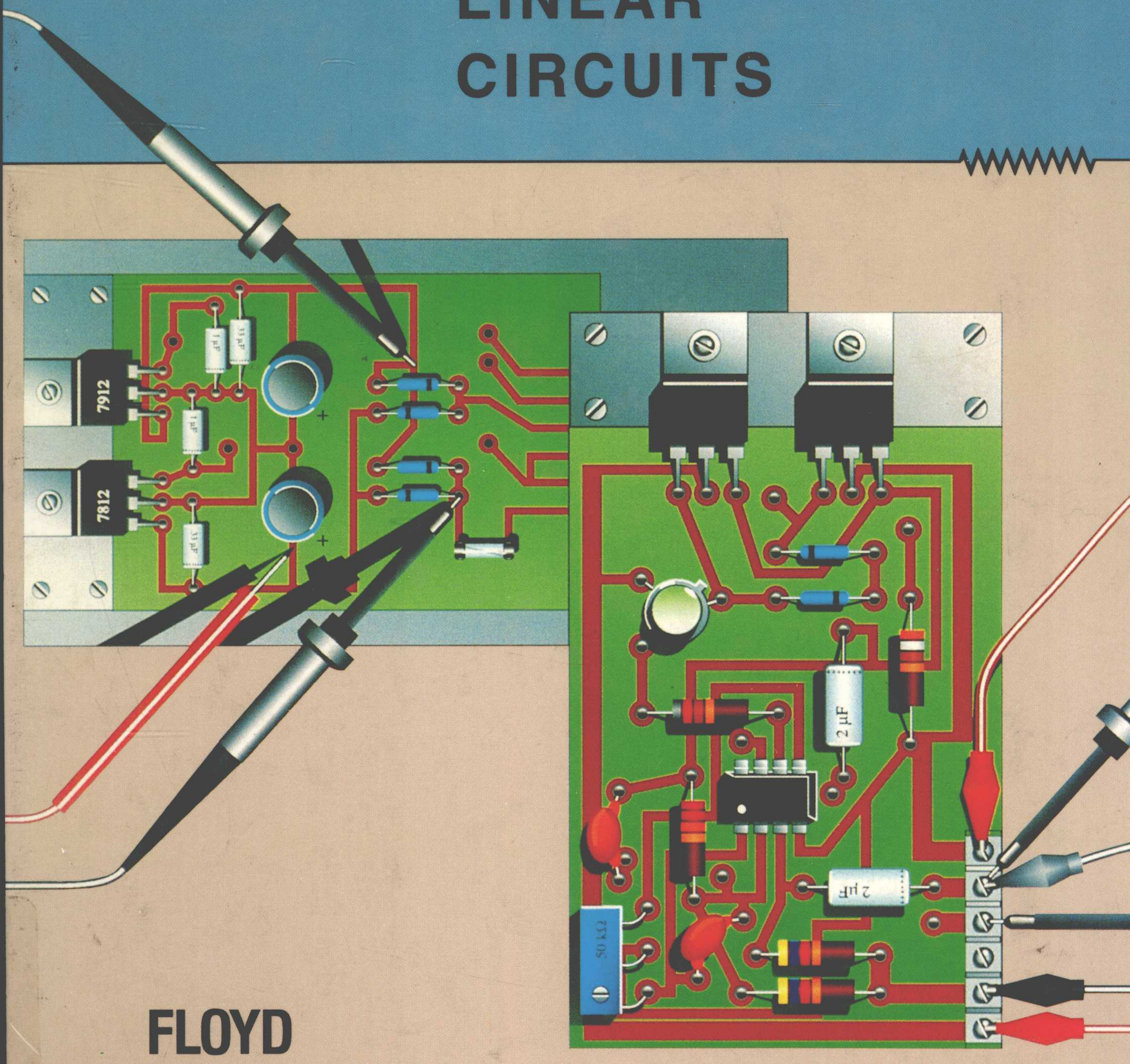
FUNDAMENTALS of LINEAR CIRCUITS



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THOMAS L. FLOYD

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PREFACE

Fundamentals of Linear Circuits provides thorough, comprehensive, and practical coverage of electronic devices, circuits, and applications. The extensive troubleshooting coverage and innovative system application sections serve as very important and necessary links between theory and the real world.

This book is divided into two basic parts. Chapters 1 through 4 cover discrete devices and circuits, while Chapters 5 through 14 deal with linear integrated circuits, with considerable emphasis on the operational amplifier.

A BRIEF OVERVIEW

Basic semiconductor theory and the concept of the pn junction diode are introduced in Chapter 1. Various types of diodes and their applications are covered in Chapter 2. Bipolar junction transistors, field-effect transistors, and thyristors are covered in Chapter 3. The discrete devices and circuits coverage is completed with Chapter 4, which covers amplifiers and oscillators.

The coverage of linear integrated circuits begins with an introduction to operational amplifiers (op-amps) in Chapter 5. Op-amp response is covered in Chapter 6, and basic op-amp circuits including comparators, summing amplifiers, integrators, and differentiators is the topic of Chapter 7. Chapter 8 is a coverage of active filters using the op-amp, and Chapter 9 deals with signal generators (oscillators) and timers. Power supply circuits are covered in Chapter 10. Special amplifiers including instrumentation amplifiers, isolation amplifiers, OTAs, log and antilog amplifiers are introduced in Chapter 11. Communications circuits are covered in Chapter 12, which includes basic AM and FM receiver principles, linear multipliers, mixers, and phase-locked loops. Chapter 13 is an introduction to data conversion circuits such as the analog switch, sample-and-hold circuits, D/A converters, A/D converters, V/F converters, and F/V converters. Finally, Chapter 14 focuses on various types of transducers, associated measurement circuits, and the zero-voltage switch.

FEATURES

- An innovative system application section in each chapter (except Chapter 1)
- A functional full-color insert keyed to selected system applications
- System-related chapter openers
- Significant troubleshooting coverage
- Functional use of second color
- Standard resistance values used throughout

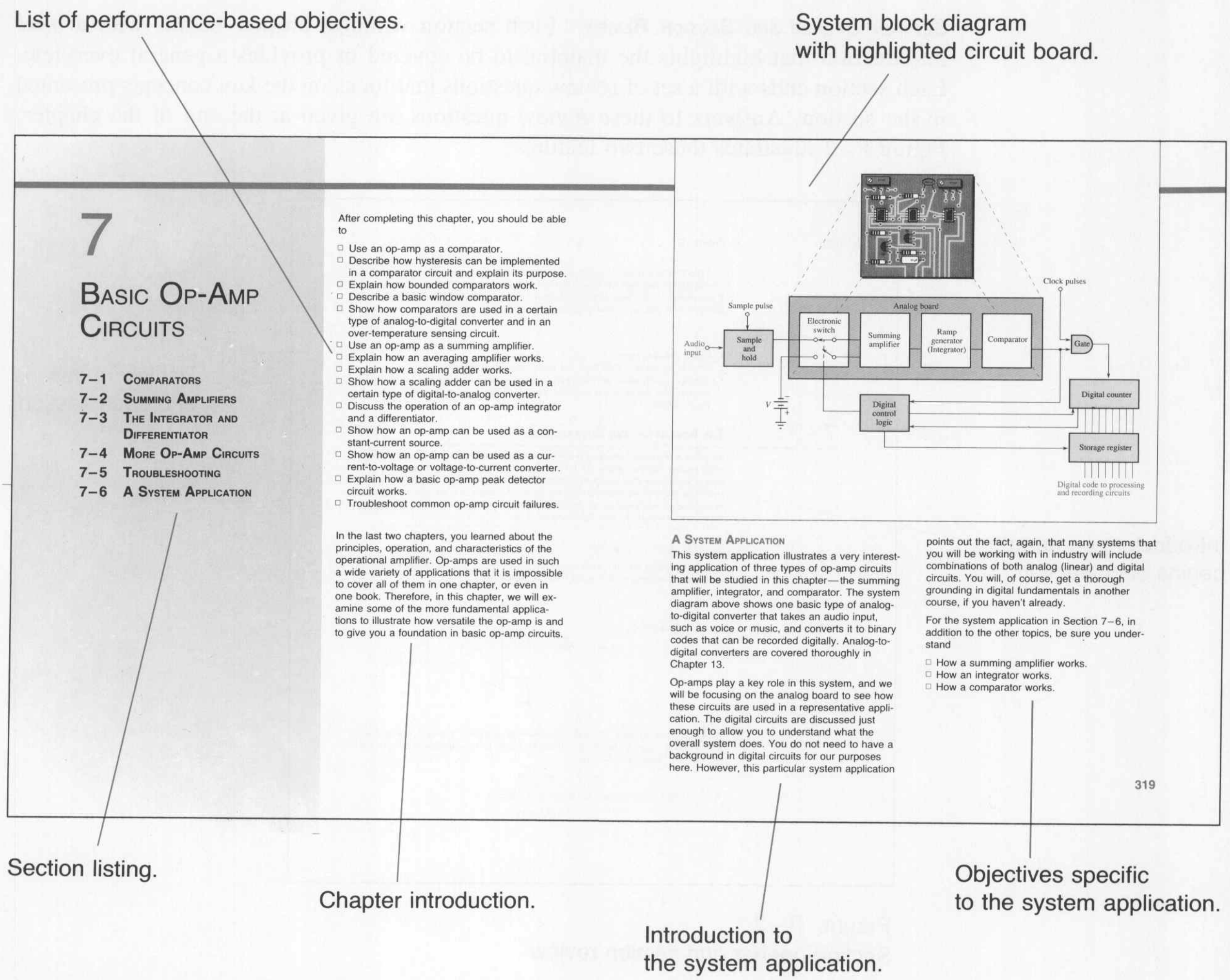
- □ An introductory message at the beginning of each section that sets the tone for that section
- □ A practice exercise for each example
- □ End-of-chapter problems
- □ Margin logos indicating troubleshooting problems and color insert references
- □ Multiple-choice self-tests
- □ Performance-based chapter objectives
- □ Data sheets available in Appendix A

The ancillary package includes the following:

- □ Transparency and transparency master package
- □ Instructor's Resource Manual with system applications worksheet masters

ILLUSTRATION OF FEATURES WITHIN EACH CHAPTER

CHAPTER OPENER As shown in Figure P–1, each chapter begins with a two-page opener. The left page contains a listing of the sections within the chapter, the chapter objectives, and a brief introduction. The right page presents a preview of the system application that will be the focus of the last section of the chapter and provides several specialized objectives oriented to this feature.



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BASIC OP-AMP CIRCUITS

7–1 COMPARATORS
7–2 SUMMING AMPLIFIERS
7–3 THE INTEGRATOR AND DIFFERENTIATOR
7–4 MORE OP-AMP CIRCUITS
7–5 TROUBLESHOOTING
7–6 A SYSTEM APPLICATION

After completing this chapter, you should be able to

- Use an op-amp as a comparator.
- Describe how hysteresis can be implemented in a comparator circuit and explain its purpose.
- Explain how bounded comparators work.
- Describe a basic window comparator.
- Show how comparators are used in a certain type of analog-to-digital converter and in an over-temperature sensing circuit.
- Use an op-amp as a summing amplifier.
- Explain how an averaging amplifier works.
- Explain how a scaling adder works.
- Show how a scaling adder can be used in a certain type of digital-to-analog converter.
- Discuss the operation of an op-amp integrator and a differentiator.
- Show how an op-amp can be used as a constant-current source.
- Show how an op-amp can be used as a current-to-voltage or voltage-to-current converter.
- Explain how a basic op-amp peak detector circuit works.
- Troubleshoot common op-amp circuit failures.

In the last two chapters, you learned about the principles, operation, and characteristics of the operational amplifier. Op-amps are used in such a wide variety of applications that it is impossible to cover all of them in one chapter, or even in one book. Therefore, in this chapter, we will examine some of the more fundamental applications to illustrate how versatile the op-amp is and to give you a foundation in basic op-amp circuits.

A SYSTEM APPLICATION

This system application illustrates a very interesting application of three types of op-amp circuits that will be studied in this chapter—the summing amplifier, integrator, and comparator. The system diagram above shows one basic type of analog-to-digital converter that takes an audio input, such as voice or music, and converts it to binary codes that can be recorded digitally. Analog-to-digital converters are covered thoroughly in Chapter 13.

Op-amps play a key role in this system, and we will be focusing on the analog board to see how these circuits are used in a representative application. The digital circuits are discussed just enough to allow you to understand what the overall system does. You do not need to have a background in digital circuits for our purposes here. However, this particular system application points out the fact, again, that many systems that you will be working with in industry will include combinations of both analog (linear) and digital circuits. You will, of course, get a thorough grounding in digital fundamentals in another course, if you haven't already.

For the system application in Section 7–6, in addition to the other topics, be sure you understand

- How a summing amplifier works.
- How an integrator works.
- How a comparator works.

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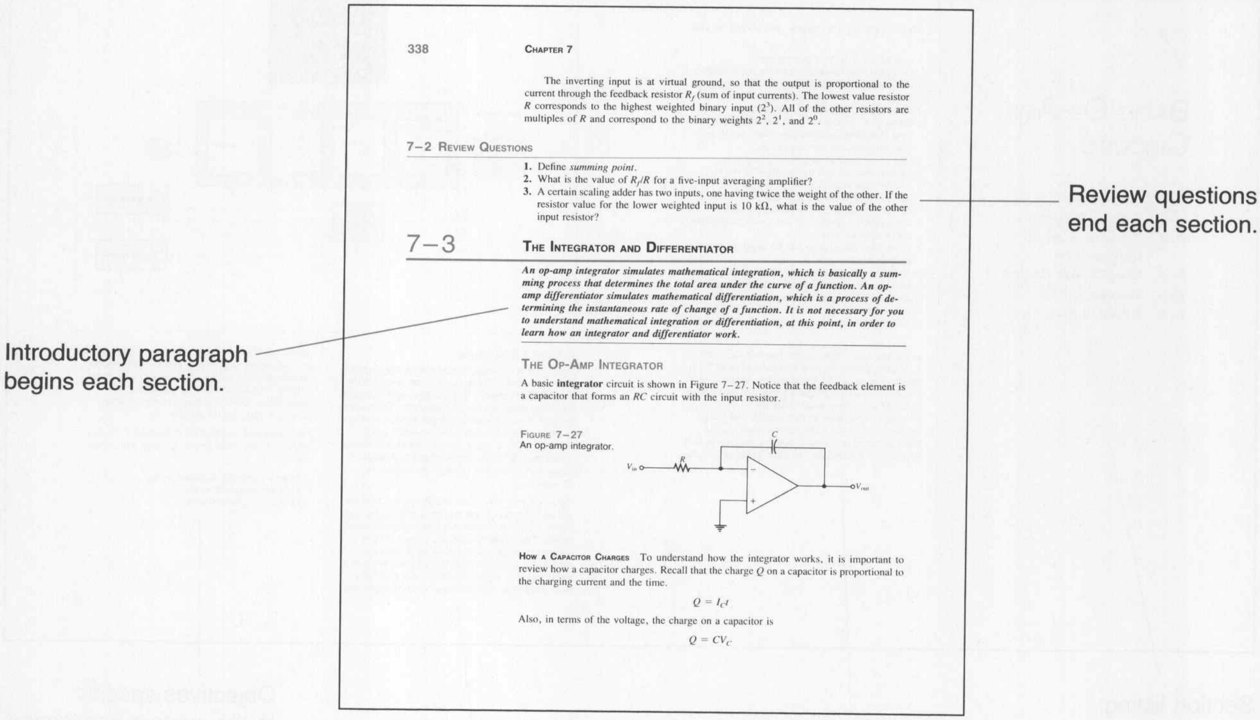
FIGURE P–1
Chapter opener

SECTION OPENER AND SECTION REVIEW Each section within a chapter begins with a brief introduction that highlights the material to be covered or provides a general overview. Each section ends with a set of review questions that focus on the key concepts presented in the section. Answers to these review questions are given at the end of the chapter. Figure P–2 illustrates these two features.


338 CHAPTER 7

The inverting input is at virtual ground, so that the output is proportional to the current through the feedback resistor R_f (sum of input currents). The lowest value resistor R corresponds to the highest weighted binary input (2^3). All of the other resistors are multiples of R and correspond to the binary weights 2^2, 2^1, and 2^0.

7–2 REVIEW QUESTIONS

1. Define *summing point*.
2. What is the value of R_f/R for a five-input averaging amplifier?
3. A certain scaling adder has two inputs, one having twice the weight of the other. If the resistor value for the lower weighted input is 10 kΩ, what is the value of the other input resistor?

7–3 THE INTEGRATOR AND DIFFERENTIATOR

An op-amp integrator simulates mathematical integration, which is basically a summing process that determines the total area under the curve of a function. An op-amp differentiator simulates mathematical differentiation, which is a process of determining the instantaneous rate of change of a function. It is not necessary for you to understand mathematical integration or differentiation, at this point, in order to learn how an integrator and differentiator work.

THE OP-AMP INTEGRATOR

A basic **integrator** circuit is shown in Figure 7–27. Notice that the feedback element is a capacitor that forms an RC circuit with the input resistor.

FIGURE 7–27
An op-amp integrator.

HOW A CAPACITOR CHARGES To understand how the integrator works, it is important to review how a capacitor charges. Recall that the charge Q on a capacitor is proportional to the charging current and the time.

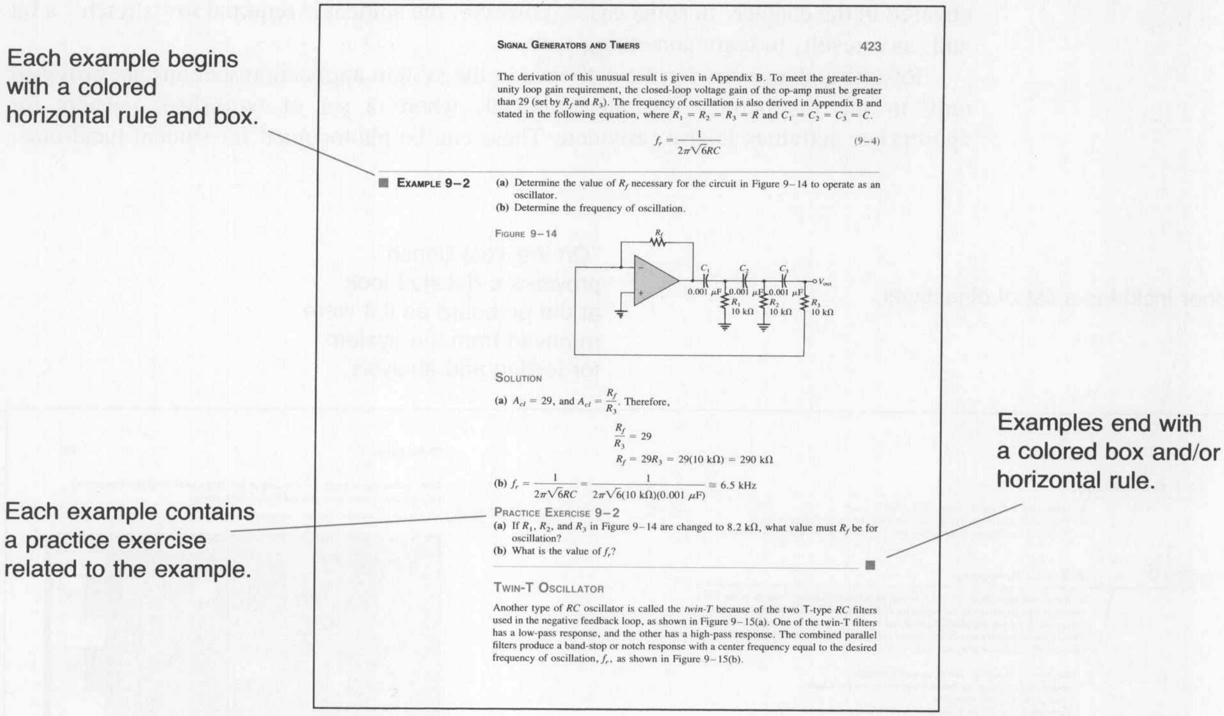
$$Q = I_C t$$

Also, in terms of the voltage, the charge on a capacitor is

$$Q = CV_C$$

FIGURE P–2
Section opener and section review

EXAMPLES AND PRACTICE EXERCISES Frequent examples help to illustrate and clarify basic concepts. At the end of each example is a practice exercise, which is intended to help reinforce or expand on the example in some way. The nature of the practice exercises varies. Some require the student to repeat the procedure demonstrated in the example but with a different set of values or conditions. Others focus on a more limited part of the example or ask questions that encourage further thought beyond the procedure contained in the example. Answers to all practice exercises are given at the end of the chapter. A typical example and practice exercise are shown in Figure P–3.



SIGNAL GENERATORS AND TIMERS 423

The derivation of this unusual result is given in Appendix B. To meet the greater-than-unity loop gain requirement, the closed-loop voltage gain of the op-amp must be greater than 29 (set by R_f and R_3). The frequency of oscillation is also derived in Appendix B and stated in the following equation, where $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$.

$$f_r = \frac{1}{2\pi\sqrt{6}RC} \qquad (9\text{–}4)$$

EXAMPLE 9–2 (a) Determine the value of R_f necessary for the circuit in Figure 9–14 to operate as an oscillator.
(b) Determine the frequency of oscillation.

FIGURE 9–14

SOLUTION

(a) $A_{cl} = 29$, and $A_{cl} = \frac{R_f}{R_3}$. Therefore,

$$\frac{R_f}{R_3} = 29$$

$$R_f = 29R_3 = 29(10\ \text{k}\Omega) = 290\ \text{k}\Omega$$

(b) $f_r = \frac{1}{2\pi\sqrt{6}RC} = \frac{1}{2\pi\sqrt{6}(10\ \text{k}\Omega)(0.001\ \mu\text{F})} \cong 6.5\ \text{kHz}$

PRACTICE EXERCISE 9–2

(a) If R_1, R_2, and R_3 in Figure 9–14 are changed to 8.2 kΩ, what value must R_f be for oscillation?
(b) What is the value of f_r?

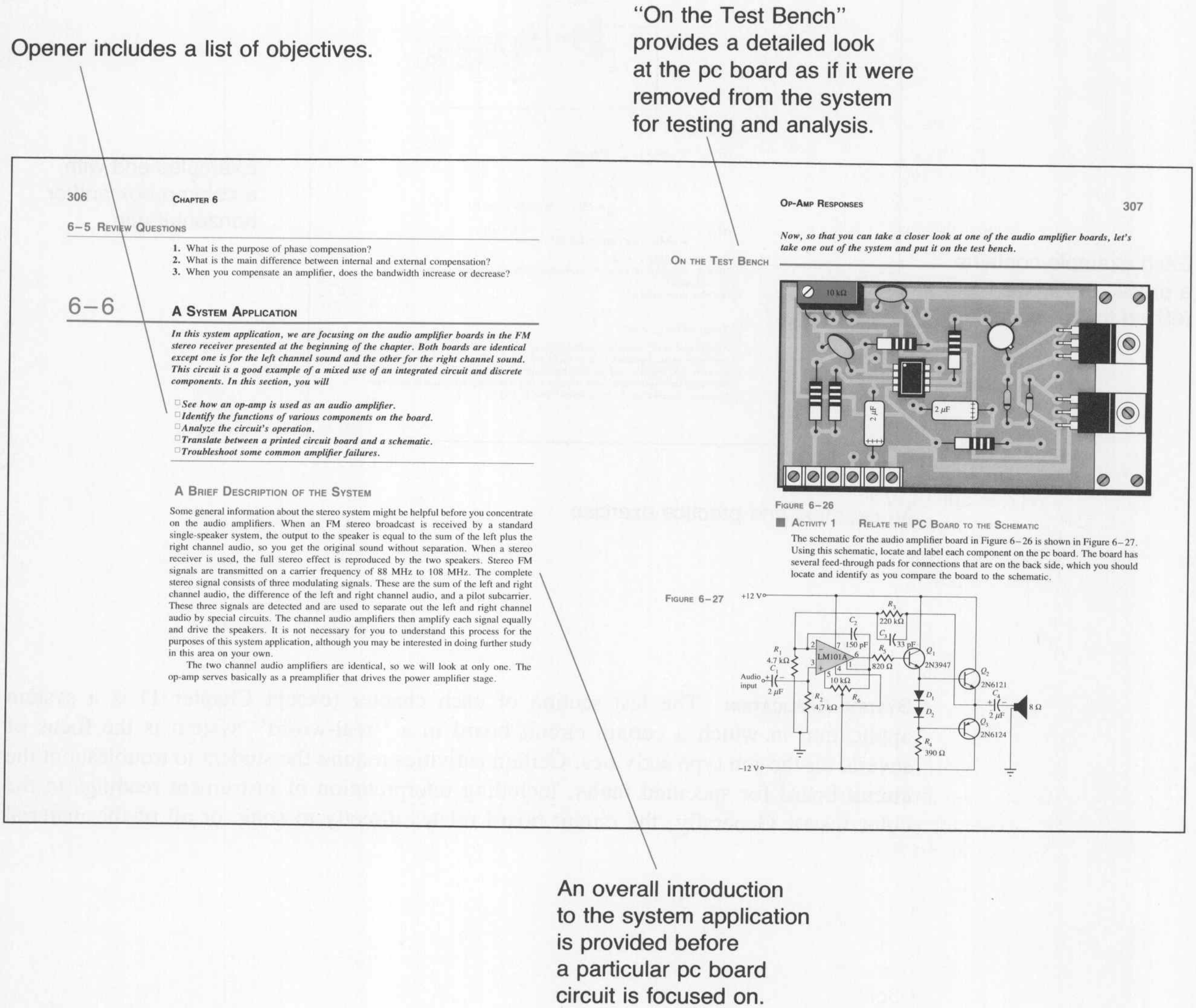
TWIN-T OSCILLATOR

Another type of RC oscillator is called the *twin-T* because of the two T-type RC filters used in the negative feedback loop, as shown in Figure 9–15(a). One of the twin-T filters has a low-pass response, and the other has a high-pass response. The combined parallel filters produce a band-stop or notch response with a center frequency equal to the desired frequency of oscillation, f_r, as shown in Figure 9–15(b).

FIGURE P–3
An example and practice exercise

SYSTEM APPLICATION The last section of each chapter (except Chapter 1) is a system application in which a certain circuit board in a ''real-world'' system is the focus of several on-the-job type activities. Certain activities require the student to troubleshoot the circuit board for specified faults, including interpretation of instrument readings in the color insert. Generally, the circuit board relates directly to some or all of the material covered in the chapter. In some cases, however, the student is required to ''stretch'' a bit and, as a result, to learn something new.

Results and answers for the activities in the system application sections are provided only in the Instructor's Resource Manual, where a set of worksheet masters for appropriate activities is also provided. These can be photocopied for student hand-outs.



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6–5 REVIEW QUESTIONS

1. What is the purpose of phase compensation?
2. What is the main difference between internal and external compensation?
3. When you compensate an amplifier, does the bandwidth increase or decrease?

6–6 A SYSTEM APPLICATION

In this system application, we are focusing on the audio amplifier boards in the FM stereo receiver presented at the beginning of the chapter. Both boards are identical except one is for the left channel sound and the other for the right channel sound. This circuit is a good example of a mixed use of an integrated circuit and discrete components. In this section, you will

- ☐ *See how an op-amp is used as an audio amplifier.*
- ☐ *Identify the functions of various components on the board.*
- ☐ *Analyze the circuit's operation.*
- ☐ *Translate between a printed circuit board and a schematic.*
- ☐ *Troubleshoot some common amplifier failures.*

A BRIEF DESCRIPTION OF THE SYSTEM

Some general information about the stereo system might be helpful before you concentrate on the audio amplifiers. When an FM stereo broadcast is received by a standard single-speaker system, the output to the speaker is equal to the sum of the left plus the right channel audio, so you get the original sound without separation. When a stereo receiver is used, the full stereo effect is reproduced by the two speakers. Stereo FM signals are transmitted on a carrier frequency of 88 MHz to 108 MHz. The complete stereo signal consists of three modulating signals. These are the sum of the left and right channel audio, the difference of the left and right channel audio, and a pilot subcarrier. These three signals are detected and are used to separate out the left and right channel audio by special circuits. The channel audio amplifiers then amplify each signal equally and drive the speakers. It is not necessary for you to understand this process for the purposes of this system application, although you may be interested in doing further study in this area on your own.

The two channel audio amplifiers are identical, so we will look at only one. The op-amp serves basically as a preamplifier that drives the power amplifier stage.

OP-AMP RESPONSES 307

ON THE TEST BENCH

Now, so that you can take a closer look at one of the audio amplifier boards, let's take one out of the system and put it on the test bench.

FIGURE 6–26

ACTIVITY 1 RELATE THE PC BOARD TO THE SCHEMATIC

The schematic for the audio amplifier board in Figure 6–26 is shown in Figure 6–27. Using this schematic, locate and label each component on the pc board. The board has several feed-through pads for connections that are on the back side, which you should locate and identify as you compare the board to the schematic.

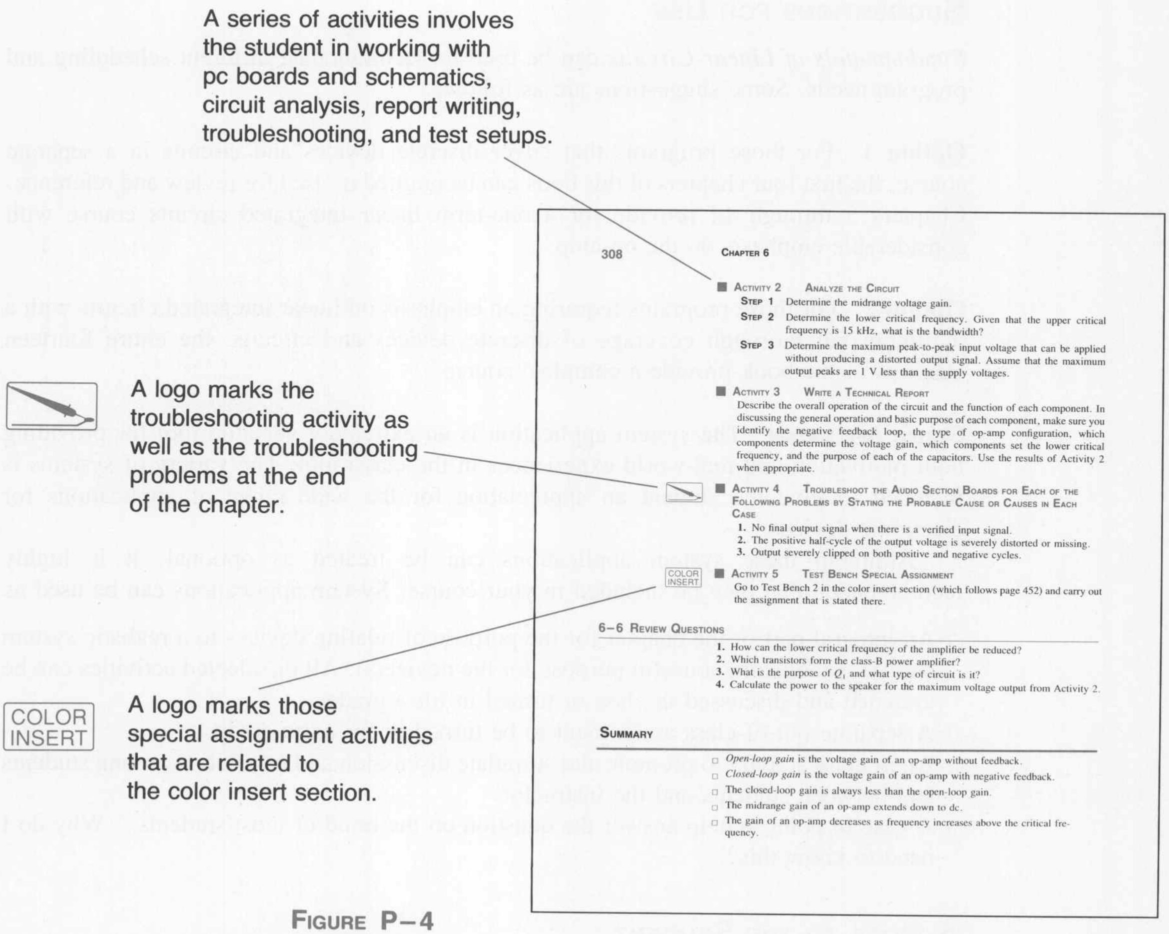
FIGURE 6–27

FIGURE P–4
A system application section

The overall objectives of the system application are

- □ To provide a transition between theoretical concepts and real-world circuitry.
- □ To help provide a "physical" sense of the devices and circuits studied in the chapter.
- □ To increase student skills with on-the-job activities.
- □ To help answer the question, "Why do I need to know this?"

A typical system application section is shown in Figure P–4.



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■ ACTIVITY 2 ANALYZE THE CIRCUIT

STEP 1 Determine the midrange voltage gain.

STEP 2 Determine the lower critical frequency. Given that the upper critical frequency is 15 kHz, what is the bandwidth?

STEP 3 Determine the maximum peak-to-peak input voltage that can be applied without producing a distorted output signal. Assume that the maximum output peaks are 1 V less than the supply voltages.

■ ACTIVITY 3 WRITE A TECHNICAL REPORT

Describe the overall operation of the circuit and the function of each component. In discussing the general operation and basic purpose of each component, make sure you identify the negative feedback loop, the type of op-amp configuration, which components determine the voltage gain, which components set the lower critical frequency, and the purpose of each of the capacitors. Use the results of Activity 2 when appropriate.

■ ACTIVITY 4 TROUBLESHOOT THE AUDIO SECTION BOARDS FOR EACH OF THE FOLLOWING PROBLEMS BY STATING THE PROBABLE CAUSE OR CAUSES IN EACH CASE

1. No final output signal when there is a verified input signal.
2. The positive half-cycle of the output voltage is severely distorted or missing.
3. Output severely clipped on both positive and negative cycles.

■ ACTIVITY 5 TEST BENCH SPECIAL ASSIGNMENT

Go to Test Bench 2 in the color insert section (which follows page 452) and carry out the assignment that is stated there.

6–6 REVIEW QUESTIONS

1. How can the lower critical frequency of the amplifier be reduced?
2. Which transistors form the class-B power amplifier?
3. What is the purpose of Q_1 and what type of circuit is it?
4. Calculate the power to the speaker for the maximum voltage output from Activity 2.

SUMMARY

- □ *Open-loop gain* is the voltage gain of an op-amp without feedback.
- □ *Closed-loop gain* is the voltage gain of an op-amp with negative feedback.
- □ The closed-loop gain is always less than the open-loop gain.
- □ The midrange gain of an op-amp extends down to dc.
- □ The gain of an op-amp decreases as frequency increases above the critical frequency.

FIGURE P–4
Continued

FULL-COLOR INSERT Three selected system applications are related to the full-color insert using a special assignment activity marked by a color insert logo. The color insert consists of circuit board test set-ups that either require the student to troubleshoot the board based on instrument readings or to determine instrument settings for testing the board for proper operation.

CHAPTER END MATTER At the end of each chapter is a summary, glossary, formula list, multiple-choice self-test, and sectionalized problem set, as well as answers to section review questions and to practice exercises. Terms that appear boldface in the text are defined in the glossary.

SUGGESTIONS FOR USE

Fundamentals of Linear Circuits can be used to accommodate different scheduling and program needs. Some suggestions are as follows.

Option 1 For those programs that cover discrete devices and circuits in a separate course, the first four chapters of this book can be omitted or used for review and reference. Chapters 5 through 14 provide for a one-term linear integrated circuits course with considerable emphasis on the op-amp.

Option 2 For those programs requiring an emphasis on linear integrated circuits with a minimum but thorough coverage of discrete devices and circuits, the entire fourteen chapters of the book provide a complete course.

SYSTEM APPLICATION The system application is an extremely versatile tool for providing both motivation and real-world experiences in the classroom. The variety of systems is intended to give the student an appreciation for the wide range of applications for electronic devices.

Although these system applications can be treated as optional, it is highly recommended that they be included in your course. System applications can be used as

- An integral part of the chapter for the purpose of relating devices to a realistic system and for establishing a useful purpose for the device(s). All or selected activities can be assigned and discussed in class or turned in for a grade.
- A separate out-of-class assignment to be turned in for extra credit.
- An in-class activity to promote and stimulate discussion and interaction among students and between students and the instructor.
- A case in point to help answer the question on the mind of most students: ''Why do I need to know this?''

A NOTE TO THE STUDENT

The material in this preface is intended to help both you and your instructor make the most effective use of this textbook as a teaching and learning tool. Although you should certainly read everything in this preface, this part is especially for you, the student.

I am sure that you realize that knowledge and skills are not obtained easily or without effort. Much hard work is required to properly prepare yourself for any career, and electronics is no exception. You should use this book as more than just a reference. You must really dig in by reading, thinking, and doing. Don't expect every concept or procedure to become immediately clear. Some topics may take several readings, working many problems, and much help from your instructor before you really understand them.

Work through each example step-by-step and then do the associated practice exercise. Answer the review questions at the end of each section. If you don't understand an example or if you can't answer a question, go back into the section until you can. Check your answers at the end of the chapter. The multiple-choice self-tests at the end of each chapter are a good way to check your overall comprehension and retention of the subjects covered. You should do the self-test before you start the problems. Check your answers at the end of the book.

The problem sets at the end of each chapter (except Chapter 1) provide exercises with varying degrees of difficulty. In any technical field, it is very important that you work lots of problems. Working through a problem gives you a level of insight and understanding that reading or classroom lectures alone do not provide. Never think that you fully understand a concept or procedure by simply watching or listening to someone else. In the final analysis, you must do it yourself and you must do it to the best of your ability.

A LOOK BACK

Now, before you begin your study of electronic devices and circuits, let's briefly look back at the beginnings of electronics and some of the important developments that have led to the electronics technology that we have today. It is always good to have a sense of the history of your career field. The names of many of the early pioneers in electricity and electromagnetics still live on in terms of familiar units and quantities. Names such as Ohm, Ampere, Volta, Farad, Henry, Coulomb, Oersted, and Hertz are some of the better known examples. More widely known names such as Franklin and Edison are also very significant in the history of electricity and electronics because of their tremendous contributions.

THE BEGINNING OF ELECTRONICS

The early experiments in electronics involved electric currents in glass vacuum tubes. One of the first to conduct such experiments was a German named Heinrich Geissler (1814–1879). Geissler removed most of the air from a glass tube and found that the tube glowed when there was an electric current through it. Around 1878, British scientist Sir William Crookes (1832–1919) experimented with tubes similar to those of Geissler. In his experiments, Crookes found that the current in the vacuum tubes seemed to consist of particles.

Thomas Edison (1847–1931), experimenting with the carbon-filament light bulb he had invented, made another important finding. He inserted a small metal plate in the bulb. When the plate was positively charged, there was a current from the filament to the plate. This device was the first thermionic diode. Edison patented it but never used it.

The electron was discovered in the 1890s. The French physicist Jean Baptiste Perrin

(1870–1942) demonstrated that the current in a vacuum tube consists of the movement of negatively charged particles in a given direction. Some of the properties of these particles were measured by Sir Joseph Thomson (1856–1940), a British physicist, in experiments he performed between 1895 and 1897. These negatively charged particles later became known as electrons. The charge on the electron was accurately measured by an American physicist, Robert A. Millikan (1868–1953), in 1909. As a result of these discoveries, electrons could be controlled, and the electronic age was ushered in.

PUTTING THE ELECTRON TO WORK A vacuum tube that allowed electrical current in only one direction was constructed in 1904 by British scientist John A. Fleming. The tube was used to detect electromagnetic waves. Called the Fleming valve, it was the forerunner of the more recent vacuum diode tubes. Major progress in electronics, however, awaited the development of a device that could boost, or amplify, a weak electromagnetic wave or radio signal. This device was the audion, patented in 1907 by Lee deForest, an American. It was a triode vacuum tube capable of amplifying small electrical ac signals.

Two other Americans, Harold Arnold and Irving Langmuir, made great improvements in the triode vacuum tube between 1912 and 1914. About the same time, deForest and Edwin Armstrong, an electrical engineer, used the triode tube in an oscillator circuit. In 1914, the triode was incorporated in the telephone system and made the transcontinental telephone network possible. The tetrode tube was invented in 1916 by Walter Schottky, a German. The tetrode, along with the pentode (invented in 1926 by Dutch engineer Tellegen), greatly improved the triode. The first television picture tube, called the kinescope, was developed in the 1920s by Vladimir Sworykin, an American researcher.

During World War II, several types of microwave tubes were developed that made possible modern microwave radar and other communications systems. In 1939, the magnetron was invented in Britain by Henry Boot and John Randall. In the same year, the klystron microwave tube was developed by two Americans, Russell Varian and his brother Sigurd Varian. The traveling-wave tube (TWT) was invented in 1943 by Rudolf Komphner, an Austrian-American.

SOLID-STATE ELECTRONICS The crystal detectors used in early radios were the forerunners of modern solid-state devices. However, the era of solid-state electronics began with the invention of the transistor in 1947 at Bell Labs. The inventors were Walter Brattain, John Bardeen, and William Shockley. Figure P–5 shows these three men.

In the early 1960s, the integrated circuit (IC) was developed. It incorporated many transistors and other components on a single small chip of semiconductor material. Integrated circuit technology has been continuously developed and improved, allowing increasingly more complex circuits to be built on smaller chips.

Around 1965, the first integrated general-purpose operational amplifier was introduced. This low-cost, highly versatile device incorporated nine transistors and twelve resistors in a small package. It proved to have many advantages over comparable discrete component circuits in terms of reliability and performance. Since this introduction, the IC operational amplifier has become a basic building block for a wide variety of linear systems.