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模拟电子技术基础

第2版 影印版

Fundamentals of Analog Circuits

Second Edition

Thomas L. Floyd
David Buchla

高等教育出版社
Higher Education Press

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前　　言

20 世纪末，以计算机和通信技术为代表的信息科学和技术对世界经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入 21 世纪，尤其随着我国加入 WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在 20 世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的 20 多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley 公司出版的贝尔实验室信息科学研究中心副总裁 Silberschatz 教授的经典著作《操作系统概念》，是我们经过反复谈判，做了很多努力才得以引进的。William Stallings 先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作者协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者 Jiawei Han 先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院的 Thomas Cormen 和麻省理工学院、哥伦比亚大学几位学者共同编著的经典著作《算法导论》，在经历了 11 年的锤炼之后于 2001 年出版了第二版。目前任教于美国 Massachusetts 大学的 James Kurose 教授，曾在美国三所高校先后 10 次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经

济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国 35 所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名 IT 企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

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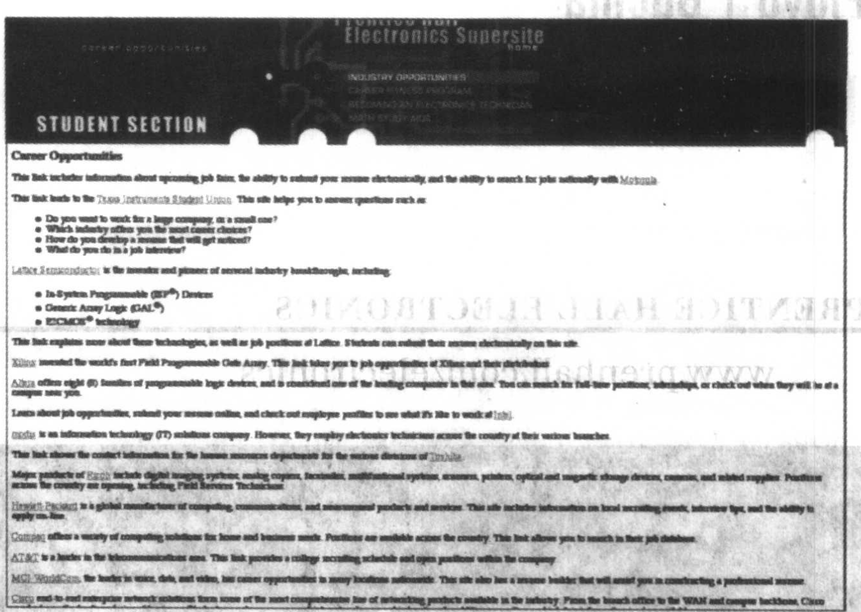
- Career Fitness Program
- Becoming an Electronics Technician
- Free On-Line Study Guides (companion web sites)



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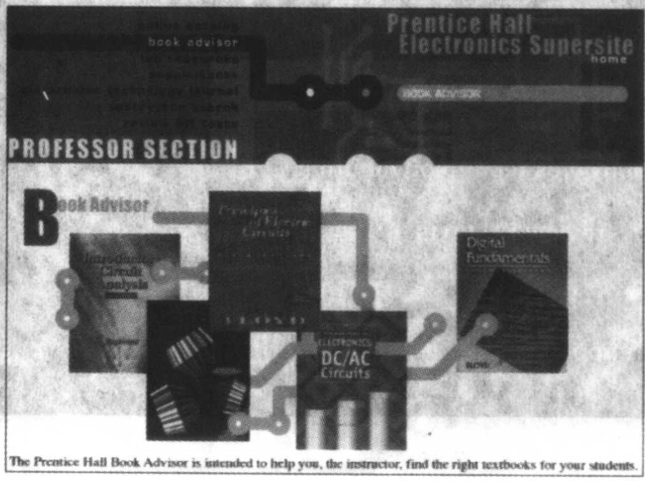

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Thanks to our wives for their affectionate support. Like fine red wine, they get better with age.

Preface

Fundamentals of Analog Circuits, Second Edition, presents an introduction to discrete linear devices and circuits followed by a thorough coverage of operational amplifiers and other linear integrated circuits. Also, this textbook provides extensive troubleshooting and applications coverage. Applications are shown with a realistic printed circuit board format in the last section of each chapter. They include a Troubleshooter's Bench exercise that presents a troubleshooting problem with the system. In addition to the Troubleshooter's Bench, troubleshooting sections are found in many parts of the text.

This second edition updates and improves coverage of the various operational amplifiers and other analog circuits introduced in the first edition. Each device was reviewed; older devices were replaced with newer ones, and a reference to the manufacturer's Internet site has been added to expedite finding additional information. In some cases, the explanation was streamlined or improved. For example, a brief discussion of triggering SCRs and triacs by microcontrollers was added in Chapter 15.

Two new features of this text include identifying key terms and adding a Troubleshooter's Quiz. Key terms are presented in the chapter opener and highlighted in color in the text with a margin icon. The Troubleshooter's Quiz reinforces critical thinking and troubleshooting skills for circuits introduced in the chapter. The Troubleshooter's Quiz consists of 8 to 12 multiple-choice questions that require students to consider how a given fault will affect voltage, current, gain, and so forth (increase, decrease, no change). Answers to the Troubleshooter's Quiz are found at the end of each chapter.

In addition, circuits have been prepared for many of the examples using Electronics Workbench™/Multisim to enable changes or troubles to be investigated. Electronics Workbench/Multisim is a computer-simulation program that is useful for testing circuits and observing the effect of parameter changes or troubles with the circuit. It uses a graphical interface to place components on a "workbench" and simulated instruments to view the results. These circuits are available on CD-ROM (ISBN: 0-13-060944-7).

Current in *Fundamentals of Analog Circuits, Second Edition,* is indicated by a meter notation rather than by directional arrows. This unique approach accomplishes two things. First, it eliminates the need to distinguish between conventional flow and electron flow because it indicates current direction by polarity signs, just as an actual ammeter does. Users can interpret current direction based on the meter polarity in accordance with their particular preference. Second, in addition to current direction, the meter notation provides relative magnitudes of the currents in a given circuit by observing the number of bars.

Overview

The first five chapters provide a fundamental coverage of basic concepts, diodes, transistors, and amplifiers. The last ten chapters focus on integrated circuit op-amps, active filters, oscillators, power supplies, special amplifiers, communications circuits, data conversion circuits, and measurement and control circuits.

Discrete Devices and Circuits The first part of the text consists of five chapters as follows: Chapter 1 presents an introduction to analog electronics, analog signals, amplifiers, and troubleshooting. Chapter 2 covers diodes, rectifiers, and regulators. Chapter 3 introduces bipolar junction transistors and BJT amplifiers. Chapter 4 gives a basic treatment of field-effect transistors and FET amplifiers. Chapter 5 deals with multistage amplifiers, radio-frequency (RF) amplifiers, and power amplifiers.

Analog Integrated Circuits The second part of the text consists of ten chapters that cover analog integrated circuits as follows: Chapter 6 provides an introduction to operational amplifiers. Op-amp frequency response is covered in Chapter 7, and basic op-amp circuits (comparators, summing amplifiers, integrators, and differentiators) is the topic of Chapter 8. Active op-amp filters are covered in Chapter 9, and oscillators and timers are introduced in Chapter 10. Power supplies are covered in Chapter 11. Special amplifiers (instrumentation amplifiers, isolation amplifiers, operational transconductance amplifiers (OTAs), and log/antilog amplifiers) are introduced in Chapter 12. Communication circuits (AM and FM receivers, linear multipliers, mixers, and phase-locked loops) are studied in Chapter 13. Data conversion circuits such as analog switches, sample-and-hold circuits, digital-to-analog and analog-to-digital converters, and voltage-to-frequency and frequency-to-voltage converters are among the topics in Chapter 14. Finally, Chapter 15 covers various types of transducers and associated measurement circuits.

Features

Fundamentals of Analog Circuits, Second Edition, is innovative in four areas:

- ❑ Current in a circuit is indicated by a polarized meter symbol that allows the user to apply the direction of preference. Also, current meters show relative current magnitude in a circuit. See Figure P–1.

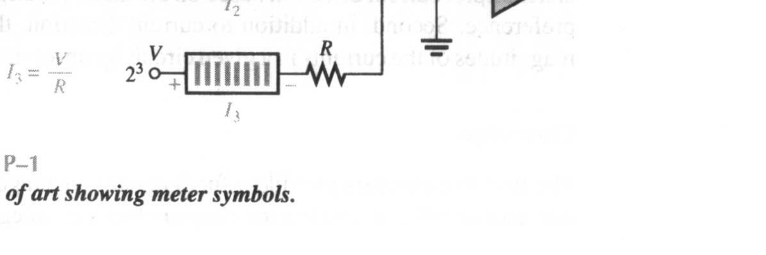


FIGURE P–1
Example of art showing meter symbols.

- Emphasis is on analog integrated circuits, but also there is a good coverage of discrete circuits.
- Topics that are generally not found in competing textbooks, such as RF amplifiers and transducers, are covered.
- System applications with Troubleshooter's Bench exercises incorporate realistic printed circuit boards, and a related full-color insert section is included.

Other features are as follows:

- Extensive troubleshooting material, including new Troubleshooter's Quiz
- Extensive use of examples
- Practice exercise in each numbered example
- Standard component values
- Two-page chapter openers with introduction, section list, objectives, key terms, and system application preview
- Section openers with overview and objectives
- End-of-section review questions
- Glossary terms boldfaced in text
- Answers to practice exercises for examples, section review questions, self-test, and Troubleshooter's Quiz at end of chapter
- Minimal mathematics, with important equations numbered
- A summary, key formula list, glossary, multiple-choice self-test, Troubleshooter's Quiz, and section problems for each chapter
- Key terms in color and with a margin icon in each chapter
- End-of-book derivations, manufacturers' specifications sheets, and answers to odd-numbered problems
- References to manufacturers' home pages for integrated circuits
- Comprehensive end-of-book glossary that includes all the terms from the end-of-chapter glossaries
- Lab Exercises manual written by David Buchla
- Instructor's Resource Manual that includes transparency masters, System Application worksheets, and test item file
- Visit the companion website to this text at www.prenhall.com/floyd.

Chapter Pedagogy

Chapter Opener Each chapter begins with a two-page spread, as indicated in Figure P–2.

Section Opener and Section Review Questions As illustrated in Figure P–3, each section within a chapter begins with an opening introduction and list of section objectives. Each section ends with a set of review questions that focus on key concepts. Answers to review questions are given at the end of the chapter.

Key Terms Certain terms are in color and are identified by a margin icon. These key terms, as well other bold terms, are defined in the end-of-chapter glossary and in the end-of-book glossary.

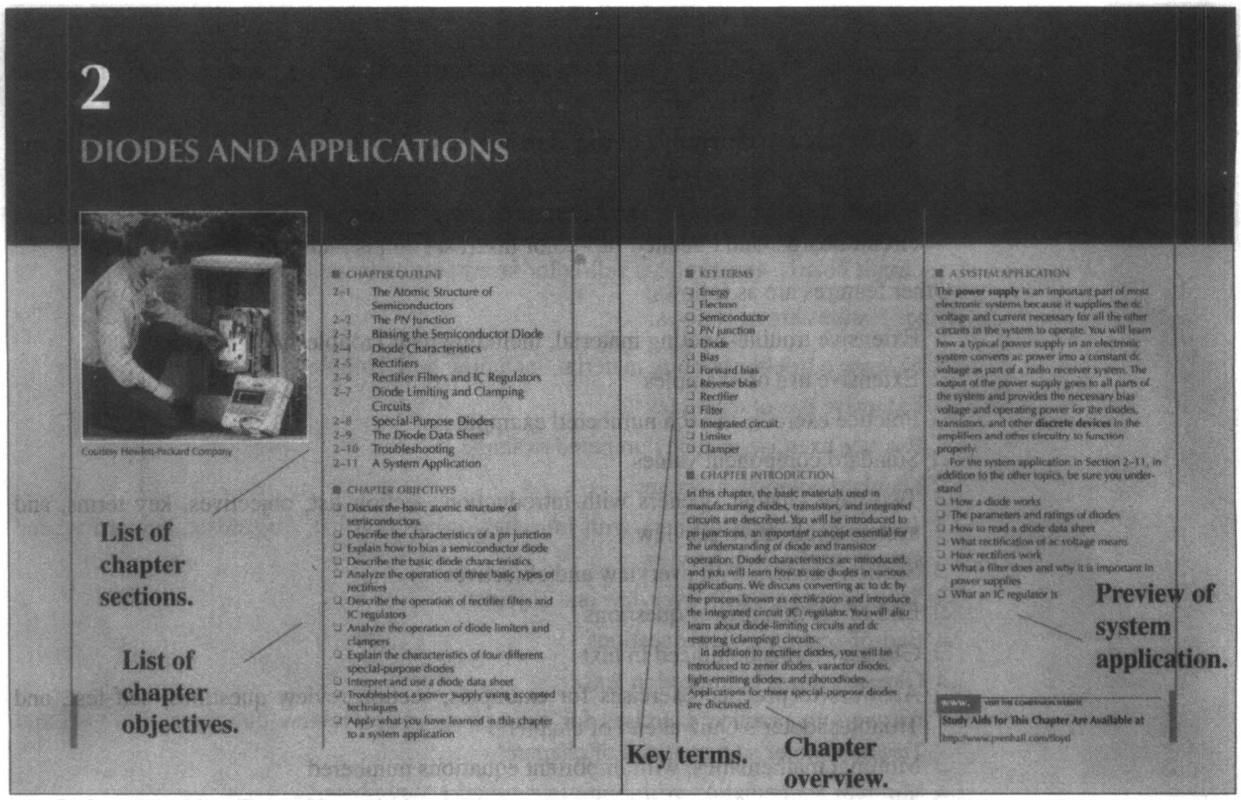


FIGURE P–2
Chapter opener.

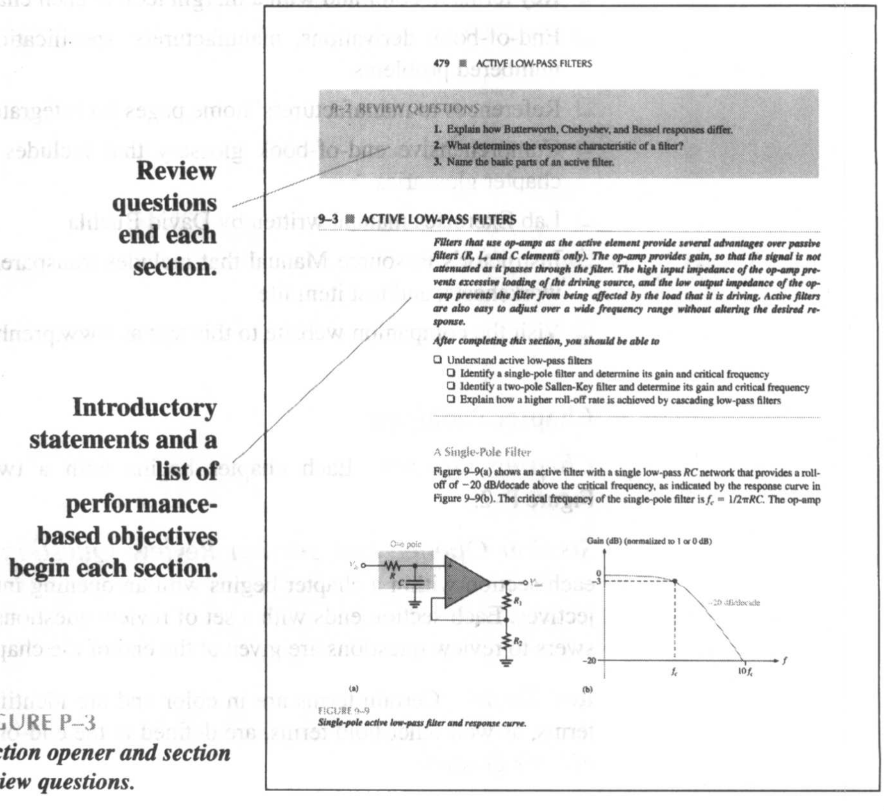


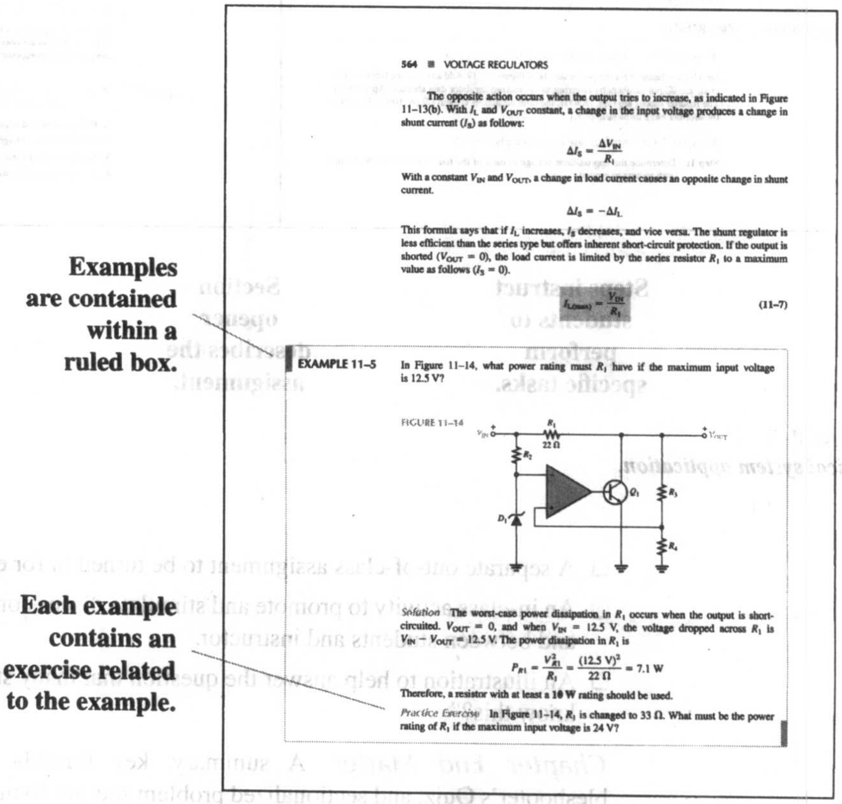
FIGURE P–3
Section opener and section review questions.

Examples and Practice Exercises Worked-out examples are used to illustrate and clarify topics covered in the text. At the end of every example and within the example box is a practice exercise that either reinforces the example or focuses on a related topic. Answers to the practice exercises are given at the end of the chapter. This feature is illustrated in Figure P–4.

System Application As illustrated in Figure P–5, the last section of each chapter (except Chapter 1) is a system application of devices and circuits related to the chapter coverage. The Troubleshooter's Bench sections provide a series of activities with a practical slant to simulate "on-the-job" situations. These activities include relating a schematic to a realistic printed circuit board, making measurements, troubleshooting, and writing reports. Three selected system applications are related to the full-color insert as indicated by a special logo. Results are provided in the Instructor's Resource Manual.

The system application is an optional feature which if omitted will not affect the coverage of any other topics. The variety of "systems" is intended to give students an appreciation for the wide range of applications for electronic devices and to provide motivation to learn the basic concepts of each chapter. The system application sections can be used as:

❑ A part of each chapter for the purpose of relating devices to a realistic application and for establishing a useful purpose for devices covered. All or selected activities can be assigned and discussed in class or turned in for a grade.


564 ■ VOLTAGE REGULATORS

The opposite action occurs when the output tries to increase, as indicated in Figure 11–13(b). With I_L and V_{OUT} constant, a change in the input voltage produces a change in shunt current (I_S) as follows:

$$\Delta I_S = \frac{\Delta V_{IN}}{R_1}$$

With a constant V_{IN} and V_{OUT}, a change in load current causes an opposite change in shunt current.

$$\Delta I_S = -\Delta I_L$$

This formula says that if I_L increases, I_S decreases, and vice versa. The shunt regulator is less efficient than the series type but offers inherent short-circuit protection. If the output is shorted ($V_{OUT} = 0$), the load current is limited by the series resistor R_1 to a maximum value as follows ($I_S = 0$).

$$I_{L(max)} = \frac{V_{IN}}{R_1} \quad (11\text{–}7)$$

EXAMPLE 11–5 In Figure 11–14, what power rating must R_1 have if the maximum input voltage is 12.5 V?

FIGURE 11–14

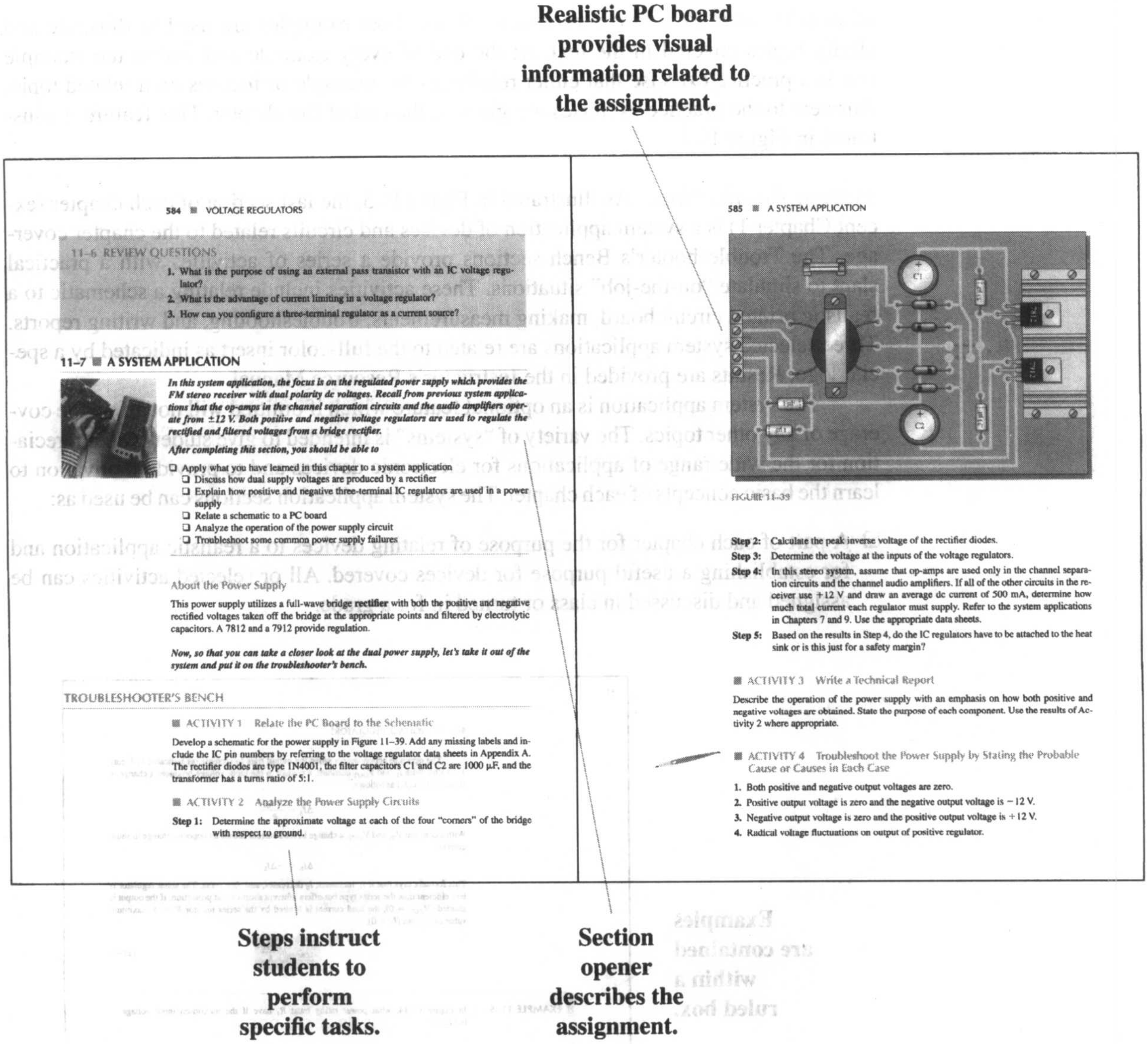
Solution The worst-case power dissipation in R_1 occurs when the output is short-circuited. $V_{OUT} = 0$, and when $V_{IN} = 12.5$ V, the voltage dropped across R_1 is $V_{IN} - V_{OUT} = 12.5$ V. The power dissipation in R_1 is

$$P_{R1} = \frac{V_{R1}^2}{R_1} = \frac{(12.5\text{ V})^2}{22\ \Omega} = 7.1\text{ W}$$

Therefore, a resistor with at least a 10 W rating should be used.

Practice Exercise In Figure 11–14, R_1 is changed to 33 Ω. What must be the power rating of R_1 if the maximum input voltage is 24 V?

FIGURE P–4
Typical example and practice exercise.



584 ■ VOLTAGE REGULATORS

11–6 REVIEW QUESTIONS

1. What is the purpose of using an external pass transistor with an IC voltage regulator?
2. What is the advantage of current limiting in a voltage regulator?
3. How can you configure a three-terminal regulator as a current source?

11–7 ■ A SYSTEM APPLICATION

In this system application, the focus is on the regulated power supply which provides the FM stereo receiver with dual polarity dc voltages. Recall from previous system applications that the op-amps in the channel separation circuits and the audio amplifiers operate from ±12 V. Both positive and negative voltage regulators are used to regulate the rectified and filtered voltages from a bridge rectifier.

After completing this section, you should be able to

- ❑ Apply what you have learned in this chapter to a system application
  - ❑ Discuss how dual supply voltages are produced by a rectifier
  - ❑ Explain how positive and negative three-terminal IC regulators are used in a power supply
  - ❑ Relate a schematic to a PC board
  - ❑ Analyze the operation of the power supply circuit
  - ❑ Troubleshoot some common power supply failures

About the Power Supply

This power supply utilizes a full-wave bridge **rectifier** with both the positive and negative rectified voltages taken off the bridge at the appropriate points and filtered by electrolytic capacitors. A 7812 and a 7912 provide regulation.

Now, so that you can take a closer look at the dual power supply, let's take it out of the system and put it on the troubleshooter's bench.

TROUBLESHOOTER'S BENCH

■ ACTIVITY 1 Relate the PC Board to the Schematic

Develop a schematic for the power supply in Figure 11–39. Add any missing labels and include the IC pin numbers by referring to the voltage regulator data sheets in Appendix A. The rectifier diodes are type 1N4001, the filter capacitors C1 and C2 are 1000 μF, and the transformer has a turns ratio of 5:1.

■ ACTIVITY 2 Analyze the Power Supply Circuits

Step 1: Determine the approximate voltage at each of the four "corners" of the bridge with respect to ground.

585 ■ A SYSTEM APPLICATION

FIGURE 11–39

Step 2: Calculate the peak inverse voltage of the rectifier diodes.
Step 3: Determine the voltage at the inputs of the voltage regulators.
Step 4: In this stereo system, assume that op-amps are used only in the channel separation circuits and the channel audio amplifiers. If all of the other circuits in the receiver use +12 V and draw an average dc current of 500 mA, determine how much total current each regulator must supply. Refer to the system applications in Chapters 7 and 9. Use the appropriate data sheets.
Step 5: Based on the results in Step 4, do the IC regulators have to be attached to the heat sink or is this just for a safety margin?

■ ACTIVITY 3 Write a Technical Report

Describe the operation of the power supply with an emphasis on how both positive and negative voltages are obtained. State the purpose of each component. Use the results of Activity 2 where appropriate.

■ ACTIVITY 4 Troubleshoot the Power Supply by Stating the Probable Cause or Causes in Each Case

1. Both positive and negative output voltages are zero.
2. Positive output voltage is zero and the negative output voltage is −12 V.
3. Negative output voltage is zero and the positive output voltage is +12 V.
4. Radical voltage fluctuations on output of positive regulator.

FIGURE P–5
A typical system application.

- ❑ 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 instructor.
- ❑ An illustration to help answer the question that many students have: "Why do I need to know this?"

Chapter End Matter A summary, key formula list, glossary, self-test, Troubleshooter's Quiz, and sectionalized problem sets are found at the end of each chapter. The answers to practice exercises for examples, section review questions, self-test, and Troubleshooter's Quiz are also provided.

To the Student

Any career training requires hard work, and electronics is no exception. The best way to learn new material is by reading, thinking, and doing. This text is designed to help you along the way by providing an overview and objectives for each section, numerous worked-out examples, practice exercises, and review questions with answers.

Don't expect every concept to be crystal clear after a single reading. Read each section of the text carefully and think about what you have read. Work through the example problems step-by-step before trying the practice exercise that goes with the example. Sometimes more than one reading of a section will be necessary. After each section, check your understanding by answering the section review questions.

Review the chapter summary, glossary, and formula list. Take the multiple-choice self-test. Finally, work the problems at the end of the chapter. Check your answers to the self-test and the odd-numbered problems against those provided. Working problems is the most important way to check your comprehension and solidify concepts.

One of the best ways to reinforce text material is through the actual construction of circuits in the laboratory. You will become a better troubleshooter as well if you "learn by doing." Circuit construction reinforces troubleshooting skills because you will find that many times a simple wiring error or other fault is accidentally introduced in your experiment. Making a circuit work correctly involves analysis of the circuit as well as logical thinking. The sort of thinking that goes into lab work is also simulated on Electronics Workbench/Multisim. Another way to develop skill in troubleshooting is to take the Troubleshooter's Quiz, located at the back of each chapter; answers are provided to check your understanding.

Milestones in Electronics

Before you begin your study of analog circuits, let's briefly look at some of the important developments that led to electronics technology as we have today. 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 significant in the history of electricity and electronics because of their tremendous contributions.

The Beginning of Electronics Early experiments with electronics involved electric currents in vacuum tubes. Heinrich Geissler (1814–1879) removed most of the air from a glass tube and found that the tube glowed when there was current through it. Later, Sir William Crookes (1832–1919) found the current in vacuum tubes seemed to consist of particles. Thomas Edison (1847–1931) experimented with carbon filament bulbs with plates and discovered that there was a current from the hot filament to a positively charged plate. He patented the idea but never used it.

Other early experimenters measured the properties of the particles that flowed in vacuum tubes. Sir Joseph Thompson (1856–1940) measured properties of these particles, later called *electrons*.

Although wireless telegraphic communication dates back to 1844, electronics is basically a 20th century concept that began with the invention of the vacuum tube amplifier. An early vacuum tube that allowed current in only one direction was constructed by John A. Fleming in 1904. Called the Fleming valve, it was the forerunner of vacuum tube diodes. In 1907, Lee deForest added a grid to the vacuum tube. The new device, called the

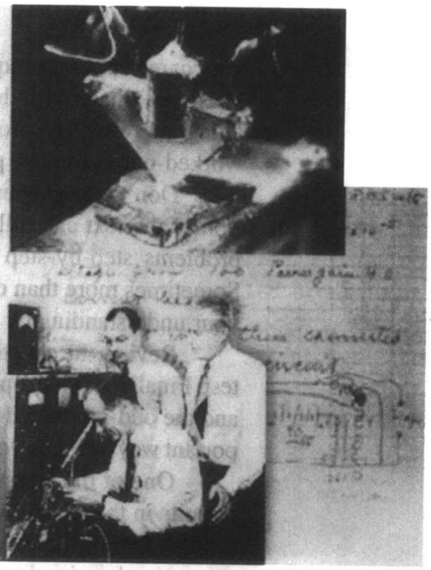


FIGURE P–6
The invention of the bipolar junction transistor. Photo copyright by Bell Laboratories. All rights reserved. Used with permission.

audiotron, could amplify a weak signal. By adding the control element, deForest ushered in the electronics revolution. It was with an improved version of his device that made transcontinental telephone service and radios possible. In 1912, a radio amateur in San Jose, California, was regularly broadcasting music!

In 1921, the secretary of commerce, Herbert Hoover, issued the first license to a broadcast radio station; within two years over 600 licenses were issued. By the end of the 1920s radios were in many homes. A new type of radio, the superheterodyne radio, invented by Edwin Armstrong, solved problems with high-frequency communication. In 1923, Vladimir Zworykin, an American researcher, invented the first television picture tube, and in 1927 Philo T. Farnsworth applied for a patent for a complete television system.

The 1930s saw many developments in radio, including metal tubes, automatic gain control, "midgit sets," directional antennas, and more. Also started in this decade was the development of the first electronic computers. Modern computers trace their origins to the work of John Atanasoff at Iowa State University. Beginning in 1937, he envisioned a binary machine that could do complex mathematical work. By 1939, he and graduate student Clifford Berry had constructed a binary machine called ABC, (for Atanasoff-Berry Computer) that used vacuum tubes for logic and condensers (capacitors) for memory. In 1939, the magnetron, a microwave oscillator, was invented in Britain by Henry Boot and John Randall. In the same year, the klystron microwave tube was invented in America by Russell and Sigurd Varian.

During World War II, electronics developed rapidly. Radar and very high-frequency communication were made possible by the magnetron and klystron. Cathode ray tubes were improved for use in radar. Computer work continued during the war. By 1946, John von Neumann had developed the first stored program computer, the Eniac, at the University of Pennsylvania. The decade ended with one of the most important inventions ever, the transistor.

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, shown in Figure P–6. PC (printed circuit) boards were introduced in 1947, the year the transistor was invented. Commercial manufacturing of transistors began in Allentown, Pennsylvania, in 1951.

The most important invention of the 1950s was the integrated circuit. On September 12, 1958, Jack Kilby, at Texas Instruments, made the first integrated circuit, for which he was awarded a Nobel prize in the fall of 2000. This invention literally created the modern computer age and brought about sweeping changes in medicine, communication, manufacturing, and the entertainment industry. Many billions of "chips"—as integrated circuits came to be called—have since been manufactured.

The 1960s saw the space race begin and spurred work on miniaturization and computers. The space race was the driving force behind the rapid changes in electronics that followed. The first successful "op-amp" was designed by Bob Widlar at Fairchild Semiconductor in 1965. Called the μA709, it was very successful but suffered from "latch-up" and other problems. Later, the most popular op-amp ever, the 741, was taking shape at Fairchild. This op-amp became the industry standard and influenced design of op-amps for years to come. Precursors to the Internet began in the 1960s with remote networked computers. Systems were in place within Lawrence Livermore National Laboratory that connected over 100 terminals to a computer system (colorfully called the "Octopus system" and used by one of this text's authors). In an experiment in 1969 with very remote computers, an exchange took place between researchers at UCLA and Stanford. The UCLA group hoped to connect to a Stanford computer and began by typing the word "login" on its terminal. A separate telephone connection was set up and the following conversation occurred.

The UCLA group asked over the phone, "Do you see the letter L?"

"Yes, we see the L."

The UCLA group typed an O. "Do you see the letter O?"

"Yes, we see the O."

The UCLA group typed a G. At this point the system crashed. Such was technology, but a revolution was in the making.

By 1971, a new company that had been formed by a group from Fairchild introduced the first microprocessor. The company was Intel and the product was the 4004 chip, which had the same processing power as the Eniac computer. Later in that same year, Intel announced the first 8-bit processor, the 8008. In 1975, the first personal computer was introduced by Altair, and *Popular Science* magazine featured it on the cover of the January, 1975, issue. The 1970s also saw the introduction of the pocket calculator and new developments in optical integrated circuits.

By the 1980s, half of all U.S. homes were using cable hookups instead of television antennas. The reliability, speed, and miniaturization of electronics continued throughout the 1980s, including automated testing and calibrating of PC boards. The computer became a part of instrumentation and the virtual instrument was created. Computers became a standard tool on the workbench.

The 1990s saw a widespread application of the Internet. In 1993, there were only 130 websites; by the start of the new century (in 2001) there were over 24 million. In the 1990s, companies scrambled to establish a home page and many of the early developments of radio broadcasting had parallels with the Internet. (The bean counters still want to know how it's going to make money!) The exchange of information and e-commerce fueled the tremendous economic growth of the 1990s. The Internet became especially important to scientists and engineers, becoming one of the most important scientific communication tools ever.