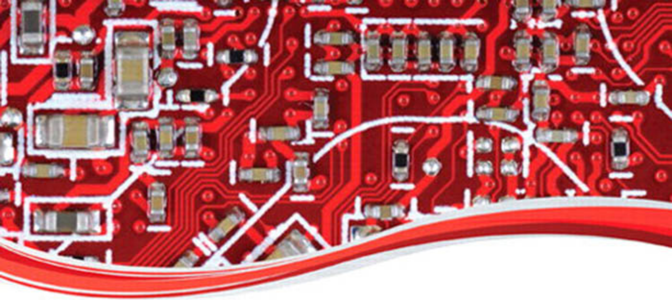
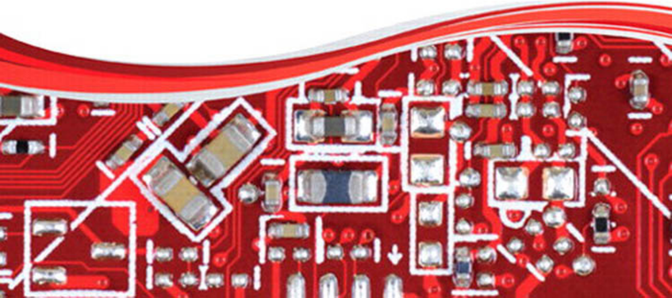


Analog Fundamentals

A SYSTEMS APPROACH

THOMAS L. FLOYD
DAVID M. BUCHLA



ANALOG FUNDAMENTALS

A SYSTEMS APPROACH

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PREFACE

This first edition of *Analog Fundamentals: A Systems Approach* provides unique coverage of analog devices and circuits with a systems emphasis. Discrete linear devices, operational amplifiers, and important analog integrated circuits are covered with examples of how these devices and circuits are used in electronic systems. Important analog integrated circuits include instrumentation amplifiers, isolation amplifiers, operational transconductance amplifiers, phase-locked loops, and analog-to-digital conversion circuits. Analog devices are still of fundamental importance, even within many "digital" systems. Consequently, many of the system examples focus on these mixed systems. Coverage of analog devices used in switching applications is also included. The text wraps up with a chapter entitled "Measurement and Control," which includes discussions on transducers and interfacing methods.

As electronics has evolved, the need to understand the relationship among system blocks, interfaces, and input/output signals has increased. We have addressed these changes by including system examples (many with block diagrams) and descriptions in every chapter. The system examples and system notes complement and illustrate the analog concepts covered in the chapter and section in which they appear. Many chapters also include a troubleshooting section that emphasizes the testing and measurements necessary at a system level. Multisim examples and troubleshooting simulations are also included in many of the examples.

The text emphasizes operation and application rather than analysis and design. Both discrete and integrated analog devices are presented from a practical view. Mathematical topics are limited to only essential coverage that a technician or technologist will need to understand the basic concepts. This includes a basic understanding of algebra and trigonometric functions; higher-level mathematics, such as calculus, is not required.

A mix of analog and digital components is very common in real-world applications and systems. Both technologies have their strengths for specific systems. Examples of mixed systems are provided at selected points in the text to illustrate how the two technologies are used together to produce a specific result.

Features

- Systems are emphasized in every chapter with System Examples that are coordinated to the section.
- System Notes throughout the text highlight important ideas or system-related issues such as electronic noise.
- Multisim is used in selected examples, figures, and problems to provide practice in simulating circuits and systems and in troubleshooting.
- Worked examples help to illustrate the function and application of both discrete and integrated analog devices. Practice exercises in each worked example to provide additional practice.
- Each chapter begins with a chapter outline, chapter objectives, key terms list, introduction, and website reference.
- Each section within a chapter begins with an introduction and section objectives.
- Links to manufacturers' online data sheets are provided for most of the devices covered in each chapter.
- Each section concludes with a set of Checkup questions, which review the main concepts in the section.
- Each chapter ends with a summary, glossary, key formulas list, self-test, troubleshooting quiz, and sectionalized problem set.

- Answers to section checkups, related problems for examples, self-test, and troubleshooting quiz are at the end of each chapter.
- A comprehensive glossary is provided at the end of the text. Key terms are highlighted in bold color and defined at the end of each chapter as well as at the end of the book. Other glossary terms are bold black when first used.
- Answers to odd-numbered problems are provided at the end of the textbook.
- The website includes Multisim files for selected examples, figures, and Multisim troubleshooting practice are in the website (www.pearsonhighered.com).

Student Resources

- *Experiments in Analog Fundamentals: A Systems Approach* (ISBN 0132988674) by David Buchla. Lab exercises are coordinated with the text and solutions are provided in the Instructor's Resource Manual.
- *Multisim Experiments for the DC/AC, Digital, and Devices Courses* (ISBN 0132113880) by Gary Snyder and David Buchla. Students take data, analyze results, and write a conclusion to simulate an actual laboratory experience.
- **Multisim Files Available on the Website** Circuit files coordinated with this text in Versions 11 and 12 of Multisim are located on the website at www.pearsonhighered.com/floyd. Circuit files with prefix F are figure circuits; files with prefix P are Multisim Troubleshooting circuits; and files with prefix SE are System Example circuits.

In order to use the Multisim circuit files, you must have Multisim software installed on your computer. Multisim software is available at **www.ni.com/Multisim**. Although the Multisim circuit files are intended to complement classroom, textbook, and laboratory study, these files are not essential to successfully using this text.

Instructor Resources

Instructor resources are available from Pearson's **Instructor's Resource Center**.

- PowerPoint® slides (ISBN 0132987708) support the topics in each chapter.
- Instructor's Resource Manual (ISBN 0132988593) contains the solutions to the text problems and the solutions to the lab manual.
- TestGen (ISBN 0132989883) This electronic bank of test questions can be used to develop customized quizzes, tests, and/or exams.

To access supplementary materials online, instructors need to request an instructor access code. Go to **www.pearsonhighered.com/irc**, where you can register for an instructor access code. Within 48 hours after registering, you will receive a confirming e-mail, including an instructor access code. Once you have received your code, go to the site and log on for full instructions on downloading the materials you wish to use.

Illustrations of Textbook Features

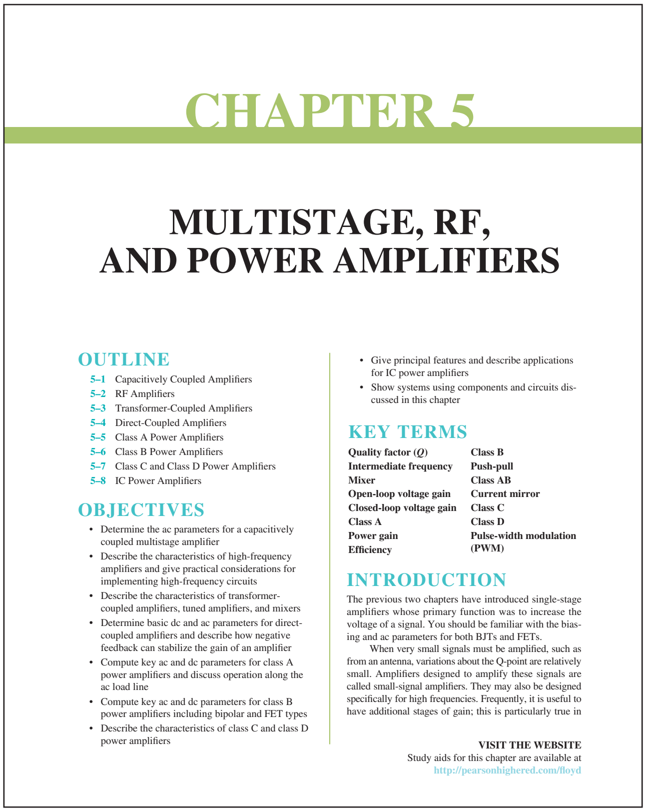
Chapter Opener A typical chapter opener is shown in Figure P–1.

Worked Example, Practice Exercise and Multisim Exercise A typical worked example with Practice Exercise, and Multisim exercise are shown in Figure P–2.

Section Opener A typical section opener and section objectives are shown in Figure P–3.

Section Checkup A typical section checkup is shown in Figure P–3.

System Note A typical system note is shown in Figure P–3.



CHAPTER 5

MULTISTAGE, RF, AND POWER AMPLIFIERS

OUTLINE

OBJECTIVES

- Determine the ac parameters for a capacitively coupled multistage amplifier
- Describe the characteristics of high-frequency amplifiers and give practical considerations for implementing high-frequency circuits
- Describe the characteristics of transformer-coupled amplifiers, tuned amplifiers, and mixers
- Determine basic dc and ac parameters for direct-coupled amplifiers and describe how negative feedback can stabilize the gain of an amplifier
- Compute key ac and dc parameters for class A power amplifiers and discuss operation along the ac load line
- Compute key ac and dc parameters for class B power amplifiers including bipolar and FET types
- Describe the characteristics of class C and class D power amplifiers
- Give principal features and describe applications for IC power amplifiers
- Show systems using components and circuits discussed in this chapter

KEY TERMS

Quality factor (*Q*)	**Class B**
Intermediate frequency	**Push-pull**
Mixer	**Class AB**
Open-loop voltage gain	**Current mirror**
Closed-loop voltage gain	**Class C**
Class A	**Class D**
Power gain	**Pulse-width modulation (PWM)**
Efficiency	

INTRODUCTION

The previous two chapters have introduced single-stage amplifiers whose primary function was to increase the voltage of a signal. You should be familiar with the biasing and ac parameters for both BJTs and FETs.

When very small signals must be amplified, such as from an antenna, variations about the Q-point are relatively small. Amplifiers designed to amplify these signals are called small-signal amplifiers. They may also be designed specifically for high frequencies. Frequently, it is useful to have additional stages of gain; this is particularly true in

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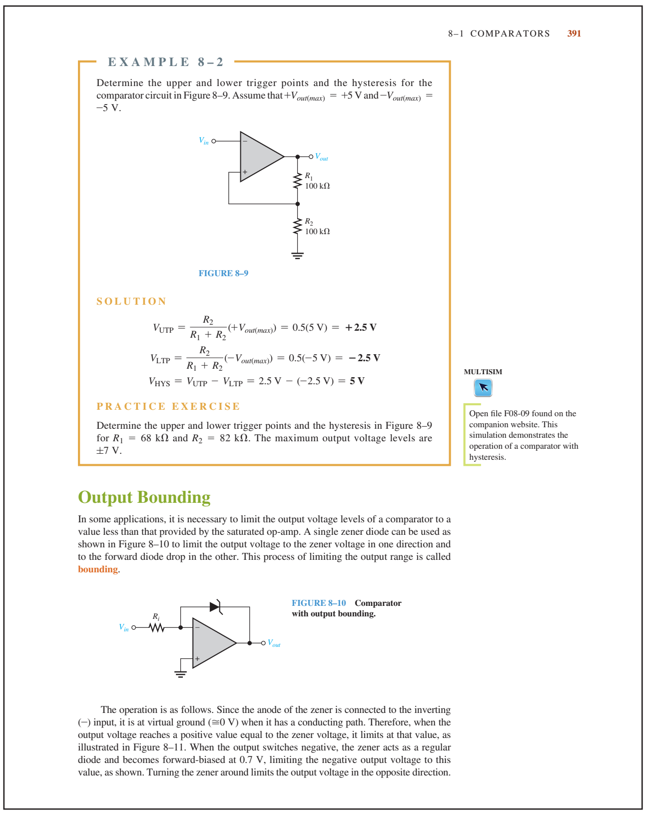
FIGURE P–1 Chapter opener.



EXAMPLE 8–2

Determine the upper and lower trigger points and the hysteresis for the comparator circuit in Figure 8–9. Assume that $+V_{out(max)} = +5$ V and $-V_{out(max)} = -5$ V.

FIGURE 8–9

SOLUTION

$$V_{UTP} = \frac{R_2}{R_1 + R_2}(+V_{out(max)}) = 0.5(5\text{ V}) = \mathbf{+2.5\text{ V}}$$

$$V_{LTP} = \frac{R_2}{R_1 + R_2}(-V_{out(max)}) = 0.5(-5\text{ V}) = \mathbf{-2.5\text{ V}}$$

$$V_{HYS} = V_{UTP} - V_{LTP} = 2.5\text{ V} - (-2.5\text{ V}) = \mathbf{5\text{ V}}$$

PRACTICE EXERCISE

Determine the upper and lower trigger points and the hysteresis in Figure 8–9 for $R_1 = 68$ kΩ and $R_2 = 82$ kΩ. The maximum output voltage levels are ±7 V.

MULTISIM

Open file F08-09 found on the companion website. This simulation demonstrates the operation of a comparator with hysteresis.

Output Bounding

In some applications, it is necessary to limit the output voltage levels of a comparator to a value less than that provided by the saturated op-amp. A single zener diode can be used as shown in Figure 8–10 to limit the output voltage to the zener voltage in one direction and to the forward diode drop in the other. This process of limiting the output range is called **bounding**.

FIGURE 8–10 Comparator with output bounding.

The operation is as follows. Since the anode of the zener is connected to the inverting (−) input, it is at virtual ground (≅0 V) when it has a conducting path. Therefore, when the output voltage reaches a positive value equal to the zener voltage, it limits at that value, as illustrated in Figure 8–11. When the output switches negative, the zener acts as a regular diode and becomes forward-biased at 0.7 V, limiting the negative output voltage to this value, as shown. Turning the zener around limits the output voltage in the opposite direction.

FIGURE P–2 Worked example with Practice Exercise and Multisim exercise.

FIGURE P–3 Section opener, Section Checkup and System note.

7–5 OP-AMP COMPENSATION 371

Noise in Systems

Many systems share power supplies between various assemblies. The longer runs of power supply cables are vulnerable to noise pickup and are conductive paths for noise. As mentioned in this section, power supply leads should have 0.1 to 1 μF tantalum capacitors installed at every circuit board and assembly at the entry point. On circuit boards, every 3 or 4 ICs should also have bypass capacitors on the supply lines. In some systems, the designer will install a separate regulator circuit in each board, to help isolate the main power supply. This is a simple modification but can cure conductive noise problems.

Systems such as radar systems have high power in the same system as sensitive receiver circuits. To avoid noise problems in these systems, it is important to isolate high power signals and utility cables from low level signal lines. Covers and shields should be checked and kept in place, both for safety and to avoid radiated noise. In many systems, electromagnetic shielding gaskets are used on doors and enclosures to block a path for electromagnetic interference (EMI). These shields are useless if a door or enclosure is left ajar, so it is important to maintain good housekeeping practices.

FIGURE SN7–1 Radio-frequency gasket material for EMI protection. (Courtesy of Leader Tech, Tampa, FL.)

SYSTEM NOTE

SECTION 7–4 CHECKUP

1. Under what feedback condition can an amplifier oscillate?
2. How much can the phase shift of an amplifier's internal *RC* network be before instability occurs? What is the phase margin at the point where instability begins?
3. What is the maximum roll-off rate of the open-loop gain of an op-amp for which the device will still be stable?

7–5 OP-AMP COMPENSATION

The last section demonstrated that instability can occur when an op-amp's response has roll-off rates exceeding −20 dB/decade and the op-amp is operated in a closed-loop configuration having a gain curve that intersects a higher roll-off rate portion of the open-loop response. In situations like those examined in the last section, the closed-loop voltage gain is restricted to very high values. In many applications, lower values of closed-loop gain are necessary or desirable. To allow op-amps to be operated at low closed-loop gain, phase lag compensation is required. This section may be treated as optional.

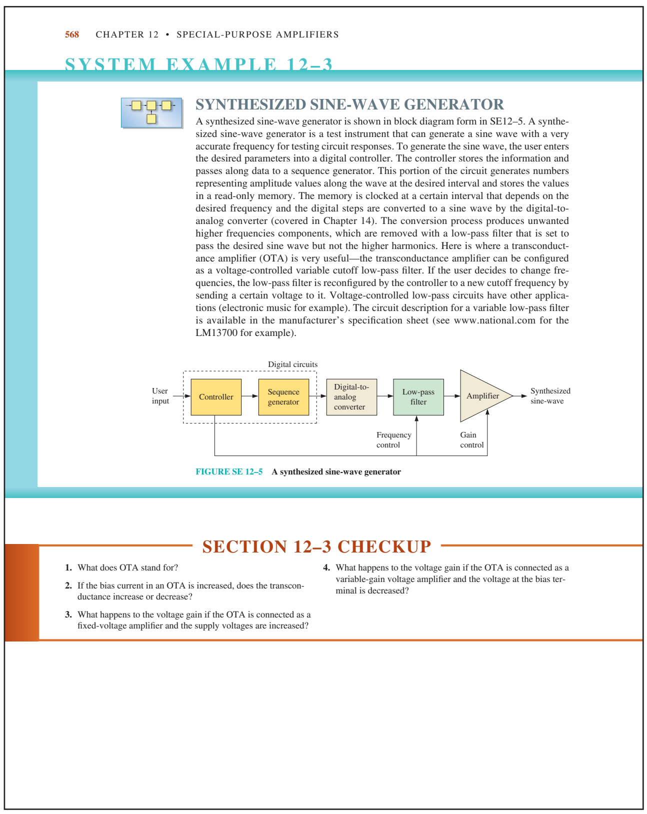
After completing this section, you should be able to

- **Explain op-amp phase compensation**
  - **Describe phase-lag compensation**
  - **Explain a compensating circuit**
  - **Apply single-capacitor compensation**
  - **Apply feedforward compensation**

System Example A typical system example is shown in Figure P–4.

Troubleshooting Section A portion of a typical troubleshooting section is shown in Figure P–5.

FIGURE P–4 System Example.



568 CHAPTER 12 • SPECIAL-PURPOSE AMPLIFIERS

SYSTEM EXAMPLE 12–3

SYNTHESIZED SINE-WAVE GENERATOR

A synthesized sine-wave generator is shown in block diagram form in SE12–5. A synthesized sine-wave generator is a test instrument that can generate a sine wave with a very accurate frequency for testing circuit responses. To generate the sine wave, the user enters the desired parameters into a digital controller. The controller stores the information and passes along data to a sequence generator. This portion of the circuit generates numbers representing amplitude values along the wave at the desired interval and stores the values in a read-only memory. The memory is clocked at a certain interval that depends on the desired frequency and the digital steps are converted to a sine wave by the digital-to-analog converter (covered in Chapter 14). The conversion process produces unwanted higher frequencies components, which are removed with a low-pass filter that is set to pass the desired sine wave but not the higher harmonics. Here is where a transconductance amplifier (OTA) is very useful—the transconductance amplifier can be configured as a voltage-controlled variable cutoff low-pass filter. If the user decides to change frequencies, the low-pass filter is reconfigured by the controller to a new cutoff frequency by sending a certain voltage to it. Voltage-controlled low-pass circuits have other applications (electronic music for example). The circuit description for a variable low-pass filter is available in the manufacturer's specification sheet (see www.national.com for the LM13700 for example).

FIGURE SE 12–5 A synthesized sine-wave generator

SECTION 12–3 CHECKUP

1. What does OTA stand for?
2. If the bias current in an OTA is increased, does the transconductance increase or decrease?
3. What happens to the voltage gain if the OTA is connected as a fixed-voltage amplifier and the supply voltages are increased?
4. What happens to the voltage gain if the OTA is connected as a variable-gain voltage amplifier and the voltage at the bias terminal is decreased?

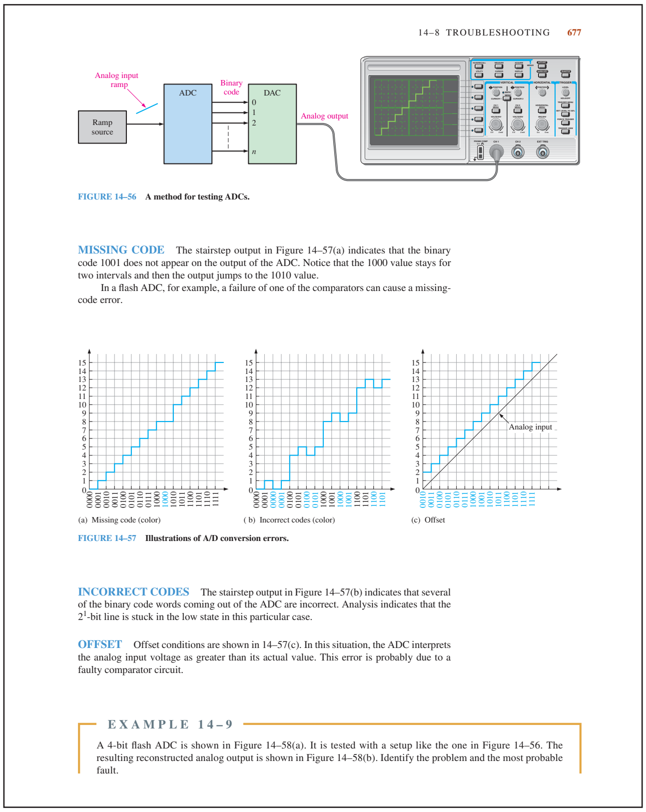


FIGURE P–5 Troubleshooting section.

Other Features

End of Chapter The following features are at the end of each chapter.

- Summary
- Glossary
- Key Formulas
- Self-test
- Troubleshooting quiz
- Sectionalized and categorized problem set
- Answers to section checkups, related problems for examples, troubleshooting quiz, and self-test

End of Book The following features are at the end of book.

- Derivations of selected equations
- Answers to odd-numbered problems
- Comprehensive glossary
- Index

To the Student

Any career training requires effort, and the electronics field is no exception. The best way for you to learn new material is by reading, thinking, and doing. This text is designed to help you along the way and to illustrate how discrete and integrated analog devices are used in systems, both large and small.

Read each section of the text carefully and think about what you have read. Sometimes you may need to read the section more than once. Work through each example problem step-by-step before you try the related problem that goes with the example. After each section, answer the checkup questions. Answers to the related problems and the section checkup questions are at the end of each chapter.

Review the chapter summary, the key term definitions, and the formula list. Review system examples and notes. Multisim examples are a good way to see circuits in action and answer "what-if?" questions you may have. Take the multiple-choice self-test, and the troubleshooting quiz. Check your answers against those at the end of the chapter. Finally, work the problems and compare your answers to the odd-numbered problems with those provided at the end of the book.

The importance of obtaining a thorough understanding of the concepts contained in this text cannot be overemphasized. These will prove to be invaluable when you are dealing with complex analog circuits and systems. If you have a good training in these concepts, an employer will train you in the specifics of the job to which you are assigned.

Acknowledgments

The concept of this series of systems-oriented textbooks is credited to suggestions and discussions with senior instructional staff at ITT Schools and Vern Anthony at Pearson Education. The staff and others at Pearson Education, by their hard work and dedication, have helped make the textbook a reality. Rex Davidson skillfully guided the work through its many detailed phases of production to create the end product that you are now looking at. Dan Trudden, the development editor, has provided effective overall guidance for this project. We also thank acquisitions editor Lindsey Prudhomme.

In addition to the hard work from the staff at Pearson, we appreciate the contributions and many suggestions for system notes and examples from Toby Boydell. In addition to many excellent suggestions, Toby did a complete review of the manuscript. We also thank Gary Snyder for his support in developing the final Multisim exercises throughout the book and his contribution of the Multisim tutorial. Finally, we offer thanks to our wives for the sacrifices made while we worked on the manuscript.

TOM FLOYD
DAVID BUCHLA

CHAPTER 1

BASIC ANALOG CONCEPTS

OUTLINE

OBJECTIVES

- Discuss the basic characteristics of analog electronics
- Describe analog signals
- Analyze signal sources
- Explain the characteristics of an amplifier
- Describe the process for troubleshooting a circuit

KEY TERMS

Characteristic curve
Analog signal
Digital signal
Period (*T*)
Cycle
Phase angle
Frequency
Thevenin's theorem
Load line
Transducer
Amplifier
Gain
Decibel (dB)
Attenuation

INTRODUCTION

With the influence of computers and other digital devices, it's easy to overlook the fact that virtually all natural phenomena that we measure (for example, pressure, flow rate, and temperature) originate as analog signals. In electronics, transducers are used to convert these analog quantities into voltage or current. Usually amplification or other processing is required for these signals. Depending on the application, either digital or analog techniques may be more efficient for processing. Analog circuits are found in nearly all power supplies, in many "real-time" applications (such as motor-speed controls), and in high-frequency communication systems. Digital processing is more effective when mathematical operations must be performed and has major advantages in reducing the noise inherent in processing analog signals. In short, the two sides of electronics (analog and digital) complement each other, and the competent technician needs to be knowledgeable of both.

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1–1 ANALOG ELECTRONICS

The field of electronics can be subdivided into various categories for study. The most basic division is to categorize signals between those that are represented by binary numbers (digital) and those that are represented by continuously variable quantities (analog). Digital electronics includes all arithmetic and logic operations such as performed in computers and calculators. Analog electronics includes virtually all other (nondigital) signals. Analog electronics includes signal-processing functions such as amplification, differentiation, and integration. It is true that today almost all information—audio, video, and data—is digitized for transmission, and some types of signal processing. But it is also true that we cannot interact directly with the digital world. We are analog machines, and analog devices continue to play an important role in modern electronics.

After completing this section, you should be able to

- **Discuss the basic characteristics of analog electronics**
  - **Contrast the characteristic curve for a linear component with that of a nonlinear component**
  - **Explain what is meant by a characteristic curve**
  - **Compare dc and ac resistance and explain how they differ**
  - **Explain the difference between conventional current and electron flow**

Modern electronics had its beginnings in 1907 when Lee deForest first inserted a metallic grid in a vacuum tube and was able to control the current in a circuit. Today, electronic systems still control voltages and currents but use solid-state devices. Basic electronic components, such as resistors or diodes, can be represented with graphs that show their characteristics in a more intuitive manner than mathematical equations. In this section, you will examine graphs representing resistors and diodes. In Chapter 3, you will see how the addition of a control element (like deForest's grid) can also be illustrated with graphs to provide a graphical picture of circuit operation.

Linear Equations

In basic algebra, a linear equation is one that plots a straight line between the variables and is usually written in the following form:

$$y = mx + b$$

where y = the dependent variable
x = the independent variable
m = the slope
b = the y-axis intercept

If the plot of the equation goes through the origin, then the y-axis intercept is zero, and the equation reduces to

$$y = mx$$

which has the same form as Ohm's law.

$$I = \frac{V}{R} \qquad \textbf{(1–1)}$$

As written here, the dependent variable in Ohm's law is current (I), the independent variable is voltage (V), and the slope is the reciprocal of resistance ($1/R$). Recall from your dc/ac course that this is simply the conductance, (G). By substitution, the linear form of Ohm's law is more obvious; that is,

$$I = GV$$

A **linear component** is one in which an increase in current is proportional to the applied voltage as given by Ohm's law. In general, a plot that shows the relationship between two variable properties of a device defines a **characteristic curve**. For most electronic devices, a characteristic curve refers to a plot of the current, *I*, plotted as a function of voltage, *V*. For example, resistors have an *IV* characteristic described by the straight lines given in Figure 1–1. Notice that current is plotted on the *y*-axis because it is the dependent variable.

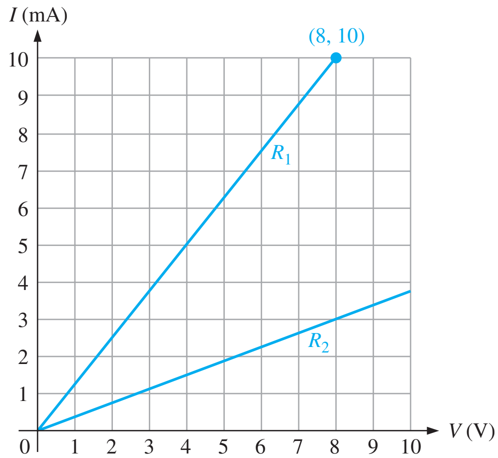


FIGURE 1–1 **IV characteristic curve for two resistors.**

EXAMPLE 1–1

Figure 1–1 shows the *IV* characteristic curve for two resistors. What are the conductance and resistance of R_1?

SOLUTION

Find the conductance, G_1, by measuring the slope of the *IV* characteristic curve for R_1. The slope is the change in the *y* variable (written Δy) divided by the corresponding change in the *x* variable (written Δx).

$$\text{slope} = \frac{\Delta y}{\Delta x}$$

Choosing the point ($x = 8$ V, $y = 10$ mA) from Figure 1–1 and the origin, ($x = 0$ V, $y = 0$ mA), you can find the slope and therefore the conductance as

$$G_1 = \frac{10\text{ mA} - 0\text{ mA}}{8.0\text{ V} - 0\text{ V}} = \mathbf{1.25\text{ mS}}$$

For a straight line, the slope is constant so you can use any two points to determine the conductance. The resistance is the reciprocal of the conductance.

$$R_1 = \frac{1}{G_1} = \frac{1}{1.25\text{ mS}} = \mathbf{0.8\text{ k}\Omega}$$

PRACTICE EXERCISE*

Find the conductance and resistance of R_2.

***Answers are at the end of the chapter.**

AC Resistance

As you have seen, the graph of the characteristic curve for a resistor is a straight line that passes through the origin. The slope of the line is constant and represents the conductance of the resistor; the reciprocal of the slope represents resistance. The ratio of voltage at

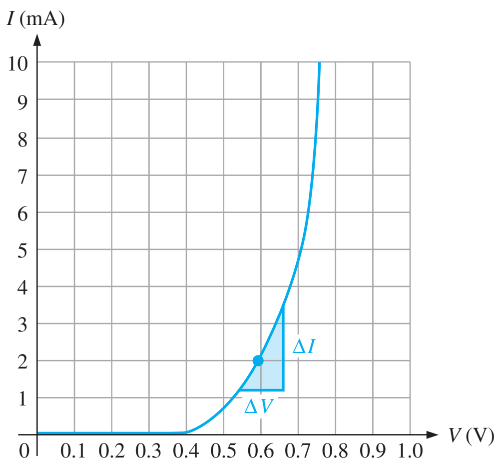


FIGURE 1–2 An IV characteristic curve for a diode.

some point to the corresponding current at that point is referred to as *dc resistance*. DC resistance is defined by Ohm's law, $R = V/I$.

Many devices studied in analog electronics have a characteristic curve for which the current is not proportional to the voltage. These devices are nonlinear by nature but are included in the study of analog electronics because they take on a continuous range of input signals.

Figure 1–2 shows an *IV* characteristic curve for a diode, a nonlinear analog device. (Diodes are discussed in Chapter 2.) Generally, it is more useful to define the resistance of a nonlinear analog device as a small *change* in voltage divided by the corresponding *change* in current, that is, $\Delta V/\Delta I$. The ratio of a small change in voltage divided by the corresponding small change in current is defined as the **ac resistance** of an analog device.

$$r_{ac} = \frac{\Delta V}{\Delta I}$$

This internal resistance (indicated with a lowercase italic *r*) is also called the *dynamic, small signal,* or *bulk resistance* of the device. The ac resistance depends on the particular point on the *IV* characteristic curve where the measurement is made.

For the diode in Figure 1–2, the slope varies dramatically; the point where the ac resistance is measured needs to be specified with any measurement. For example, the slope at the point $x = 0.6$ V, $y = 2$ mA is found by computing the ratio of the change in current to the change in voltage as defined by the small triangle shown in the figure. The change in current, ΔI, is 3.4 mA − 1.2 mA = 2.2 mA and the change in voltage, ΔV, is 0.66 V − 0.54 V = 0.12 V. The ratio of $\Delta I/\Delta V$ is 2.2 mA/0.12 V = 18.3 mS. This represents the conductance, *g*, at the specified point. The internal ac resistance is the reciprocal of this value:

$$r = \frac{1}{g} = \frac{1}{18.3\text{ mS}} = 54.5\ \Omega$$

Conventional Current Versus Electron Flow

From your dc/ac circuits course, you know that current is the rate of flow of charge. The original definition of current was based on Benjamin Franklin's belief that electricity was an unseen substance that moved from positive to negative. *Conventional current* assumes for analysis purposes that current is out of the positive terminal of a voltage source, through the circuit, and into the negative terminal of the source. Engineers use this definition and many textbooks show current with arrows drawn with this viewpoint.

Today, it is known that in solid metallic conductors, the moving charge is actually negatively charged electrons. Electrons move from the negative to the positive point, opposite to the defined direction of conventional current. The movement of electrons in a conductor is called *electron flow*. Many schools and textbooks show electron flow with current arrows drawn out of the negative terminal of a voltage source.

Unfortunately, the controversy between whether it is better to show conventional current or electron flow in representing circuit behavior has continued for many years and does not appear to be subsiding. It is not important which direction you use to form a mental picture of current. In practice, there is only one correct direction to connect a dc ammeter to make current measurements. Throughout this text, the proper polarity for dc meters is shown when appropriate. Current paths are indicated with special bar meter symbols. In a given circuit, larger or smaller currents are indicated by the relative number of bars shown on a bar graph meter.

SECTION 1–1 CHECKUP*

1. What is a characteristic curve for a component?
2. How does the characteristic curve for a large resistor compare to the curve for a smaller resistor?
3. What is the difference between dc resistance and ac resistance?

*Answers are at the end of the chapter.

1–2 ANALOG SIGNALS

A signal is any physical quantity that carries information. It can be an audible, visual, or other indication of information. In electronics, the term *signal* refers to the information that is carried by electrical waves, either in a conductor or as an electromagnetic field.

After completing this section, you should be able to

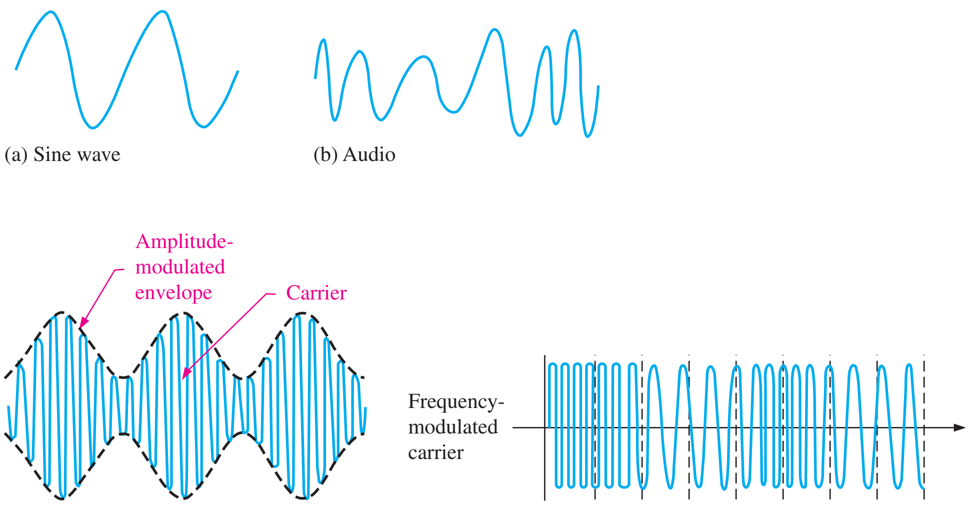
- **Describe analog signals**
  - **Compare an analog signal with a digital signal**
  - **Define *sampling* and *quantizing***
  - **Apply the equation for a sinusoidal wave to find the instantaneous value of a voltage or current**
  - **Find the peak, rms, or average value, given the equation for a sinusoidal wave**
  - **Explain the difference between the time-domain signal and the frequency-domain signal**

Analog and Digital Signals

Signals can be classified as either continuous or discrete. A continuous signal changes smoothly, without interruption. A discrete signal can have only certain values. The terms *continuous* and *discrete* can be applied either to the amplitude or to the time characteristic of a signal.

In nature, most signals take on a continuous range of values within limits; such signals are referred to as **analog signals**. For example, consider a potentiometer that is used as a shaft encoder as shown in Figure 1–3(a). The output voltage can be continuously varied within the limit of the supply voltage, resulting in an analog signal that is related to the angular position of the shaft.

An analog quantity, such as voltage, that is repetitive or varies in a certain manner is an analog signal. An analog signal can be a repetitive waveform, such as the sine wave in Figure SN1–1(a), or a continuously varying audio signal that carries information (music, the spoken word, or other sounds), as shown in part (b). Other examples of analog signals are amplitude-modulated signals (AM) and frequency-modulated signals (FM), as illustrated in parts (c) and (d). In AM, a lower-frequency information signal, such as voice, varies the amplitude of a high-frequency sine wave. In FM, the information signal varies the frequency of the sine wave.



(a) Sine wave

(b) Audio

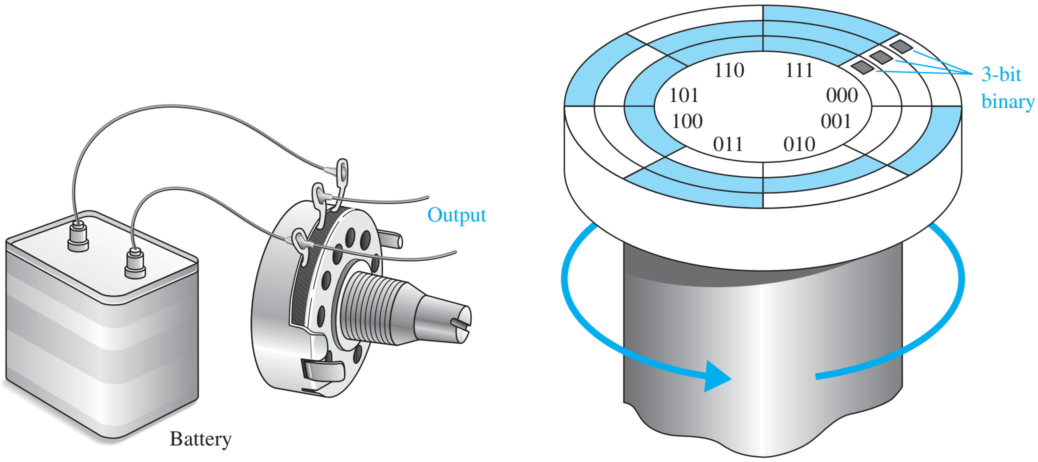
(c) Amplitude-modulated signal

(d) Frequency-modulated signal

FIGURE SN1–1

SYSTEM NOTE

On the other hand, another type of encoder has a certain number of steps that can be selected as shown in Figure 1–3(b). When numbers are assigned to these steps, the result is called a **digital signal**.



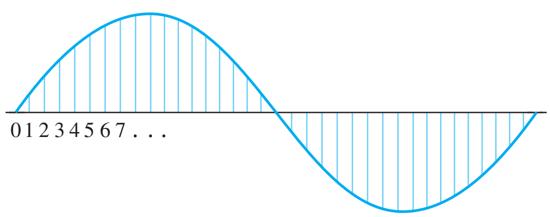
(a) Analog shaft encoder (b) Digital shaft encoder

FIGURE 1–3 Analog and digital shaft encoders.

Analog circuits are generally simple, have high speed and low cost, and can readily simulate natural phenomena. They are often used for operations such as performing linearizing functions, waveshaping, transforming voltage to current or current to voltage, multiplying, and mixing. By contrast, digital circuits have high noise immunity, no drift, and the ability to process data rapidly and to perform various calculations. In many electronic systems, a mix of analog and digital signals are required to optimize the overall system's performance or cost.

Many signals have their origin in a natural phenomenon such as a measurement of pressure or temperature. Transducer outputs are typically analog in nature; a microphone, for example, provides an analog signal to an amplifier. Frequently, the analog signal is converted to digital form for storing, processing, or transmitting.

Conversion from analog to digital form is accomplished by a two-step process: sampling and quantizing. **Sampling** is the process of breaking the analog waveform into time "slices" that approximate the original wave. This process always loses some information; however, the advantages of digital systems (noise reduction, digital storage, and processing) outweigh the disadvantages. After sampling, the time slices are assigned a numeric value. This process, called **quantizing,** produces numbers that can be processed by digital computers or other digital circuits. Figure 1–4 illustrates the sampling and quantizing process.



0) 0 0 0 0 0 0 0 0
1) 0 0 1 0 1 0 1 1
2) 0 1 0 1 0 1 1 0
3) 0 1 1 1 1 1 0 0
4) 1 0 1 0 0 0 0 1
5) 1 0 1 1 1 1 1 1
6) 1 1 0 1 1 0 0 0
7) 1 1 1 1 0 0 1 1
.
.
.

(a) Sampling (b) Quantizing

FIGURE 1–4 Digitizing an analog waveform.

Frequently, digital signals need to be converted back to their original analog form to be useful in their final application. For instance, the digitized sound on a CD must be converted to an analog signal and eventually back to sound by a loudspeaker.

A cellular phone is a common example of a system that employs both analog and digital signals. The microphone captures voice data which is an *analog* signal. The analog voice data is converted into a *digital* signal and then modulated on an *analog* RF carrier signal. It is then transmitted via the antenna to a cell tower.

In the same way, the incoming signal from the cell tower is received as *digital* intelligence modulated on an *analog* carrier. It is amplified by a low-noise amplifier (LNA) and down-converted using an *analog* carrier frequency. The *digital* voice data is then converted back to *analog* and sent to the audio power amp and finally the speaker.

SYSTEM NOTE

Periodic Signals

To carry information, some property such as the voltage or frequency of an electrical wave needs to vary. Frequently, an electrical signal repeats at a regular interval of time. Repeating waveforms are said to be **periodic**. The **period** (***T***) represents the time for a periodic wave to complete one cycle. A **cycle** is the complete sequence of values that a waveform exhibits before another identical pattern occurs. The period can be measured between any two corresponding points on successive cycles.

Periodic waveshapes are used extensively in electronics. Many practical electronic circuits such as oscillators generate periodic waves. Most oscillators are designed to produce a particular shaped waveform—either a sinusoidal wave or nonsinusoidal waves such as the square, rectangular, triangle, and sawtooth waves.

The most basic and important periodic waveform is the sinusoidal wave. Both the trigonometric sine and cosine functions have the shape of a sinusoidal wave. The term *sine wave* usually implies the trigonometric function, whereas the term *sinusoidal wave* means a waveform with the shape of a sine wave. A sinusoidal waveform is generated as the natural waveform from many ac generators and in radio waves. Sinusoidal waves are also present in physical phenomena from the generation of laser light, the vibration of a tuning fork, or the motion of ocean waves.

A **vector** is any quantity that has both magnitude and direction. A sinusoidal curve can be generated by plotting the projection of the end point of a rotating vector that is turning with uniform circular motion, as illustrated in Figure 1–5. Successive revolutions of the point generate a periodic curve which can be expressed mathematically as

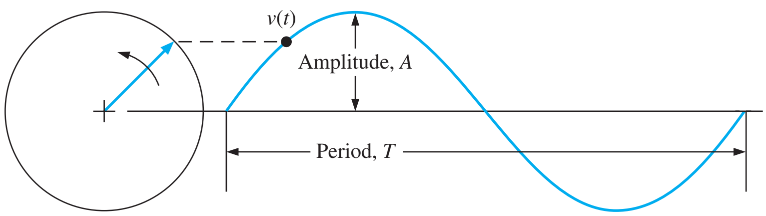


FIGURE 1–5 Generation of a sinusoidal waveform from the projection of a rotating vector.

$$y(t) = A\sin(\omega t \pm \phi) \qquad (1\text{–}2)$$

where $y(t)$ = vertical displacement of a point on the curve from the horizontal axis. The bracketed quantity (t) is an optional indicator, called *functional notation,* to emphasize that the signals vary with time. Functional notation is frequently omitted when it isn't important to emphasize the time relationship but is introduced to familiarize you with the concept when it is shown.

A = amplitude. This is the maximum displacement from the horizontal axis.

ω = angular frequency of the rotating vector in radians per second.

t = time in seconds to a point on the curve.

ϕ = phase angle in radians. The **phase angle** is simply a fraction of a cycle that a waveform is shifted from a reference waveform of the same frequency. It is positive if the curve begins before $t = 0$ and is negative if the curve starts after $t = 0$.

Equation (1–2) illustrates that the sinusoidal wave can be defined in terms of three basic parameters. These are the frequency, amplitude, and phase angle.

FREQUENCY AND PERIOD When the rotating vector has made one complete cycle, it has rotated through 2π radians. The number of complete cycles generated per second is called the **frequency**. Dividing the angular frequency (ω, in rad/s) of the rotating vector by the number of radians in one cycle (2π rad/cycle) gives the frequency in hertz.[1]

$$f(\text{Hz}) = \frac{\omega\ (\text{rad/s})}{2\pi\ (\text{rad/cycle})} \tag{1–3}$$

One cycle per second is equal to 1 Hz. The frequency (f) of a periodic wave is the number of cycles in one second and the period (T) is the time for one cycle, so it is logical that the reciprocal of the frequency is the period and the reciprocal of the period is the frequency.

$$T = \frac{1}{f} \tag{1–4}$$

and

$$f = \frac{1}{T} \tag{1–5}$$

For example, if a signal repeats every 10 ms, then its period is 10 ms and its frequency is

$$f = \frac{1}{T} = \frac{1}{10\ \text{ms}} = 0.1\ \text{kHz}$$

INSTANTANEOUS VALUE OF A SINUSOIDAL WAVE If the sinusoidal waveform shown in Figure 1–5 represents a voltage, Equation (1–2) is written

$$v(t) = V_p \sin(\omega t \pm \phi)$$

In this equation, $v(t)$ is a variable that represents the voltage. Since it changes as a function of time, it is often referred to as the *instantaneous voltage*.

PEAK VALUE OF A SINUSOIDAL WAVE The amplitude of a sinusoidal wave is the maximum displacement from the horizontal axis as shown in Figure 1–5. For a voltage waveform, the amplitude is called the peak voltage, V_p. When making voltage measurements with an oscilloscope, it is often easier to measure the peak-to-peak voltage, V_{pp}. The peak-to-peak voltage is twice the peak value.

AVERAGE VALUE OF A SINUSOIDAL WAVE During one cycle, a sinusoidal waveform has equal positive and negative excursions. Therefore, the mathematical definition of the average value of a sinusoidal waveform must be zero. However, the term *average value* is generally used to mean the average over a cycle without regard to the sign. That is, the average is usually computed by converting all negative values to positive values, then averaging. The average voltage is defined in terms of the peak voltage by the following equation:

$$V_{avg} = \frac{2V_p}{\pi}$$

Simplifying,

$$V_{avg} = 0.637V_p \tag{1–6}$$

[1]The unit of frequency was cycles per second (cps) prior to 1960 but was renamed the hertz (abbreviated Hz) in honor of Heinrich Hertz, a German physicist who demonstrated radio waves. The old unit designation was more descriptive of the definition of frequency.

The average value is useful in certain practical problems. For example, if a rectified sinusoidal waveform is used to deposit material in an electroplating operation, the quantity of material deposited is related to the average current:

$$I_{avg} = 0.637 I_p$$

EFFECTIVE VALUE (rms VALUE) OF A SINUSOIDAL WAVE If you apply a dc voltage to a resistor, a steady amount of power is dissipated in the resistor and can be calculated using the following power law:

$$P = IV \quad (1\text{–}7)$$

where V = dc voltage across the resistor (volts)
I = dc current in the resistor (amperes)
P = power dissipated (watts)

A sinusoidal waveform transfers maximum power at the peak excursions of the curve and no power at all at the instant the voltage crosses zero. In order to compare ac and dc voltages and currents, ac voltages and currents are defined in terms of the equivalent heating value of dc. This equivalent heating value is computed with calculus, and the result is called the rms (for *root-mean-square*) voltage or current. The rms voltage is related to the peak voltage by the following equation:

$$V_{rms} = 0.707 V_p \quad (1\text{–}8)$$

Likewise, the effective or rms current is

$$I_{rms} = 0.707 I_p$$

EXAMPLE 1–2

A certain voltage waveform is described by the following equation:

$$v(t) = 15\text{ V}\sin(600t)$$

(a) From this equation, determine the peak voltage and the average voltage. Give the angular frequency in rad/s.

(b) Find the instantaneous voltage at a time of 10 ms.

SOLUTION

(a) The form of the equation is

$$y(t) = A\sin(\omega t)$$

The peak voltage is the same as the amplitude (A).

$$V_p = \mathbf{15\text{ V}}$$

The average voltage is related to the peak voltage.

$$V_{avg} = 0.637V_p = 0.637(15\text{ V}) = \mathbf{9.56\text{ V}}$$

The angular frequency, ω, is **600 rad/s.**

(b) The instantaneous voltage at a time of 10 ms is

$$v(t) = 15\text{ V}\sin(600t) = 15\text{ V}\sin(600)(10\text{ ms}) = \mathbf{-4.19\text{ V}}$$

Note the negative value indicates that the waveform is below the axis at this point.

PRACTICE EXERCISE

Find the rms voltage, the frequency in hertz, and the period of the waveform described in the example.

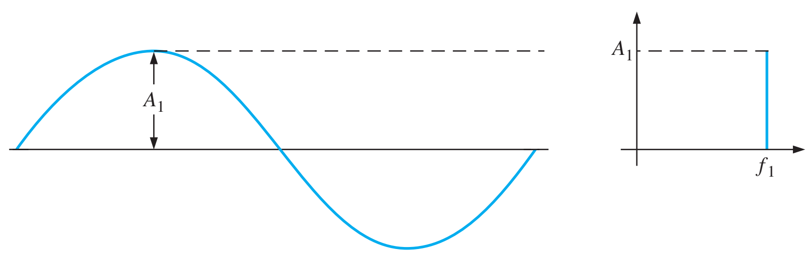
Time-Domain Signals

Thus far, the signals you have looked at vary with time, and it is natural to associate time as the independent variable. Some instruments, such as the oscilloscope, are designed to record signals as a function of time. Time is therefore the independent variable. The values assigned to the independent variable are called the **domain**. Signals that have voltage, current, resistance, or other quantity vary as a function of time are called *time-domain* signals.

Frequency-Domain Signals

Sometimes it is useful to view a signal where frequency is represented on the horizontal axis and the signal amplitude (usually in logarithmic form) is plotted along the vertical axis. Since frequency is the independent variable, the instrument works in the *frequency domain,* and the plot of amplitude versus frequency is called a **spectrum**. The spectrum analyzer is an instrument used to view the spectrum of a signal. These instruments are extremely useful in radio frequency (RF) measurements for analyzing the frequency response of a circuit, testing for harmonic distortion, checking the percent modulation from transmitters, and many other applications.

You have seen how the sinusoidal wave can be defined in terms of three basic parameters. These are the amplitude, frequency, and phase angle. A continuous sinusoidal wave can be shown as a time-varying signal defined by these three parameters. The same sinusoidal wave can also be shown as a single line on a frequency spectrum. The frequency-domain representation gives information about the amplitude and frequency, but it does not show the phase angle. These two representations of a sinusoidal wave are compared in Figure 1–6. The height of the line on the spectrum is the amplitude of the sinusoidal wave.



(a) Time domain (b) Frequency domain

FIGURE 1–6 Time-domain and frequency-domain representations of a sinusoidal wave.

HARMONICS A nonsinusoidal repetitive waveform is composed of a fundamental frequency and harmonic frequencies. The fundamental frequency is the basic repetition rate of the waveform, and the **harmonics** are higher-frequency sinusoidal waves that are multiples of the fundamental. Interestingly, these multiples are all related to the fundamental by integers (whole numbers).

Odd harmonics are frequencies that are odd multiples of the fundamental frequency of a waveform. For example, a 1 kHz square wave consists of a fundamental of 1 kHz and odd harmonics of 3 kHz, 5 kHz, 7 kHz, and so on. The 3 kHz frequency in this case is called the third harmonic, the 5 kHz frequency is called the fifth harmonic, and so on.

Even harmonics are frequencies that are even multiples of the fundamental frequency. For example, if a certain wave has a fundamental of 200 Hz, the second harmonic is 400 Hz, the fourth harmonic is 800 Hz, and the sixth harmonic is 1200 Hz.

Any variation from a pure sinusoidal wave produces harmonics. A nonsinusoidal wave is a composite of the fundamental and certain harmonics. Some types of waveforms have only odd harmonics, some have only even harmonics, and some contain both. The shape of the wave is determined by its harmonic content. Generally, only the fundamental and the

MULTISIM

Open file F01-07 found on the companion website. This simulation illustrates the difference between time-domain and frequency-domain measurements. It also demonstrates how the odd-order harmonics of a fundamental sine wave combine to produce a square wave.

first few harmonics are important in determining the waveshape. For example, a square wave is formed from the fundamental and odd harmonics, as illustrated in Figure 1–7.

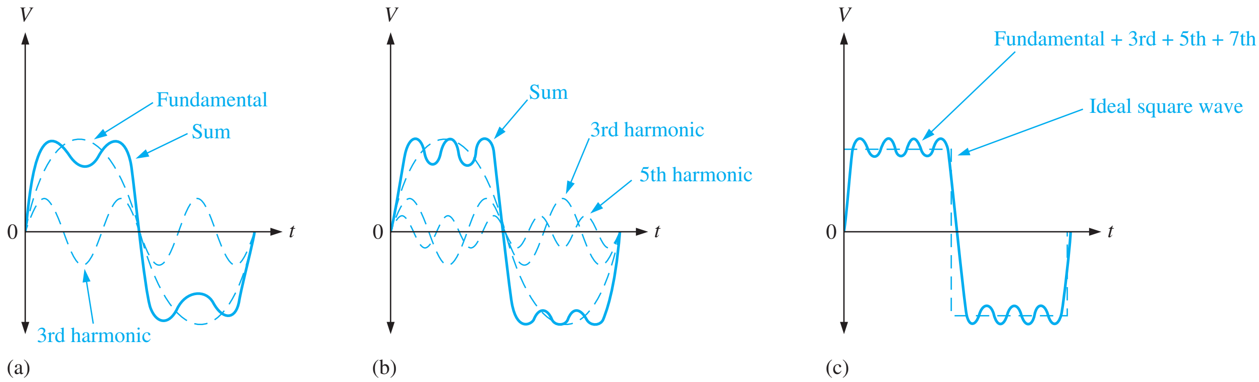


FIGURE 1–7 **Odd harmonics combine to produce a square wave.**

Signal distortion is always a concern in any system. One source of distortion is the *harmonic distortion* produced by nonlinear devices. A nonlinear device is one in which the output current is not proportional to changes in the applied voltage. Overdriving an amplifier is one common cause.

Nonlinear devices can also produce another type of distortion called *intermodulation distortion* (IMD). If two or more frequencies are processed by a nonlinear device, intermodulation products that are the sum and difference of the fundamentals and the integer multiples (harmonics) are produced. This is a much less desirable type of distortion.

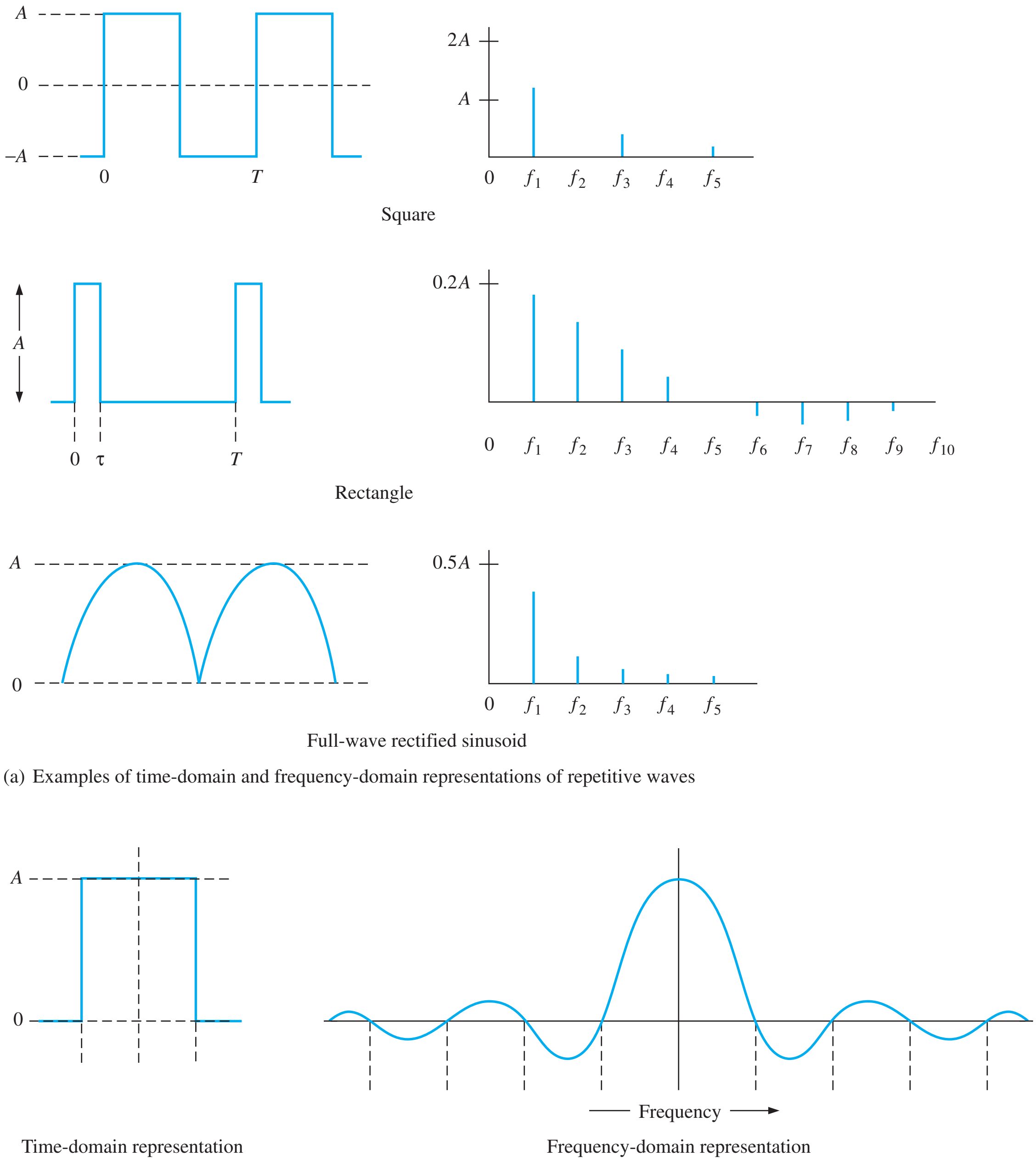
SYSTEM NOTE

FOURIER SERIES All periodic waves except the sinusoidal wave itself are complex waveforms composed of a series of sinusoidal waves. Jean Fourier, a French mathematician interested in problems of heat conduction, formed a mathematical series of trigonometry terms to describe periodic waves. This series is appropriately called the Fourier series.[2] With the Fourier series, one can mathematically determine the amplitude of each of the sinusoidal waves that compose a complex waveform.

The frequency spectrum developed by Fourier is often shown as an amplitude spectrum with units of voltage or power on the y-axis plotted against Hz on the x-axis. Figure 1–8(a) illustrates the amplitude spectrum for several different periodic waveforms. Notice that all spectrums for periodic waves are depicted as lines located at harmonics of the fundamental frequency. These individual frequencies can be measured with a spectrum analyzer.

Nonperiodic signals such as speech, or other transient waveforms, can also be represented by a spectrum; however, the spectrum is no longer a series of lines as in the case of repetitive waves. Transient waveforms are computed by another method called the *Fourier transform.* The spectrum of a transient waveform contains a continuum of frequencies rather than just harmonically related components. A representative Fourier pair of signals for a nonrepetitive pulse are shown in Figure 1–8(b).

[2]Although Fourier's work was significant and he was awarded a prize, his colleagues were uneasy about it. The famous mathematician, Legrange, argued in the French Academy of Science that Fourier's claim was impossible. For further information, see Scientific American, June 1989, p. 86.



(b) Examples of the frequency spectrum of a nonrepetitive pulse waveform

FIGURE 1–8 **Comparison of the frequency spectrum of repetitive and nonrepetitive waves.**

SYSTEM EXAMPLE 1–1

ANALOG SYSTEMS

An **analog system** is one that processes data in analog form only. One example is a public address system, used to amplify sound so that it can be heard by a large audience. The basic diagram in Figure SE1–1. illustrates that sound waves, which are analog in nature, are picked up by a microphone and converted to a small analog voltage called the audio signal. This voltage varies continuously as the volume and frequency of the sound changes and is applied to the input of a linear amplifier. The output of the amplifier, which is an increased reproduction of input voltage, goes to the speaker(s). The speaker changes the amplified audio signal back to sound waves that have a much greater volume than the original sound waves picked up by the microphone.

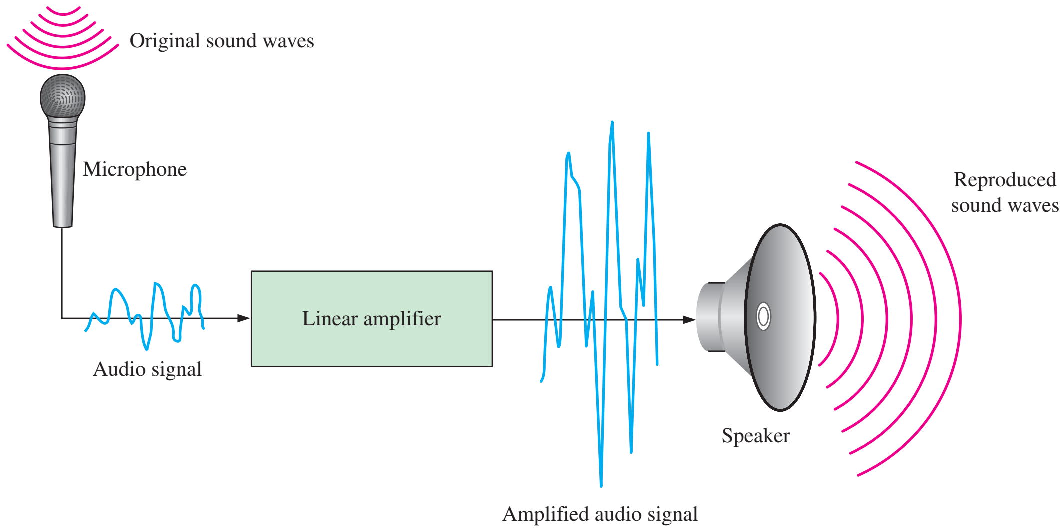


FIGURE SE1–1 **A basic audio public address system.**

Another example of an analog system is the FM receiver. The system processes the incoming frequency-modulated carrier signal, extracts the audio signal for amplification, and produces audible sound waves. A block diagram is shown in Figure SE1–2 with a representative signal shown at each point in the system.

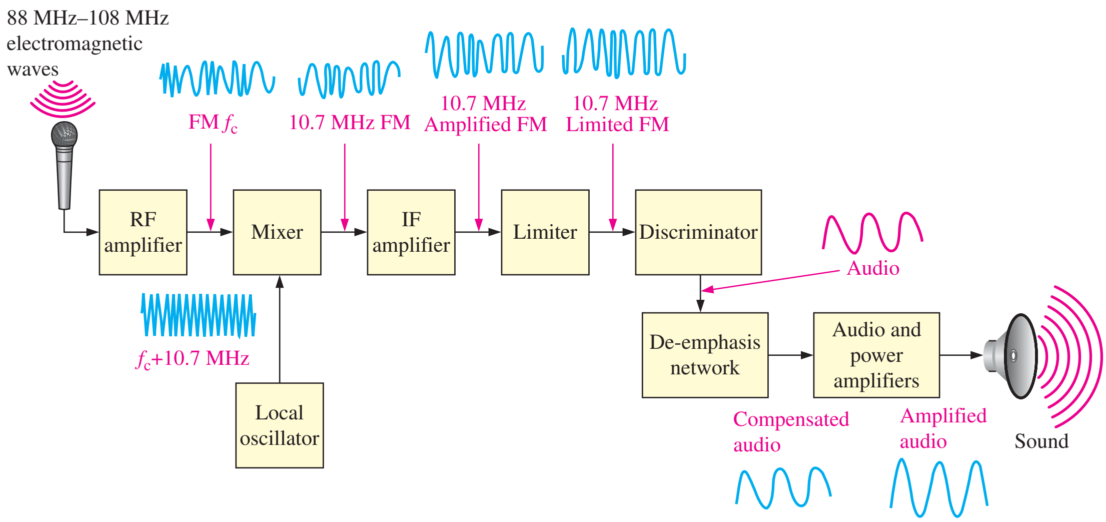


FIGURE SE1–2 **Block diagram of superheterodyne FM receiver.**

SECTION 1–2 CHECKUP

1. What is the difference between an analog signal and a digital signal?
2. Describe the spectrum for a square wave.
3. How does the spectrum for a repetitive waveform differ from that of a nonrepetitive waveform?

1–3 SIGNAL SOURCES

You may recall from basic electronics that Thevenin's theorem allows you to replace a complicated linear circuit with a single voltage source and a series resistance. The circuit is viewed from the standpoint of two output terminals. Likewise, Norton's theorem allows you to replace a complicated two-terminal, linear circuit with a single current source and a parallel resistance. These important theorems are useful for simplifying the analysis of a wide variety of circuits and should be thoroughly understood.

After completing this section, you should be able to

- **Analyze signal sources**
  - **Define two types of independent sources**
  - **Draw a Thevenin or Norton equivalent circuit for a dc resistive circuit**
  - **Show how to draw a load line for a Thevenin circuit**
  - **Explain the meaning of Q-point**
  - **Explain how a passive transducer can be modeled with a Thevenin equivalent circuit**

Independent Sources

Signal sources can be defined in terms of either voltage or current and may be defined for either dc or ac. An ideal independent voltage source generates a voltage which does not depend on the load current. An ideal independent current source produces a current in the load which does not depend on the voltage across the load.

The value of an ideal independent source can be specified without regard to any other circuit parameter. Although a truly ideal source cannot be realized, in some cases, (such as a regulated power supply), it can be closely approximated. Actual sources can be modeled as consisting of an ideal source and a resistor (or other passive component for ac sources).

Thevenin's Theorem

Thevenin's theorem allows you to replace a complicated, two-terminal linear circuit with an ideal independent voltage source and a series resistance as illustrated in Figure 1–9. The source can be either a dc or ac source (a dc source is shown). **Thevenin's theorem** provides an equivalent circuit from the standpoint of the two output terminals. That is, the original circuit and the Thevenin circuit will produce exactly the same voltage and current in any load. Thevenin's theorem is particularly useful for analysis of linear circuits such as amplifiers, a topic that will be covered in Section 1–4.

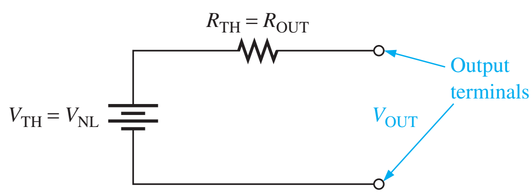
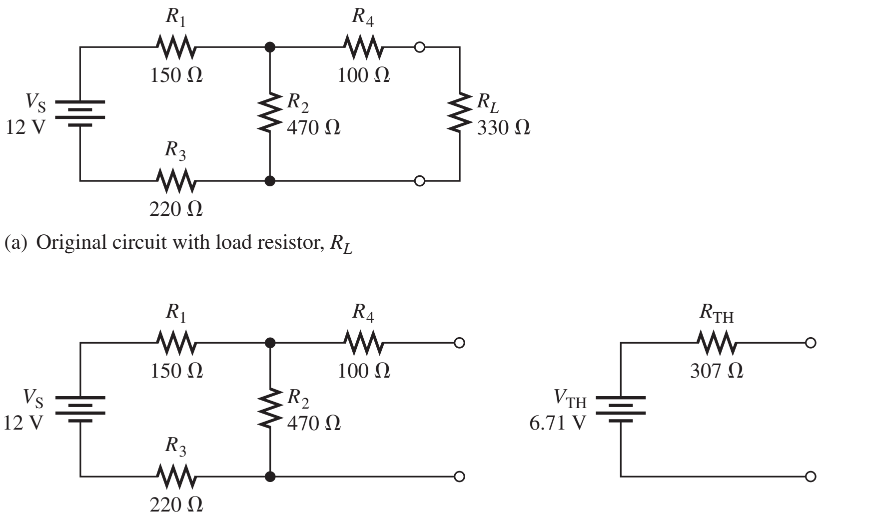


FIGURE 1–9 **Thevenin's equivalent for a dc circuit.**

Only two quantities are needed to determine the equivalent Thevenin circuit—the Thevenin voltage and the Thevenin resistance. The Thevenin voltage, V_{TH}, is the open circuit (no load, NL) voltage from the original circuit. The Thevenin resistance, R_{TH}, is the resistance from the point of view of the output terminals with all voltage or current sources replaced by their internal resistance.

EXAMPLE 1–3

Find the equivalent Thevenin circuit for the dc circuit shown in Figure 1–10(a). The output terminals are represented by the open circles.



(a) Original circuit with load resistor, R_L

(b) Original circuit with load resistor, R_L, removed

(c) Thevenin equivalent of original circuit

FIGURE 1–10 Simplifying a circuit with Thevenin's theorem.

SOLUTION

Find the Thevenin voltage by computing the voltage on the output terminals *as if the load were removed* as shown in Figure 1–10(b). With no load, there is no path for current through R_4. Therefore, there is no current and no voltage drop will appear across it. The output (Thevenin) voltage must be the same as the drop across R_2. Applying the voltage-divider rule for the equivalent series combination of R_1, R_2, and R_3, the voltage across R_2 is

$$V_{TH} = V_2 = V_S\left(\frac{R_2}{R_1 + R_2 + R_3}\right)$$

$$= 12\text{ V}\left(\frac{470\ \Omega}{150\ \Omega + 470\ \Omega + 220\ \Omega}\right) = \mathbf{6.71\ V}$$

The Thevenin resistance is the resistance from the perspective of the output terminals with sources replaced with their internal resistance. The internal resistance of a voltage source is zero (ideally). Replacing the source with zero resistance places R_1 and R_3 in series and the combination in parallel with R_2. The equivalent resistance of these three resistors is in series with R_4. Thus, the Thevenin resistance for this circuit is

$$R_{TH} = [(R_1 + R_3) \parallel R_2] + R_4$$

$$= [(150\ \Omega + 220\ \Omega) \parallel 470\ \Omega] + 100\ \Omega = \mathbf{307\ \Omega}$$

The Thevenin circuit is shown in Figure 1–10(c).

PRACTICE EXERCISE

Use the Thevenin circuit to find the voltage across the 330 Ω load resistor.

Thevenin's theorem is a useful way of combining linear circuit elements to form an equivalent circuit that can be used to answer questions with respect to various loads. The requirement that the Thevenin circuit elements are linear places some restrictions on the use of Thevenin's theorem. In spite of this, if the circuit to be replaced is approximately linear, Thevenin's theorem may produce useful results. This is the case for many amplifier circuits that we will investigate later.

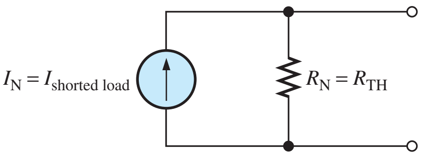


FIGURE 1–11 Norton circuit. The arrow in the current source symbol always points to the positive side of the source.

Norton's Theorem

Norton's theorem provides another equivalent circuit similar to the Thevenin equivalent circuit. Norton's equivalent circuit can also replace any two-terminal linear circuit with a reduced equivalent. Instead of a voltage source, the Norton equivalent circuit uses a current source in parallel with a resistance, as illustrated in Figure 1–11.

The magnitude of the Norton current source is found by replacing the load with a short and determining the current in the load. The Norton resistance is the same as the Thevenin resistance.

EXAMPLE 1–4

Find the equivalent Norton circuit for the dc circuit shown in Figure 1–12(a). The output terminals are represented by the open circles.

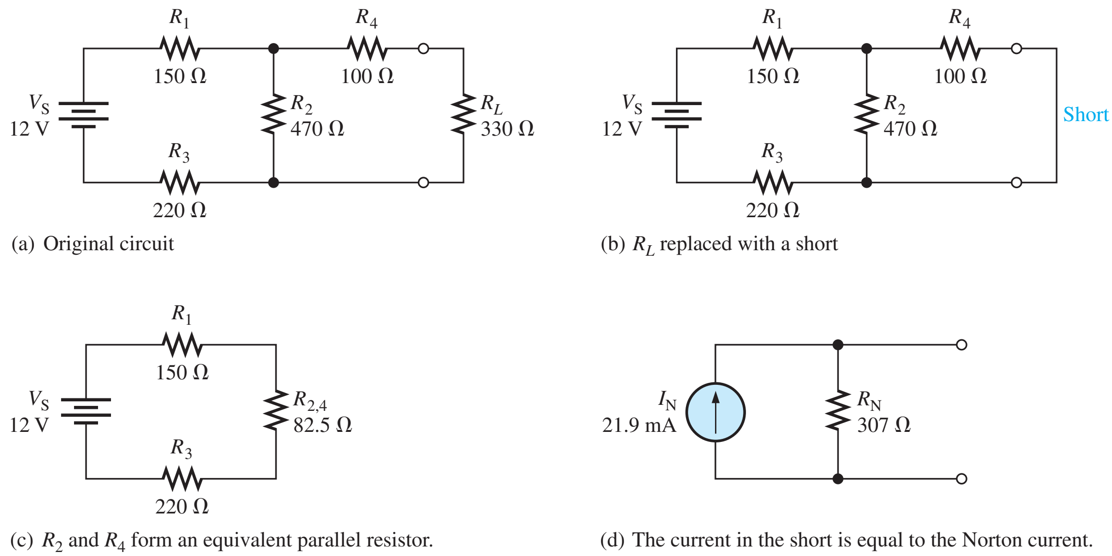


FIGURE 1–12 Simplifying a circuit with Norton's theorem.

SOLUTION

Find the Norton current by computing the current in the load *as if it were replaced by a short* as shown in Figure 1–12(b). The shorted load causes R_4 to appear in parallel with R_2 as shown in Figure 1–12(b). The total current in the equivalent circuit of Figure 1–12(c) can be found by applying Ohm's law to the total resistance.

$$I = \frac{V_S}{R_T} = \frac{12\text{ V}}{R_1 + R_{2,4} + R_3} = \frac{12.0\text{ V}}{452.5\ \Omega} = 26.5\text{ mA}$$

The current (I_{SL}) in the shorted load is found by applying the current-divider rule to the R_2 and R_4 junction in the circuit of Figure 1–12(b).

$$I_{SL} = I_T\left(\frac{R_2}{R_2 + R_4}\right) = 26.5\text{ mA}\left(\frac{470\ \Omega}{470\ \Omega + 100\ \Omega}\right) = \mathbf{21.9\ mA}$$

The current in the shorted load is the Norton current. The Norton resistance is equal to the Thevenin resistance, as found in Example 1–3. Notice that the Norton resistance is in parallel with the Norton current source. The equivalent circuit is shown in Figure 1–12(d).

PRACTICE EXERCISE

Use Norton's theorem to find the voltage across the 330 Ω load resistor. Show that Norton's theorem gives the same result as Thevenin's theorem for this circuit (see Practice Exercise in Example 1–3).

Load Lines

An interesting way to obtain a "conceptual picture" of circuit operation is through the use of a load line for the circuit. Load lines are introduced here and will be explored further in Chapter 3.

Imagine a linear circuit that has an equivalent Thevenin circuit as shown in Figure 1–13. Let's see what happens if various loads are placed across the output terminals. First, assume there is a short (zero resistance). In this case, the voltage across the load is zero and the current is given by Ohm's law.

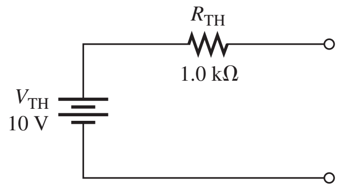


FIGURE 1–13

$$I_L = \frac{V_{TH}}{R_{TH}} = \frac{10\text{ V}}{1.0\text{ k}\Omega} = 10\text{ mA}$$

Now assume the load is an open (infinite resistance). In this case, the load current is zero, and the voltage across the load is equal to the Thevenin voltage.

The two tested conditions represent the maximum and minimum current in the load. Table 1–1 shows the results of trying some more points to see what happens with different loads. Plotting the data as shown in Figure 1–14 establishes an *IV* curve for the Thevenin circuit. Because the circuit is a linear circuit, *any load that is placed across the output terminals falls onto the same straight line.* This line is called the **load line** for the circuit and describes the driving circuit (in this case, the Thevenin circuit), not the load itself. Since the load line is a straight line, the first two calculated conditions (a short and an open load) are all that are needed to establish it.

TABLE 1–1 • Various load conditions for the circuit in Figure 1–13.

R_L	V_L	I_L
0 Ω	0.0 V	10.0 mA
250 Ω	2.00 V	8.00 mA
500 Ω	3.33 V	6.67 mA
750 Ω	4.29 V	5.72 mA
1.0 kΩ	5.00 V	5.00 mA
2.0 kΩ	6.67 V	3.33 mA
4.0 kΩ	8.00 V	2.00 mA
open	10.0 V	0.00 mA

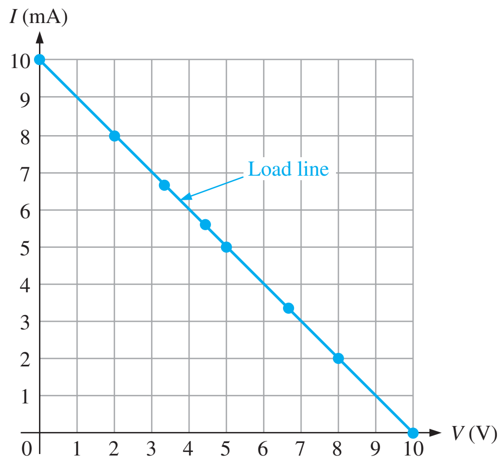


FIGURE 1–14 **Load line for the circuit in Figure 1–13.**

Before we leave the topic of load lines, consider one more idea. Recall that a resistor (or any other device) has its own characteristic that can be described by its *IV* curve. The characteristic curve for a resistor represents all of the possible operating points for the device, whereas the load line represents all of the possible operating points for the circuit. Combining these ideas, you can superimpose the *IV* curve for a resistor on the plot of the load line for the Thevenin circuit. The intersection of these two lines gives the operating point for the combination.

Figure 1–15(a) shows an 800 Ω load resistor added to the Thevenin circuit from Figure 1–13. The load line for the Thevenin circuit and the characteristic curve for resistor R_1 from Figure 1–1 are shown in Figure 1–15(b). R_1 now serves as a load resistor, R_L. The intersection of the two lines represents the operating point, or **quiescent point,** commonly referred to as the Q-point. Note that the load voltage (4.4 V) and load current (5.6 mA) can be read directly from the graph. In Chapter 3, you will see that this idea can be extended to transistors and other devices to give a graphical tool for understanding circuit operation.

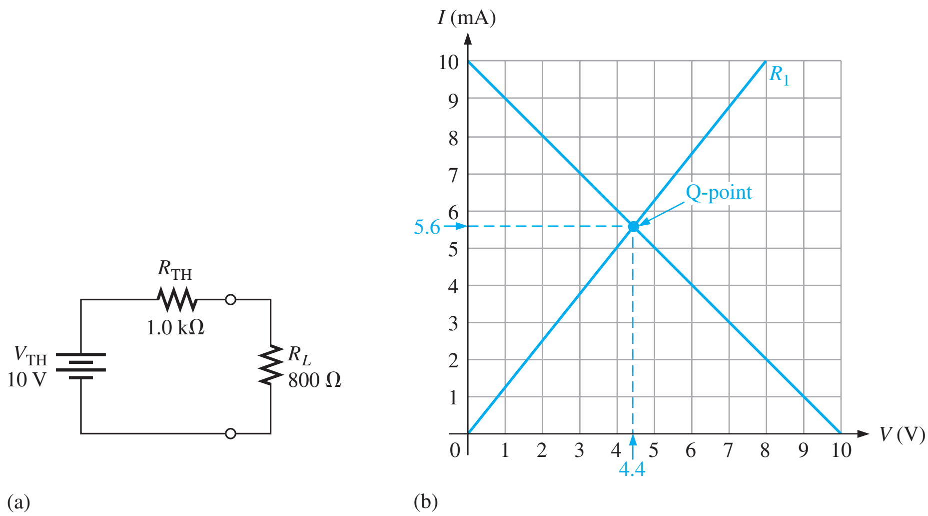


FIGURE 1–15 **Load line and a resistor IV curve showing the Q-point.**

Transducers

Analog circuits are frequently used in conjunction with a measurement that needs to be made. A **transducer** is a device that converts a physical quantity (such as position, pressure, or temperature) from one form to another; for electronic systems, input transducers convert a physical quantity to be measured into an electrical quantity (voltage, current, resistance). Transducers will be covered further in Chapter 15.

The signal from transducers is frequently very small, requiring amplification before being suitable for further processing. Passive transducers, such as strain gages, require a separate source of electrical power (called *excitation*) to perform their job. Others, such as thermocouples, are active transducers; they are self-generating devices that convert a small portion of the quantity to be measured into an electrical signal. Both passive and active transducers are often simplified to a Thevenin or Norton equivalent circuit for analysis.

In order to choose an appropriate amplifier, it is necessary to consider both the size of the source voltage and the size of the equivalent Thevenin or Norton resistance. When the equivalent resistance is very small, Thevenin's equivalent circuit is generally more useful because the circuit approximates an ideal voltage source. When the equivalent resistance is large, Norton's theorem is generally more useful because the circuit approximates an ideal current source. When the source resistance is very high, such as the case with a pH meter, a very high input impedance amplifier must be used. Other considerations, such as the frequency response of the system or the presence of noise, affect the choice of amplifier.

EXAMPLE 1–5

A piezoelectric crystal is used in a vibration monitor. Assume the output of the transducer should be a 60 mV rms sine wave with no load. When a technician connects an oscilloscope with a 10 MΩ input impedance across the output, the voltage is observed to be only 40 mV rms. Based on these observations, draw the Thevenin equivalent circuit for this transducer.

SOLUTION

The open circuit ac voltage is the Thevenin voltage; thus, $V_{th} = \mathbf{60\ mV}$. The Thevenin resistance can be found indirectly using the voltage-divider rule. The oscilloscope input impedance is considered the load resistance, R_L, in this case. The voltage across the load is

$$V_{R_L} = V_{th}\left(\frac{R_L}{R_L + R_{th}}\right)$$

Rearranging terms,

$$\frac{R_L + R_{th}}{R_L} = \frac{V_{th}}{V_{R_L}}$$

Now solving for R_{th} and substituting the given values,

$$R_{th} = R_L\left(\frac{V_{th}}{V_{R_L}} - 1\right) = 10\text{ M}\Omega\left(\frac{60\text{ mV}}{40\text{ mV}} - 1\right) = \mathbf{5.0\text{ M}\Omega}$$

The equivalent transducer circuit is shown in Figure 1–16.

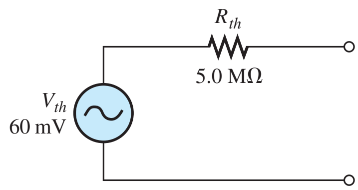


FIGURE 1–16

PRACTICE EXERCISE

Draw the Norton's equivalent circuit for the same transducer.

As you know, an analog quantity is one with continuous values and most quantities in nature are analog. If you graphed the temperature in a typical summer day, you would have a smooth curve of values. A transducer converts the temperature into an electrical quantity (usually a voltage). This voltage is then used as the analog input to a system; a weather station may have several types of transducers each with its own input but all with an electrical output that is then fed to a weather monitoring system.

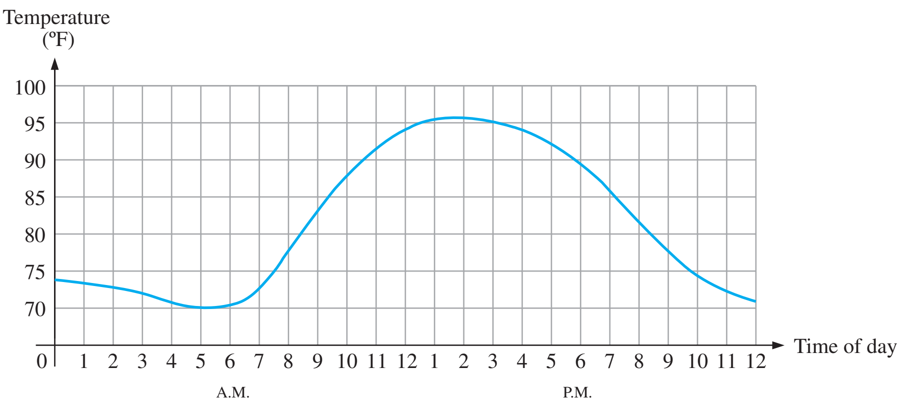


FIGURE SN1–2 Graph of an analog quantity (temperature versus time).

SYSTEM NOTE

SECTION 1–3 CHECKUP

1. What is an independent source?
2. What is the difference between a Thevenin and a Norton circuit?
3. What is the difference between a passive and an active transducer?

1–4 AMPLIFIERS

Before processing, most signals require amplification. Amplification is simply increasing the magnitude of a signal (either voltage, current, or both) and is one of the most important operations in electronics. Other operations in the field of linear electronics include signal generation (oscillators), waveshaping, frequency conversion, modulation, and many other processes. In addition to strictly linear or strictly digital circuits, many electronic circuits involve a combination of digital and linear electronics. These include an important class of interfacing circuits that convert analog-to-digital and digital-to-analog. These circuits will be considered in Chapter 14.

After completing this section, you should be able to

- **Explain the characteristics of an amplifier**
  - **Write the equations for voltage gain and power gain**
  - **Draw the transfer curve for an amplifier**
  - **Show how an amplifier can be modeled as Thevenin or Norton equivalent circuits to represent the input circuit and the output circuit**
  - **Describe how an amplifier can be formed by cascading stages**
  - **Determine the loading effect of one amplifier stage on another**
  - **Use a calculator to find the logarithm or antilog of a given number**
  - **Compute decibel voltage and power gain for an amplifier or circuit**

Linear Amplifiers

The previous discussion on linear circuits can be extended to **amplifiers**. Linear amplifiers produce a magnified replica (**amplification**) of the input signal in order to produce a useful outcome (such as driving a loudspeaker). The concept of an *ideal amplifier* means that the amplifier introduces no noise or distortion to the signal; the output varies in time and replicates the input exactly.

Amplifiers are designed primarily to amplify either voltage or power. For a voltage amplifier, the output signal, $V_{out}(t)$, is proportional to the input signal, $V_{in}(t)$, and the ratio of output voltage to input voltage is voltage **gain**. To simplify the gain equation, you can omit the functional notation, (t), and simply show the ratio of the output signal voltage to the input signal voltage as

$$A_v = \frac{V_{out}}{V_{in}} \tag{1–9}$$

where A_v = voltage gain
V_{out} = output signal voltage
V_{in} = input signal voltage

A useful way of looking at any circuit is to show the output for a given input. This plot, called a **transfer curve,** shows the response of the circuit. An ideal amplifier is characterized by a straight line that goes to infinity. For an actual linear amplifier, the transfer curve is a straight line until saturation is reached as shown in Figure 1–17. From this plot, the output voltage can be read for a given input voltage.

All amplifiers have certain limits, beyond which they no longer act as ideal. The output of the amplifier illustrated in Figure 1–17 eventually cannot follow the input; at this point the amplifier is no longer linear. Additionally, all amplifiers must operate from a source of energy, usually in the form of a dc power supply. Essentially, amplifiers convert some of this dc energy from the power supply into signal power. Thus, the output signal has larger power than the input signal. Frequently, block diagrams and other circuit representations omit the power supply, but it is understood to be present.

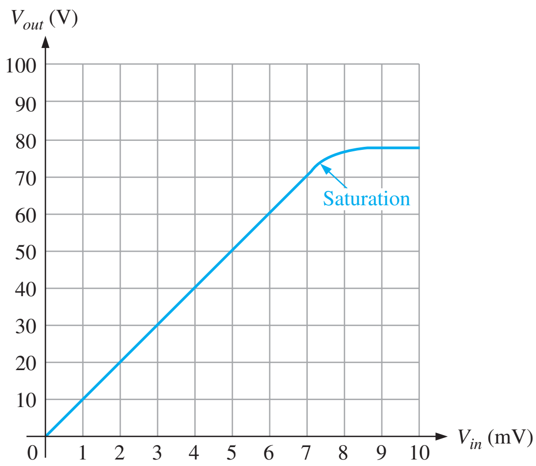


FIGURE 1–17 **Transfer curve for a linear amplifier.**

The Nonlinear Amplifier

Amplifiers are frequently used in situations where the output is not intended to be a replica of the input. These amplifiers form an important part of the field of analog electronics. They include two main categories: waveshaping and switching. A *waveshaping amplifier* is used to change the shape of a waveform. A *switching amplifier* produces a rectangular output from some other waveform. The input can be any waveform, for example, sinusoidal, triangle, or sawtooth. The rectangular output wave is often used as a control signal for some digital applications.

EXAMPLE 1–6

The input and output signals for a linear amplifier are shown in Figure 1–18 and represent an oscilloscope display. What is the voltage gain of the amplifier?

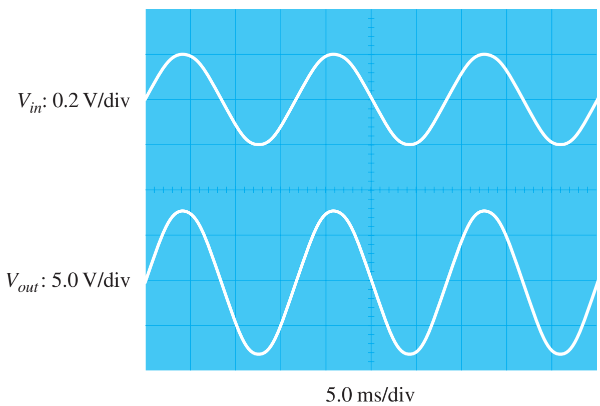


FIGURE 1–18 **Oscilloscope display.**

SOLUTION

The input signal is 2.0 divisions from peak to peak.

$$V_{in} = 2.0 \text{ div} \times 0.2 \text{ V/div} = 0.4 \text{ V}$$

The output signal is 3.2 divisions from peak to peak.

$$V_{out} = 3.2 \text{ div} \times 5.0 \text{ V/div} = 16 \text{ V}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{16 \text{ V}}{0.4 \text{ V}} = \mathbf{40}$$

Note that voltage gain is a ratio of voltages and therefore has no units. The answer is the same if rms or peak values had been used for both the input and output voltages.

PRACTICE EXERCISE

The input to an amplifier is 20 mV. If the voltage gain is 300, what is the output signal?

Another gain parameter is power gain, A_p, defined as the ratio of the signal power out to the signal power in. Power is generally calculated using rms values of voltage or current; however, power gain is a ratio so you can use any consistent units. Power gain, shown as a function of time, is given by the following equation:

$$A_p = \frac{P_{out}}{P_{in}} \quad (1\text{–}10)$$

where A_p = power gain
P_{out} = power out
P_{in} = power in

Power can be expressed by any of the standard power relationships studied in basic electronics. For instance, given the voltage and current of the input and output signals, the power gain can be written

$$A_p = \frac{I_{out}V_{out}}{I_{in}V_{in}}$$

where I_{out} = output signal current to the load
I_{in} = input signal current

Power gain can also be expressed by substituting $P = V^2/R$ for the input and output power.

$$A_p = \left(\frac{V_{out}^2/R_L}{V_{in}^2/R_{in}}\right)$$

where R_L = load resistor
R_{in} = input resistance of the amplifier

The particular equation you choose depends on what information is given.

Amplifier Model

An amplifier is a device that increases the magnitude of a signal for use by a load. Although amplifiers are complicated arrangements of transistors, resistors, and other components, a simplified description is all that is necessary when the requirement is to analyze the source and load behavior. The amplifier can be thought of as the interface between the source and load, as shown in Figure 1–19(a) and 1–19(b). You can apply the concept of equivalent circuits, learned in basic electronics courses, to the more complicated case of an amplifier. By drawing an amplifier as an equivalent circuit, you can simplify equations related to its performance.

The input signal from a source is applied to the input terminals of the amplifier, and the output is taken from a second set of terminals. (Terminals are represented by open circles on a schematic.) The amplifier's input terminals present an input resistance, R_{in}, to the source. This input resistance affects the input voltage to the amplifier because it forms a voltage divider with the source resistance.

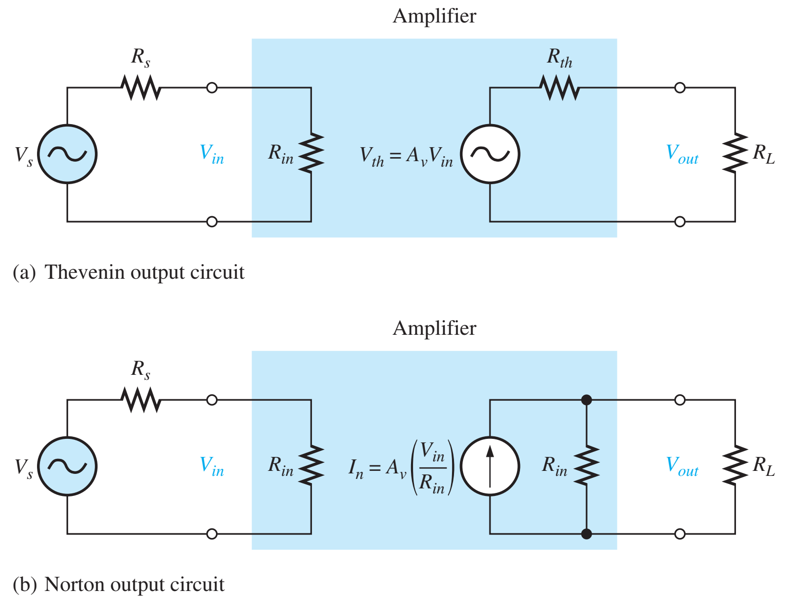


FIGURE 1–19 **Basic amplifier models showing the equivalent input resistance and dependent output circuits.**

The output of the amplifier can be drawn as either a Thevenin or Norton source, as shown in Figure 1–19. The magnitude of this source is dependent on the unloaded gain (A_v) and the input voltage; thus, the amplifier's output circuit (drawn as a Thevenin or Norton equivalent) is said to contain a *dependent* source. The value of a dependent source always depends on voltage or current elsewhere in the circuit.[3] The voltage or current values for the Thevenin and Norton cases are shown in Figure 1–19.

Cascaded Stages

The Thevenin and Norton models reduce an amplifier to its "bare-bones" for analysis purposes. In addition to considering the simplified model for source and load effects, the simplified model is also useful to analyze the internal loading when two or more stages are cascaded to form a single amplifier. Consider two stages cascaded as shown in Figure 1–20. The overall gain is affected by loading effects from each of the three loops. The loops are simple series circuits, so voltages can easily be calculated with the voltage-divider rule.

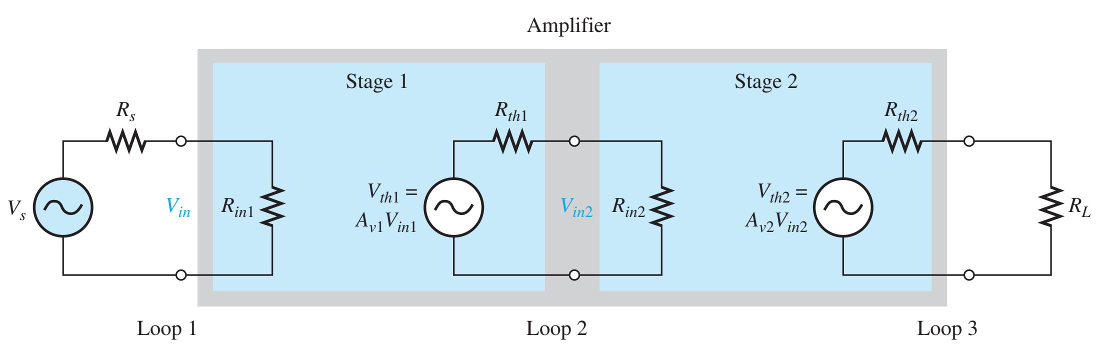


FIGURE 1–20 **Cascaded stages in an amplifier.**

[3]The relationship between the dependent source and its reference cannot be broken. The superposition theorem, which allows sources to be treated separately, does not apply to dependent sources.

EXAMPLE 1–7

Assume a transducer with a Thevenin (unloaded) source, V_s, of 10 mV and a Thevenin source resistance, R_s, of 50 kΩ is connected to a two-stage cascaded amplifier, as shown in Figure 1–21. Compute the voltage across a 1.0 kΩ load.

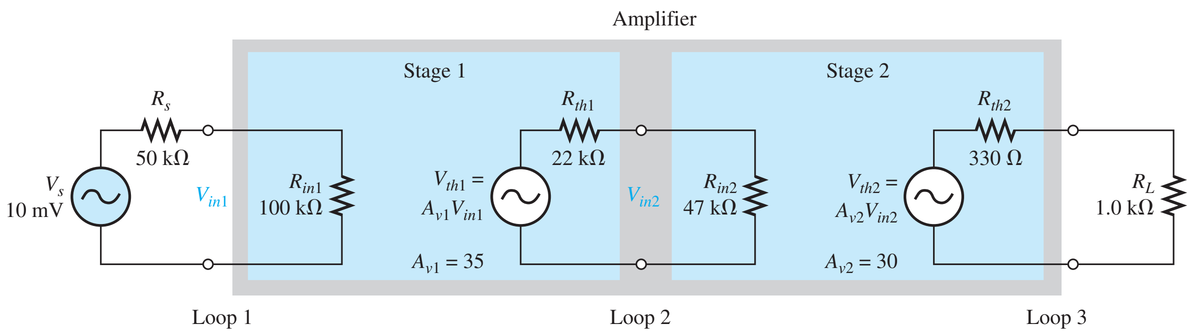


FIGURE 1–21 **Two-stage cascaded amplifier.**

SOLUTION

Compute the input voltage to stage 1 from the voltage-divider rule applied to loop 1.

$$V_{in1} = V_s\left(\frac{R_{in1}}{R_{in1} + R_s}\right) = 10\text{ mV}\left(\frac{100\text{ k}\Omega}{100\text{ k}\Omega + 50\text{ k}\Omega}\right) = 6.67\text{ mV}$$

The Thevenin voltage for stage 1 is

$$V_{th1} = A_{v1}V_{in1} = (35)(6.67\text{ mV}) = 233\text{ mV}$$

Compute the input voltage to stage 2 again from the voltage-divider rule, this time applied to loop 2.

$$V_{in2} = V_{th1}\left(\frac{R_{in2}}{R_{in2} + R_{th1}}\right) = 233\text{ mV}\left(\frac{47\text{ k}\Omega}{47\text{ k}\Omega + 22\text{ k}\Omega}\right) = 159\text{ mV}$$

The Thevenin voltage for stage 2 is

$$V_{th2} = A_{v2}V_{in2} = (30)(159\text{ mV}) = 4.77\text{ V}$$

Apply the voltage-divider rule one more time to loop 3. The voltage across the 1.0 kΩ load is

$$V_{R_L} = V_{th2}\left(\frac{R_L}{R_L + R_{th2}}\right) = 4.77\text{ V}\left(\frac{1.0\text{ k}\Omega}{1.0\text{ k}\Omega + 330\ \Omega}\right) = \mathbf{3.59\ V}$$

PRACTICE EXERCISE

Assume a transducer with a Thevenin source voltage of 5.0 mV and a source resistance of 100 kΩ is connected to the same amplifier. Compute the voltage across the 1.0 kΩ load.

MULTISIM

Open file F01-21 found on the companion website. This circuit is designed to simulate the circuit in Example 1-7 and demonstrate loading effects in cascaded amplifiers.

Logarithms

A widely used unit in electronics is the *decibel,* which is based on logarithms. Before defining the decibel, let's quickly review logarithms (sometimes called *logs*). A **logarithm** is simply an exponent. Consider the equation

$$y = b^x$$

The value of y is determined by the exponent of the base (b). The exponent, x, is said to be the logarithm of the number represented by the letter y.

Two bases are in common use—base ten and base e (discussed in mathematics courses). To distinguish the two, the abbreviation "log" is written to mean base ten, and the letters "ln" are written to mean base *e*. Base ten is standard for work with decibels. Thus, for base ten,

$$y = 10^x$$

Solving for x,

$$x = \log_{10} y$$

The subscript 10 can be omitted because it is implied by the abbreviation "log."

Logarithms are useful when you multiply or divide very large or small numbers. When two numbers written with exponents are multiplied, the exponents are simply added. That is,

$$10^x \times 10^y = 10^{x+y}$$

This is equivalent to writing

$$\log xy = \log x + \log y$$

This concept will be applied to problems involving multiple stages of amplification or attenuation.

EXAMPLE 1–8

(a) Determine the logarithm (base ten) for the numbers 2, 20, 200, and 2000.

(b) Find the numbers whose logarithms are 0.5, 1.5, and 2.5.

SOLUTION

(a) Determine the logarithms by entering each number in a calculator and pressing the [log] key. The results are

$$\log 2 = \mathbf{0.30103} \qquad \log 20 = \mathbf{1.30103}$$
$$\log 200 = \mathbf{2.30103} \qquad \log 2000 = \mathbf{3.30103}$$

Notice that each factor-of-ten increase in y is an increase of 1.0 in the log.

(b) Find the number whose logarithm is a given value by entering the given value in a calculator and pressing the [10^x] function (or [INV] [log]). The results are

$$10^{0.5} = \mathbf{3.16228} \qquad 10^{1.5} = \mathbf{31.6228} \qquad 10^{2.5} = \mathbf{316.228}$$

Notice that each increase of 1 in x (the logarithm) is a factor-of-10 increase in the number.

PRACTICE EXERCISE

(a) Find the logarithms for the numbers 0.04, 0.4, 4, and 40.

(b) What number has a logarithm of 4.8?

Decibel Power Ratios

Power ratios are often very large numbers. Early in the development of telephone communication systems, engineers devised the decibel as a means of describing large ratios of gain or attenuation (a signal reduction). The **decibel (dB)** is defined as 10 multiplied by the logarithmic ratio of the power gain.

$$\text{dB} = 10 \log\left(\frac{P_2}{P_1}\right) \qquad \textbf{(1–11)}$$

where P_1 and P_2 are the two power levels being compared.

Previously, power gain was introduced and defined as the ratio of power delivered from an amplifier to the power supplied to the amplifier. To show power gain, A_p, as a decibel ratio, we use a prime in the abbreviation.

$$A'_p = 10 \log\left(\frac{P_{out}}{P_{in}}\right) \qquad (1\text{–}12)$$

where A'_p = power gain expressed as a decibel ratio
P_{out} = power delivered to a load
P_{in} = power delivered to the amplifier

The decibel (dB) is a dimensionless quantity because it is a ratio. Any two power measurements with the same ratio are the same number of decibels. For example, the power ratio between 500 W and 1 W is 500:1, and the number of decibels this ratio represents is 27 dB. There is exactly the same number of decibels between 100 mW and 0.2 mW (500:1) or 27 dB. When the power ratio is less than 1, there is a power loss or **attenuation**. The decibel ratio is *positive* for power gain and *negative* for power loss.

One important power ratio is 2:1. This ratio is the defining power ratio for specifying the cutoff frequency of instruments, amplifiers, filters, and the like. By substituting into Equation (1–11), the dB equivalent of a 2:1 power ratio is

$$\text{dB} = 10 \log\left(\frac{P_2}{P_1}\right) = 10 \log\left(\frac{2}{1}\right) = 3.01 \text{ dB}$$

This result is usually rounded to 3 dB.

Since 3 dB represents a doubling of power, 6 dB represents another doubling of the original power (a power ratio of 4:1). Nine decibels represents an 8:1 ratio of power and so forth. If the ratio is the same, but P_2 is smaller than P_1, the decibel result remains the same except for the sign.

$$\text{dB} = 10 \log\left(\frac{P_2}{P_1}\right) = 10 \log\left(\frac{1}{2}\right) = -3.01 \text{ dB}$$

The negative result indicates that P_2 is less than P_1.

Another useful ratio is 10:1. Since the log of 10 is 1, 10 dB equals a power ratio of 10:1. With this in mind, you can quickly estimate the overall gain (or attenuation) in certain situations. For example, if a signal is attenuated by 23 dB, it can be represented by two 10 dB attenuators and a 3 dB attenuator. Two 10 dB attenuators are a factor of 100 and another 3 dB represents another factor of 2 for an overall attenuation ratio of 1:200.

EXAMPLE 1–9

Compute the overall power gain of the amplifier in Example 1–7. Express the answer as both power gain and decibel power gain.

SOLUTION

The power delivered to the amplifier is

$$P_{in1} = \frac{V_{in1}^2}{R_{in1}} = \frac{(6.67 \text{ mV})^2}{100 \text{ k}\Omega} = 445 \text{ pW}$$

The power delivered to the load is

$$P_{out} = \frac{V_{R_L}^2}{R_L} = \frac{(3.59 \text{ V})^2}{1.0 \text{ k}\Omega} = 12.9 \text{ mW}$$

The power gain, A_p, is the ratio of P_{out}/P_{in1}.

$$A_p = \frac{P_{out}}{P_{in1}} = \frac{12.9 \text{ mW}}{445 \text{ pW}} = 29.0 \times 10^6$$

Expressed in dB,

$$A'_p = 10\log 29.0 \times 10^6 = \mathbf{74.6\ dB}$$

PRACTICE EXERCISE

Compute the power gain (in dB) for an amplifier with an input power of 50 μW and a power delivered to the load of 4 W.

It is common in certain applications of electronics (microwave transmitters, for example) to combine several stages of gain or attenuation. When working with several stages of gain or attenuation, the total voltage gain is the product of the gains in absolute form.

$$A_{v(tot)} = A_{v1} \times A_{v2} \times \cdots \times A_{vn}$$

Decibel units are useful when combining these gains or losses because they involve just addition or subtraction. The algebraic addition of decibel quantities is equivalent to multiplication of the gains in absolute form.

$$A'_{v(tot)} = A'_{v1} + A'_{v2} + \cdots + A'_{vn}$$

EXAMPLE 1–10

Assume the transmitted power from a radar is 10 kW. A directional coupler (a device that samples the transmitted signal) has an output that represents −40 dB of attenuation. Two 3 dB attenuators are connected in series to this output, and the attenuated signal is terminated with a 50 Ω terminator (load resistor). What is the power dissipated in the terminator?

SOLUTION

$$\text{dB} = 10\log\left(\frac{P_2}{P_1}\right)$$

The transmitted power is attenuated by 46 dB (sum of the attenuators). Substituting,

$$-46\text{ dB} = 10\log\left(\frac{P_2}{10\text{ kW}}\right)$$

Divide both sides by 10 and remove the log function.

$$10^{-4.6} = \frac{P_2}{10\text{ kW}}$$

Therefore,

$$P_2 = \mathbf{251\ mW}$$

PRACTICE EXERCISE

Assume one of the 3 dB attenuators is removed.

(a) What is the total attenuation?

(b) What is the new power dissipated in the terminator?

Although decibel power ratios are generally used to compare two power levels, they are occasionally used for absolute measurements when the reference power level is understood. Although different standard references are used depending on the application, the most common absolute measurement is the dBm. A **dBm** is the power level when the reference is understood to be 1 mW developed in some assumed load impedance. For radio frequency systems, this is commonly 50 Ω; for audio systems, it is generally 600 Ω. The dBm is defined as

$$\text{dBm} = 10 \log\left(\frac{P_2}{1 \text{ mW}}\right)$$

The dBm is commonly used to specify the output level of signal generators and is used in telecommunication systems to simplify the computation of power levels.

Decibel Voltage Ratios

Since power is given by the ratio of V^2/R, the decibel power ratio can be written as

$$\text{dB} = 10 \log\left(\frac{V_2^2/R_2}{V_1^2/R_1}\right)$$

where R_1, R_2 = resistances in which P_1 and P_2 are developed
V_1, V_2 = voltages across the resistances R_1 and R_2

If the resistances are equal, they cancel.

$$\text{dB} = 10 \log\left(\frac{V_2^2}{V_1^2}\right)$$

A property of logarithms is

$$\log x^2 = 2 \log x$$

Thus, the decimal voltage ratio is

$$\text{dB} = 20 \log\left(\frac{V_2}{V_1}\right)$$

When V_2 is the output voltage (V_{out}) and V_1 is the input voltage (V_{in}) for an amplifier, the equation defines the decibel voltage gain. By substitution,

$$A'_v = 20 \log\left(\frac{V_{out}}{V_{in}}\right) \quad \text{(1–13)}$$

where A'_v = voltage gain expressed as a decibel ratio
V_{out} = voltage delivered to a load
V_{in} = voltage delivered to the amplifier

Equation (1–13) gives the decibel voltage gain, a logarithmic ratio of amplitudes. The equation was originally derived from the decibel power equation when both the input and load resistances are the same (as in telephone systems).

Both the decibel voltage gain equation and decibel power gain equation give the same ratio if the input and load resistances are the same. However, it has become common practice to apply the decibel voltage equation to cases where the resistances are *not* the same. When the resistances are not equal, the two equations do not give the same result.

In the case of decibel voltage gain, note that if the amplitudes have a ratio of 2:1, the decibel voltage ratio is very close to 6 dB (since 20 log 2 = 6). If the signal is attenuated by a factor of 2 (ratio = 1:2), the decibel voltage ratio is −6 (since 20 log 1/2 = −6). Another useful ratio is when the amplitudes have a 10:1 ratio; in this case, the decibel voltage ratio is 20 dB (since 20 log 10 = 20).

EXAMPLE 1–11

An amplifier with an input resistance of 200 kΩ drives a load resistance of 16 Ω. If the input voltage is 100 μV and the output voltage is 18 V, calculate the decibel power gain and the decibel voltage gain.

SOLUTION

The power delivered to the amplifier is

$$P_{in} = \frac{V_{in}^2}{R_{in}} = \frac{(100\ \mu\text{V})^2}{200\ \text{k}\Omega} = 5 \times 10^{-14}\ \text{W}$$

The output power (delivered to the load) is

$$P_{out} = \frac{V_{out}^2}{R_L} = \frac{(18\ \text{V})^2}{16\ \Omega} = 20.25\ \text{W}$$

The decibel power gain is

$$A'_p = 10 \log\left(\frac{P_{out}}{P_{in}}\right) = 10 \log\left(\frac{20.25\ \text{W}}{5 \times 10^{-14}\ \text{W}}\right) = \mathbf{146\ dB}$$

The decibel voltage gain is

$$A'_v = 20 \log\left(\frac{V_{out}}{V_{in}}\right) = 20 \log\left(\frac{18\ \text{V}}{100\ \mu\text{V}}\right) = \mathbf{105\ dB}$$

PRACTICE EXERCISE

A video amplifier with an input resistance of 75 Ω drives a load of 75 Ω.

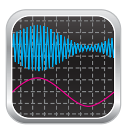
(a) How do the power gain and voltage gains compare?

(b) If the input voltage is 20 mV and the output voltage is 1.0 V, what is the decibel voltage gain?

SECTION 1–4 CHECKUP

1. What is an ideal amplifier?
2. What is a dependent source?
3. What is a decibel?

1–5 TROUBLESHOOTING



Technicians must diagnose and repair malfunctioning circuits or systems. Troubleshooting is the application of logical thinking to correct the malfunctioning circuit or system. Troubleshooting skills will be emphasized throughout the text.

After completing this section, you should be able to

- **Describe the process for troubleshooting a circuit**
  - **Explain what is meant by *half-splitting***
  - **Cite basic rules for replacing a part in a printed circuit (PC) board**
  - **Describe basic bench test equipment for troubleshooting**

Analysis, Planning, and Measuring

When troubleshooting any circuit, the first step is to analyze the clues (symptoms) of a failure. The analysis can begin by determining the answer to several questions: Has the circuit ever worked? If so, under what conditions did it fail? What are the symptoms of a failure? What are possible causes of this failure? The process of asking these questions is part of the analysis of a problem.

After analyzing the clues, the second step in the troubleshooting process is forming a logical plan for troubleshooting. A lot of time can be saved by planning the process. As part of this plan, you must have a working understanding of the circuit you are troubleshooting. Take the time to review schematics, operating instructions, or other pertinent information if you are not certain how the circuit should operate. It may turn out that the failure was that of the operator, not the circuit! A schematic with proper voltages or waveforms marked at various test points is particularly useful for troubleshooting.

Logical thinking is the most important tool of troubleshooting but rarely can solve the problem by itself. The third step is to narrow the possible failures by making carefully thought-out measurements. These measurements usually confirm the direction you are taking in solving the problem or point to a new direction. Occasionally, you may find a totally unexpected result!

The thinking process that is part of analysis, planning, and measuring is best illustrated with an example. Suppose you have a string of 16 decorative lamps connected in series to a 120 V source as shown in Figure 1–22. Assume that this circuit worked at one time and stopped after being moved to a new location. When plugged in, the lamps fail to turn on. How would you go about finding the trouble?

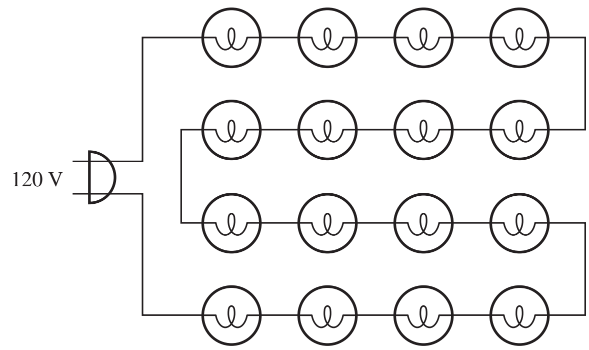


FIGURE 1–22 **A series of lights. Is one of them open?**

You might think like this: Since the circuit worked before it was moved, the problem could be that there is no voltage at this location. Or perhaps the wiring was loose and pulled apart when moved. It's possible a bulb burned out or became loose. This reasoning has considered possible causes and failures that could have occurred. The fact that the circuit was once working eliminates the possibility that the original circuit may have been incorrectly wired. In a series circuit, the possibility of two open paths occurring together is unlikely. You have analyzed the problem and now you are ready to plan the troubleshooting approach.

The first part of your plan is to measure (or test) for voltage at the new location. If voltage is present, then the problem is in the light string. If voltage is not present, check the circuit breakers at the input panel to the house. Before resetting breakers, you should think about why a breaker may be tripped.

The second part of your plan assumes voltage is present and the string is bad. You can disconnect power from the string and make resistance checks to begin isolating the problem. Alternatively, you could apply power to the string and measure voltage at various points. The decision whether to measure resistance or voltage is a toss-up and can be made based on the ease of making the test. Seldom is a troubleshooting plan developed so completely that all possible contingencies are included. The troubleshooter will frequently need to modify the plan as tests are made. You are ready to make measurements.

Suppose you have a digital multimeter (DMM) handy. You check the voltage at the source and find 120 V present. Now you have eliminated one possibility (no voltage). You know the problem is in the string, so you proceed with the second part of your plan. You might think: Since I have voltage across the entire string, and apparently no current in the circuit (since no bulb is on), there is almost certainly an open in the path—either a bulb or a connection. To eliminate testing each bulb, you decide to break the circuit in the middle and to check the *resistance* of each half of the circuit.

Now you are using logical thinking to reduce the effort needed. The technique you are using is a common troubleshooting procedure called *half-splitting*. By measuring the resistance of half the bulbs at once, you can reduce the effort required to find the open. Continuing along these lines, by half-splitting again, will lead to the solution in a few tests.

Unfortunately, most troubleshooting is more difficult than this example. However, analysis and planning are important for effective troubleshooting. As measurements are made, the plan is modified; the experienced troubleshooter narrows the search by fitting the symptoms and measurements into a possible cause.

Soldering

When repairing circuit boards, sooner or later the technician will need to replace a soldered part. When you replace any part, it is important to be able to remove the old part without damaging the board by excessive force or heat. Transfer of heat for removal of a part is facilitated with a chisel tip (as opposed to a conical tip) on the soldering iron.

Before installing a new part, the area must be clean. Old solder should be completely removed without exposing adjacent devices to excess heat. A degreasing cleaner or alcohol is suggested for cleaning (remember—solder won't stick to a dirty board!). Solder must be a resin core type (acid solder is never used in electronic circuits and shouldn't even be on your workbench!). Solder is applied to the joint (not to the iron). As the solder cools, it must be kept still. A good solder connection is a smooth, shiny one and the solder *flows* into the printed circuit trace. A poor solder connection looks dull. During repair, it is possible for excessive solder to short together two parts or two pins on an integrated circuit (this rarely happens when boards are machine soldered). This is called a solder bridge, and the technician must be alert for this type of error when repairing boards. After the repair is completed, any flux must be removed from the board with alcohol or other cleaner.

Basic Test Equipment

The ability to troubleshoot effectively requires the technician to have a set of test equipment available and to be familiar with the operation of the instruments. An oscilloscope, DMM, and power supply are basic instruments for troubleshooting. These instruments are shown in Figure 1–23. No one instrument is best for all situations, so it is important to understand the limitations of the test equipment at hand. All electronic measuring instruments become part of the circuit they are measuring and thus affect the measurement itself (an effect called *instrument loading*). In addition, instruments are specified for a range of frequencies and must be properly calibrated if readings are to be trusted. An expert troubleshooter must consider these effects when making electronic measurements.

For general-purpose troubleshooting of analog circuits, all technicians need access to an oscilloscope and a DMM. The oscilloscope needs to be a good two-channel scope, fast enough to spot noise or ringing when it occurs. A set of switchable probes, with the ability to switch between ×1 and ×10, is useful for looking at large or small signals. (Note that in the ×1 position, the scope loses bandwidth.)

The DMM is a general-purpose meter that has the advantage of very high input impedance but may yield errors if used in circuits with frequencies above a few kilohertz.

(a) Oscilloscope

(b) Digital multimeter

(c) Power supply

FIGURE 1–23 **Test instruments.** **(Copyright © Tektronix, Inc. Reprinted by permission.)**

Many new DMMs offer special features, such as continuity testing and diode checking, and may include capacitance and frequency measurements. While DMMs are excellent test instruments, the VOM (volt-ohm-milliammeter) has some advantages (for example, spotting trends faster than a digital meter). Although generally not as accurate as a DMM, a VOM has very small capacitance to ground, and it is isolated from the line voltage. Also, because a VOM is a passive device, it will not tend to inject noise into a circuit under test.

Many times the circuit under test needs to have a test signal injected to simulate operation in a system. The circuit's response is then observed with a scope or other instrument. This type of testing is called *stimulus-response testing* and is commonly used when a portion of a complete system is tested. For general-purpose troubleshooting, the function generator is used as the stimulus instrument. All function generators have a sine wave, square wave, and triangle wave output; the frequency range varies widely, from a low frequency of 1 μHz to a high of 50 MHz (or more) depending on the generator. Higher-quality function generators offer the user a choice of other waveforms (pulses and ramps, for example) and may have triggered or gated outputs as well as other features.

The basic function generator waveforms (sine, square, and triangle) are used in many tests of electronic circuits and equipment. A common application of a function generator is to inject a sine wave into a circuit to check the circuit's response. The signal is capacitively coupled to the circuit to avoid upsetting the bias network; the response is observed on an oscilloscope. With a sine wave, it is easy to ascertain if the circuit is operating properly by checking the amplitude and shape of the sine wave at various points or to look for possible troubles such as high-frequency oscillation.

A common test for wide-band amplifiers is to inject a square wave into a circuit to test the frequency response. Recall that a square wave consists of the fundamental frequency and an infinite number of odd harmonics (as discussed in Section 1–2). The square wave is applied to the input of the test circuit and the output is monitored. The shape of the output square wave indicates if specific frequencies are selectively attenuated.

Figure 1–24 illustrates square wave distortions due to selective attenuation of low or high frequencies. A good amplifier should show a high-quality replica of the input. If the square wave sags, as in Figure 1–24(b), low frequencies are not being passed properly by the circuit. The rising edge contains mostly higher-frequency harmonics. If the square wave rolls over before reaching the peak, as in Figure 1–24(c), high frequencies are being attenuated. The rise time of the square wave is an indirect measurement of the bandwidth of the circuit.

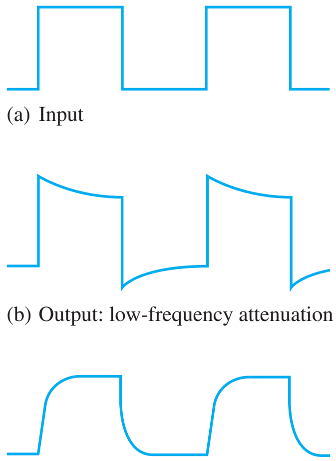


FIGURE 1–24 Square-wave response of wide-band amplifiers.

For testing dc voltages or providing power to a circuit under test, a multiple output power supply, with both positive and negative outputs, is necessary. The outputs should be variable from 0 to 15 V. A separate low voltage supply is also handy for powering logic circuits or as a dc source for analog circuits.

For certain situations and applications, there are specialized measuring instruments designed for the application. Some of this specialized equipment is designed for a specific frequency range or for a specific application, so they won't be discussed here. The digital storage oscilloscope (DSO) has mostly replaced the analog CRT-based scope. It has some particular advantages for troubleshooting because it can be used to store and compare waveforms from a known good unit or to capture a failure that occurs intermittently. It also has the ability to display events that occur before and after the trigger event, a feature that is invaluable with intermittent problems.

A complete list of "nice to have" accessories could be quite long indeed, but another handy set of instruments is a pulser and pulse tracer. These tools are useful for tracing a short such as one from the power supply to ground. The pulser stimulates the circuit with a series of very short pulses. The current tracer can follow the path of the current and lead right to the short. These tools are useful for both digital and analog circuits.

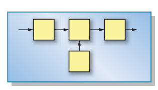
Other Troubleshooting Materials

In general, some materials that are useful for general-purpose troubleshooting that fall under the "must have" category include the following:

- A basic set of hand tools for electronics, including long-nose pliers, diagonal wire cutters, wire strippers, screwdrivers (especially jeweler's screwdrivers), and a small flashlight.
- Soldering and desoldering tools, including solder wick and a magnifying glass for inspecting work or looking for hairline cracks, solder splashes, or other problems.
- A collection of spare parts (resistors, capacitors, transistors, diodes, switches, ICs). In this category, you will also need extra clip leads, cables with various connectors, banana to alligator converters, heat shrink, and the like.
- A capacitor and a resistor substitution box. This is a useful tool for various tests such as changing the time constant in a circuit under test.
- A hair dryer and freeze spray for testing thermal effects of a circuit.
- A static safe wrist strap (and static-free work station, if possible) to prevent damaging static-sensitive circuits.

SYSTEM EXAMPLE 1–2

THERMOGRAPHY FOR DIAGNOSING SYSTEM FAULTS



All electronic systems, and all the components within that system, dissipate power in one form or another. Discrete components, integrated circuits, and even the wires or circuit board traces that connect components, dissipate some amount of power. The most common byproduct of power dissipation is heat. Power amplifiers, by their very nature, tend to produce more heat than small-signal amplifiers. Monitoring the amount of heat that a system produces can be a strong indicator of whether a circuit or sub circuit within a given system is operating within expected parameters. We will begin this topic with a brief discussion of radiant energy.

Figure SE1–3 shows the electromagnetic spectrum. Electromagnetic energy is a continuous band of frequencies that includes visible light, but this is only a small fraction of the electromagnetic spectrum. At longer wavelengths than the visible region there is infrared radiation. The infrared region is subdivided into the *near-infrared, mid-infrared,* and the *far-infrared*. It is this far-infrared region that temperature-sensitive nerve endings in our skin sense as thermal energy, as when we are in direct sunlight or stand next to a heat source such as a hot stove. Below the far-infrared are microwave frequencies and radio waves. Above the visible light region are the ultraviolet and x-ray regions.

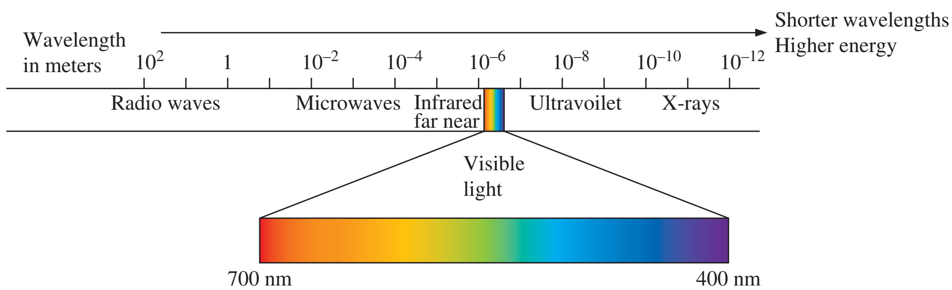


FIGURE SE1–3 **The Electromagnetic spectrum**

The surfaces of all bodies radiate some electromagnetic energy. You might wonder why if all bodies emit energy all of the time, why don't they eventually radiate all of their energy and cool to absolute zero? The reason is that they also continuously absorb energy from their surroundings. If the amount of energy they absorb is greater than what is radiated, the temperature of the body rises; if it is less, its temperature falls. The wavelength that is emitted depends on the temperature of the body. If a body is hot enough, it radiates energy in the visible spectrum; if it is cooler the radiated energy is primarily in the infrared region.

Although our skin is very sensitive to heat, we have physical limitations in our ability to detect the location and the amount of heat being produced. Thermal imaging instruments provide a radiometric image of any target system that enhances our ability to locate and quantize the amount of heat being produced by the components within the system.

A **radiometric image** is a thermal image that contains temperature measurement calculations for various points within the image. The image is displayed on a screen where colors correspond to the amount of infrared radiation emitted by the components within the target system—the more infrared energy emitted, the more heat being produced.

Figure SE1–4 shows a thermal imager being used to evaluate a piece of electronic equipment. The imager generates a false-color picture of the infrared energy emitted by (and thus the temperature of) the components within the circuit under test. This makes the thermal imager a valuable tool, both in development and testing, as well as in troubleshooting. Note that the thermal imager is not connected to the system and does not impact on its performance in any way.

All electronic systems have a recognizable thermal signature when they are operating correctly. Any variation to this reference thermal signature indicates an abnormal condition which is easily detected, even when a visual inspection shows little indication of a failure. An incorrect thermal signature often precedes a catastrophic failure. Thermal imaging can indicate a poor design before it goes into production, or diagnose a problem before the system fails.

FIGURE SE1–4 **Thermal imager showing the temperature profile of the target system** (Photo provided courtesy of Fluke Corporation.)

SECTION 1–5 CHECKUP

1. What is the first step in troubleshooting a circuit?
2. What is meant by half-splitting?
3. What is meant by instrument loading?

SUMMARY

- A linear component is one in which an increase in current is proportional to the applied voltage.
- An analog signal takes on a continuous range of values within limits. A digital signal is a discrete signal that can have only certain values. Many circuits use a combination of analog and digital circuits.
- Waveforms that repeat in a certain interval of time are said to be periodic. A cycle is the complete sequence of values that a waveform exhibits before an identical pattern occurs. The period is the time interval for one cycle.
- Signals that have voltage, current, resistance, or other quantity vary as a function of time are called time-domain signals. When the frequency is made the independent variable, the result is a frequency-domain signal. Any signal can be observed in either the time domain or the frequency domain.
- Thevenin's theorem replaces a complicated, two-terminal, linear circuit with an ideal independent voltage source and a series resistance. The Thevenin circuit is equivalent to the original circuit for any load that is connected to the output terminals.
- Norton's theorem replaces a complicated, two-terminal, linear circuit with an ideal independent current source and a parallel resistance. The Norton circuit is equivalent to the original circuit for any load that is connected to the output terminals.
- A transducer is a device that converts a physical quantity from one form to another; for electronic systems, input transducers convert a physical quantity to an electrical quantity (voltage, current, resistance).
- An ideal amplifier increases the magnitude of an input signal in order to produce a useful outcome. For a voltage amplifier, the output signal, $v_{out}(t)$, is proportional to the input signal, $v_{in}(t)$. The ratio of the output voltage to the input voltage is called the voltage gain, A_v.

- The decibel is a dimensionless number that is ten times the logarithmic ratio of two powers. Decibel gains and losses are combined by algebraic addition.
- Troubleshooting begins with analyzing the symptoms of a failure; then forming a logical plan. Carefully thought-out measurements are made to narrow the search for the cause of the failure. These measurements may modify or change the plan.
- For general-purpose troubleshooting, a reasonable fast, two-channel oscilloscope and a DMM are the principal measuring instruments. The most common stimulus instruments are a function generator and a regulated power supply.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Amplifier An electronic circuit having the capability of amplification and designed specifically for that purpose.

Analog signal A signal that can take on a continuous range of values within certain limits.

Attenuation The reduction in the level of power, current, or voltage.

Characteristic curve A plot which shows the relationship between two variable properties of a device. For most electronic devices, a characteristic curve refers to a plot of the current, I, plotted as a function of voltage, V.

Cycle The complete sequence of values that a waveform exhibits before another identical pattern occurs.

Decibel A dimensionless quantity that is 10 times the logarithm of a power ratio or 20 times the logarithm of a voltage ratio.

Digital signal A noncontinuous signal that has discrete numerical values assigned to specific steps.

Frequency The number of repetitions per unit of time for a periodic waveform.

Gain The amount of amplification. Gain is a ratio of an output quantity to an input quantity (e.g., voltage gain is the ratio of the output voltage to the input voltage).

Load line A straight line plotted on a current versus voltage plot that represents all possible operating points for an external circuit.

Period (T) The time for one cycle of a repeating wave.

Phase angle (in radians) The fraction of a cycle that a waveform is shifted from a reference waveform of the same frequency.

Thevenin's theorem An equivalent circuit that replaces a complicated two-terminal linear circuit with a single voltage source and a series resistance.

Transducer A device that converts a physical quantity from one form to another; for example, a microphone converts sound into voltage.

KEY FORMULAS

(1–1)	$I = \frac{V}{R}$	Ohm's law
(1–2)	$y(t) = A\sin(\omega t \pm \phi)$	Instantaneous value of a sinusoidal wave
(1–3)	$f(\text{Hz}) = \frac{\omega\ (\text{rad/s})}{2\pi\ (\text{rad/cycle})}$	Conversion from radian frequency (rad/s) to hertz (Hz)
(1–4)	$T = \frac{1}{f}$	Conversion from frequency to period
(1–5)	$f = \frac{1}{T}$	Conversion from period to frequency
(1–6)	$V_{avg} = 0.637V_p$	Conversion from peak voltage to average voltage for a sinusoidal wave
(1–7)	$P = IV$	Power law
(1–8)	$V_{rms} = 0.707V_p$	Conversion from peak voltage to rms voltage for a sinusoidal wave
(1–9)	$A_v = \frac{V_{out}}{V_{in}}$	Voltage gain

(1–10)	$A_p = \frac{P_{out}}{P_{in}}$	Power gain
(1–11)	$\text{dB} = 10\log\left(\frac{P_2}{P_1}\right)$	Definition of the decibel
(1–12)	$A'_p = 10\log\left(\frac{P_{out}}{P_{in}}\right)$	Decibel power gain
(1–13)	$A'_v = 20\log\left(\frac{V_{out}}{V_{in}}\right)$	Decibel voltage gain

SELF-TEST

Answers are at the end of the chapter.

1. The graph of a linear equation
(a) always has a constant slope **(b)** always goes through the origin
(c) must have a positive slope **(d)** answers (a), (b), and (c)
(e) none of these answers

2. AC resistance is defined as
(a) voltage divided by current
(b) a change in voltage divided by a corresponding change in current
(c) current divided by voltage
(d) a change in current divided by a corresponding change in voltage

3. A discrete signal
(a) changes smoothly **(b)** can take on any value
(c) is the same thing as an analog signal **(d)** answers (a), (b), and (c)
(e) none of these answers

4. The process of assigning numeric values to a signal is called
(a) sampling **(b)** multiplexing **(c)** quantizing **(d)** digitizing

5. The reciprocal of the repetition time of a periodic signal is the
(a) frequency **(b)** angular frequency **(c)** period **(d)** amplitude

6. If a sinusoidal wave has a peak amplitude of 10 V, the rms voltage is
(a) 0.707 V **(b)** 6.37 V **(c)** 7.07 V **(d)** 20 V

7. If a sinusoidal wave has a peak-to-peak amplitude of 325 V, the rms voltage is
(a) 103 V **(b)** 115 V **(c)** 162.5 V **(d)** 460 V

8. Assume the equation for a sinusoidal wave is $v(t) = 200 \sin(500t)$. The peak voltage is
(a) 100 V **(b)** 200 V **(c)** 400 V **(d)** 500 V

9. A harmonic is
(a) an integer multiple of a fundamental frequency
(b) an unwanted signal that adds noise to a system
(c) a transient signal
(d) a pulse

10. A Thevenin circuit consists of a
(a) current source in parallel with a resistor **(b)** current source in series with a resistor
(c) voltage source in parallel with a resistor **(d)** voltage source in series with a resistor

11. A Norton circuit consists of a
(a) current source in parallel with a resistor **(b)** current source in series with a resistor
(c) voltage source in parallel with a resistor **(d)** voltage source in series with a resistor

12. A load line is a plot that describes
(a) the *IV* characteristic curve for a load resistor
(b) a driving circuit
(c) both (a) and (b)
(d) neither (a) nor (b)