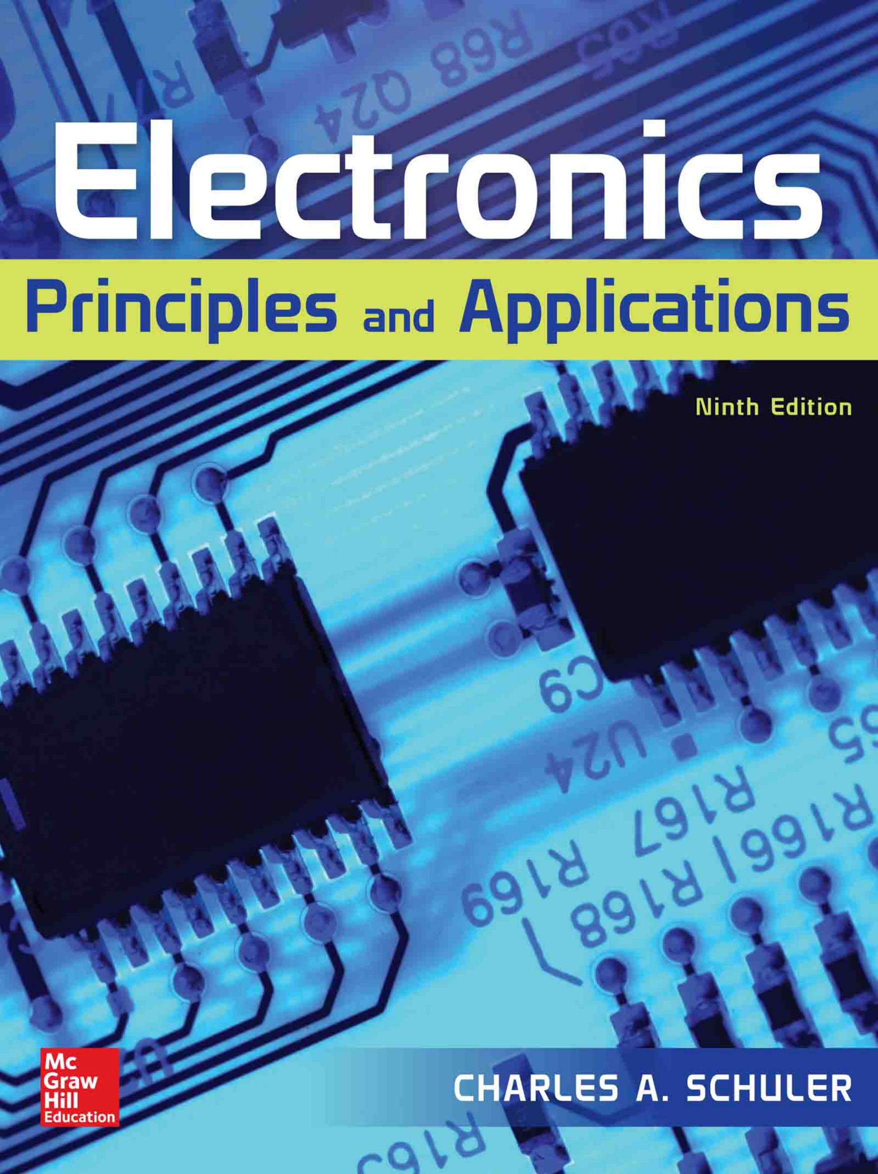


Electronics

Principles and Applications

Ninth Edition

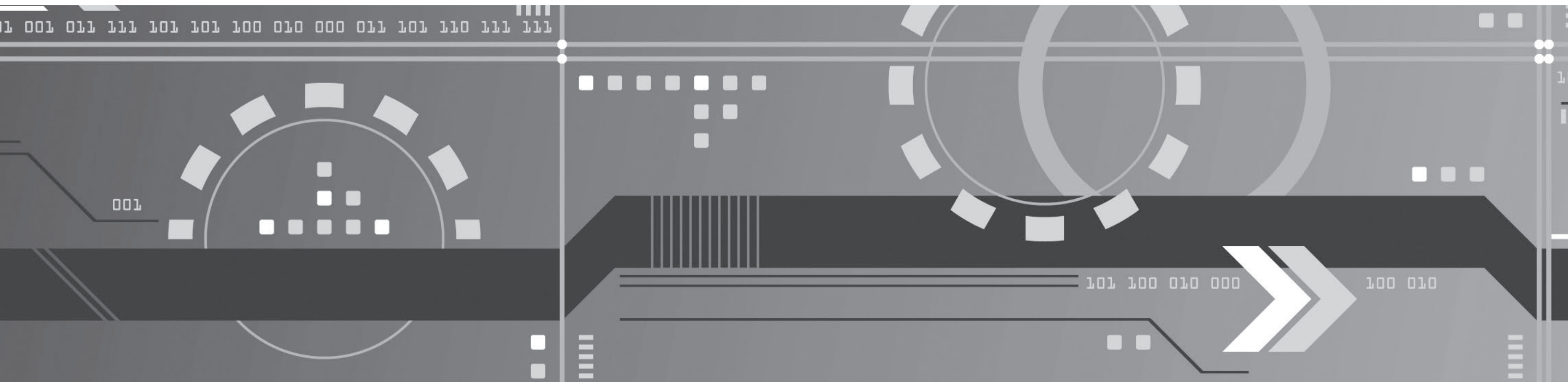
CHARLES A. SCHULER

McGraw Hill Education

Ninth Edition

Electronics

Principles & Applications



Charles A. Schuler

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Contents

Editor's Foreword

The McGraw-Hill Career Education *Trade and Technology list* has been designed to provide entry-level competencies in a wide range of occupations in the electrical and electronic fields. It consists of coordinated instructional materials designed especially for the career-oriented student. A textbook, an experiments manual, and an instructor productivity center support each major subject area covered. All of these focus on the theory, practices, applications, and experiences necessary for those preparing to enter technical careers.

There are two fundamental considerations in the preparation of a text like *Electronics: Principles and Applications:* the needs of the learner and the needs of the employer. This text meets these needs in an expert fashion. The author and editors have drawn upon their broad teaching and technical experiences to accurately interpret and meet the needs of the student. The needs of business and industry have been identified through personal interviews, industry publications, government occupational trend reports, and reports by industry associations.

The processes used to produce and refine the series have been ongoing. Technological change is rapid, and the content has been revised to focus on current trends. Refinements in pedagogy have been defined and implemented based on classroom testing and feedback from students and instructors using the series. Every effort has been made to offer the best possible learning materials. These include animated PowerPoint presentations, circuit files for simulation, a test generator with correlated test banks, dedicated Web sites for both students and instructors, basic instrumentation labs, and other items as well. All of these are well coordinated and have been prepared by the authors.

The widespread acceptance of *Electronics: Principles and Applications* and the positive responses from users confirm the basic soundness in content and design of all of the components as well as their effectiveness as teaching and learning tools. Instructors will find the texts and manuals in each of the subject areas logically structured, well paced, and developed around a framework of modern objectives. Students will find the materials to be readable, lucidly illustrated, and interesting. They will also find a generous amount of self-study, review items, and examples to help them determine their own progress.

Charles A. Schuler, Project Editor

Basic Skills in Electricity and Electronics

Charles A. Schuler, Project Editor

Editions in This Series

Electricity: Principles and Applications, Eighth Edition, Richard J. Fowler
Electronics: Principles and Applications, Ninth Edition, Charles A. Schuler
Digital Electronics: Principles and Applications, Eighth Edition, Roger Tokheim

Preface

Electronics: Principles and Applications, 9e, introduces analog devices, circuits, and systems. It also presents various digital techniques that are now commonly used in what was once considered the sole domain of analog electronics. It is intended for students who have a basic understanding of Ohm's law; Kirchhoff's laws; power; schematic diagrams; and basic components such as resistors, capacitors, and inductors. The digital material is self-contained and will not pose a problem for those students who have not completed a course in digital electronics. The only mathematics prerequisite is a command of basic algebra.

The major objective of this text is to provide entry-level knowledge and skills for a wide range of occupations in electricity and electronics. Its purpose is to assist in the education and preparation of technicians who can effectively diagnose, repair, verify, install, and upgrade electronic circuits and systems. It also provides a solid and practical foundation in analog electronic concepts, device theory, and modern digital solutions for those who may need or want to go on to more advanced study.

The ninth edition, like the earlier ones, combines theory and applications in a logical, evenly paced sequence. It is important that a student's first exposure to electronic devices and circuits be based on a smooth integration of theory and practice. This approach helps the student develop an understanding of how devices such as diodes, transistors, and integrated circuits function and how they are used in practice. Then the understanding of these functions can be applied to the solution of practical problems such as performance analysis and troubleshooting.

This is an extremely practical text. The devices, circuits, and applications are typical of those used in all phases of electronics. Reference is made to common aids such as parts catalogs, component identification systems, and substitution guides, and real-world troubleshooting techniques are applied whenever appropriate. The information, theory, and calculations presented are the same as those used by practicing technicians. The formulas presented are immediately applied in examples that make sense and relate to the kinds of calculations actually made by technical workers.

The 16 chapters progress from an introduction to the broad field of electronics through solid-state theory, transistors, and the concepts of gain, amplifiers, oscillators, electronic communications and data transfer, integrated circuits, control circuitry, regulated power supplies, and digital signal processing. As an example of the practicality of the text, an entire chapter is devoted to troubleshooting circuits and systems. In other chapters, entire sections are devoted to this vital topic. Since the last edition, the electronics industry has continued its march toward more digital and mixed-signal applications to replace what used to be purely analog functions. The distinction between analog and digital continues to blur. This is the only text of its kind that addresses this issue.

New to this Edition

This edition updates devices and equipment. For example, more emphasis is placed on digital meter readings and less on analog displays. It also portrays up-to-date test equipment. Lastly, devices that are no longer available have been eliminated.

Perhaps the most significant change is the emphasis on thermal issues and power devices. As technicians ply their craft, they will likely deal with devices such as power transistors. This is because power devices have a higher failure rate and the replacement of power devices is often more cost-effective than the replacement of other parts. One entirely new section is devoted to power transistors and another to troubleshooting thermal issues.

More information about topics such as total harmonic distortion has been included. Along with that, spectral analysis to measure total harmonic distortion is presented. Measurements that once required very expensive test equipment can now be made using affordable personal computers and software. That is also true with certain radio-frequency measurements that can be made with a PC. This edition covers wireless network troubleshooting and presents more information about digital modulation methods.

Last but not least, there is now more troubleshooting information. In addition to using software and PCs, methods of using basic calculations to predict circuit performance are discussed. For example, a regulated power supply circuit is analyzed to determine normal voltage readings. This is becoming more important as fewer voltage readings and fewer waveforms are supplied with schematics. Technicians are forced to become more self-reliant and better educated about the circuit principles and theory that are covered here. The practicality of this book has always been very strong and has continued to evolve over time.

Additional Resources

Online Learning Center

The *Online Learning Center* (OLC) contains a wealth of features, including extra review questions, links to industry sites, chapter study overviews, assignments, the Instructor's Manual, and a MultiSim Primer, all for students. The following is a list of features that can be found on the OLC.

Student Side of the Online Learning Center

Student PowerPoint presentations
Soldering PowerPoint presentation and .pdf file
Circuit interrupter PowerPoint (GFCI and AFCI)
Breadboarding PowerPoint presentation
Data sheets in .pdf format
Digital signal processing simulations (4 programs)
"Audio Examples" PowerPoint presentation
HP instrumentation simulator
Instrumentation PowerPoint presentations
Circuit files (EWB 5 and Multisim versions 6, 7, 8, and 11)
MultiSim Primer (by Patrick Hoppe of Gateway Technical College), which provides a tutorial for new users of the software

Instructor Side of the Online Learning Center

Instructor's Manual
PowerPoint presentations for classroom use
Electronic test bank questions for each chapter
Parts and equipment lists
Learning Outcomes
Answers to textbook questions:
  Chapter review questions
  Critical thinking questions
Answers and data for lab experiments and assignments
Projects
HP instrumentation simulator
Instrumentation PowerPoint presentations (lab 1 to lab 4)
Instrumentation lab experiments in .pdf format
Breadboarding PowerPoint presentation
Soldering (.pdf file)
Circuit interrupters (GFCI & AFCI) PowerPoint presentations
Circuit simulation files (EWB 5 and MultiSim versions 6, 7, 8, 11, and 14)
Digital Signal Processing simulations (four programs)
"Audio Examples" PowerPoint presentation for Chapter 16
Calculus PowerPoint presentation, with EWB and Multisim circuit files
Data sheets in .pdf format
Statistics .pdf files
Pro Electron Type Numbering .pdf file

Visit the Online Learning Center at www.mhhe.com/schuler9e.

Experiments Manual

A correlated Experiments Manual provides a wide array of hands-on labwork, problems, and circuit simulations. MultiSim files are provided for both the simulation activities and the hands-on activities. These files are located on the Student Side of the Online Learning Center.

About the Author

Charles A. Schuler received his Ed.D. from Texas A&M University in 1966, where he was an N.D.E.A. fellow. He has published many articles and seven textbooks on electricity and electronics, almost as many laboratory manuals, and another book that deals with ISO 9000. He taught electronics technology and electrical engineering technology at California University of Pennsylvania for 30 years. He is currently a full-time writer, as he continues his passion to make the difficult easy to understand.

Walkthrough

Electronics: Principles and Applications takes a concise and practical approach to this fascinating subject. The textbook's easy-to-read style, color illustrations, and basic math level make it ideal for students who want to learn the essentials of modern electronics and apply them to real job-related situations.

> **Learning Outcomes**
>
> *This chapter will help you to:*
>
> **1-1** *Identify* some major events in the history of electronics. [1-1]
> **1-2** *Classify* circuit operation as digital or analog. [1-2]
> **1-3** *Name* major analog circuit functions. [1-3]
> **1-4** *Begin* developing a system viewpoint for troubleshooting. [1-3]
> **1-5** *Analyze* circuits with both dc and ac sources. [1-4]
> **1-6** *List* the current trends in electronics. [1-5]

Each chapter starts with ***Learning Outcomes*** that give the reader an idea of what to expect in the following pages, and what he or she should be able to accomplish by the end of the chapter. These outcomes are distinctly linked to the chapter subsections.

Key Terms, noted in the margins, call the reader's attention to key concepts.

> **I-2 Digital or Analog**
>
> Today, electronics is such a huge field that it is often necessary to divide it into smaller subfields. You will hear terms such as medical electronics, instrumentation electronics, automotive electronics, avionics, consumer electronics, industrial electronics, and others. One way that electronics can be divided is into digital or analog.
>
> **Digital electronic device**
>
> A *digital electronic device* or circuit will recognize or produce an output of only several limited states. For example, most digital circuits will respond to only two input conditions: low or high. *Digital circuits* may also be called *binary* since they are based on a number system with only two digits: 0 and 1.
>
> **Digital circuit**
>
> **Linear circuit**
>
> **Analog circuit**
>
> An *analog circuit* can respond to or produce an output for an infinite number of states. An analog input or output might vary between 0 and 10 volts (V). Its actual value [illegible] be 1.5, 2.8

EXAMPLE 1-1

An audio compact disk (CD) uses 16 bits to represent each sample of the signal. How many steps or volume levels are possible? Use the appropriate power of 2:

$$2^{16} = 65{,}536$$

This is easy to solve using a calculator with an x^y key. Press 2, then x^y, and then 16 followed by the = key.

Numerous solved ***Example*** problems throughout the chapters demonstrate the use of formulas and the methods used to analyze electronic circuits.

HISTORY OF ELECTRONICS

Niels Bohr and the Atom

Scientists change the future by improving on the ideas of others. Niels Bohr proposed a model of atomic structure in 1913 that applied energy levels (quantum mechanics) to the Rutherford model of the atom. Bohr also used some of the work of Max Planck.

Source: Library of Congress Prints and Photographs Division [LC-USZ62-112063]

You May Recall

Chokes are so named because they "choke off" high-frequency current flow.

History of Electronics, ***You May Recall***, and ***About Electronics*** add historical depth to the topics and highlight new and interesting technologies or facts.

ABOUT ELECTRONICS

Materials Used for Dopants, Semiconductors, and Microwave Devices

- Gallium arsenide (GaAs) works better than silicon in microwave devices because it allows faster movement of electrons.
- Materials other than boron and arsenic are used as dopants.
- It is theoretically possible to make semiconductor devices from crystalline carbon.
- Crystal radio receivers were an early application of semiconductors.

All critical facts and principles are reviewed in the ***Summary and Review*** section at the end of each chapter.

Chapter 1 Summary and Review

Summary

1. Electronics is a relatively young field. Its history began in the twentieth century.
2. Electronic circuits can be classified as digital or analog.
3. The number of states or voltage levels is limited in a digital circuit (usually to two).
4. An analog circuit has an infinite number of voltage levels.
5. In a linear circuit, the output signal is a replica of the input.
6. All linear circuits are analog, but not all analog circuits are linear. Some analog circuits distort signals.

10. The number of output levels from a D/A converter is equal to 2 raised to the power of the number of bits used.
11. Digital signal processing uses computers to enhance signals.
12. Block diagrams give an overview of electronic system operation.
13. Schematic diagrams show individual part wiring and are usually required for component-level troubleshooting.
14. Troubleshooting begins at the system level.
15. Alternating current and direct current signals are often combined in electronic circuits.

All of the important chapter formulas are summarized at the end of each chapter in ***Related Formulas***. ***Chapter Review Questions*** are found at the end of each chapter; and separate, more challenging ***Chapter Review Problems*** sections are available in appropriate chapters.

Related Formulas

Number of levels in a binary system: levels $= 2^n$

Capacitive reactance: $X_C = \dfrac{1}{2\pi fC}$

Inductive reactance: $X_L = 2\pi fL$

Chapter Review Questions

Determine whether each statement is true or false.

1-1. Most digital circuits can output only two states, high and low. (1-2)

1-2. Digital circuit outputs are usually sine waves. (1-2)

1-3. The output of a linear circuit is an exact replica of the input. (1-2)

1-4. Linear circuits are classified as analog. (1-2)

1-5. All analog circuits are linear. (1-2)

1-6. The output of a 4-bit D/A converter can produce 128 different voltage levels. (1-2)

1-7. An attenuator is an electronic circuit used to make signals stronger. (1-3)

1-8. Block diagrams are best for component-level troubleshooting. (1-3)

1-9. In Fig. 1-8, if the signal at point 4 is faulty, then the signal at point 3 must also be faulty. (1-3)

1-10. Refer to Fig. 1-8. The power supply should be checked first. (1-3)

Finally, each chapter ends with ***Critical Thinking Questions*** and ***Answers to Self-Tests***.

Answers to Self-Tests

1. T	7. T	13. F	19. capacitors
2. T	8. F	14. F	20. bypass
3. F	9. T	15. T	21. coupling (dc block)
4. T	10. F	16. F	22. F
5. F	11. F	17. −7.5 V	23. T
6. T	12. T	18. 12.5 V, 0 V	24. F

Critical Thinking Questions

1-1. Functions now accomplished by using electronics may be accomplished in different ways in the future. Can you think of any examples?

1-2. Can you describe a simple system that uses only two wires but will selectively signal two different people?

1-3. What could go wrong with capacitor C_2 in Fig. 1-10, and how would the fault affect the waveform at Node D?

1-4. What could go wrong with capacitor C_2 in Fig. 1-13, and how would the fault affect the waveform at Node D?

Acknowledgments

Where does one begin? This book is part of a series that started with a research project. Many people contributed to that effort . . . both in education and in industry. Their dedication and diligence helped launch what has become a very successful series. Then, there are all those instructors and students who have given sage and thoughtful advice over the years. And there are those gifted and hardworking folks at McGraw-Hill. Finally, there is my family, who indulge my passion and encourage my efforts.

Safety

Electric and electronic circuits can be dangerous. Safe practices are necessary to prevent electrical shock, fires, explosions, mechanical damage, and injuries resulting from the improper use of tools.

Perhaps the greatest hazard is electrical shock. A current through the human body in excess of 10 milliamperes can paralyze the victim and make it impossible to let go of a "live" conductor or component. Ten milliamperes is a rather small amount of current flow: It is only *ten one-thousandths* of an ampere. An ordinary flashlight can provide more than 100 times that amount of current!

Flashlight cells and batteries are safe to handle because the resistance of human skin is normally high enough to keep the current flow very small. For example, touching an ordinary 1.5-V cell produces a current flow in the microampere range (a microampere is one one-millionth of an ampere). This amount of current is too small to be noticed.

High voltage, on the other hand, can force enough current through the skin to produce a shock. If the current approaches 100 milliamperes or more, the shock can be fatal. Thus, the danger of shock increases with voltage. Those who work with high voltage must be properly trained and equipped.

When human skin is moist or cut, its resistance to the flow of electricity can drop drastically. When this happens, even moderate voltages may cause a serious shock. Experienced technicians know this, and they also know that so-called low-voltage equipment may have a high-voltage section or two. In other words, they do not practice two methods of working with circuits: one for high voltage and one for low voltage. They follow safe procedures at all times. They do not assume protective devices are working. They do not assume a circuit is off even though the switch is in the OFF position. They know the switch could be defective.

Even a low-voltage, high-current-capacity system like an automotive electrical system can be quite dangerous. Short-circuiting such a system with a ring or metal watchband can cause very severe burns—especially when the ring or band welds to the points being shorted.

As your knowledge and experience grow, you will learn many specific safe procedures for dealing with electricity and electronics. In the meantime,

1. Always follow procedures.
2. Use service manuals as often as possible. They often contain specific safety information. Read, and comply with, all appropriate material safety data sheets.
3. Investigate before you act.
4. When in doubt, *do not act*. Ask your instructor or supervisor.

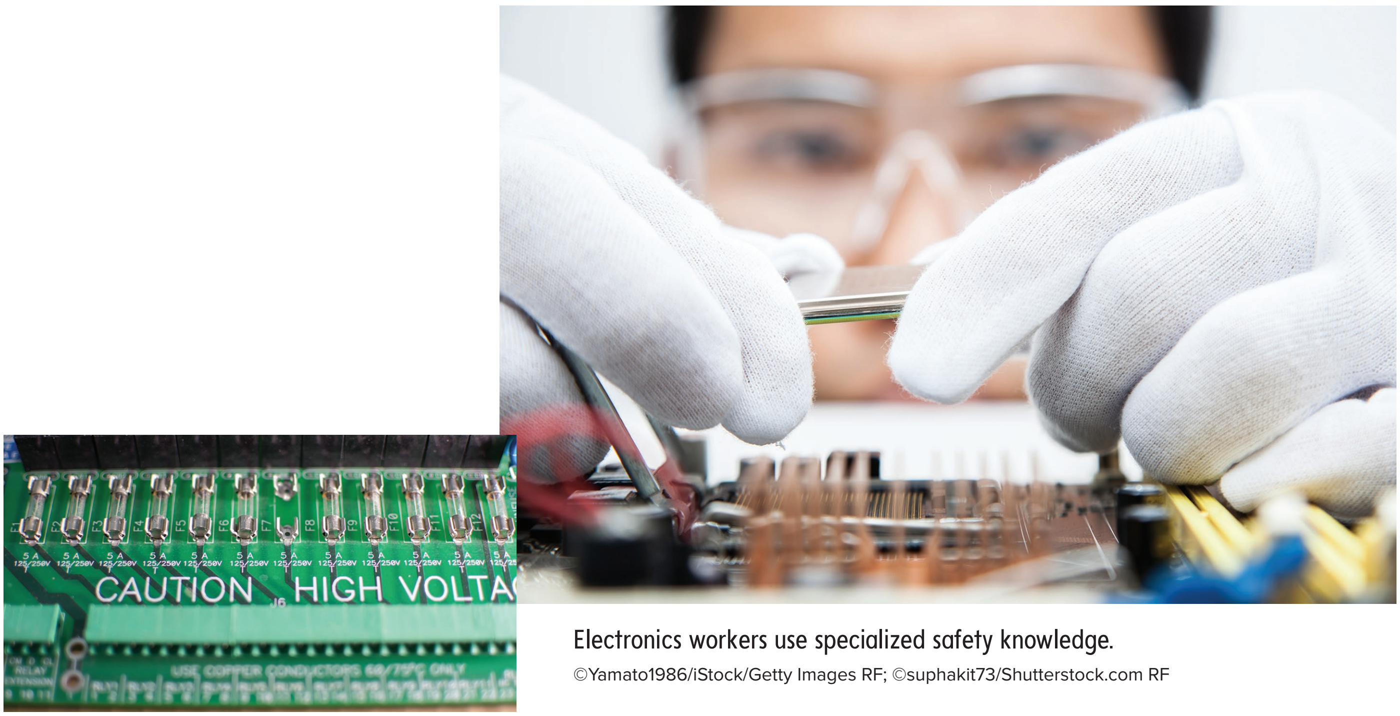
General Safety Rules for Electricity and Electronics

Safe practices will protect you and your fellow workers. Study the following rules. Discuss them with others, and ask your instructor about any you do not understand.

1. Do not work when you are tired or taking medicine that makes you drowsy.
2. Do not work in poor light.
3. Do not work in damp areas or with wet shoes or clothing.
4. Use approved tools, equipment, and protective devices.
5. Avoid wearing rings, bracelets, and similar metal items when working around exposed electric circuits.
6. Never assume that a circuit is off. Double-check it with an instrument that you are sure is operational.
7. Some situations require a "buddy system" to guarantee that power will not be turned on while a technician is still working on a circuit.
8. Never tamper with or try to override safety devices such as an interlock (a type of switch that automatically removes power when a door is opened or a panel removed).
9. Keep tools and test equipment clean and in good working condition. Replace insulated probes and leads at the first sign of deterioration.

10. Some devices, such as capacitors, can store a *lethal* charge. They may store this charge for long periods of time. You must be certain these devices are discharged before working around them.
11. Do not remove grounds, and do not use adaptors that defeat the equipment ground.
12. Use only an approved fire extinguisher for electrical and electronic equipment. Water can conduct electricity and may severely damage equipment. Carbon dioxide (CO_2) or halogenated-type extinguishers are usually preferred. Foam-type extinguishers may also be desired in *some* cases. Commercial fire extinguishers are rated for the type of fires for which they are effective. Use only those rated for the proper working conditions.
13. Follow directions when using solvents and other chemicals. They may be toxic or flammable, or they may damage certain materials such as plastics. Always read and follow the appropriate material safety data sheets.
14. A few materials used in electronic equipment are toxic. Examples include tantalum capacitors and beryllium oxide transistor cases. These devices should not be crushed or abraded, and you should wash your hands thoroughly after handling them. Other materials (such as heat shrink tubing) may produce irritating fumes if overheated. Always read and follow the appropriate material safety data sheets.
15. Certain circuit components affect the safe performance of equipment and systems. Use only exact or approved replacement parts.
16. Use protective clothing and safety glasses when handling high-vacuum devices such as picture tubes and cathode-ray tubes.
17. Don't work on equipment before you know proper procedures and are aware of any potential safety hazards.
18. Many accidents have been caused by people rushing and cutting corners. Take the time required to protect yourself and others. Running, horseplay, and practical jokes are strictly forbidden in shops and laboratories.
19. Never look directly into light-emitting diodes or fiber-optic cables. Some light sources, although invisible, can cause serious eye damage.
20. Lithium batteries can explode and start fires. They must be used only as intended and only with approved chargers. Lead-acid batteries produce hydrogen gas, which can explode. They too must be used and charged properly.

Circuits and equipment must be treated with respect. Learn how they work and the proper way of working on them. Always practice safety: your health and life depend on it.



Electronics workers use specialized safety knowledge.

CHAPTER 1

Introduction

Learning Outcomes

This chapter will help you to:

1-1 *Identify* some major events in the history of electronics. [1-1]
1-2 *Classify* circuit operation as digital or analog. [1-2]
1-3 *Name* major analog circuit functions. [1-3]
1-4 *Begin* developing a system viewpoint for troubleshooting. [1-3]
1-5 *Analyze* circuits with both dc and ac sources. [1-4]
1-6 *List* the current trends in electronics. [1-5]

Electronics is a recent technology that has undergone explosive growth. It is widespread and touches all our lives in many ways. This chapter will help you to understand how electronics developed over the years and how it is currently divided into specialty areas. It will help you to understand some basic functions that take place in electronic circuits and systems and will also help you to build on what you have already learned about circuits and components.

1-1 A Brief History

It is hard to place an exact date on the beginning of electronics. The year 1899 is one possibility. During that year, J. J. Thomson, at the University of Cambridge in England, discovered the electron. Two important developments at the beginning of the 20th century made people interested in electronics. The first was in 1901, when Guglielmo Marconi sent a message across the Atlantic Ocean using *wireless* telegraphy. Today we call wireless communication *radio*. The second development came in 1906, when Lee De Forest invented the audion vacuum tube. The term *audion* related to its first use, to make sounds ("audio") louder. It was not long before the wireless inventors used the *vacuum tube* to improve their equipment.

Audion

Vacuum tube

Another development in 1906 is worth mentioning. Greenleaf W. Pickard used the first crystal radio detector. This great improvement helped make radio and electronics more popular. It also suggested the use of *semiconductors* (crystals) as materials with future promise for the new field of radio and electronics.

Semiconductor

Commercial radio was born in Pittsburgh, Pennsylvania, at station KDKA in 1920. This development marked the beginning of a new era, with electronic devices appearing in the average home. By 1937 more than half the homes in the United States had a radio. Commercial television began around 1946. In 1947 several hundred thousand home radio receivers were manufactured and sold. Complex television receivers and complicated electronic devices made technicians wish for something better than vacuum tubes.

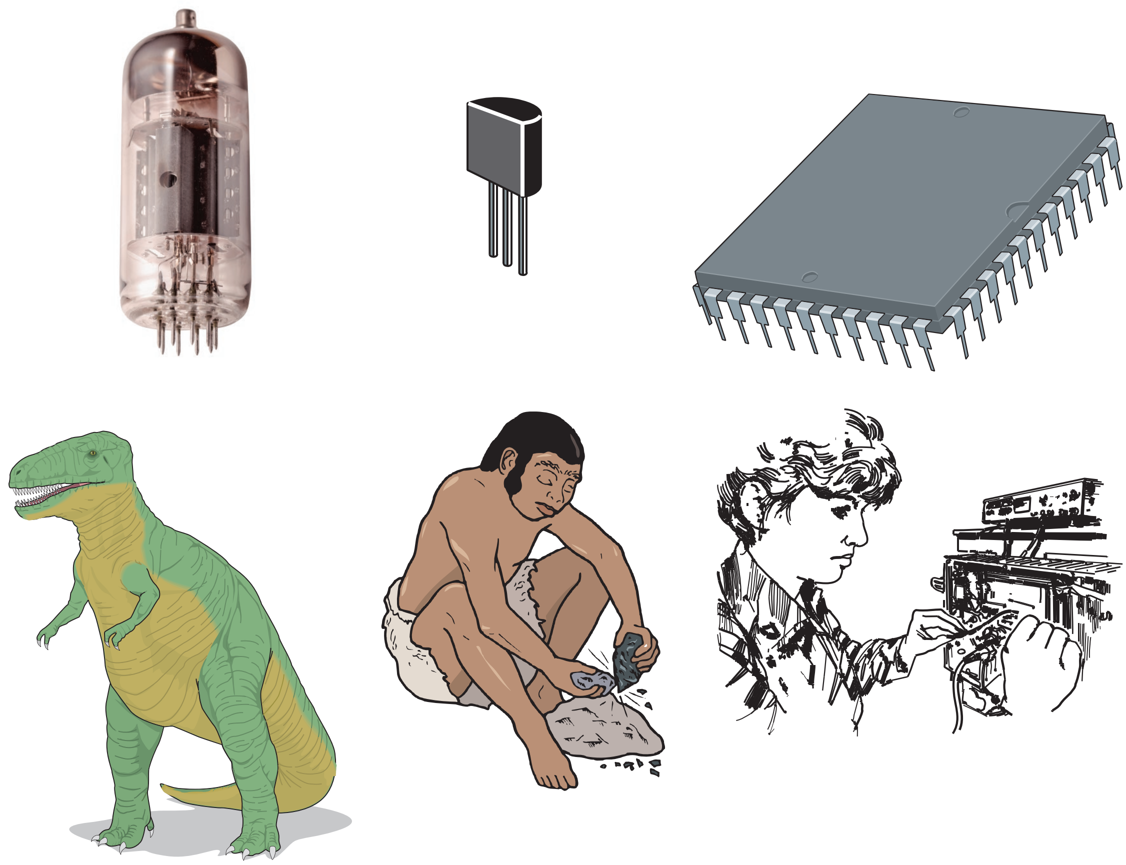
The first vacuum tube computer project was funded by the U.S. government, and the research began in 1943. Three years later, the ENIAC was formally dedicated at the Moore School of Electrical Engineering of the University of Pennsylvania on February 15, 1946. It was the world's first electronic digital computer:

- Size: 30 ft × 50 ft
- Weight: 30 tons
- Vacuum tubes: 17,468
- Resistors: 70,000
- Capacitors: 10,000
- Relays: 1,500
- Switches: 6,000
- Power: 150,000 W
- Cost: $486,000 (about $5 million today)
- Reliability: 7 minutes mean time between failures (MTBF)

A group of students at the Moore School participated in the fiftieth-year anniversary celebration of the ENIAC by developing an equivalent complementary metal oxide semiconductor (CMOS) chip:

- Size: 7.44 mm × 5.29 mm
- Package: 132 pin pin grid array (PGA)
- Transistors: 174,569
- Cost: several dollars (estimated, per unit, if put into production)
- Power: approximately 1 W
- Reliability: 50 years (estimated)

Scientists had known for a long time that many of the jobs done by vacuum tubes could be done more efficiently by semiconducting



The vacuum tube, the transistor, and then the integrated circuit. The evolution of electronics can be compared with the evolution of life.

(top left): ©Dimitry Sladkov/123RF

crystals, but they could not make crystals pure enough to do the job. The breakthrough came in 1947. Three scientists working with Bell Laboratories made the first working transistor. This was such a major contribution to science and technology that the three men—John Bardeen, Walter H. Brattain, and William B. Shockley—were awarded the Nobel Prize.

Around the same time (1948) Claude Shannon, also then at Bell Laboratories, published a paper on communicating in binary code. His work formed the basis for the digital communications revolution, from cell phones to the Internet. Shannon was also the first to apply Boolean algebra to telephone switching networks when he worked at the Massachusetts Institute of Technology in 1940. Shannon's work forms much of the basis for what we now enjoy in both telecommunications and computing.

Improvements in transistors came rapidly, and now they have all but completely replaced the vacuum tube. *Solid state* has become a household term. Many people believe that the transistor is one of the greatest developments ever.

Solid-state circuits were small, efficient, and more reliable. But the scientists and engineers still were not satisfied. Work done by Jack Kilby of Texas Instruments led to the development of the *integrated circuit* in 1958. Robert Noyce, working at Fairchild, developed a similar project. The two men shared a Nobel Prize in Physics for inventing the integrated circuit.

Integrated circuits are complex combinations of several kinds of devices on a common base, called a *substrate,* or in a tiny piece of silicon. They offer low cost, high performance, good efficiency, small size, and better reliability than an equivalent circuit built from separate parts. The complexity of some integrated circuits allows a single chip of silicon only 0.64 centimeter (cm) [0.25 inch (in.)] square to replace huge pieces of equipment. Although the chip can hold thousands of transistors, it still has diodes, resistors, and capacitors too!

In 1971 Intel Corporation in California announced one of the most sophisticated of all integrated circuits—the microprocessor. A *microprocessor* is most of the circuitry of a computer reduced to a single integrated circuit. Microprocessors, some containing the equivalent of billions of transistors, have provided billions of dollars worth of growth for the electronics industry and have opened up entire new areas of applications.

Microprocessor

The Intel 4004 contained 2,300 transistors, and today a Xeon processor has more than 6 billion. The 4004 had features as small as 10 micrometers (μm), and today the feature size is shrinking toward 10 nanometers (nm).

In 1977 the cellular telephone system entered its testing phase. Since then, the system has experienced immense growth. Its overwhelming success has fostered the development of new technology, such as digital communications and linear integrated circuits for communications.

Solid state

In 1982, Texas Instruments offered a single chip digital signal processor (DSP). This made it practical to apply DSP to many new product designs. The growth has continued ever since, and DSP is now one of the most rapidly expanding segments of the semiconductor industry.

Integrated circuit

The integrated circuit is producing an electronics explosion. Now electronics is being applied in more ways than ever before. At one time radio was almost its only application. Today electronics makes a major contribution to our society and to every field of human endeavor. It affects us in ways we may not be aware of. We are living in the electronic age.

Substrate

Self-Test

Determine whether each statement is true or false.

1. Electronics is a young technology that began in the 20th century.
2. The early histories of radio and electronics are closely linked.
3. Transistors were invented before vacuum tubes.
4. A modern integrated circuit can contain thousands of transistors.
5. A microprocessor is a small circuit used to replace radio receivers.

I-2 Digital or Analog

Today, electronics is such a huge field that it is often necessary to divide it into smaller subfields. You will hear terms such as medical electronics, instrumentation electronics, automotive electronics, avionics, consumer electronics, industrial electronics, and others. One way that electronics can be divided is into digital or analog.

Digital electronic device

A *digital electronic device* or circuit will recognize or produce an output of only several limited states. For example, most digital circuits will respond to only two input conditions: low or high. *Digital circuits* may also be called *binary* since they are based on a number system with only two digits: 0 and 1.

Digital circuit

Linear circuit

Analog circuit

An *analog circuit* can respond to or produce an output for an infinite number of states. An analog input or output might vary between 0 and 10 volts (V). Its actual value could be 1.5, 2.8, or even 7.653 V. In theory, an *infinite* number of voltages are possible. On the other hand, the typical digital circuit recognizes inputs ranging from 0 to 0.4 V as low (binary 0) and those ranging from 2.0 to 5 V as high (binary 1). A digital circuit does not respond any differently for an input of 2 V than it does for one at 4 V. Both of these voltages are in the high range. Input voltages between 0.4 and 2.0 V are not allowed in digital systems because they cause an output that is unpredictable.

For a long time, almost all electronic devices and circuits operated in the analog fashion. This seemed to be the most obvious way to do a particular job. After all, most of the things that we measure are analog in nature. Your height, weight, and the speed at which you travel in a car are all analog quantities. Your voice is analog. It contains an infinite number of levels and frequencies. So, if you wanted a circuit to amplify your voice, you would probably think of using an analog circuit.

Telephone switching and computer circuits forced engineers to explore digital electronics. They needed circuits and devices to make logical decisions based on certain input conditions. They needed highly reliable circuits that would always operate the same way. By limiting the number of conditions or states in which the circuits must operate, they could be made more reliable. An infinite number of states—the analog circuit—was not what they needed.

DSP

Figure 1-1 gives examples of circuit behavior to help you identify digital or analog operation. The signal going into the circuit is on the left, and the signal coming out is on the right. For now, think of a signal as some electrical quantity, such as voltage, that changes with time. The circuit marked *A* is an example of a digital device. Digital waveforms are rectangular. The output signal is a rectangular wave; the input signal is not exactly a rectangular wave. Rectangular waves have only two voltage levels and are very common in digital devices.

Circuit *B* in Fig. 1-1 is an analog device. The input and the output are sine waves. The output is larger than the input, and it has been shifted above the zero axis. The most important feature is that the output signal is a combination of an infinite number of voltages. In a *linear circuit,* the output is an exact replica of the input. Though circuit *B* is linear, not all analog circuits are linear. For example, a certain audio amplifier could have a distorted sound. This amplifier would still be in the analog category, but it would be nonlinear.

Circuits *C* through *F* are all digital. Note that the outputs are all *rectangular* waves (two levels of voltage). Circuit *F* deserves special attention. Its input is a rectangular wave. This could be an analog circuit responding to only two voltage levels except that something has happened to the signal, which did not occur in any of the other examples. The output frequency is different from the input frequency. Digital circuits that accomplish this are called *counters*, or *dividers.*

It is now common to convert analog signals to a digital format that can be stored in computer memory, on magnetic or optical disks, or on magnetic tape. Digital storage has advantages. Everyone who has heard music played from a digital disk knows that it is usually noise free. Digital recordings do not deteriorate with use as analog recordings do.

Another advantage of converting analog signals to digital is that computers can then be used to enhance the signals. Computers are digital machines. They are powerful, high-speed number crunchers. A computer can do various things to signals such as eliminate noise and distortion, correct for frequency and phase errors, and identify signal patterns. This area of electronics is known as digital signal processing (DSP). DSP is used in medical electronics to enhance scanned images of the human body, in audio to remove noise from old recordings, and in many other ways. DSP is covered in Chap. 16.

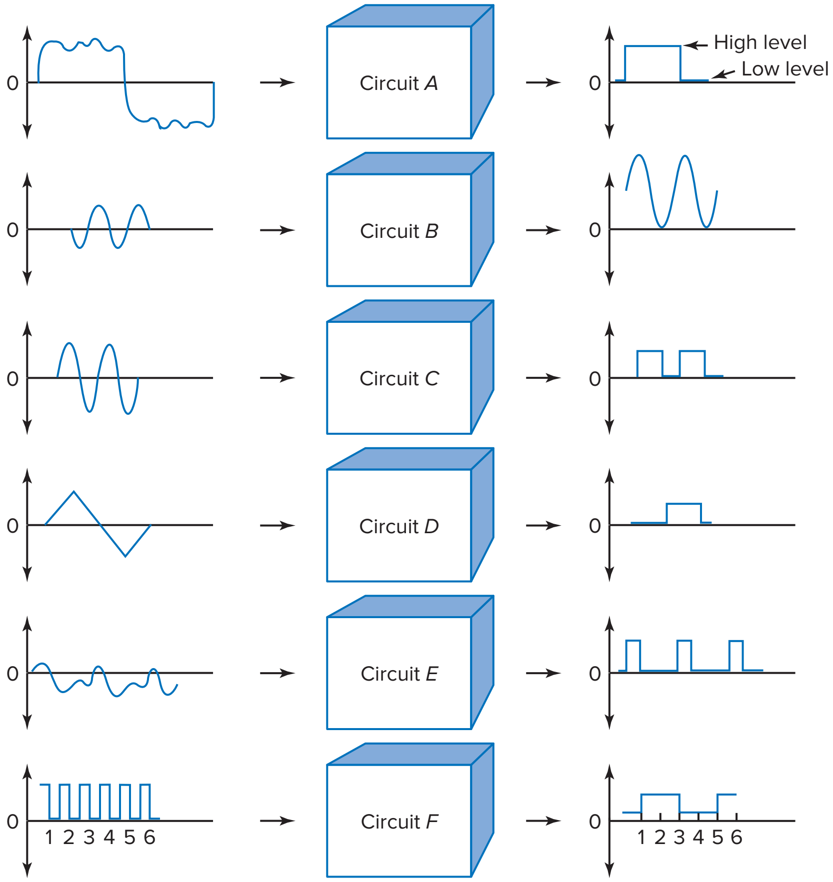


Fig. 1-1 A comparison of digital and analog circuits.

Figure 1-2 shows a system that converts an analog signal to digital and then back to analog. An *analog-to-digital (A/D) converter* is a circuit that produces a binary (only 0s and 1s) output. Note that the numbers stored in memory are binary. A clock (a timing circuit) drives the A/D converter to sample the analog signal on a repetitive basis. Figure 1-3 shows the analog waveform in greater detail. This waveform is sampled by the A/D converter every 20 microseconds (μs). Thus, over a period of 0.8 millisecond (ms), forty samples are taken. The required sampling rate for any analog signal is a function of the frequency of that signal. The higher the frequency of the signal, the higher the sampling rate.

A/D converter

Refer back to Fig. 1-2. The analog signal can be recreated by sending the binary contents of memory to a *digital-to-analog (D/A) converter.* The binary information is clocked out of memory at the same rate as the original signal was sampled. Figure 1-4 shows the output of the D/A converter. It can be seen that the waveform is not exactly the same as the original analog signal. It is a series of discrete steps. However, by using more steps, a much closer representation of the original signal can be achieved. Step size is determined by the number of binary digits (bits) used. The number of steps is found by raising 2 to the power of the number of bits. A 5-bit system provides

$$2^5 = 32 \text{ steps}$$

An 8-bit system would provide

$$2^8 = 256 \text{ steps}$$

D/A converter

EXAMPLE 1-1

An audio compact disk (CD) uses 16 bits to represent each sample of the signal. How many steps or volume levels are possible? Use the appropriate power of 2:

$$2^{16} = 65{,}536$$

This is easy to solve using a calculator with an x^y key. Press 2, then x^y, and then 16 followed by the = key.