This International Student Edition is for use outside of the U.S.

SIXTH EDITION

MICROELECTRONIC Circuit Design

McGraw Hill

Richard C. Jaeger | Travis N. Blalock | Benjamin J. Blalock

MICROELECTRONIC CIRCUIT DESIGN

SIXTH EDITION

MICROELECTRONIC CIRCUIT DESIGN

RICHARD C. JAEGER
Auburn University

TRAVIS N. BLALOCK
University of Virginia

BENJAMIN J. BLALOCK
University of Tennessee, Knoxville

Mc Graw Hill

MICROELECTRONIC CIRCUIT DESIGN

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 27 26 25 24 23 22

ISBN 978-1-260-59785-1
MHID 1-260-59785-7

Cover Image: *Maxim Marinkovskiy/Shutterstock*

mheducation.com/highered

TO

To Joan, my loving wife and life-long partner

—Richard C. Jaeger

In memory of my father, Professor Theron Vaughn Blalock, an inspiration to me and to the countless students whom he mentored both in electronic design and in life.

—Travis N. Blalock

To my family, for their love, support, and inspiration.

—Benjamin J. Blalock

BRIEF CONTENTS

CONTENTS

PART TWO
ANALOG ELECTRONICS 311

CHAPTER 6
INTRODUCTION TO AMPLIFIERS 313

CHAPTER 7
THE TRANSISTOR AS AN AMPLIFIER 352

CHAPTER 9

AMPLIFIER FREQUENCY RESPONSE 544

PART THREE
OPERATIONAL AMPLIFIERS AND FEEDBACK 647

CHAPTER 10
IDEAL OPERATIONAL AMPLIFIERS 649

CHAPTER 11
NONIDEAL OPERATIONAL AMPLIFIERS AND FEEDBACK AMPLIFIER STABILITY 683

CHAPTER 15

TRANSISTOR FEEDBACK AMPLIFIERS AND OSCILLATORS 1030

SUPPLEMENTAL CHAPTERS (E-Book Only)

DIGITAL ELECTRONICS

CHAPTER S6

INTRODUCTION TO DIGITAL ELECTRONICS S6-3

Electronics in Action

PREFACE

Through study of this text, the reader will develop a comprehensive understanding of the basic techniques of modern analog electronic circuit design. Even though most readers may not ultimately be engaged in the design of integrated circuits (ICs) themselves, a thorough understanding of the internal circuit structure of ICs is prerequisite to avoiding many pitfalls that prevent the effective and reliable application of integrated circuits in system design.

The writing integrates the authors' extensive industrial backgrounds in precision analog and digital design with their many years of experience in the classroom. A broad spectrum of topics is included, and material can easily be selected to satisfy either a two-semester or three-quarter sequence in electronics.

In order to reduce the length, cost, and weight of the text, the digital electronics chapters from earlier editions have been included as supplemental chapters in the e-book version of the textbook that is available in Connect.

IN THIS EDITION

This edition continues to update the material to achieve improved readability and accessibility to the student. In addition to general material updates, a number of specific changes have been included.

The five chapters of Part One have been reorganized to improve material flow. Chapter 4, "Bipolar Junction Transistors" now follows directly after the diode chapter, and "Field-Effect Transistors" becomes Chapter 5. A new low-power, low-voltage, and weak inversion thread begins in Part One. Chapter 5 specifically introduces the behavior and modeling of the FET in the moderate and weak inversion regions, and this thread continues throughout Parts Two and Three.

Other important elements include:

- At least 30 percent revised or new problems.
- Updated PowerPoint slides are available from the authors at www.JaegerBlalock.com or Connect.
- Popular digital features can be found through McGraw Hill Education's Connect platform, details of which can be found later in the Preface.
- The structured problem-solving approach continues throughout the examples.
- Popular Electronics in Action features have been revised and expanded to include IEEE Societies, Historical Development of SPICE, Body Sensor Networks, Jones Mixer, Advanced CMOS Technology, Fully Differential Amplifiers, and DACs and ADCs to name a few.

Chapter openers enhance the reader's understanding of historical developments in electronics. Design notes highlight important ideas that the circuit designer should remember. The Internet is viewed as an integral extension of the text.

Features of the book are outlined below.

- The Structured Problem-Solving Approach is used throughout the examples.
- Electronics in Action features in each chapter.
- Chapter openers highlighting developments in the field of electronics.
- Design Notes and emphasis on practical circuit design.
- Broad use of SPICE throughout the text, examples, and problems.
- Integrated treatment of device modeling in SPICE.
- Numerous Exercises, Examples, and Design Examples.
- Large number of problems.
- Integrated web materials.

Part Two consists of Chapters 6 through 9 and begins with an overview of general amplifier characteristics, followed by small-signal modeling of transistors and comprehensive discussion of classical single-stage amplifier design including frequency response.

The first three chapters of Part Three focus on ideal and nonideal operational amplifiers, including feedback and amplifier stability. The last three chapters concentrate on analog integrated circuit design and design techniques.

DESIGN

Design remains a difficult issue in educating engineers. The use of the well-defined problem-solving methodology presented in this text can significantly enhance the students ability to understand issues related to design. The design examples assist in building an understanding of the design process.

Methods for making design estimates and decisions are stressed throughout the analog portion of the text. Expressions for amplifier behavior are simplified beyond the standard hybrid-pi model expressions whenever appropriate. For example, the expression for the voltage gain of an amplifier in most texts is simply written as $|A_v| = g_m R_L$, which tends to hide the power supply voltage as the fundamental design variable. Rewriting this expression in approximate form as $g_m R_L \cong 10V_{CC}$ for the BJT, or $g_m R_L \cong V_{DD}$ for the FET, explicitly displays the dependence of amplifier design on the choice of power supply voltage and provides a simple first-order design estimate for the voltage gain of the common-emitter and common-source amplifiers. The gain advantage of the BJT stage is also clear. These approximation techniques and methods for performance estimation are included as often as possible. Comparisons and design tradeoffs between the properties of BJTs and FETs are included throughout Part Three.

Worst-case and Monte-Carlo analysis techniques are introduced at the end of the first chapter. These are not topics traditionally included in undergraduate courses. However, the ability to design circuits in the face of wide component tolerances and variations is a key component of electronic circuit design, and the design of circuits using standard components and tolerance assignment are discussed in examples and included in many problems.

PROBLEMS AND INSTRUCTOR SUPPORT

Specific design problems, computer problems, and SPICE problems are included at the end of each chapter. Design problems are indicated by , computer problems are indicated by , and SPICE problems are indicated by . The problems are keyed to the topics in the text with the more difficult or time-consuming problems indicated by * and **. An Instructor's Manual containing solutions to all the problems is available to instructors from the authors. In addition, the graphs and figures are available as PowerPoint files and can be retrieved on the Instructor's Resources section of Connect, along with various web materials referenced in the textbook for students. Instructor notes are available as PowerPoint slides.

To access the Instructor Resources through Connect, you must first contact your McGraw Hill Learning Technology Representative to obtain a password. If you do not know your McGraw Hill representative, please go to www.mhhe.com/rep, to find your representative.

Once you have your password, please go to connect.mheducation.com, and log in. Click on the course for which you are using *Microelectronic Circuit Design, 6e*. If you have not added a course, click "Add Course," and select "Engineering-Electrical and Computer" from the drop-down menu. Select this textbook and click "Next."

Once you have added the course, click on the "Library" link, and then click "Instructor Resources."

ACKNOWLEDGMENTS

We want to thank the large number of people who have had an impact on the material in this text and on its preparation. Our students have helped immensely in polishing the manuscript and have managed to survive the many revisions of the manuscript. Our department heads, J. D. Irwin and Mark Nelms of Auburn University, N. Sidiropoulos of the University of Virginia and Gregory Peterson of the University of Tennessee, have always been highly supportive of faculty efforts to develop improved texts.

We want to thank all reviewers, including the following:

Stanley Burns	*University of Minnesota, Duluth*
Numan Dogan	*North Carolina Agricultural and Technical State University*
Melinda Holtzman	*Portland State University*
Bradley Jackson	*California State University, Northridge*
Serhiy Levkov	*New Jersey Institute of Technology*
Jayne Wu (Jie Wu)	*The University of Tennessee, Knoxville*

We are also thankful for inspiration from the classic text *Applied Electronics* by J. F. Pierce and T. J. Paulus. Professor Travis Blalock Learned Electronics from Professor Pierce many years ago and still appreciates many of the analytical techniques employed in their long out-of-print text.

Those familiar with Professor Don Pederson's "Yellow Peril" will see its influence throughout this text. Shortly after Professor Jaeger became Professor Art

Brodersen's student at the University of Florida, he was fortunate to be given a copy of Pederson's book to study from cover to cover.

Finally, we want to thank the team at McGraw Hill, including Theresa Collins and Erin Kamm, Product Developers; Jane Mohr, Content Project Manager; Lisa Granger, Marketing Manager; and Sadika Rehman, Full-Service Project Manager.

In developing this text, we have attempted to integrate our industrial backgrounds in analog and digital design with many years of experience in the classroom. We hope we have at least succeeded to some extent. Constructive suggestions and comments will be appreciated.

Richard C. Jaeger
Auburn University

Travis N. Blalock
University of Virginia

Benjamin J. Blalock
University of Tennessee, Knoxville

CHAPTER-BY-CHAPTER SUMMARY

PART ONE—SOLID-STATE ELECTRONICS AND DEVICES

Chapter 1 provides a historical perspective on the field of electronics beginning with vacuum tubes and advancing to Tera-scale integration and its impact on the global economy. Chapter 1 also provides a classification of electronic signals and a review of some important tools from network analysis, including the ideal operational amplifier. Because developing a good problem-solving methodology is of such import to an engineer's career, the comprehensive Structured Problem Solving Approach is used to help students develop their problem solving skills. The structured approach is discussed in detail in the first chapter and used in the subsequent examples in the text. Component tolerances and variations play an extremely important role in practical circuit design, and Chapter 1 closes with introductions to tolerances, temperature coefficients, worst-case design, and Monte Carlo analysis.

Chapter 2 discusses semiconductor materials including the covalent-bond and energy-band models of semiconductors. The chapter includes material on intrinsic carrier density, electron and hole populations, *n*- and *p*-type material, and impurity doping. Mobility, resistivity, and carrier transport by both drift and diffusion are included as topics. Velocity saturation is discussed, as well as an introductory discussion of microelectronic fabrication.

Chapter 3 introduces the structure and *i-v* characteristics of solid-state diodes. Discussions of Schottky diodes, variable capacitance diodes, photo-diodes, solar cells, and LEDs are also included. This chapter introduces the concepts of device modeling and the use of different levels of modeling to achieve various approximations to reality. The SPICE model for the diode is discussed. The concepts of bias, operating point, and load-line are all introduced, and iterative mathematical solutions are also used to find the operating point with MATLAB and spreadsheets. Diode applications in rectifiers are discussed in detail and a discussion of the dynamic switching characteristics of diodes is also presented.

Chapter 4 introduces the bipolar junction transistor and presents a heuristic development of the transport (simplified Gummel-Poon) model of the BJT based upon superposition. The various regions of operation are discussed in detail. Common-emitter and common-base current gains are defined, and base transit-time, diffusion capacitance, and cutoff frequency are all discussed. Bipolar technology and physical structure are introduced. The four-resistor bias circuit is discussed in detail. The SPICE model for the BJT and SPICE model parameters are also discussed in Chapter 4.

Chapter 5 discusses MOS and junction field-effect transistors, starting with a qualitative description of the MOS capacitor. Models are developed for the FET *i-v* characteristics, and a complete discussion of the regions of operation of the device is presented. Body effect is included. MOS transistor performance limits—including scaling, cut-off frequency, and subthreshold conduction—are discussed as well as basic Λ-based layout methods. Biasing circuits and load-line analysis are presented. The concept of velocity saturation from Chapter 2 is reinforced with the addition of the unified MOS model of Rabaey and Chandrakasan to Chapter 5. FET SPICE models and model parameters are discussed in Chapter 5. In the 6th edition, the discussion of moderate and weak inversion is expanded, and a low voltage/weak inversion thread continues through the rest of the text.

PART TWO—ANALOG ELECTRONICS

Chapter 6 provides a succinct introduction to analog electronics. The concepts of voltage gain, current gain, and power gain are developed using two-port circuit models. Much care has been taken to be consistent in the use of the notation that defines these quantities as well as in the use of dc, ac, and total signal notation throughout the book. Bode plots are reviewed and amplifiers are classified by frequency response. MATLAB is utilized as a tool for producing Bode plots. SPICE simulation using built-in SPICE models is introduced.

Chapter 7 begins the general discussion of linear amplification using the BJT and FET as C-E and C-S amplifiers. Biasing for linear operation and the concept of small-signal modeling are both introduced, and small-signal models of the diode, BJT, and FET are all developed. The limits for small-signal operation are all carefully defined. The use of coupling and bypass capacitors and inductors to separate the ac and dc designs is explored. The important $10V_{CC}$ and V_{DD} design estimates for the voltage gain of the C-E and C-S amplifiers are introduced, and the role of the transistor's intrinsic gain in bounding circuit performance is discussed. The role of Q-point design on power dissipation and signal range is also introduced.

Chapter 8 proceeds with an in-depth comparison of the characteristics of single-transistor amplifiers, including small-signal amplitude limitations. Appropriate points for signal injection and extraction are identified, and amplifiers are classified as inverting amplifiers (C-E, C-S), noninverting amplifiers (C-B, C-G), and followers (C-C, C-D). The treatment of MOS and bipolar devices is merged from Chapter 8 on, and design tradeoffs between the use of the BJT and the FET in amplifier circuits is an important thread that is followed through all of Part Two. A detailed discussion of the design of coupling and bypass capacitors and the role of these capacitors in controlling the low frequency response of amplifiers appears in this chapter.

Chapter 9 discusses the frequency response of analog circuits. The behavior of each of the three categories of single-stage amplifiers (C-E/C-S, C-B/C-G, and C-C/C-D) is discussed in detail, and BJT behavior is contrasted with that of the FET. The frequency response of the transistor is discussed, and the high frequency, small-signal models are developed for both the BJT and FET. Miller multiplication is used to obtain estimates of the lower and upper cutoff frequencies of complex multistage amplifiers. Gain-bandwidth products and gain-bandwidth tradeoffs in design are discussed. Cascode amplifier frequency response, and tuned amplifiers are included in this chapter. The important short-circuit and open-circuit time-constant techniques for estimating the dominant low- and high-frequency poles are covered in detail.

Because of the renaissance and pervasive use of RF circuits, Chapter 9 includes an introductory section on RF amplifiers, including shunt peaked and tuned amplifiers. A discussion of gate resistance in FETs mirrors that of base resistance in the BJT. The discussion of the impact of the frequency-dependent current gain of the FET includes both the input and output impedances of the source follower configuration. Material on mixers includes passive and active single- and double-balanced mixers and the widely used Jones Mixer.

PART THREE—OPERATIONAL AMPLIFIERS AND FEEDBACK

Chapter 10 reviews classic ideal operational amplifier circuits that include the inverting, noninverting, summing, and difference amplifiers as well as the integrator, differentiator, and low-pass and high-pass filters.

Chapter 11 focuses on a comprehensive discussion of the characteristics and limitations of real operational amplifiers, including the effects of finite gain and input resistance, nonzero output resistance, input offset voltage, input bias and offset currents, output voltage and current limits, finite bandwidth, and common-mode rejection. A consistent loop-gain analysis approach is used to study the four classic feedback configurations, and Blackman's theorem is utilized to find input and output resistances of closed-loop amplifiers. The important successive voltage and current injection technique for finding loop-gain is included in Chapter 11. Stability of first-, second-, and third-order systems is discussed, and the concepts of phase and gain margin are introduced. Relationships between Nyquist and Bode techniques are explicitly discussed. A section concerning the relationship between phase margin and time domain response is included. The macro model concept is introduced and the discussion of SPICE simulation of op-amp circuits using various levels of models continues in Chapter 11.

Chapter 12 covers a wide range of operational amplifier applications that include multistage amplifiers, the instrumentation amplifier, and continuous time and discrete time active filters. Cascade amplifiers are investigated including a discussion of the bandwidth of multistage amplifiers. An introduction to D/A and A/D converters appears in this chapter. The Barkhausen criterion for oscillation are presented and followed by a discussion of op-amp-based sinusoidal oscillators. High frequency oscillators are discussed in Chapter 15. Nonlinear circuits applications including rectifiers, Schmitt triggers, and multivibrators conclude the material in Chapter 12.

Chapter 13 explores the design of multistage direct coupled amplifiers. An evolutionary approach to multistage op amp design is used. MOS and bipolar differential amplifiers are first introduced. Subsequent addition of a second gain stage and then an output stage convert the differential amplifiers into simple op amps. Class A, B, and AB operations are defined. Electronic current sources are designed and used for biasing of the basic operational amplifiers. Discussion of important FET-BJT design tradeoffs are included wherever appropriate. Additional low voltage/weak inversion problems have been added to Chapters 13, 14, and 15.

Chapter 14 introduces techniques that are of particular import in integrated circuit design. A variety of current mirror circuits are introduced and applied in bias circuits and as active loads in operational amplifiers. A wealth of circuits and analog design techniques are explored through the detailed analysis of the classic 741 operational amplifier. The Brokaw bandgap reference and Gilbert analog multiplier as well as the MOS weak inversion reference are introduced in Chapter 14.

Chapter 15 presents detailed examples of feedback as applied to transistor amplifier circuits. The loop-gain analysis approach introduced in Chapter 11 is used to find the closed-loop gain of various amplifiers, and Blackman's theorem is utilized to find input and output resistances of closed-loop amplifiers.

Amplifier stability is also discussed in Chapter 15, and Nyquist diagrams and Bode plots (with MATLAB) are used to explore the phase and gain margin of amplifiers. Basic single-pole op-amp compensation is discussed, and the unity gain-bandwidth product is related to amplifier slew rate. Design of op-amp compensation to achieve a desired phase margin is presented. The discussion of transistor oscillator circuits includes the classic Colpitts, Hartley, and negative G_m configurations. Crystal oscillators, ring oscillators and a discussion of positive feedback in flip-flops are also included.

The Digital Electronics chapters from the fifth edition are now included as supplemental chapters in the e-book version of this text, which is available to users of this edition through Connect.

Four Appendices include tables of standard component values (Appendix A), summary of the device models and sample SPICE parameters (Appendix B), review of two-port networks (Appendix C), and Physical Constants and Transistor Model Summary (Appendix D). Data sheets for representative solid-state devices and operational amplifiers are available via the Internet. A table in Appendix C helps relate various two-port parameters that often appear in specification sheets to the FET and BJT model parameters that appear in the text.

SUPPORT AT every step

Students: Get Learning that Fits You

Effective tools for efficient studying

Connect is designed to help you be more productive with simple, flexible, intuitive tools that maximize your study time and meet your individual learning needs. Get learning that works for you with Connect.

Study anytime, anywhere

Download the free ReadAnywhere app and access your online eBook, SmartBook 2.0, or Adaptive Learning Assignments when it's convenient, even if you're offline. And since the app automatically syncs with your Connect account, all of your work is available every time you open it. Find out more at **www.mheducation.com/readanywhere**

"I really liked this app—it made it easy to study when you don't have your text-book in front of you."

- Jordan Cunningham, Eastern Washington University

Calendar: owattaphotos/Getty Images

Everything you need in one place

Your Connect course has everything you need—whether reading on your digital eBook or completing assignments for class, Connect makes it easy to get your work done.

Learning for everyone

McGraw Hill works directly with Accessibility Services Departments and faculty to meet the learning needs of all students. Please contact your Accessibility Services Office and ask them to email accessibility@mheducation.com, or visit **www.mheducation.com/about/accessibility** for more information.

Top: Jenner Images/Getty Images, Left: Hero Images/Getty Images, Right: Hero Images/Getty Images

PART ONE

SOLID-STATE ELECTRONICS AND DEVICES

CHAPTER 1

INTRODUCTION TO ELECTRONICS

Chapter Outline

Chapter Goals

- Present a brief history of electronics
- Quantify the explosive development of integrated circuit technology
- Discuss initial classification of electronic signals
- Review important notational conventions and concepts from circuit theory
- Introduce methods for including tolerances in circuit analysis
- Present the problem-solving approach used in this text

Figure 1.1 John Bardeen, William Shockley, and Walter Brattain in Brattain's laboratory in 1948.
Reprinted with permission of Alcatel-Lucent USA Inc.

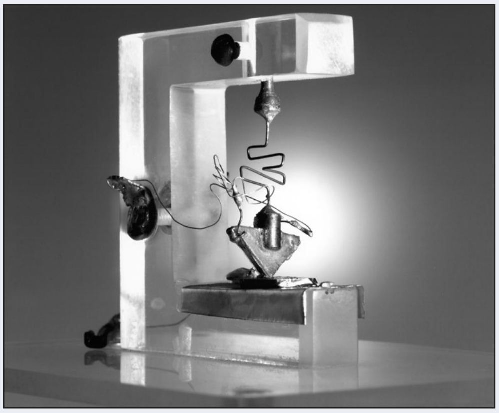

Figure 1.2 The first germanium bipolar transistor.
Reprinted with permission of Alcatel-Lucent USA Inc.

November 2022 is the 75th anniversary of the 1947 discovery of the bipolar transistor by John Bardeen and Walter Brattain at Bell Laboratories, a seminal event that marked the beginning of the semiconductor age (see Figs. 1.1 and 1.2). The invention of the transistor and the subsequent development of microelectronics have done more to shape the modern era than any other event. The transistor and microelectronics have reshaped how business is transacted, machines are designed, information moves, wars are fought, people interact, and countless other areas of our lives.

This textbook develops the basic operating principles and design techniques governing the behavior of the devices and circuits that form the backbone of much of the infrastructure of our modern world. This knowledge will enable students who aspire to design and create the next generation of this technological revolution to build a solid foundation for more advanced design courses. In addition, students who expect to work in some other technology area will learn material that will help them understand microelectronics, a technology that will continue to have impact on how their chosen field develops. This understanding will enable them to fully exploit microelectronics in their own technology area. Now let us return to our short history of the transistor.

After the discovery of the transistor, it was but a few months until William Shockley developed a theory that described the operation of the bipolar junction transistor.

Only 10 years later, in 1956, Bardeen, Brattain, and Shockley received the Nobel Prize in physics for the discovery of the transistor.

In June 1948 Bell Laboratories held a major press conference to announce the discovery. In 1952 Bell Laboratories, operating under legal consent decrees, made licenses for the transistor available for the modest fee of $25,000 plus future royalty payments. About this time, Gordon Teal, another member of the solid-state group, left Bell Laboratories to work on the transistor at Geophysical Services, Inc., which subsequently became Texas Instruments (TI). There he made the first silicon transistors, and TI marketed the first all-transistor radio. Another early licensee of the transistor was Tokyo Tsushin Kogyo, which became the Sony Company in 1955. Sony subsequently sold a transistor radio with a marketing strategy based on the idea that everyone could now have a personal radio; thus was launched the consumer market for transistors. A very interesting account of these and other developments can be found in [1, 2] and their references.

Activity in electronics began more than a century ago with the first radio transmissions in 1895 by Marconi, and these experiments were followed after only a few years by the invention of the first electronic amplifying device, the triode vacuum tube. In this period, electronics—loosely defined as the design and application of electron devices—has had such a significant impact on our lives that we often overlook just how pervasive electronics has really become. One measure of the degree of this impact can be found in the gross domestic product (GDP) of the world. In 2020 the world GDP was approximately U.S. $90 trillion, and of this total more than 15 percent was directly traceable to electronics [3–5].

We commonly encounter electronics in the form of cellular phones, radios, televisions, and audio equipment, but electronics can be found even in seemingly mundane appliances such as vacuum cleaners, washing machines, and refrigerators. Wherever one looks in industry, electronics is found. The corporate world obviously depends heavily on data processing systems to manage its operations. In fact, it is hard to see how the computer industry could have evolved without the use of its own products. In addition, the design process depends ever more heavily on computer-aided design (CAD) systems, and manufacturing relies on electronic systems for process control—in petroleum refining, automobile tire production, food processing, power generation, and so on.

1.1 A BRIEF HISTORY OF ELECTRONICS: FROM VACUUM TUBES TO GIGA-SCALE INTEGRATION

Because most of us have grown up with electronic products all around us, we often lose perspective of how far the industry has come in a relatively short time. At the beginning of the twentieth century, there were no commercial electron devices, and transistors were not invented until the late 1940s! Explosive growth was triggered by first the commercial availability of the bipolar transistor in the late 1950s, and then the realization of the integrated circuit (IC) in 1961. Since that time, signal processing using electron devices and electronic technology has become a pervasive force in our lives.

Table 1.1 lists a number of important milestones in the evolution of the field of electronics. The Age of Electronics began in the early 1900s with the invention of the first electronic two-terminal devices, called **diodes.** The **vacuum diode,** or diode **vacuum tube,** was invented by Fleming in 1904; in 1906 Pickard created a diode by forming a point contact to a silicon crystal. (Our study of electron devices begins with the introduction of the solid-state diode in Chapter 3.)

Deforest's invention of the three-element vacuum tube known as the **triode** was an extremely important milestone. The addition of a third element to a diode enabled electronic amplification to take place with good isolation between the input and output ports of the device.

TABLE 1.1
Milestones in Electronics

YEAR	EVENT
1874	Ferdinand Braun invents the solid-state rectifier.
1884	American Institute of Electrical Engineers (AIEE) formed.
1895	Marconi makes first radio transmissions.
1904	Fleming invents diode vacuum tube—Age of Electronics begins.
1906	Pickard creates solid-state point-contact diode (silicon).
1906	Deforest invents triode vacuum tube (audion).
1910–1911	"Reliable" tubes fabricated.
1912	Institute of Radio Engineers (IRE) founded.
1907–1927	First radio circuits developed from diodes and triodes.
1920	Armstrong invents super heterodyne receiver.
1925	TV demonstrated.
1925	Lilienfeld files patent application on the field-effect device.
1927–1936	Multigrid tubes developed.
1933	Armstrong invents FM modulation.
1935	Heil receives British patent on a field-effect device.
1940	Radar developed during World War II—TV in limited use.
1947	Bardeen, Brattain, and Shockley at Bell Laboratories invent bipolar transistors.
1950	First demonstration of color TV.
1952	Shockley describes the unipolar field-effect transistor.
1952	Commercial production of silicon bipolar transistors begins at Texas Instruments.
1952	Ian Ross and George Dacey demonstrate the junction field-effect transistor.
1956	Bardeen, Brattain, and Shockley receive Nobel Prize for invention of bipolar transistors.
1958	Integrated circuit developed simultaneously by Kilby at Texas Instruments and Noyce and Moore at Fairchild Semiconductor.
1961	First commercial digital IC available from Fairchild Semiconductor.
1963	AIEE and IRE merge to become the Institute of Electrical and Electronic Engineers (IEEE)
1967	First semiconductor RAM (64 bits) discussed at the IEEE International Solid-State Circuits Conference (ISSCC).
1968	First commercial IC operational amplifier—the µA709—introduced by Fairchild Semiconductor.
1970	One-transistor dynamic memory cell invented by Dennard at IBM.
1970	Low-loss optical fiber invented.
1971	4004 microprocessor introduced by Intel.
1972	First 8-bit microprocessor—the 8008—introduced by Intel.
1973	Martin Cooper demonstrated a prototype of Motorola's handheld mobile phone.
1974	First commercial 1-kilobit memory chip developed.
1974	8080 microprocessor introduced.
1978	First 16-bit microprocessor developed.
1984	Megabit memory chip introduced.
1985	Flash memory introduced at ISSCC.
1987	Erbium doped, laser-pumped optical fiber amplifiers demonstrated.
1995	Experimental gigabit memory chip presented at the IEEE ISSCC.
2000	Alferov, Kilby, and Kromer share the Nobel Prize in physics for optoelectronics, invention of the integrated circuit, and heterostructure devices, respectively.
2007	Fert and Grünberg share the Nobel Prize in physics for the discovery of giant magnetoresistance.
2009	Kao shares one-half of the 2009 Nobel Prize in physics for fiber optic communication using light with Boyle and Smith for invention of the Charge-Coupled Device (CCD).
2010	Geim and Novoaelov share the Nobel Prize in physics for groundbreaking experiments regarding the two-dimensional material graphene.
2014	Akasaki, Amano, and Nakamura share the Nobel Prize in physics for the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources.
2018	Ten billion transistor integrated circuit chip presented at ISSCC.
2019	Goodenough, Whittingham, and Yoshino share the Nobel Prize in chemistry for the development of lithium-ion batteries.

Silicon-based three-element devices now form the basis of virtually all electronic systems. Fabrication of tubes that could be used reliably in circuits followed the invention of the triode by a few years and enabled rapid circuit innovation. Amplifiers and oscillators were developed that significantly improved radio transmission and reception. Armstrong invented the super heterodyne receiver in 1920 and FM modulation in 1933. Electronics developed rapidly during World War II, with great advances in the field of radio communications and the development of radar. Although first demonstrated in 1930, television did not begin to come into widespread use until the 1950s.

An important event in electronics occurred in 1947, when John Bardeen, Walter Brattain, and William Shockley at Bell Telephone Laboratories invented the **bipolar transistor.**[1] Although field-effect devices had actually been conceived by Lilienfeld in 1925, Heil in 1935, and Shockley in 1952 [2], the technology to produce such devices on a commercial basis did not yet exist. Bipolar devices, however, were rapidly commercialized.

Then in 1958, the nearly simultaneous invention of the **integrated circuit (IC)** by Kilby at Texas Instruments and Noyce and Moore at Fairchild Semiconductor produced a new technology that would profoundly change our lives. The miniaturization achievable through IC technology made available complex electronic functions with high performance at low cost. The attendant characteristics of high reliability, low power, and small physical size and weight were additional important advantages.

In 2000, Jack St. Clair Kilby received a share of the Nobel Prize for the invention of the integrated circuit. In the mind of the authors, this was an exceptional event as it represented one of the first awards to an electronic technologist.

Most of us have had some experience with personal computers, and nowhere is the impact of the integrated circuit more evident than in the area of digital electronics. For example, 4-gigabit (Gb) dynamic memory chips, similar to those in Fig. 1.3(c), contain more than 4 billion transistors. A 128-Gb flash memory chip stores 2 or 3 bits per memory cell using multilevel storage techniques and has more than 17 billion transistors in the memory array alone, not counting address decoding and sensing circuitry. Creating this much memory using individual vacuum tubes [depicted in Fig. 1.3(a)] or even discrete transistors [shown in Fig. 1.3(b)] would be almost inconceivable (see Prob. 1.9).

Levels of Integration

The dramatic progress of integrated circuit miniaturization is shown graphically in Figs. 1.4 and 1.5. The complexities of memory chips and microprocessors have grown exponentially with time. In over four decades since 1970, the number of transistors on a microprocessor chip has increased by a factor of 10 million as depicted in Fig. 1.4. Similarly, memory density has grown by a factor of more than 10 million from a 64-bit chip in 1968 to the announcement of 32-Gb chip production in 2018.

Since the commercial introduction of the integrated circuit, these increases in density have been achieved through a continued reduction in the minimum line width, or **minimum feature size,** that can be defined on the surface of the integrated circuit (see Fig. 1.5). Today most corporate semiconductor laboratories around the world are actively working on deep submicron processes with feature sizes below 10 nm—less than one five-thousandth the diameter of a human hair.

As the miniaturization process has continued, a series of commonly used abbreviations has evolved to characterize the various levels of integration. Prior to the invention of the integrated circuit, electronic systems were implemented in discrete form. Early ICs, with fewer than

[1] The term **transistor** is said to have originated as a contraction of "transfer resistor," based on the voltage-controlled resistance of the characteristics of the MOS transistor.

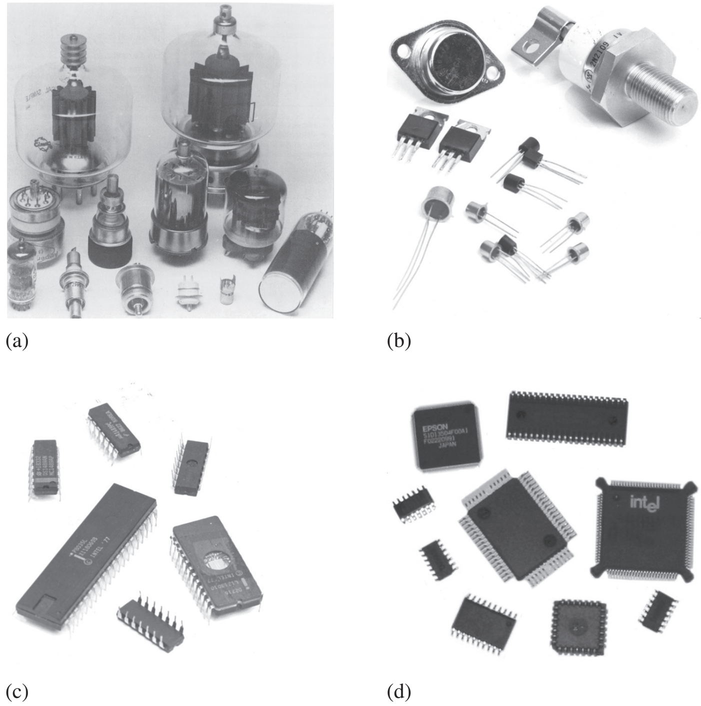

Figure 1.3 Comparison of (a) vacuum tubes, (b) individual transistors, (c) integrated circuits in dual-in-line packages (DIPs), and (d) ICs in surface mount packages.
Source: (a) Courtesy of ARRL Handbook for Radio Amateurs, 1992; (b, c, and d) Richard Jaeger

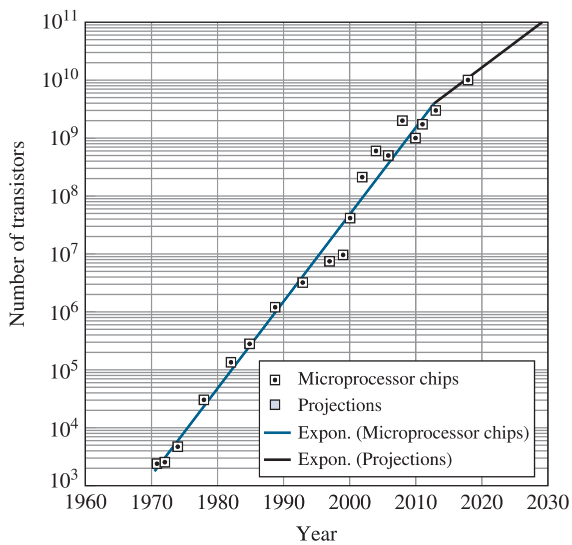

Figure 1.4 Microprocessor complexity versus time.

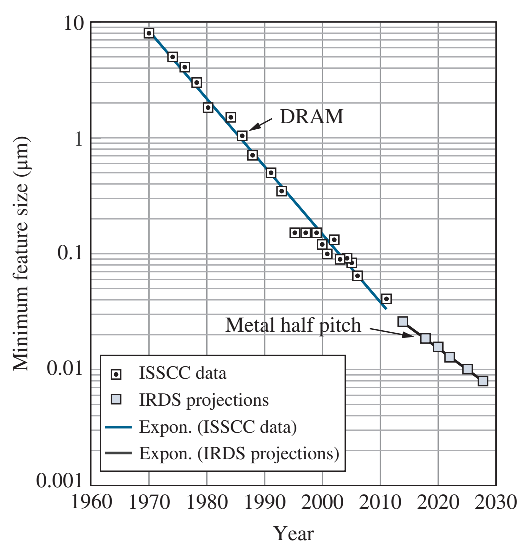

Figure 1.5 DRAM feature size versus year.

100 components, were characterized as **small-scale integration,** or **SSI.** As density increased, circuits became identified as **medium-scale integration** (**MSI,** 100–1000 components/chip), **large-scale integration** (**LSI,** 10^3–10^4 components/chip), and **very-large-scale integration** (**VLSI,** 10^4–10^9 components/chip). Today discussions focus on **giga-scale integration** (**GSI,** above 10^9 components/chip) and beyond.

ELECTRONICS IN ACTION

Cellular Phone Evolution

The impact of technology scaling is ever present in our daily lives. One example appears visually in the pictures of cellular phone evolution below. Early mobile phones were often large and had to be carried in a relatively large pouch (hence the term "bag phone"). The next generation of analog phones could easily fit in your hand, but they had poor battery life caused by their analog communications technology. Implementations of fourth- and fifth-generation digital cellular technology are considerably smaller and have much longer battery life. As IC density increased, additional functions such as high-function cameras, GPS, Bluetooth, and Wifi were integrated with the digital phone.

(a) (b) (c)

A decade of cellular phone evolution: (a) early Uniden "bag phone," (b) Nokia analog phone, and (c) Apple iPhone.
Source: (a and b) Richard Jaeger; (c) Yalcin Sonat/Shutterstock

Cell phones also represent excellent examples of the application of **mixed-signal** integrated circuits that contain both analog and digital circuitry on the same chip. ICs in the cell phone contain analog radio-frequency receiver and transmitter circuitry, analog-to-digital and digital-to-analog converters, CMOS logic and memory, power conversion circuits, imaging chips, accelerometers, and more.

1.2 CLASSIFICATION OF ELECTRONIC SIGNALS

The signals that electronic devices are designed to process can be classified into two broad categories: analog and digital. **Analog signals** can take on a continuous range of values, and thus represent continuously varying quantities; purely **digital signals** can appear at only one of several discrete levels. Examples of these types of signals are described in more detail in the next two subsections, along with the concepts of digital-to-analog and analog-to-digital conversion, which make possible the interface between the two systems.

1.2.1 DIGITAL SIGNALS

When we speak of digital electronics, we are most often referring to electronic processing of **binary digital signals,** or signals that can take on only one of two discrete amplitude levels as illustrated in Fig. 1.6. The status of binary systems can be represented by two symbols: a logical 1 is assigned to represent one level, and a logical 0 is assigned to the second level.[2] The two

[2] This assignment facilitates the use of Boolean algebra, reviewed in Chapter S6 of the eBook.

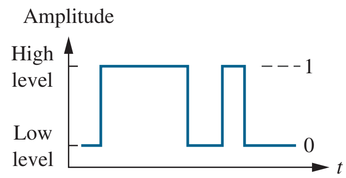

Figure 1.6 A time-varying binary digital signal.

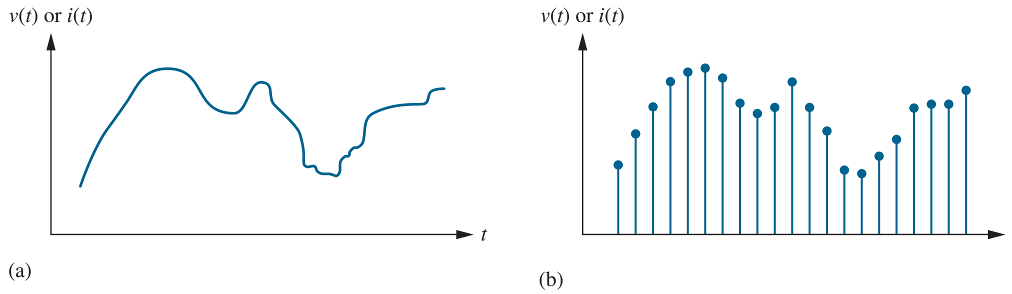

Figure 1.7 (a) A continuous analog signal; (b) sampled data version of signal in (a).

logic states generally correspond to two separate voltages—V_H and V_L—representing the high and low amplitude levels, and a number of voltage ranges are in common use. Although $V_H = 5$ V and $V_L = 0$ V represented the primary standard for many years, these have given way to lower voltage levels because of power consumption and semiconductor device limitations. Systems employing $V_H = 3.3$, down to 1 V or less with $V_L = 0$ V, are now used in many types of electronics.

However, binary voltage levels can also be negative or even bipolar. One high-performance logic family called ECL uses $V_H = -0.8$ V and $V_L = -2.0$ V, and the early standard RS-422 and RS-232 communication links between a small computer and its peripherals used $V_H = +12$ V and $V_L = -12$ V. In addition, the time-varying binary signal in Fig. 1.6 could equally well represent the amplitude of a current or that of an optical signal being transmitted down a fiber in an optical digital communication system. Recent USB and similar standards returned to the use of a single positive supply voltage.

Detailed discussion of logic circuits that were included in earlier editions can now be found in Chapters S6–S9 of the e-book. These include PMOS, NMOS, and CMOS logic,[3] which use field-effect transistors, and the TTL and ECL families, which are based on bipolar transistors.

1.2.2 ANALOG SIGNALS

Although quantities such as electronic charge and electron spin or the position of a switch are discrete, much of the physical world is really analog in nature. Our senses of vision, hearing, smell, taste, and touch are all analog processes. Analog signals directly represent variables such as temperature, humidity, pressure, light intensity, or sound—all of which may take on any value, typically within some finite range. In practice, classification of digital and analog signals is largely one of perception. If we look at a digital signal similar to the one in Fig. 1.6 with an oscilloscope, we find that it actually makes a continuous transition between the high and low levels. The signal cannot make truly abrupt transitions between two levels. Designers of high-speed digital systems soon realize that they are really dealing with analog signals. The time-varying voltage or current plotted in Fig. 1.7(a) could be the electrical representation of temperature, flow rate, or pressure versus time, or the continuous audio output from a microphone. Some analog transducers

[3] For now, let us accept these initials as proper names without further definition. The details of each of these circuits are developed in Chapters S6–S9 of the eBook.