniques, providing exhaustive coverage of both Karnaugh mapping and Quine-McCluskey techniques, are discussed in chapter six. The discussion includes application of these minimization techniques for multi-output Boolean functions and Boolean functions with larger number of variables. The concepts underlying different fundamental topics of digital electronics and discussed in first six chapters have been amply illustrated with solved examples.

As a follow-up to logic gates – the most basic building block of combinational logic – chapters 7 and 8 are devoted to more complex combinational logic circuits. While chapter seven covers arithmetic circuits, including different types of adders and subtractors, such as half and full adder and subtractor, adder-subtractor, larger bit adders and subtractors, multipliers, look ahead carry generator, magnitude comparator, and arithmetic logic unit, chapter eight covers multiplexers, de-multiplexers, encoders and decoders. This is followed by a detailed account of programmable logic devices in chapter nine. Simple programmable logic devices (SPLDs) such as PAL, PLA, GAL and HAL devices, complex programmable logic devices (CPLDs) and field programmable gate arrays (FPGAs) have been exhaustively treated in terms of their architecture, features and applications. Popular devices, from various international manufacturers, in the three above-mentioned categories of programmable logic devices are also covered with regard to their architecture, features and facilities.

The next two chapters, 10 and 11, cover the sequential logic circuits. Discussion begins with the most fundamental building block of sequential logic, that is, *flip flop*. Different types of flip flops are covered in detail with regard to their operational fundamentals, different varieties in each of the categories of flip flops and their applications. Multivibrator circuits, being operationally similar to flip flops, are also covered at length in this chapter. Counters and registers are the other very important building blocks of sequential logic with enormous application potential. These are covered in chapter 11. Particular emphasis is given to timing requirements and design of counters with varying count sequence requirements. The chapter also includes a detailed description of the design principles of counters with arbitrary count sequences. Different types of shift registers and some special counters that have evolved out of shift registers have been covered in detail.

Chapter 12 covers data conversion circuits including digital-to-analogue and analogue-to-digital converters. Topics covered in this chapter include operational basics, characteristic parameters, types and applications. Emphasis is given to definition and interpretation of the terminology and the performance parameters that characterize these devices. Different types of digital-to-analogue and analogue-to-digital converters, together with their merits and drawbacks are also addressed. Particular attention is given to their applications. Towards the end of the chapter, application oriented information in the form of popular type numbers along with their major performance specifications, pin connection diagrams etc. is presented. Another highlight of the chapter is the inclusion of detailed descriptions of newer types of converters, such as quad slope and sigma-delta types of analogue-to-digital converters.

Chapters 13 and 14 discuss microprocessors and microcontrollers – the two versatile devices that have revolutionized the application potential of digital devices and integrated circuits. The entire range of microprocessors and microcontrollers along with their salient features, operational aspects and application guidelines are covered in detail. As a natural follow-up to these, microcomputer fundamentals, with regard to their architecture, input/output devices and memory devices, are discussed in chapter 15.

The last chapter covers digital troubleshooting techniques and digital instrumentation. Troubleshooting guidelines for various categories of digital electronics circuits are discussed. These will particularly benefit practising engineers and electronics enthusiasts. The concepts are illustrated with the help of a large number of troubleshooting case studies pertaining to combinational, sequential and memory devices. A wide range of digital instruments is covered after a discussion on troubleshooting guidelines. The instruments covered include digital multimeters, digital oscilloscopes, logic probes, logic analysers, frequency synthesizers, and synthesized function generators. Computer-instrument interface standards and the concept of virtual instrumentation are also discussed at length towards the end of the chapter.

As an extra resource, a companion website for my book contains lot of additional application relevant information on digital devices and integrated circuits. The information on this website includes numerical and functional indices of digital integrated circuits belonging to different logic families, pin connection diagrams and functional tables of different categories of general purpose digital integrated circuits and application relevant information on microprocessors, peripheral devices and microcontrollers. Please go to URL http://www.wiley.com/go/maini_digital.

The motivation to write this book and the selection of topics to be covered were driven mainly by the absence a book, which, in one volume, covers all the important aspects of digital technology. A large number of books in print on the subject cover all the routine topics of digital electronics in a conventional way with total disregard to the needs of application engineers and professionals. As the author, I have made an honest attempt to cover the subject in entirety by including comprehensive treatment of newer topics that are either ignored or inadequately covered in the available books on the subject of digital electronics. This is done keeping in view the changed requirements of my intended audience, which includes undergraduate and graduate level students, R&D scientists, professionals and application engineers.

Anil K. Maini

1

Number Systems

The study of *number systems* is important from the viewpoint of understanding how data are represented before they can be processed by any digital system including a digital computer. It is one of the most basic topics in digital electronics. In this chapter we will discuss different number systems commonly used to represent data. We will begin the discussion with the decimal number system. Although it is not important from the viewpoint of digital electronics, a brief outline of this will be given to explain some of the underlying concepts used in other number systems. This will then be followed by the more commonly used number systems such as the binary, octal and hexadecimal number systems.

1.1 Analogue Versus Digital

There are two basic ways of representing the numerical values of the various physical quantities with which we constantly deal in our day-to-day lives. One of the ways, referred to as *analogue*, is to express the numerical value of the quantity as a continuous range of values between the two expected extreme values. For example, the temperature of an oven settable anywhere from 0 to 100 °C may be measured to be 65 °C or 64.96 °C or 64.958 °C or even 64.9579 °C and so on, depending upon the accuracy of the measuring instrument. Similarly, voltage across a certain component in an electronic circuit may be measured as 6.5 V or 6.49 V or 6.487 V or 6.4869 V. The underlying concept in this mode of representation is that variation in the numerical value of the quantity is continuous and could have any of the infinite theoretically possible values between the two extremes.

The other possible way, referred to as *digital*, represents the numerical value of the quantity in steps of discrete values. The numerical values are mostly represented using binary numbers. For example, the temperature of the oven may be represented in steps of 1 °C as 64 °C, 65 °C, 66 °C and so on. To summarize, while an analogue representation gives a continuous output, a digital representation produces a discrete output. Analogue systems contain devices that process or work on various physical quantities represented in analogue form. Digital systems contain devices that process the physical quantities represented in digital form.

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Digital techniques and systems have the advantages of being relatively much easier to design and having higher accuracy, programmability, noise immunity, easier storage of data and ease of fabrication in integrated circuit form, leading to availability of more complex functions in a smaller size. The real world, however, is analogue. Most physical quantities – position, velocity, acceleration, force, pressure, temperature and flowrate, for example – are analogue in nature. That is why analogue variables representing these quantities need to be digitized or discretized at the input if we want to benefit from the features and facilities that come with the use of digital techniques. In a typical system dealing with analogue inputs and outputs, analogue variables are digitized at the input with the help of an analogue-to-digital converter block and reconverted back to analogue form at the output using a digital-to-analogue converter block. Analogue-to-digital and digital-to-analogue converter circuits are discussed at length in the latter part of the book. In the following sections we will discuss various number systems commonly used for digital representation of data.

1.2 Introduction to Number Systems

We will begin our discussion on various number systems by briefly describing the parameters that are common to all number systems. An understanding of these parameters and their relevance to number systems is fundamental to the understanding of how various systems operate. Different characteristics that define a number system include the number of independent digits used in the number system, the place values of the different digits constituting the number and the maximum numbers that can be written with the given number of digits. Among the three characteristic parameters, the most fundamental is the number of independent digits or symbols used in the number system. It is known as the *radix* or *base* of the number system. The decimal number system with which we are all so familiar can be said to have a radix of 10 as it has 10 independent digits, i.e. 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. Similarly, the binary number system with only two independent digits, 0 and 1, is a radix-2 number system. The octal and hexadecimal number systems have a radix (or base) of 8 and 16 respectively. We will see in the following sections that the radix of the number system also determines the other two characteristics. The place values of different digits in the integer part of the number are given by r^0, r^1, r^2, r^3 and so on, starting with the digit adjacent to the radix point. For the fractional part, these are r^{-1}, r^{-2}, r^{-3} and so on, again starting with the digit next to the radix point. Here, r is the radix of the number system. Also, maximum numbers that can be written with n digits in a given number system are equal to r^n.

1.3 Decimal Number System

The decimal number system is a radix-10 number system and therefore has 10 different digits or symbols. These are 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. All higher numbers after '9' are represented in terms of these 10 digits only. The process of writing higher-order numbers after '9' consists in writing the second digit (i.e. '1') first, followed by the other digits, one by one, to obtain the next 10 numbers from '10' to '19'. The next 10 numbers from '20' to '29' are obtained by writing the third digit (i.e. '2') first, followed by digits '0' to '9', one by one. The process continues until we have exhausted all possible two-digit combinations and reached '99'. Then we begin with three-digit combinations. The first three-digit number consists of the lowest two-digit number followed by '0' (i.e. 100), and the process goes on endlessly.

The place values of different digits in a mixed decimal number, starting from the decimal point, are 10^0, 10^1, 10^2 and so on (for the integer part) and 10^{-1}, 10^{-2}, 10^{-3} and so on (for the fractional part).

The value or magnitude of a given decimal number can be expressed as the sum of the various digits multiplied by their place values or weights.

As an illustration, in the case of the decimal number 3586.265, the integer part (i.e. 3586) can be expressed as

$$3586 = 6 \times 10^0 + 8 \times 10^1 + 5 \times 10^2 + 3 \times 10^3 = 6 + 80 + 500 + 3000 = 3586$$

and the fractional part can be expressed as

$$265 = 2 \times 10^{-1} + 6 \times 10^{-2} + 5 \times 10^{-3} = 0.2 + 0.06 + 0.005 = 0.265$$

We have seen that the place values are a function of the radix of the concerned number system and the position of the digits. We will also discover in subsequent sections that the concept of each digit having a place value depending upon the position of the digit and the radix of the number system is equally valid for the other more relevant number systems.

1.4 Binary Number System

The binary number system is a radix-2 number system with '0' and '1' as the two independent digits. All larger binary numbers are represented in terms of '0' and '1'. The procedure for writing higher-order binary numbers after '1' is similar to the one explained in the case of the decimal number system. For example, the first 16 numbers in the binary number system would be 0, 1, 10, 11, 100, 101, 110, 111, 1000, 1001, 1010, 1011, 1100, 1101, 1110 and 1111. The next number after 1111 is 10000, which is the lowest binary number with five digits. This also proves the point made earlier that a maximum of only 16 ($= 2^4$) numbers could be written with four digits. Starting from the binary point, the place values of different digits in a mixed binary number are 2^0, 2^1, 2^2 and so on (for the integer part) and 2^{-1}, 2^{-2}, 2^{-3} and so on (for the fractional part).

Example 1.1

Consider an arbitrary number system with the independent digits as 0, 1 and X. What is the radix of this number system? List the first 10 numbers in this number system.

Solution

- The radix of the proposed number system is 3.
- The first 10 numbers in this number system would be 0, 1, X, 10, 11, 1X, X0, X1, XX and 100.

1.4.1 Advantages

Logic operations are the backbone of any digital computer, although solving a problem on computer could involve an arithmetic operation too. The introduction of the mathematics of logic by George Boole laid the foundation for the modern digital computer. He reduced the mathematics of logic to a binary notation of '0' and '1'. As the mathematics of logic was well established and had proved itself to be quite useful in solving all kinds of logical problem, and also as the mathematics of logic (also known as Boolean algebra) had been reduced to a binary notation, the binary number system had a clear edge over other number systems for use in computer systems.

Yet another significant advantage of this number system was that all kinds of data could be conveniently represented in terms of 0s and 1s. Also, basic electronic devices used for hardware implementation could be conveniently and efficiently operated in two distinctly different modes. For example, a bipolar transistor could be operated either in cut-off or in saturation very efficiently.

Lastly, the circuits required for performing arithmetic operations such as addition, subtraction, multiplication, division, etc., become a simple affair when the data involved are represented in the form of 0s and 1s.

1.5 Octal Number System

The octal number system has a radix of 8 and therefore has eight distinct digits. All higher-order numbers are expressed as a combination of these on the same pattern as the one followed in the case of the binary and decimal number systems described in Sections 1.3 and 1.4. The independent digits are 0, 1, 2, 3, 4, 5, 6 and 7. The next 10 numbers that follow '7', for example, would be 10, 11, 12, 13, 14, 15, 16, 17, 20 and 21. In fact, if we omit all the numbers containing the digits 8 or 9, or both, from the decimal number system, we end up with an octal number system. The place values for the different digits in the octal number system are 8^0, 8^1, 8^2 and so on (for the integer part) and 8^{-1}, 8^{-2}, 8^{-3} and so on (for the fractional part).

1.6 Hexadecimal Number System

The hexadecimal number system is a radix-16 number system and its 16 basic digits are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E and F. The place values or weights of different digits in a mixed hexadecimal number are 16^0, 16^1, 16^2 and so on (for the integer part) and 16^{-1}, 16^{-2}, 16^{-3} and so on (for the fractional part). The decimal equivalent of A, B, C, D, E and F are 10, 11, 12, 13, 14 and 15 respectively, for obvious reasons.

The hexadecimal number system provides a condensed way of representing large binary numbers stored and processed inside the computer. One such example is in representing addresses of different memory locations. Let us assume that a machine has 64K of memory. Such a memory has 64K ($= 2^{16} = 65\,536$) memory locations and needs 65 536 different addresses. These addresses can be designated as 0 to 65 535 in the decimal number system and 00000000 00000000 to 11111111 11111111 in the binary number system. The decimal number system is not used in computers and the binary notation here appears too cumbersome and inconvenient to handle. In the hexadecimal number system, 65 536 different addresses can be expressed with four digits from 0000 to FFFF. Similarly, the contents of the memory when represented in hexadecimal form are very convenient to handle.

1.7 Number Systems – Some Common Terms

In this section we will describe some commonly used terms with reference to different number systems.

1.7.1 Binary Number System

Bit is an abbreviation of the term 'binary digit' and is the smallest unit of information. It is either '0' or '1'. A *byte* is a string of eight bits. The byte is the basic unit of data operated upon as a single unit in computers. A *computer word* is again a string of bits whose size, called the 'word length' or 'word size', is fixed for a specified computer, although it may vary from computer to computer. The word length may equal one byte, two bytes, four bytes or be even larger.