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Microelectronic Circuits

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ABOUT THE COVER

In the background is a processed wafer of silicon on which a large number of identical circuit chips are fabricated. When cut from such a wafer, a chip can be housed in a package such as the one shown here with its cover removed. This single chip is a segmented memory array with a very large number of active devices in a variety of intricate circuit structures. The growing need for efficient and reliable low-cost components such as these underlies the importance of the various circuit design and circuit analysis techniques discussed in this text.

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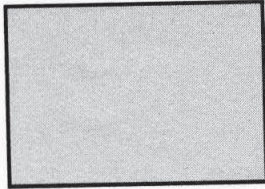
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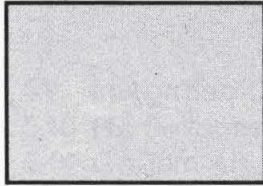
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CHAPTER

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Introduction to Electronics

Introduction

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| 1.2 Frequency Spectrum of Signals | 1.6 Frequency Response of Amplifiers |
| 1.3 Analog and Digital Signals | Summary ■ Bibliography ■ Problems |
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INTRODUCTION

The subject of this book is modern electronics, a field that has come to be known as **microelectronics**. **Microelectronics** refers to the integrated-circuit (IC) technology that at the time of this writing is capable of producing circuits that contain more than 1 million components in a small piece of silicon (known as a **silicon chip**) whose area is in the order of 60 mm^2 . One such microelectronic circuit, for example, is a complete digital computer, which accordingly is known as a **microcomputer** or, more generally, a **microprocessor**.

In this book we shall study electronic devices that can be used singly (in the design of **discrete circuits**) or as components of an integrated-circuit chip. We shall study the design and analysis of interconnections of these devices, which form discrete and integrated circuits of varying complexity and perform a wide variety of functions. We shall also learn about available IC chips and their application in the design of electronic systems.

The purpose of this first chapter is to introduce some basic concepts and terminology. In particular, we shall learn about signals and about one of the most important signal-processing functions electronic circuits are designed to perform, namely, signal amplification. We shall then look at models for linear amplifiers. These models will be employed in subsequent chapters in the design and analysis of actual amplifier circuits.

In addition to motivating the study of electronics, this chapter serves as a bridge between the study of linear circuits and that of the subject of this book: the design and analysis of electronic circuits.

1.1 SIGNALS

Signals contain information about a variety of things and activities in our physical world. Examples abound: Information about the weather is contained in signals that represent the air temperature, pressure, wind speed, etc. The voice of a radio announcer reading the news into a microphone provides an acoustic signal that contains information about world affairs. To monitor the status of a nuclear reactor, instruments are used to measure a multitude of relevant parameters, each instrument producing a signal.

To extract required information from a set of signals, the observer (be it a human or a machine) invariably needs to **process** the signals in some predetermined manner. This **signal processing** is usually most conveniently performed by electronic systems. For this to be possible, however, the signal must first be converted into an electric signal, that is, a voltage or a current. This process is accomplished by devices known as **transducers**. A variety of transducers exist, each suitable for one of the various forms of physical signals. For instance, the sound waves generated by a human can be converted to electric signals using a microphone, which is in effect a pressure transducer. It is not our purpose here to study transducers; rather, we shall assume that the signals of interest already exist in the electrical domain and represent them by one of the two equivalent forms shown in Fig. 1.1. In Fig. 1.1(a) the signal is represented by a voltage source $v_s(t)$ having a source resistance R_s . In the alternate representation of Fig. 1.1(b) the signal is represented by a current source $i_s(t)$ having a source resistance R_s . Although the two representations are equivalent, that in Fig. 1.1(a) (known as the Thévenin form) is preferred when R_s is low. The representation of Fig. 1.1(b) (known as the Norton form) is preferred when R_s is high.

From the discussion above it should be apparent that a signal is a time-varying quantity that can be represented by a graph such as that shown in Fig. 1.2. In fact, the information content of the signal is represented by the changes in its magnitude as time progresses; that is, the information is contained in the “wiggles” in the signal waveform. In general, such waveforms are difficult to characterize mathematically. In other words, it is not easy to describe succinctly an arbitrary looking waveform such as that of Fig. 1.2. Of course, such a description is of great importance for the purpose of designing appropriate signal-processing circuits that perform desired functions on the given signal.

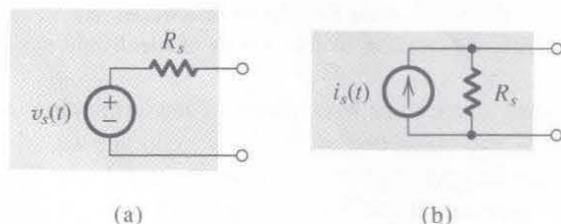
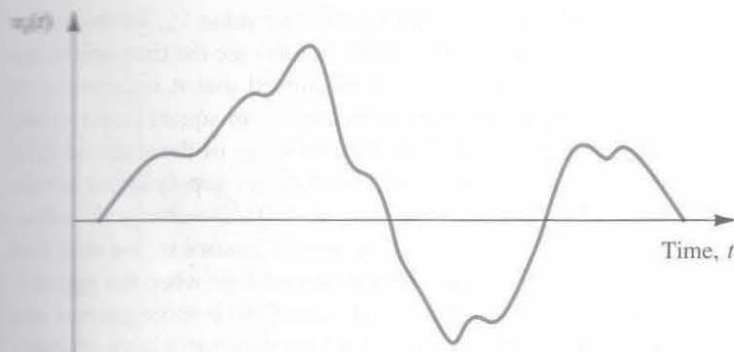


Fig. 1.1 Two alternative representations of a signal source: (a) the Thévenin form, and (b) the Norton form.

Fig. 1.2 An arbitrary voltage signal $v_s(t)$.

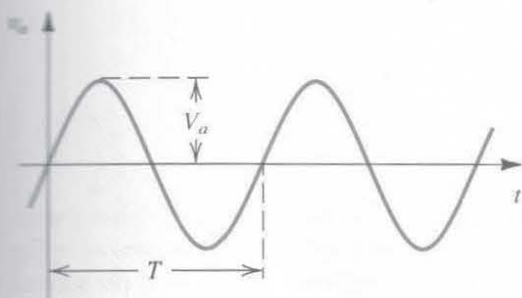
1.2 FREQUENCY SPECTRUM OF SIGNALS

An extremely useful characterization of a signal, and for that matter of any arbitrary function of time, is in terms of its **frequency spectrum**. Such a description of signals is obtained through the mathematical tools of **Fourier series** and **Fourier transform**.¹ We are not interested at this point in the details of these transformations; suffice it to say that they provide the means for representing a voltage signal $v_s(t)$ or a current signal $i_s(t)$ as the sum of sine-wave signals of different frequencies and amplitudes. This makes the sine wave a very important signal in the analysis, design, and testing of electronic circuits. Therefore, we shall briefly review the properties of the sinusoid.

Figure 1.3 shows a sine-wave voltage signal $v_a(t)$,

$$v_a(t) = V_a \sin \omega t \quad (1.1)$$

where V_a denotes the peak value or amplitude in volts and ω denotes the angular frequency in radians per second; that is, $\omega = 2\pi f$ rad/s, where f is the frequency in hertz, $f = 1/T$ Hz, and T is the period in seconds.

Fig. 1.3 Sine-wave voltage signal of amplitude V_a and frequency $f = 1/T$ Hz. The angular frequency $\omega = 2\pi f$ rad/s.

¹The reader who has not yet studied these topics should not be alarmed. No detailed application of this material will be made until Chapter 7. Nevertheless, a general understanding of Section 1.2 should be very helpful when studying early parts of the book.

The sine-wave signal is completely characterized by its peak value V_a , its frequency ω , and its phase with respect to an arbitrary reference time. In this case the time origin has been chosen so that the phase angle is 0. It should be mentioned that it is common to express the amplitude of a sine-wave signal in terms of its root-mean-square (rms) value, which is equal to the peak value divided by $\sqrt{2}$. Thus the rms value of the sinusoid $v_a(t)$ of Fig. 1.2 is $V_a/\sqrt{2}$. For instance, when we speak of the wall power supply in our homes as being 120 V, we mean that it has a sine waveform of $120\sqrt{2}$ volts peak value.

Returning now to the representation of signals as the sum of sinusoids, we note that the Fourier series is utilized to accomplish this task for the special case when the signal is a periodic function of time. On the other hand, the Fourier transform is more general and can be used to obtain the frequency spectrum of a signal whose waveform is an arbitrary function of time.

The Fourier series allows us to express a given periodic function of time as the sum of an infinite number of sinusoids whose frequencies are harmonically related. For instance, the symmetrical square-wave signal in Fig. 1.4 can be expressed as

$$v(t) = \frac{4V}{\pi} (\sin \omega_0 t + \frac{1}{3} \sin 3\omega_0 t + \frac{1}{5} \sin 5\omega_0 t + \cdots) \quad (1.2)$$

where V is the amplitude of the square wave and $\omega_0 = 2\pi/T$ (T is the period of the square wave) is called the **fundamental frequency**. Note that because the amplitudes of the harmonics progressively decrease, the infinite series can be truncated, with the truncated series providing an approximation to the square waveform.

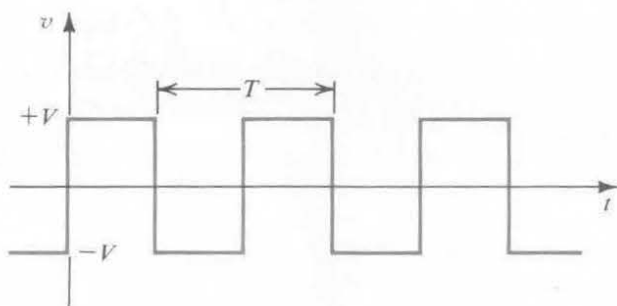


Fig. 1.4 A symmetrical square-wave signal of amplitude V .

The sinusoidal components in the series of Eq. (1.2) constitute the frequency spectrum of the square-wave signal. Such a spectrum can be graphically represented as in Fig. 1.5, where the horizontal axis represents the angular frequency ω in radians per second.

The Fourier transform can be applied to a nonperiodic function of time, such as that depicted in Fig. 1.2, and provides its frequency spectrum as a continuous function of frequency, as indicated in Fig. 1.6. Unlike the case of periodic signals, where the spectrum consists of discrete frequencies (at ω_0 and its harmonics), the spectrum of a nonperiodic signal contains in general all possible frequencies. Nevertheless, the essential parts of

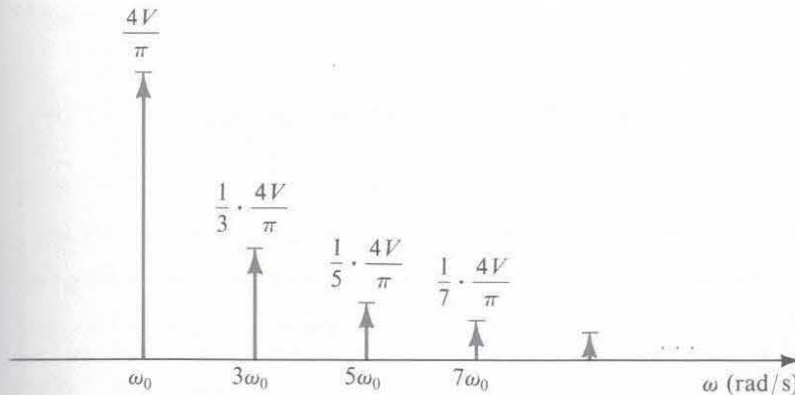


Fig. 1.5 Frequency spectrum (also known as line spectrum) of the periodic square wave of Fig. 1.4.

the spectra of practical signals are usually confined to relatively short segments of the frequency (ω) axis—an observation that is very useful in the processing of such signals. For instance, the spectrum of audible sounds such as speech and music extends from about 20 Hz to about 20 kHz—a frequency range known as the **audio band**. Here we should note that although some musical tones have frequencies above 20 kHz, the human ear is incapable of hearing frequencies that are much above 20 kHz.

We conclude this section by noting that a signal can be represented either by the manner in which its waveform varies with time, as for the voltage signal $v_a(t)$ shown in Fig. 1.2, or in terms of its frequency spectrum, as in Fig. 1.6. The two alternative representations are known as the time-domain representation and the frequency-domain representation, respectively. The frequency-domain representation of $v_a(t)$ will be denoted by the symbol $V_a(\omega)$.

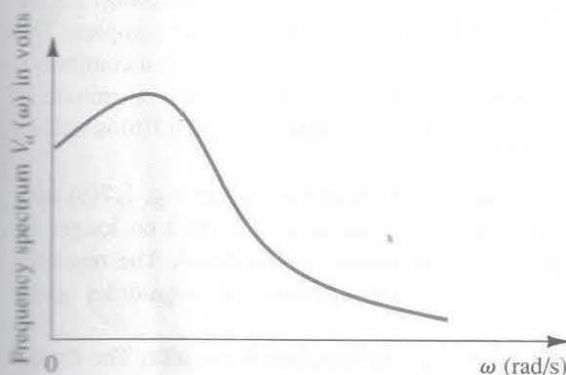


Fig. 1.6 Frequency spectrum of an arbitrary waveform such as that in Fig. 1.2.

Exercises 1.1 Find the frequencies f and ω of a sine-wave signal with a period of 1 ms.

Ans. $f = 1000$ Hz; $\omega = 2\pi \times 10^3$ rad/s

1.2 What is the period T of sine waveforms characterized by frequencies of (a) $f = 60$ Hz? (b) $f = 10^{-3}$ Hz? (c) $f = 1$ MHz?

Ans. 16.7 ms; 1000 s; 1 μ s

1.3 When the square-wave signal of Fig. 1.4, whose Fourier series is given in Eq. (1.2), is applied to a resistor, the total power dissipated may be calculated directly using the relationship $P = 1/T \int_0^T (v^2/R) dt$, or indirectly by summing the contribution of each of the harmonic components, that is, $P = P_1 + P_3 + P_5 + \dots$, which may be found directly from rms values. Verify that the two approaches are equivalent. What fraction of the energy of a square wave is in its fundamental? In its first five harmonics? In its first seven? First nine? In what number of harmonics is 90% of the energy? (Note that in counting harmonics, the fundamental at ω_0 is the first, the one at $2\omega_0$ is the second, etc.)

Ans. 0.81; 0.93; 0.95; 0.96; 3

1.3 ANALOG AND DIGITAL SIGNALS

The voltage signal depicted in Fig. 1.2 is called an **analog signal**. The name derives from the fact that such a signal is analogous to the physical signal that it represents. The magnitude of an analog signal can take on any value; that is, the amplitude of an analog signal exhibits a continuous variation over its range of activity. The vast majority of signals in the world around us are analog. Electronic circuits that process such signals are known as **analog circuits**. A variety of analog circuits will be studied in this book.

An alternative form of signal representation is that of a sequence of numbers, each number representing the signal magnitude at an instant of time. The resulting signal is called a **digital signal**. To see how a signal can be represented in this form—that is, how signals can be converted from analog to digital form—consider Fig. 1.7(a). Here the curve represents a voltage signal, identical to that in Fig. 1.2. At equal intervals along the time axis we have marked the time instants t_0, t_1, t_2 , and so on. At each of these time instants the magnitude of the signal is measured, a process known as **sampling**. Figure 1.7(b) shows a representation of the signal of Fig. 1.7(a) in terms of its samples. The signal of Fig. 1.7(b) is defined only at the sampling instants; it no longer is a continuous function of time, but rather, it is a **discrete-time signal**. However, since the magnitude of each sample can take any value in a continuous range, the signal in Fig. 1.7(b) is still an analog signal.

Now if we represent the magnitude of each of the signal samples in Fig. 1.7(b) by a number having a finite number of digits, then the signal amplitude will no longer be continuous; rather, it is said to be **quantized, discretized, or digitized**. The resulting digital signal then is simply a sequence of numbers that represent the magnitudes of the successive signal samples.

Electronic circuits that process digital signals are called **digital circuits**. The digital computer is a system constructed of digital circuits. All the internal signals in a digital

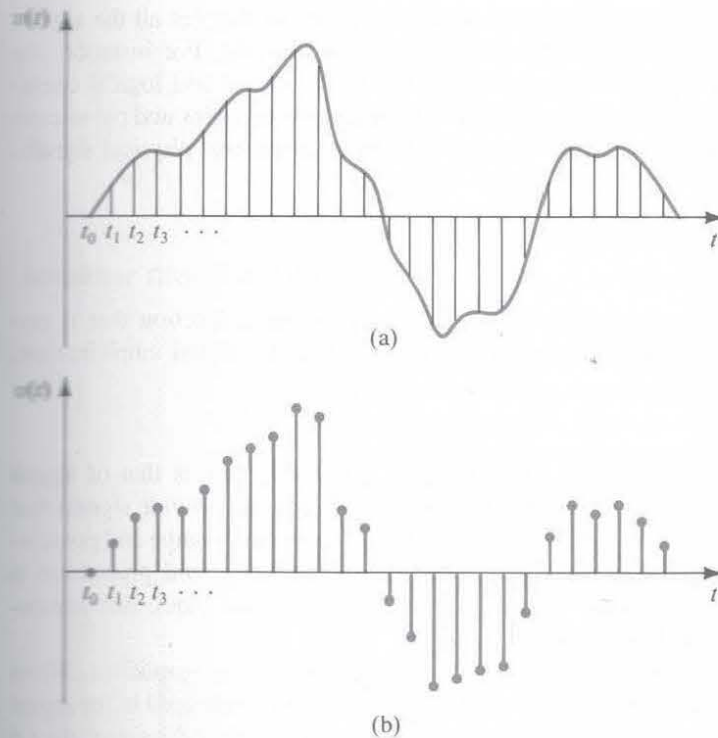


Fig. 1.7 Sampling the continuous-time analog signal in (a) results in the discrete-time signal in (b).

computer are digital signals. Digital processing of signals has become quite popular primarily because of the tremendous advances made in the design and fabrication of digital circuits. Another reason for the popularity of digital signal processing is that one generally prefers to deal with numbers. For instance, there is little doubt that the majority of us find the digital display of time (as in a digital watch) much more convenient than the analog display (hands moving relative to a graduated dial). While the latter form of display calls for interpretation on the part of the observer, the former is explicit, eliminating any subjective judgment. This is an important point that perhaps is better appreciated in the context of an instrumentation system, such as that for monitoring the status of a nuclear reactor. In such a system human interpretation of instrument readings and the associated inevitable lack of consistency could be hazardous. Furthermore, in such an instrumentation system the measurement results usually have to be fed to a digital computer for further analysis. It would be convenient therefore if the signals obtained by the measuring instruments were already in digital form.

Digital processing of signals is economical and reliable. Furthermore, it allows a wide variety of processing functions to be performed—functions that are either impossible or impractical to implement by analog means. Nevertheless, as already mentioned, most of the signals in the physical world are analog. Also, there remain many signal-processing tasks that are best performed by analog circuits. It follows that a good electronics engineer must be proficient in both forms of signal processing. Such is the philosophy adopted in this text.

Before leaving this discussion of signals we should point out that not all the signals with which electronic systems deal originate in the physical world. For instance, the electronic calculator and the digital computer perform mathematical and logical operations to solve problems. The internal digital signals represent the variables and parameters of these problems and are obviously not supplied directly from external physical signals.

1.4 AMPLIFIERS

In this section we shall introduce a fundamental signal-processing function that is employed in some form in almost every electronic system, namely, signal amplification.

Signal Amplification

From a conceptual point of view the simplest signal processing task is that of **signal amplification**. The need for amplification arises because transducers provide signals that are said to be "weak," that is, in the microvolt (μV) or millivolt (mV) range and possessing little energy. Such signals are too small for reliable processing, and processing is much easier if the signal magnitude is made larger. The functional block that accomplishes this task is the **signal amplifier**.

It is appropriate at this point to discuss the need for **linearity** in amplifiers. When amplifying a signal, care must be exercised so that the information contained in the signal is not changed and no new information is introduced. Thus when feeding the signal shown in Fig. 1.2 to an amplifier we want the output signal of the amplifier to be an exact replica of that at the input, except of course for having larger magnitude. In other words, the "wiggles" in the output waveform must be identical to those in the input waveform. Any change in waveform is considered to be **distortion** and is obviously undesirable.

An amplifier that preserves the details of the signal waveform is characterized by the relationship

$$v_o(t) = Av_i(t) \quad (1.3)$$

where v_i and v_o are the input and output signals, respectively, and A is a constant representing the magnitude of amplification, known as **amplifier gain**. Equation (1.3) is a linear relationship; hence the amplifier it describes is a **linear amplifier**. It should be easy to see that if the relationship between v_o and v_i contains higher powers of v_i , then the waveform of v_o will no longer be identical to that of v_i . The amplifier is then said to exhibit **nonlinear distortion**.

The amplifiers discussed so far are primarily intended to operate on very small input signals. Their purpose is to make the signal magnitude larger and therefore are thought of as **voltage amplifiers**. The **preamplifier** in the home stereo system is an example of a voltage amplifier. However, it usually does more than just amplify the signal; specifically, it performs some shaping of the frequency spectrum of the input signal. This topic, however, is beyond our need at this moment.

At this time we wish to mention another type of amplifier, namely, the power amplifier. Such an amplifier may provide only a modest amount of voltage gain but substantial current gain. Thus while absorbing little power from the input signal source to which it is

PART

III

DIGITAL CIRCUITS

CHAPTER

13 MOS Digital Circuits

CHAPTER

14 Bipolar Digital Circuits

INTRODUCTION

Part III is devoted to the study of digital circuits. In a digital circuit, signals take on a limited number of values. The most common digital systems employ two values and are said to be *binary* systems. In such a system, voltage signals are either “high” or “low” and the symbols 1 and 0 are used to denote the two possible levels.

Digital circuits operate on binary-valued input signals and produce binary-valued output signals. The operation of digital circuits can be described by a special kind of algebra called *Boolean algebra*. It is not our intention here to study Boolean algebra, a topic normally covered in digital systems texts. We shall in fact assume that the reader is familiar with the basic concepts of digital systems, and concentrate here on digital electronics.

Digital circuits play a very important role in today’s electronic systems. They are employed in almost every facet of electronics, including communications, control, instrumentation, and, of course, computing. This widespread usage is due mainly to the availability of inexpensive integrated-circuit packages that contain powerful digital circuitry. The circuit complexity of a digital IC chip ranges from a small number of logic gates to a complete computer (a *microprocessor*) or 16 million bits of memory.

The conventional approach to designing digital systems consists of assembling the system using standard IC packages of various levels of complexity (and hence integration). As an alternative to using “off-the-shelf” components, the designer might opt for implementing part or all of the system using one or more customized very-large-scale-integrated (VLSI) circuits. However, custom IC design is usually justified only when the production volume is large (greater than about 100,000 parts). An intermediate approach, known as *semicustom design*, utilizes *gate array* chips. These are integrated circuits containing up to 10,000 unconnected logic gates. Their interconnection can be achieved by a final metallization step according to a pattern specified by the user so as to implement the user’s particular functions. A more recently available type of gate arrays, known as *field programmable gate arrays* (FPGA), can, as their name indicates, be programmed directly by the user.

Whatever approach is taken in digital design, some familiarity with the various digital circuit technologies and design techniques is essential. The material to follow is intended to provide the reader with a basic understanding of digital electronics. It should also serve as an introduction to VLSI circuit design.

Prerequisite to the study of the topics covered in Part III is the material on basic electronic devices presented in Part I.

MOS Digital Circuits

Introduction

- | | | | |
|------|-------------------------------------|-------|-----------------------------------|
| 13.1 | Logic Circuits—Some Basic Concepts | 13.6 | CMOS Gate Circuits |
| 13.2 | NMOS Inverter with Enhancement Load | 13.7 | Latches and Flip-Flops |
| 13.3 | NMOS Inverter with Depletion Load | 13.8 | Multivibrator Circuits |
| 13.4 | NMOS Logic Circuits | 13.9 | Random-Access Memory (RAM) |
| 13.5 | The CMOS Inverter | 13.10 | Read-Only Memory (ROM) |
| | | 13.11 | Gallium-Arsenide Digital Circuits |
| | | | Summary ■ Bibliography ■ Problems |

INTRODUCTION

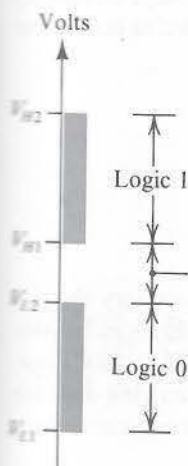
This chapter is concerned with the study of MOS digital integrated circuits, by far the most popular technology for the implementation of digital systems. The small size, ease of fabrication, and low power dissipation of MOSFETs enable extremely high levels of integration of both logic and memory circuits.

Following an introduction to basic logic-circuit concepts (Section 13.1) that apply to both MOSFET and BJT circuits, the two families of MOS logic circuits are presented: NMOS in Sections 13.2–13.4, and CMOS in Sections 13.5 and 13.6. Although NMOS allows very high packing densities (that is, a very large number of gates per chip) and thus is particularly useful in VLSI design, CMOS is currently the most popular and versatile of all logic-circuit types and technologies. It is useful in almost every kind of application and is fabricated at all levels of integration, from SSI to VLSI. Its speed of operation, however, falls short of that achieved with bipolar circuits (Chapter 14) and with the emerging gallium-arsenide circuits presented in the concluding section of this chapter.

In addition to combinational logic circuits, this chapter presents such other essential digital-system building blocks as flip-flops and multivibrators, as well as providing an overview and introduction to memory circuits.

13.1 LOGIC

Digital Signals



Logic Circuit F

Finally, in preparation for the study of MOS digital circuits, the reader is urged to review the characteristics and basic circuits of MOSFETs (Chapter 5).

13.1 LOGIC CIRCUITS—SOME BASIC CONCEPTS

In this section we consider some basic concepts that underlie the design and specification of logic gate circuits. The material presented applies to both MOS and bipolar digital circuits.

Digital Signals

In binary digital circuits, two distinct voltage levels can represent the two values of binary variables. However, in order to allow for the inevitable component tolerances and miscellaneous other effects that change the signal voltage levels, two distinct voltage ranges are usually defined. As shown in Fig. 13.1, if the signal voltage lies in the range V_{L1} to V_{L2} , the signal is interpreted (by the digital circuit) as a logic 0. If the signal amplitude falls in the range V_{H1} to V_{H2} , it is interpreted as a logic 1. The two voltage bands are separated by a range in which the signal amplitude is not supposed to lie. This forbidden band represents an undefined or excluded region.

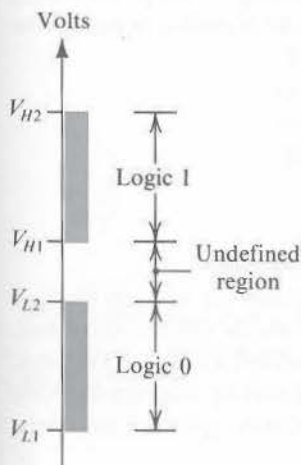


Fig. 13.1 Two distinct voltage ranges are used to represent the two values of binary variables.

Since the logic-1 voltages are higher than those that represent logic 0, the system illustrated in Fig. 13.1 is said to use **positive logic**. We can of course reverse our voltage band assignment, thus obtaining a **negative-logic** system. Throughout this book we shall assume the positive-logic convention. Furthermore, on many occasions we shall use the words “high” and “low” interchangeably with 1 and 0, respectively.

Logic Circuit Families

Integrated logic circuits are classified into a number of different families. Members of each family are made with the same technology, have similar circuit structure, and exhibit

the same basic features. In this chapter we shall study two MOS families: NMOS and CMOS. The first utilizes n -channel MOSFETs exclusively; the latter uses both n - and p -channel transistors in complementary symmetric circuit configurations. In the next chapter we shall study two BJT logic families: transistor-transistor logic (TTL) and emitter-coupled logic (ECL). CMOS, TTL, and ECL are available as off-the-shelf components for conventional logic design, as well as being utilized in the design of special VLSI circuits. NMOS, on the other hand, is used only in the design of VLSI circuits such as microprocessors and memory chips.

It will be shown that each of the four logic circuit families offers a unique set of advantages and disadvantages. In designing a digital system one selects an appropriate logic family and attempts to implement as much of the system as possible using packages that belong to this family. In this way interconnection of the various packages is relatively straightforward. If, on the other hand, packages from more than one family have to be used, one has to design suitable *interface circuits*. The selection of a logic family is based on such considerations as logic flexibility, speed of operation, availability of complex functions, noise immunity, operating-temperature range, power dissipation, and cost. We will discuss some of these considerations in this chapter and the next.

Scale of Integration

Many types of logic functions are usually available within each logic family. Depending on the complexity of the circuit of the IC chip, the package can be classified as one of four types:

1. small-scale integrated (SSI) circuit
2. medium-scale integrated (MSI) circuit
3. large-scale integrated (LSI) circuit
4. very-large-scale integrated (VLSI) circuit

Although the boundaries between the different levels of integration are not very sharp, a rough guide, based on the number of "equivalent logic gates" on the chip, is as follows: SSI, 1 to 10 gates; MSI, 10 to 100 gates; LSI, 100 to 1000 gates; and VLSI, >1000 gates.

The basic circuit properties of a logic family can be established by studying the basic inverter circuit of that family. In the following we shall consider the general characteristics and structure of the logic inverter circuit.

The Basic Inverter

The logic inverter is basically a voltage-controlled switch such as that represented schematically in Fig. 13.2. As shown, the switch connected between terminals 2 and 3 is controlled by the input signal v_I applied between terminals 1 and 3 (terminal 3 is connected to the reference or ground point). The inverter output voltage v_O is taken across the switch—that is, between 2 and ground. When v_I is low (around 0 V) the switch is open and the output voltage v_O is high (equal to the supply voltage V^+). When v_I is high (above a specified threshold voltage, as explained below) the switch is closed and the output voltage is low (0 V). It should be obvious that this circuit realizes the logic inversion operation.

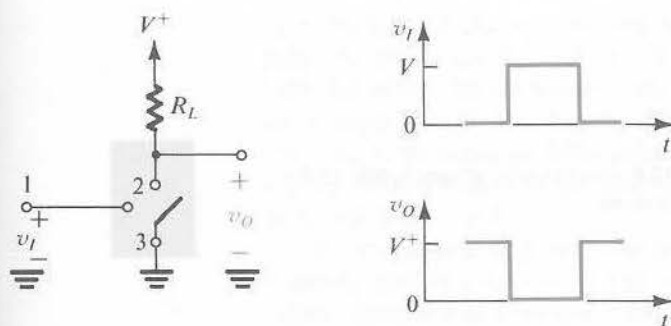


Fig. 13.2 A conceptual representation of the logic inverter as a voltage-controlled switch.

Practical logic inverter circuits differ from the conceptual circuit in Fig. 13.2 in a number of ways. First, the input terminal of the inverter usually draws some current from the driving source. Second, the switch is not ideal; specifically, when the switch is closed it does not behave as a short circuit but rather has a finite closure resistance (called **on resistance**) and sometimes an additional voltage drop (called **offset voltage**). Figure 13.3 shows an equivalent circuit of the switch in the closed position. As a result of these imperfections, the voltage v_O will not be zero in the on state. Third, the inverter switch may not switch instantaneously; rather, there may be a delay time between the application of the input change and the appearance of the output change. Even if the inverter switches instantaneously, the capacitance inevitably present between the output terminals will cause the output waveform to have finite rise and fall times. This point will be discussed in some detail shortly. Fourth, actual inverters may not exhibit a well-defined switching threshold as implied by the discussion of the conceptual circuit of Fig. 13.2. Transfer characteristics of logic inverters are discussed next.

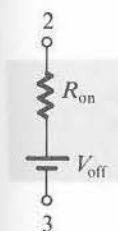


Fig. 13.3 Equivalent circuit for a typical switch in the on position.

Practical implementations of the logic inverter utilize a transistor (a MOSFET or a BJT) as the switching element and a resistor or another transistor for the load resistor R_L . Since MOS transistors require much smaller chip areas than medium- and high-valued resistors, MOS logic circuits almost always utilize MOSFETs as load elements.

The Inverter Transfer Characteristic

Figure 13.4 shows the ideal transfer characteristic for a logic inverter operated from a power supply V^+ . As indicated, the inverter exhibits a threshold voltage $V_{th} = \frac{1}{2}V^+$. Input signals below this threshold voltage are interpreted as being low, and the inverter output is equal to the supply voltage V^+ . Input signals above the threshold are interpreted as high,

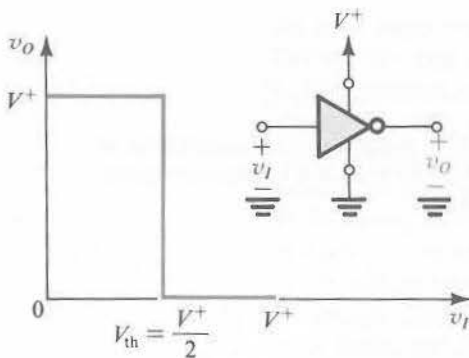


Fig. 13.4 Ideal transfer characteristic of the logic inverter.

and the inverter output is equal to 0 V. Note that this inverter is quite tolerant of errors in the value of the input signal. Also, with the threshold voltage at half the power supply, this tolerance is equally distributed between the two domains of input signal (low and high). Finally, the inverter characteristics are ideal in the sense that, independent of the exact value of input signal, the output is either V^+ or 0 V.

Actual logic inverters have transfer characteristics that only approximate the ideal one of Fig. 13.4. Figure 13.5 shows a typical inverter transfer characteristic. Note that the threshold voltage is no longer well defined and that there exists a *transition region* between the high and low states. Also, the high output (V_{OH}) and low output (V_{OL}) are no longer equal to V^+ and 0 V, respectively.

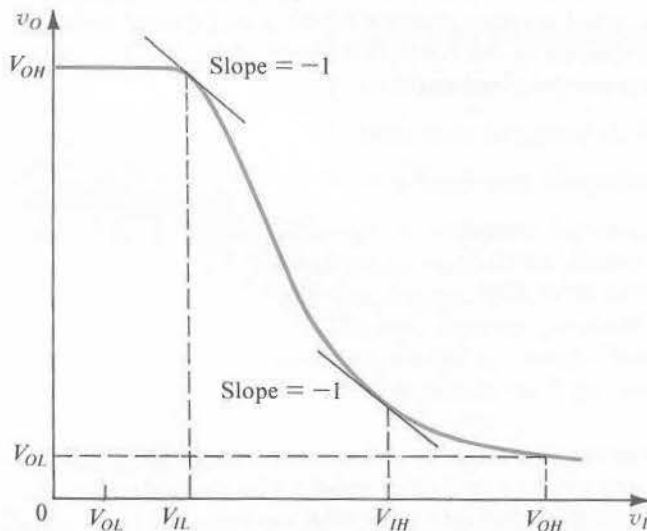


Fig. 13.5 Typical transfer characteristic of a logic inverter, illustrating the definition of the critical points.

Examining the inverter transfer characteristic in Fig. 13.5 in more detail, we note that there are three distinct regions:

1. The low-input region: $v_I < V_{IL}$
2. The transition (or uncertain) region: $V_{IL} \leq v_I \leq V_{IH}$
3. The high-input region: $v_I > V_{IH}$

Since the transition between one region and the next might not be sharp, it is customary to define V_{IL} and V_{IH} as the points at which the slope of the voltage transfer curve is -1 , as indicated in Fig. 13.5. Of course, the slope in the transition region is much greater than unity. Input voltages less than V_{IL} are acknowledged by the gate as representing logic 0. Thus, V_{IL} is the maximum allowable logic-0 value. Similarly, input voltages greater than V_{IH} are acknowledged by the gate as representing logic 1. Thus, V_{IH} is the minimum allowable logic-1 value.

We should note in passing that the inverter transfer characteristic indicates that it is a grossly nonlinear device. In fact, digital circuits are extreme cases of the nonlinear circuits discussed in Chapters 3 and 12. If the inverter whose transfer characteristic is depicted in Fig. 13.5 were to be used as a linear amplifier, it would be biased at a point somewhere in the transition region, and the input signal swing would be kept small to restrict operation to a short, almost-linear segment in the transition region of the characteristic.

Noise Margins

A great advantage of binary digital circuits is their tolerance to variations in value of input signals. As long as the input signal is correctly interpreted as low or high, the accuracy of operation is not affected. This tolerance to variation in signal level can be considered as immunity to noise superimposed on the input signal. Here *noise* refers to extraneous signals that can be capacitively or inductively coupled into the digital circuit from other parts of the system or from outside the system. We shall now quantify the ability of a logic gate to reject noise.¹

Consider once more the inverter transfer characteristic of Fig. 13.5, where the four parameters V_{IL} , V_{IH} , V_{OL} , and V_{OH} are indicated. On the horizontal axis we have also marked the points corresponding to the output levels V_{OL} and V_{OH} . In a logic system, one gate usually drives another. Thus a gate whose output is high, at V_{OH} , drives an identical gate whose specified minimum input logic-1 level is V_{IH} . The difference $V_{OH} - V_{IH}$ represents a margin of safety, for if noise were superimposed on the output signal of the driving gate (V_{OH}), the driven gate would not be bothered as long as the amplitude of the noise voltage was lower than $(V_{OH} - V_{IH})$. This difference is therefore called the **logic-1** or **“high” noise margin** and is denoted NM_H ; that is,

$$NM_H \equiv V_{OH} - V_{IH} \quad (13.1)$$

The **logic-0** or **“low” noise margin**, NM_L , is similarly defined as

$$NM_L \equiv V_{IL} - V_{OL} \quad (13.2)$$

Due to the unavoidable variabilities in the values of circuit components and power-supply voltage, the manufacturer usually specifies *worst-case* values for the four parameters V_{OH} , V_{IH} , V_{OL} , and V_{IL} . These values are defined as follows:

V_{OH} the minimum voltage that will be available at a gate output when the output is supposed to be logic 1 (high)

¹Unlike in analog circuits, where injected noise propagates throughout the system, in digital circuits, once a gate rejects noise at the input, the gate output will be correct and we need no longer concern ourselves with the input noise.

- V_{IH} the minimum gate input voltage that will be unambiguously recognized by the gate as corresponding to logic 1
- V_{OL} the maximum voltage that will be available at a gate output when the output is supposed to be logic 0 (low)
- V_{IL} the maximum gate input voltage that will be unambiguously recognized by the gate as corresponding to logic 0

Instead of drawing the complete transfer characteristic, one usually is satisfied with the logic band diagram of Fig. 13.6. From this diagram it can be inferred that to maximize and equalize NM_L and NM_H , one ideally desires that $V_{IL} = V_{IH} =$ a value midway in the logic swing V_{OL} to V_{OH} . This implies that the transfer characteristic should switch abruptly; that is, it should exhibit high gain in the transition region. It also implies that switching should occur in the middle of the logic swing. To maximize this swing, V_{OL} should be as low as possible (ideally 0 V) and V_{OH} should be as high as possible (ideally equal to the power supply voltage V^+). Such an idealized transfer characteristic is shown in Fig. 13.4. As will be seen in Section 13.5, the CMOS logic family provides an excellent approximation to the ideal performance.

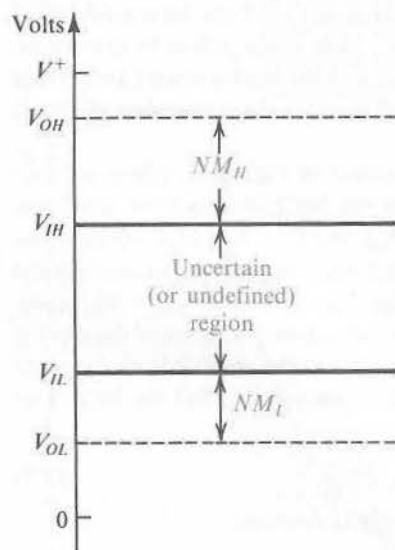


Fig. 13.6 Logic band diagram indicating the noise margins.

Power Dissipation

Of interest to a logic circuit designer is the amount of power consumed by the circuit. Knowledge of power dissipation enables the designer to determine the current that the power supply for a digital system must provide. The power dissipated in a logic circuit is composed of two components: static and dynamic. The **static power** is the power dissipated while the circuit is not changing states. Thus for the idealized inverter of Fig. 13.2 we see that when the output is high, the static power is zero; however, when the output is