THE ART OF ELECTRONICS

PAUL HOROWITZ
WINFIELD HILL

THIRD EDITION

The Art of Electronics

Third Edition

At long last, here is the thoroughly revised and updated, and long-anticipated, third edition of the hugely successful *The Art of Electronics*. Widely accepted as the best single authoritative text and reference on electronic circuit design, both analog and digital, the first two editions were translated into eight languages, and sold more than a million copies worldwide. The art of electronics is explained by stressing the methods actually used by circuit designers – a combination of some basic laws, rules of thumb, and a nonmathematical treatment that encourages understanding why and how a circuit works.

Paul Horowitz is a Research Professor of Physics and of Electrical Engineering at Harvard University, where in 1974 he originated the Laboratory Electronics course from which emerged *The Art of Electronics*. In addition to his work in circuit design and electronic instrumentation, his research interests have included observational astrophysics, x-ray and particle microscopy, and optical interferometry. He is one of the pioneers of the search for intelligent life beyond Earth (SETI). He is the author of some 200 scientific articles and reports, has consulted widely for industry and government, and is the designer of numerous scientific and photographic instruments.

Winfield Hill is by inclination an electronics circuit-design guru. After dropping out of the Chemical Physics graduate program at Harvard University, and obtaining an E.E. degree, he began his engineering career at Harvard's Electronics Design Center. After 7 years of learning electronics at Harvard he founded Sea Data Corporation, where he spent 16 years designing instruments for Physical Oceanography. In 1988 he was recruited by Edwin Land to join the Rowland Institute for Science. The institute subsequently merged with Harvard University in 2003. As director of the institute's Electronics Engineering Lab he has designed some 500 scientific instruments. Recent interests include high-voltage RF (to 15 kV), high-current pulsed electronics (to 1200 A), low-noise amplifiers (to sub-nV and pA), and MOSFET pulse generators.

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THE ART OF ELECTRONICS

Third Edition

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To Vida and Ava

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In Memoriam: Jim Williams, 1948–2011

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CONTENTS

LIST OF TABLES

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PREFACE TO THE FIRST EDITION

This volume is intended as an electronic circuit design textbook and reference book; it begins at a level suitable for those with no previous exposure to electronics and carries the reader through to a reasonable degree of proficiency in electronic circuit design. We have used a straightforward approach to the essential ideas of circuit design, coupled with an in-depth selection of topics. We have attempted to combine the pragmatic approach of the practicing physicist with the quantitative approach of the engineer, who wants a thoroughly evaluated circuit design.

This book evolved from a set of notes written to accompany a one-semester course in laboratory electronics at Harvard. That course has a varied enrollment – undergraduates picking up skills for their eventual work in science or industry, graduate students with a field of research clearly in mind, and advanced graduate students and postdoctoral researchers who suddenly find themselves hampered by their inability to "do electronics."

It soon became clear that existing textbooks were inadequate for such a course. Although there are excellent treatments of each electronics specialty, written for the planned sequence of a four-year engineering curriculum or for the practicing engineer, those books that attempt to address the whole field of electronics seem to suffer from excessive detail (the handbook syndrome), from oversimplification (the cookbook syndrome), or from poor balance of material. Much of the favorite pedagogy of beginning textbooks is quite unnecessary and, in fact, is not used by practicing engineers, while useful circuitry and methods of analysis in daily use by circuit designers lie hidden in application notes, engineering journals, and hard-to-get data books. In other words, there is a tendency among textbook writers to represent the theory, rather than the art, of electronics.

We collaborated in writing this book with the specific intention of combining the discipline of a circuit design engineer with the perspective of a practicing experimental physicist and teacher of electronics. Thus, the treatment in this book reflects our philosophy that electronics, as currently practiced, is basically a simple art, a combination of some basic laws, rules of thumb, and a large bag of tricks. For these reasons we have omitted entirely the usual discussions of solid-state physics, the *h*-parameter model of transistors, and complicated network theory, and reduced to a bare minimum the mention of load lines and the *s*-plane. The treatment is largely nonmathematical, with strong encouragement of circuit brainstorming and mental (or, at most, back-of-the-envelope) calculation of circuit values and performance.

In addition to the subjects usually treated in electronics books, we have included the following:

- an easy-to-use transistor model;
- extensive discussion of useful subcircuits, such as current sources and current mirrors;
- single-supply op-amp design;
- easy-to-understand discussions of topics on which practical design information is often difficult to find: op-amp frequency compensation, low-noise circuits, phase-locked loops, and precision linear design;
- simplified design of active filters, with tables and graphs;
- a section on noise, shielding, and grounding;
- a unique graphical method for streamlined low-noise amplifier analysis;
- a chapter on voltage references and regulators, including constant current supplies;
- a discussion of monostable multivibrators and their idiosyncrasies;
- a collection of digital logic pathology, and what to do about it;
- an extensive discussion of interfacing to logic, with emphasis on the new NMOS and PMOS LSI;
- a detailed discussion of A/D and D/A conversion techniques;
- a section on digital noise generation;
- a discussion of minicomputers and interfacing to data buses, with an introduction to assembly language;
- a chapter on microprocessors, with actual design examples and discussion – how to design them into instruments, and how to make them do what you want;
- a chapter on construction techniques: prototyping, printed circuit boards, instrument design;

- a simplified way to evaluate high-speed switching circuits;
- a chapter on scientific measurement and data processing: what you can measure and how accurately, and what to do with the data;
- bandwidth narrowing methods made clear: signal averaging, multichannel scaling, lock-in amplifiers, and pulse-height analysis;
- amusing collections of "bad circuits," and collections of "circuit ideas";
- useful appendixes on how to draw schematic diagrams, IC generic types, *LC* filter design, resistor values, oscilloscopes, mathematics review, and others;
- tables of diodes, transistors, FETs, op-amps, comparators, regulators, voltage references, microprocessors, and other devices, generally listing the characteristics of both the most popular and the best types.

Throughout we have adopted a philosophy of naming names, often comparing the characteristics of competing devices for use in any circuit, and the advantages of alternative circuit configurations. Example circuits are drawn with real device types, not black boxes. The overall intent is to bring the reader to the point of understanding clearly the choices one makes in designing a circuit – how to choose circuit configurations, device types, and parts values. The use of largely nonmathematical circuit design techniques does not result in circuits that cut corners or compromise performance or reliability. On the contrary, such techniques enhance one's understanding of the real choices and compromises faced in engineering a circuit and represent the best approach to good circuit design.

This book can be used for a full-year electronic circuit design course at the college level, with only a minimum mathematical prerequisite; namely, some acquaintance with trigonometric and exponential functions, and preferably a bit of differential calculus. (A short review of complex numbers and derivatives is included as an appendix.) If the less essential sections are omitted, it can serve as the text for a one-semester course (as it does at Harvard).

A separately available laboratory manual, *Laboratory Manual for the Art of Electronics* (Horowitz and Robinson, 1981), contains twenty-three lab exercises, together with reading and problem assignments keyed to the text.

To assist the reader in navigation, we have designated with open boxes in the margin those sections within each chapter that we feel can be safely passed over in an abbreviated reading. For a one-semester course it would probably be wise to omit, in addition, the materials of Chapter 5 (first half), 7, 12, 13, 14, and possibly 15, as explained in the introductory paragraphs of those chapters.

We would like to thank our colleagues for their thoughtful comments and assistance in the preparation of the manuscript, particularly Mike Aronson, Howard Berg, Dennis Crouse, Carol Davis, David Griesinger, John Hagen, Tom Hayes, Peter Horowitz, Bob Kline, Costas Papaliolios, Jay Sage, and Bill Vetterling. We are indebted to Eric Hieber and Jim Mobley, and to Rhona Johnson and Ken Werner of Cambridge University Press, for their imaginative and highly professional work.

Paul Horowitz
Winfield Hill
April 1980

PREFACE TO THE SECOND EDITION

Electronics, perhaps more than any other field of technology, has enjoyed an explosive development in the last four decades. Thus it was with some trepidation that we attempted, in 1980, to bring out a definitive volume teaching the art of the subject. By "art" we meant the kind of mastery that comes from an intimate familiarity with real circuits, actual devices, and the like, rather than the more abstract approach often favored in textbooks on electronics. Of course, in a rapidly evolving field, such a nuts-and-bolts approach has its hazards – most notably a frighteningly quick obsolescence.

The pace of electronics technology did not disappoint us! Hardly was the ink dry on the first edition before we felt foolish reading our words about "the classic [2Kbyte] 2716 EPROM. . . with a price tag of about $25." They're so classic you can't even get them anymore, having been replaced by EPROMs 64 times as large, and costing less than half the price! Thus a major element of this revision responds to improved devices and methods – completely rewritten chapters on microcomputers and microprocessors (using the IBM PC and the 68008) and substantially revised chapters on digital electronics (including PLDs, and the new HC and AC logic families), on op-amps and precision design (reflecting the availability of excellent FET-input op-amps), and on construction techniques (including CAD/CAM). Every table has been revised, some substantially; for example, in Table 4.1 (operational amplifiers) only 65% of the original 120 entries survived, with 135 new op-amps added.

We have used this opportunity to respond to readers' suggestions and to our own experiences using and teaching from the first edition. Thus we have rewritten the chapter on FETs (it was too complicated) and repositioned it before the chapter on op-amps (which are increasingly of FET construction). We have added a new chapter on low-power and micropower design (both analog and digital), a field both important and neglected. Most of the remaining chapters have been extensively revised. We have added many new tables, including A/D and D/A converters, digital logic components, and low-power devices, and throughout the book we have expanded the number of figures. The book now contains 78 tables (available separately as *The Horowitz and Hill Component Selection Tables*) and over 1000 figures.

Throughout the revision we have strived to retain the feeling of informality and easy access that made the first edition so successful and popular, both as reference and text. We are aware of the difficulty students often experience when approaching electronics for the first time: the field is densely interwoven, and there is no path of learning that takes you, by logical steps, from neophyte to broadly competent designer. Thus we have added extensive cross-referencing throughout the text; in addition, we have expanded the separate *Laboratory Manual* into a *Student Manual* (*Student Manual for The Art of Electronics*, by Thomas C. Hayes and Paul Horowitz), complete with additional worked examples of circuit designs, explanatory material, reading assignments, laboratory exercises, and solutions to selected problems. By offering a student supplement, we have been able to keep this volume concise and rich with detail, as requested by our many readers who use the volume primarily as a reference work.

We hope this new edition responds to all our readers' needs – both students and practicing engineers. We welcome suggestions and corrections, which should be addressed directly to Paul Horowitz, Physics Department, Harvard University, Cambridge, MA 02138.

In preparing this new edition, we are appreciative of the help we received from Mike Aronson and Brian Matthews (AOX, Inc.), John Greene (University of Cape Town), Jeremy Avigad and Tom Hayes (Harvard University), Peter Horowitz (EVI, Inc.), Don Stern, and Owen Walker. We thank Jim Mobley for his excellent copyediting, Sophia Prybylski and David Tranah of Cambridge University Press for their encouragement and professional dedication, and the never-sleeping typesetters at Rosenlaui Publishing Services, Inc. for their masterful composition in TEX.

Finally, in the spirit of modern jurisprudence, we remind you to read the legal notice here appended.

Paul Horowitz
Winfield Hill
March 1989

Legal notice

In this book we have attempted to teach the techniques of electronic design, using circuit examples and data that we believe to be accurate. However, the examples, data, and other information are intended solely as teaching aids and should not be used in any particular application without independent testing and verification by the person making the application. Independent testing and verification are especially important in any application in which incorrect functioning could result in personal injury or damage to property.

For these reasons, we make no warranties, express or implied, that the examples, data, or other information in this volume are free of error, that they are consistent with industry standards, or that they will meet the requirements for any particular application. THE AUTHORS AND PUBLISHER EXPRESSLY DISCLAIM THE IMPLIED WARRANTIES OF MERCHANTABILITY AND OF FITNESS FOR ANY PARTICULAR PURPOSE, even if the authors have been advised of a particular purpose, and even if a particular purpose is indicated in the book. The authors and publisher also disclaim all liability for direct, indirect, incidental, or consequential damages that result from any use of the examples, data, or other information in this book.

PREFACE TO THE THIRD EDITION

Moore's Law continues to assert itself, unabated, since the publication of the second edition a quarter century ago. In this new third (and final!) edition we have responded to this upheaval with major enhancements:

- an emphasis on devices and circuits for *A/D* and *D/A conversion* (Chapter 13), because embedded microcontrollers are everywhere
- illustration of specialized peripheral ICs for use with microcontrollers (Chapter 15)
- detailed discussions of logic family choices, and of interfacing logic signals to the real world (Chapters 10 and 12)
- greatly expanded treatment of important topics in the essential analog portion of instrument design:
  - precision circuit design (Chapter 5)
  - low-noise design (Chapter 8)
  - power switching (Chapters 3, 9, and 12)
  - power conversion (Chapter 9)

And we have added many entirely new topics, including:

- digital audio and video (including cable and satellite TV)
- transmission lines
- circuit simulation with SPICE
- transimpedance amplifiers
- depletion-mode MOSFETs
- protected MOSFETs
- high-side drivers
- quartz crystal properties and oscillators
- a full exploration of JFETs
- high-voltage regulators
- optoelectronics
- power logic registers
- delta–sigma converters
- precision multislope conversion
- memory technologies
- serial buses
- illustrative "Designs by the Masters"

In this new edition we have responded, also, to the reality that previous editions have been enthusiastically embraced by the community of practicing circuit designers, even though *The Art of Electronics* (now 35 years in print) originated as a course textbook. So we've continued the "how *we* do it" approach to circuit design; and we've expanded the depth of treatment, while (we hope) retaining the easy access and explanation of basics. At the same time we have split off some of the specifically course-related teaching and lab material into a separate *Learning the Art of Electronics* volume, a substantial expansion of the previous edition's companion *Student Manual for The Art of Electronics*.[1]

Digital oscilloscopes have made it easy to capture, annotate, and combine measured waveforms, a capability we have exploited by including some 90 'scope screenshots illustrating the behavior of working circuits. Along with those doses of reality, we have included (in tables and graphs) substantial quantities of highly useful measured data – such as transistor noise and gain characteristics (e_n, i_n, $r_{bb'}$; h_{fe}, g_m, g_{oss}), analog switch characteristics (R_{ON}, Q_{inj}, capacitance), op-amp input and output characteristics (e_n and i_n over frequency, input common-mode range, output swing, auto-zero recovery, distortion, available packages), and approximate prices (!) – the sort of data often buried or omitted in datasheets but which you need (and don't have the time to measure) when designing circuits.

We've worked diligently, over the 20 years it has taken to prepare this edition, to include important circuit design information, in the form of some 350 graphs, 50 photographs, and 87 tables (listing more than 1900 active components), the last enabling intelligent choice of circuit components by listing essential characteristics (both specified and measured) of available parts.

Because of the significant expansion of topics and depth of detail, we've had to leave behind some topics that were treated in the second edition,[2] notwithstanding the use of larger pages, more compact fonts, and most figures sized to fit in a single column. Some additional related material that we had hoped to include in this volume (on real-world properties of components, and advanced topics in BJTs, FETs, op-amps, and power control) will instead be published in a forthcoming companion volume, *The Art*

[1] Both by Hayes, T. and Horowitz, P., Cambridge University Press, 1989 and 2016.

[2] Which, however, will continue to be available as an e-book.

of Electronics: The x-Chapters. References in this volume to those x-chapter sections and figures are set in italics. A newly updated `artofelectronics.com` website will provide a home for a continuation of the previous edition's collections of *Circuit ideas* and *Bad circuits*; it is our hope that it will become a community, also, for a lively electronic circuit forum.

As always, we welcome corrections and suggestions (and, of course, fan mail), which can be sent to horowitz@physics.harvard.edu or to hill@rowland.harvard.edu.

With gratitude. Where to start, in thanking our invaluable colleagues? Surely topping the list is David Tranah, our indefatigable editor at the Cambridge University Press mother-ship, our linchpin, helpful LaTeXpert, wise advisor of all things bookish, and (would you believe?) *compositor*! This guy slogged through 1,905 pages of marked-up text, retrofitting the LaTeX source files with corrections from multiple personalities, then entering a few thousand index entries, and making it all work with its 1,500+ linked figures and tables. And then putting up with a couple of fussy authors. We are totally indebted to David. We owe him a pint of ale.

We are grateful to Jim Macarthur, circuit designer extraordinaire, for his careful reading of chapter drafts, and invariably helpful suggestions for improvement; we adopted every one. Our colleague Peter Lu taught us the delights of Adobe Illustrator, and appeared at a moment's notice when we went off the rails; the book's figures are testament to the quality of his tutoring. And our always-entertaining colleague Jason Gallicchio generously contributed his master Mathematica talents to reveal graphically the properties of delta–sigma conversion, nonlinear control, filter functions; he left his mark, also, in the microcontroller chapter, contributing both wisdom and code.

For their many helpful contributions we thank Bob Adams, Mike Burns, Steve Cerwin, Jesse Colman, Michael Covington, Doug Doskocil, Jon Hagen, Tom Hayes, Phil Hobbs, Peter Horowitz, George Kontopidis, Maggie McFee, Curtis Mead, Ali Mehmed, Angel Peterchev, Jim Phillips, Marco Sartore, Andrew Speck, Jim Thompson, Jim van Zee, GuYeon Wei, John Willison, Jonathan Wolff, John Woodgate, and Woody Yang. We thank also others whom (we're sure) we've here overlooked, with apologies for the omission. Additional contributors to the book's content (circuits, inspired web-based tools, unusual measurements, etc., from the likes of Uwe Beis, Tom Bruhns, and John Larkin) are referenced throughout the book in the relevant text.

Simon Capelin has kept us out of the doldrums with his unflagging encouragement and his apparent inability to scold us for missed deadlines (our contract called for delivery of the finished manuscript in December. . . of *1994!* We're only 20 years late). In the production chain we are indebted to our project manager Peggy Rote, our copy editor Vicki Danahy, and a cast of unnamed graphic artists who converted our pencil circuit sketches into beautiful vector graphics.

We remember fondly our late colleague and friend Jim Williams for wonderful insider stories of circuit failures and circuit conquests, and for his take-no-prisoners approach to precision circuit design. His no-bullshit attitude is a model for us all.

And finally, we are forever indebted to our loving, supportive, and ever-tolerant spouses Vida and Ava, who suffered through decades of abandonment as we obsessed over every detail of our second encore.

A note on the tools. Tables were assembled in Microsoft Excel, and graphical data was plotted with Igor Pro; both were then beautified with Adobe Illustrator, with text and annotations in the sans-serif Helvetica Neue LT typeface. Oscilloscope screenshots are from our trusty Tektronix TDS3044 and 3054 "lunchboxes," taken to finishing school in Illustrator, by way of Photoshop. The photographs in the book were taken primarily with two cameras: a Calumet Horseman 6×9 cm view camera with a 105 mm Schneider Symmar $f/5.6$ lens and Kodak Plus-X 120 roll film (developed in Microdol-X 1:3 at 75°F and digitized with a Mamiya multiformat scanner), and a Canon 5D with a Scheimpflug[3]-enabling 90 mm tilt-shift lens. The authors composed the manuscript in LaTeX, using the PCTeX software from Personal TeX, Incorporated. The text is set in the Times New Roman and Helvetica typefaces, the former dating from 1931,[4] the latter designed in 1957 by Max Miedinger.

Paul Horowitz
Winfield Hill
January 2015
Cambridge, Massachusetts

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[3] What's *that*? Google it!

[4] Developed in response to a criticism of the antiquated typeface in *The Times* (London).

Legal Notice Addendum

In addition to the Legal Notice appended to the Preface to the Second Edition, we also make no representation regarding whether use of the examples, data, or other information in this volume might infringe others' intellectual property rights, including US and foreign patents. It is the reader's sole responsibility to ensure that he or she is not infringing any intellectual property rights, even for use which is considered to be experimental in nature. By using any of the examples, data, or other information in this volume, the reader has agreed to assume all liability for any damages arising from or relating to such use, regardless of whether such liability is based on intellectual property or any other cause of action, and regardless of whether the damages are direct, indirect, incidental, consequential, or any other type of damage. The authors and publisher disclaim any such liability.

FOUNDATIONS

CHAPTER 1

1.1 Introduction

The field of electronics is one of the great success stories of the 20th century. From the crude spark-gap transmitters and "cat's-whisker" detectors at its beginning, the first half-century brought an era of vacuum-tube electronics that developed considerable sophistication and found ready application in areas such as communications, navigation, instrumentation, control, and computation. The latter half-century brought "solid-state" electronics – first as discrete transistors, then as magnificent arrays of them within "integrated circuits" (ICs) – in a flood of stunning advances that shows no sign of abating. Compact and inexpensive consumer products now routinely contain many millions of transistors in VLSI (very large-scale integration) chips, combined with elegant optoelectronics (displays, lasers, and so on); they can process sounds, images, and data, and (for example) permit wireless networking and shirt-pocket access to the pooled capabilities of the Internet. Perhaps as noteworthy is the pleasant trend toward increased performance per dollar.[1] The cost of an electronic microcircuit routinely decreases to a fraction of its initial cost as the manufacturing process is perfected (see Figure 10.87 for an example). In fact, it is often the case that the panel controls and cabinet hardware of an instrument cost more than the electronics inside.

On reading of these exciting new developments in electronics, you may get the impression that you should be able to construct powerful, elegant, yet inexpensive, little gadgets to do almost any conceivable task – all you need to know is how all these miracle devices work. If you've had that feeling, this book is for you. In it we have attempted to convey the excitement and know-how of the subject of electronics.

In this chapter we begin the study of the laws, rules of thumb, and tricks that constitute the art of electronics as we see it. It is necessary to begin at the beginning – with talk of voltage, current, power, and the components that make up electronic circuits. Because you can't touch, see, smell, or hear electricity, there will be a certain amount of abstraction (particularly in the first chapter), as well as some dependence on such visualizing instruments as oscilloscopes and voltmeters. In many ways the first chapter is also the most mathematical, in spite of our efforts to keep mathematics to a minimum in order to foster a good intuitive understanding of circuit design and behavior.

In this new edition we've included some intuition-aiding approximations that our students have found helpful. And, by introducing one or two "active" components ahead of their time, we're able to jump directly into some applications that are usually impossible in a traditional textbook "passive electronics" chapter; this will keep things interesting, and even exciting.

Once we have considered the foundations of electronics, we will quickly get into the active circuits (amplifiers, oscillators, logic circuits, etc.) that make electronics the exciting field it is. The reader with some background in electronics may wish to skip over this chapter, since it assumes no prior knowledge of electronics. Further generalizations at this time would be pointless, so let's just dive right in.

1.2 Voltage, current, and resistance

1.2.1 Voltage and current

There are two quantities that we like to keep track of in electronic circuits: voltage and current. These are usually changing with time; otherwise nothing interesting is happening.

Voltage (symbol V or sometimes E). Officially, the voltage between two points is the cost in energy (work done) required to move a unit of positive charge from the more negative point (lower potential) to the more positive point (higher potential). Equivalently, it is the energy released when a unit charge moves "downhill" from the higher potential to the lower.[2] Voltage is also called

[1] A mid-century computer (the IBM 650) cost $300,000, weighed 2.7 tons, and contained 126 lamps on its control panel; in an amusing reversal, a contemporary energy-efficient lamp contains a computer of greater capability *within its base*, and costs about $10.

[2] These are the *definitions*, but hardly the way circuit designers think of voltage. With time, you'll develop a good intuitive sense of what voltage really is, in an electronic circuit. Roughly (*very* roughly) speaking, voltages are what you apply to cause currents to flow.

potential difference or *electromotive force* (EMF). The unit of measure is the *volt*, with voltages usually expressed in volts (V), kilovolts ($1\,\text{kV} = 10^3\,\text{V}$), millivolts ($1\,\text{mV} = 10^{-3}\,\text{V}$), or microvolts ($1\,\mu\text{V} = 10^{-6}\,\text{V}$) (see the box on prefixes). A joule (J) of work is done in moving a coulomb (C) of charge through a potential difference of 1 V. (The coulomb is the unit of electric charge, and it equals the charge of approximately 6×10^{18} electrons.) For reasons that will become clear later, the opportunities to talk about nanovolts ($1\,\text{nV} = 10^{-9}\,\text{V}$) and megavolts ($1\,\text{MV} = 10^6\,\text{V}$) are rare.

Current (symbol I). Current is the rate of flow of electric charge past a point. The unit of measure is the ampere, or amp, with currents usually expressed in amperes (A), milliamperes ($1\,\text{mA} = 10^{-3}\,\text{A}$), microamperes ($1\,\mu\text{A} = 10^{-6}\,\text{A}$), nanoamperes ($1\,\text{nA} = 10^{-9}\,\text{A}$), or occasionally picoamperes ($1\,\text{pA} = 10^{-12}\,\text{A}$). A current of 1 amp equals a flow of 1 coulomb of charge per second. By convention, current in a circuit is considered to flow from a more positive point to a more negative point, even though the actual electron flow is in the opposite direction.

Important: from these definitions you can see that currents flow *through* things, and voltages are applied (or appear) *across* things. So you've got to say it right: always refer to the voltage *between* two points or *across* two points in a circuit. Always refer to current *through* a device or connection in a circuit.

To say something like "the voltage through a resistor ..." is nonsense. However, we do frequently speak of the voltage *at a point* in a circuit. This is always understood to mean the voltage between that point and "ground," a common point in the circuit that everyone seems to know about. Soon you will, too.

We *generate* voltages by doing work on charges in devices such as batteries (conversion of electrochemical energy), generators (conversion of mechanical energy by magnetic forces), solar cells (photovoltaic conversion of the energy of photons), etc. We *get* currents by placing voltages across things.

At this point you may well wonder how to "see" voltages and currents. The single most useful electronic instrument is the oscilloscope, which allows you to look at voltages (or occasionally currents) in a circuit as a function of time.[3] We will deal with oscilloscopes, and also voltmeters, when we discuss signals shortly; for a preview see Appendix O, and the multimeter box later in this chapter.

[3] It has been said that engineers in other disciplines are envious of electrical engineers, because we have such a splendid visualization tool.

In real circuits we connect things together with wires (metallic conductors), each of which has the same voltage on it everywhere (with respect to ground, say).[4] We mention this now so that you will realize that an actual circuit doesn't have to look like its schematic diagram, because wires can be rearranged.

Here are some simple rules about voltage and current:

1. The sum of the currents into a point in a circuit equals the sum of the currents out (conservation of charge). This is sometimes called Kirchhoff's current law (KCL). Engineers like to refer to such a point as a *node*. It follows that, for a series circuit (a bunch of two-terminal things all connected end-to-end), the current is the same everywhere.

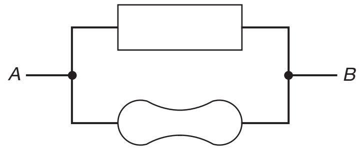

Figure 1.1. Parallel connection.

2. Things hooked in parallel (Figure 1.1) have the same voltage across them. Restated, the sum of the "voltage drops" from A to B via one path through a circuit equals the sum by any other route, and is simply the voltage between A and B. Another way to say it is that the sum of the voltage drops around any closed circuit is zero. This is Kirchhoff's voltage law (KVL).
3. The power (energy per unit time) consumed by a circuit device is

$$P = VI \tag{1.1}$$

This is simply (energy/charge) $\times$ (charge/time). For V in volts and I in amps, P comes out in watts. A watt is a joule per second ($1\text{W} = 1\,\text{J/s}$). So, for example, the current flowing through a 60W lightbulb running on 120 V is 0.5 A.

Power goes into heat (usually), or sometimes mechanical work (motors), radiated energy (lamps, transmitters), or stored energy (batteries, capacitors, inductors). Managing the heat load in a complicated system (e.g., a large computer, in which many kilowatts of electrical energy are converted to heat, with the energetically insignificant byproduct of a few pages of computational results) can be a crucial part of the system design.

[4] In the domain of high frequencies or low impedances, that isn't strictly true, and we will have more to say about this later, and in Chapter *1x*. For now, it's a good approximation.

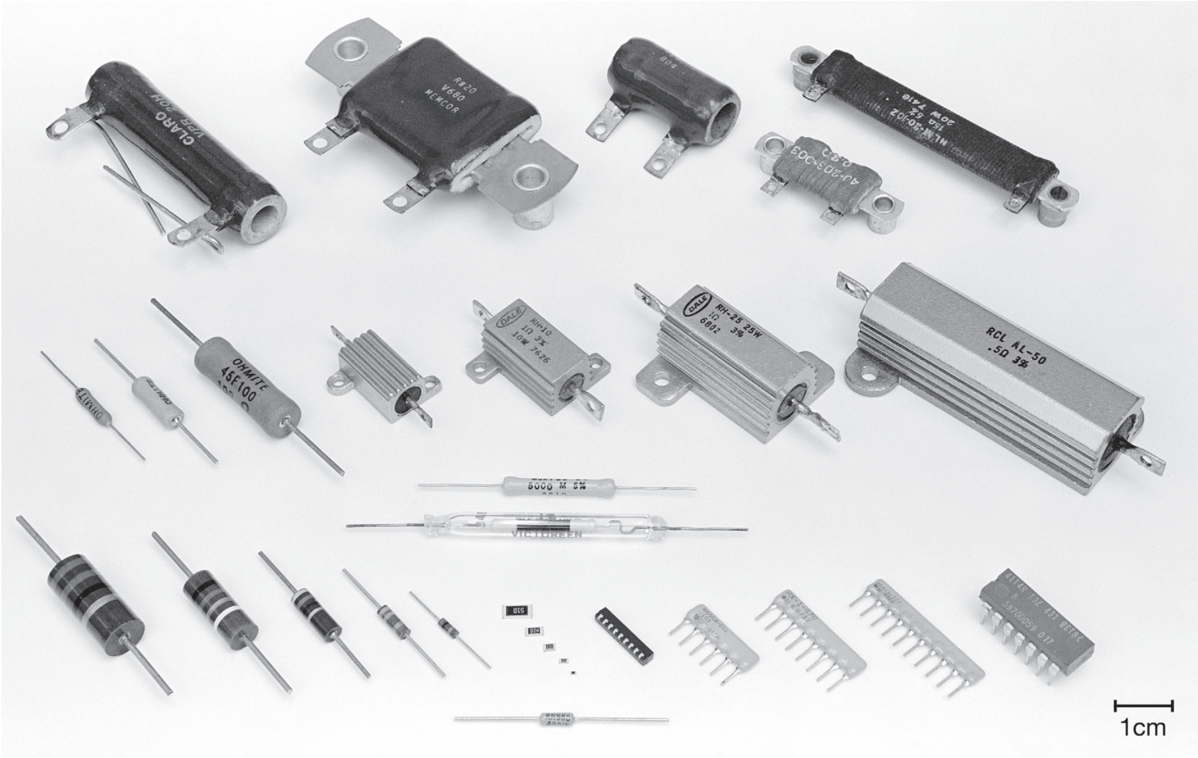

Figure 1.2. A selection of common resistor types. Top row, left to right (wirewound ceramic power resistors): 20W vitreous enamel with leads, 20W with mounting studs, 30W vitreous enamel, 5W and 20W with mounting studs. Middle row (wirewound power resistors): 1W, 3W, and 5W axial ceramic; 5W, 10W, 25W, and 50W conduction-cooled ("Dale-type"). Bottom row: 2W, 1W, $\frac{1}{2}$W, $\frac{1}{4}$W, and $\frac{1}{8}$W carbon composition; surface-mount thick-film (2010, 1206, 0805, 0603, and 0402 sizes); surface-mount resistor array; 6-, 8-, and 10-pin single in-line package arrays; dual in-line package array. The resistor at bottom is the ubiquitous RN55D $\frac{1}{4}$W, 1% metal-film type; and the pair of resistors above are Victoreen high-resistance types (glass, 2 GΩ; ceramic, 5 GΩ).

Soon, when we deal with periodically varying voltages and currents, we will have to generalize the simple equation $P = VI$ to deal with *average* power, but it's correct as a statement of *instantaneous* power just as it stands.

Incidentally, don't call current "amperage"; that's strictly bush league.[5] The same caution will apply to the term "ohmage"[6] when we get to resistance in the next section.

1.2.2 Relationship between voltage and current: resistors

This is a long and interesting story. It is the heart of electronics. Crudely speaking, the name of the game is to make and use gadgets that have interesting and useful I-versus-V characteristics. Resistors (I simply proportional to V), capacitors (I proportional to rate of change of V), diodes (I flows in only one direction), thermistors (temperature-dependent resistor), photoresistors (light-dependent resistor), strain gauges (strain-dependent resistor), etc., are examples. Perhaps more interesting still are *three-terminal* devices, such as transistors, in which the current that can flow between a pair of terminals is controlled by the voltage applied to a third terminal. We will gradually get into some of these exotic devices; for now, we will start with the most mundane (and most widely used) circuit element, the resistor (Figure 1.3).

Figure 1.3. Resistor.

[5] Unless you're a power engineer working with giant 13 kV transformers and the like – those guys are allowed to say amperage.

[6] ...also, Dude, "ohmage" is not the preferred nomenclature: *resistance*, please.

A. Resistance and resistors

It is an interesting fact that the current through a metallic conductor (or other partially conducting material) is proportional to the voltage across it. (In the case of wire

PREFIXES

Multiple	*Prefix*	*Symbol*	*Derivation*
10^{24}	yotta	Y	end-1 of Latin alphabet, hint of Greek *iota*
10^{21}	zetta	Z	end of Latin alphabet, hint of Greek *zeta*
10^{18}	exa	E	Greek *hexa* (six: power of 1000)
10^{15}	peta	P	Greek *penta* (five: power of 1000)
10^{12}	tera	T	Greek *teras* (monster)
10^{9}	giga	G	Greek *gigas* (giant)
10^{6}	mega	M	Greek *megas* (great)
10^{3}	kilo	k	Greek *khilioi* (thousand)
10^{-3}	milli	m	Latin *milli* (thousand)
10^{-6}	micro	μ	Greek *mikros* (small)
10^{-9}	nano	n	Greek *nanos* (dwarf)
10^{-12}	pico	p	from Italian/Spanish *piccolo/pico* (small)
10^{-15}	femto	f	Danish/Norwegian *femten* (fifteen)
10^{-18}	atto	a	Danish/Norwegian *atten* (eighteen)
10^{-21}	zepto	z	end of Latin alphabet, mirrors *zetta*
10^{-24}	yocto	y	end-1 of Latin alphabet, mirrors *yotta*

These prefixes are universally used to scale units in science and engineering. Their etymological derivations are a matter of some controversy and should not be considered historically reliable. When abbreviating a unit with a prefix, the symbol for the unit follows the prefix without space. Be careful about uppercase and lowercase letters (especially m and M) in both prefix and unit: 1 mW is a milliwatt, or one-thousandth of a watt; 1 MHz is a megahertz or 1 million hertz. In general, units are spelled with lowercase letters, even when they are derived from proper names. The unit name is not capitalized when it is spelled out and used with a prefix, only when abbreviated. Thus: hertz and kilohertz, but Hz and kHz; watt, milliwatt, and megawatt, but W, mW, and MW.

conductors used in circuits, we usually choose a thick-enough gauge of wire so that these "voltage drops" will be negligible.) This is by no means a universal law for all objects. For instance, the current through a neon bulb is a highly nonlinear function of the applied voltage (it is zero up to a critical voltage, at which point it rises dramatically). The same goes for a variety of interesting special devices – diodes, transistors, lightbulbs, etc. (If you are interested in understanding why metallic conductors behave this way, read §§4.4–4.5 in Purcell and Morin's splendid text *Electricity and Magnetism*).

A resistor is made out of some conducting stuff (carbon, or a thin metal or carbon film, or wire of poor conductivity), with a wire or contacts at each end. It is characterized by its resistance:

$$R = V/I; \tag{1.2}$$

R is in ohms for V in volts and I in amps. This is known as Ohm's law. Typical resistors of the most frequently used type (metal-oxide film, metal film, or carbon film) come in values from 1 ohm (1 Ω) to about 10 megohms (10 MΩ). Resistors are also characterized by how much power they can safely dissipate (the most commonly used ones are rated at 1/4 or 1/8 W), their physical size,[7] and by other parameters such as tolerance (accuracy), temperature coefficient, noise, voltage coefficient (the extent to which R depends on applied V), stability with time, inductance, etc. See the box on resistors, Chapter *1x*, and Appendix C for further details. Figure 1.2 shows a collection of resistors, with most of the available morphologies represented.

Roughly speaking, resistors are used to convert a

[7] The sizes of *chip resistors* and other components intended for surface mounting are specified by a four-digit size code, in which each pair of digits specifies a dimension in units of 0.010″ (0.25 mm). For example, an 0805 size resistor is 2 mm×1.25 mm, or 80 mils×50 mils (1 mil is 0.001″); the height must be separately specified. To add confusion to this simple scheme, the four-digit size code may instead be *metric* (sometimes without saying so!), in units of 0.1 mm: thus an "0805" (English) is also a "2012" (metric).

RESISTORS

Resistors are truly ubiquitous. There are almost as many types as there are applications. Resistors are used in amplifiers as loads for active devices, in bias networks, and as feedback elements. In combination with capacitors they establish time constants and act as filters. They are used to set operating currents and signal levels. Resistors are used in power circuits to reduce voltages by dissipating power, to measure currents, and to discharge capacitors after power is removed. They are used in precision circuits to establish currents, to provide accurate voltage ratios, and to set precise gain values. In logic circuits they act as bus and line terminators and as "pullup" and "pull-down" resistors. In high-voltage circuits they are used to measure voltages and to equalize leakage currents among diodes or capacitors connected in series. In radiofrequency (RF) circuits they set the bandwidth of resonant circuits, and they are even used as coil forms for inductors.

Resistors are available with resistances from 0.0002 Ω through 10^{12} Ω, standard power ratings from 1/8 watt through 250 watts, and accuracies from 0.005% through 20%. Resistors can be made from metal films, metal-oxide films, or carbon films; from carbon-composition or ceramic-composition moldings; from metal foil or metal wire wound on a form; or from semiconductor elements similar to field-effect transistors (FETs). The most commonly used resistor type is formed from a carbon, metal, or oxide film, and comes in two widely used "packages": the cylindrical *axial-lead* type (typified by the generic RN55D 1% 1/4 W metal-film resistor),[8] and the much smaller *surface-mount* "chip resistor." These common types come in 5%, 2%, and 1% tolerances, in a standard set of values ranging from 1 Ω to 10 MΩ. The 1% types have 96 values per decade, whereas the 2% and 5% types have 48 and 24 values per decade (see Appendix C). Figure 1.2 illustrates most of the common resistor packages.

Resistors are so easy to use and well behaved that they're often taken for granted. They're not perfect, though, and you should be aware of some of their limitations so that you won't be surprised someday. The principal defects are variations in resistance with temperature, voltage, time, and humidity. Other defects relate to inductance (which may be serious at high frequencies), the development of thermal hot spots in power applications, or electrical noise generation in low-noise amplifiers. We treat these in the advanced Chapter *1x*.

voltage to a current, and vice versa. This may sound awfully trite, but you will soon see what we mean.

B. Resistors in series and parallel

From the definition of *R*, some simple results follow:

1. The resistance of two resistors in series (Figure 1.4) is

$$R = R_1 + R_2. \tag{1.3}$$

   By putting resistors in series, you always get a *larger* resistor.

2. The resistance of two resistors in parallel (Figure 1.5) is

$$R = \frac{R_1 R_2}{R_1 + R_2} \quad \text{or} \quad R = \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}}. \tag{1.4}$$

By putting resistors in parallel, you always get a *smaller* resistor. Resistance is measured in ohms (Ω), but in practice we frequently omit the Ω symbol when referring to resistors that are more than 1000 Ω (1 kΩ). Thus, a 4.7 kΩ resistor is often referred to as a 4.7k resistor, and a 1 MΩ resistor as a 1M resistor (or 1 meg).[9] If these preliminaries bore you, please have patience – we'll soon get to numerous amusing applications.

Figure 1.4. Resistors in series.

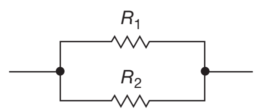

Figure 1.5. Resistors in parallel.

Exercise 1.1. You have a 5k resistor and a 10k resistor. What is their combined resistance (a) in series and (b) in parallel?

Exercise 1.2. If you place a 1 ohm resistor across a 12 volt car battery, how much power will it dissipate?

Exercise 1.3. Prove the formulas for series and parallel resistors.

[8] Conservatively rated at 1/8 watt in its RN55 military grade ("MIL-spec"), but rated at 1/4 watt in its CMF-55 industrial grade.

[9] A popular "international" alternative notation replaces the decimal point with the unit multiplier, thus 4k7 or 1M0. A 2.2 Ω resistor becomes 2R2. There is an analogous scheme for capacitors and inductors.

Exercise 1.4. Show that several resistors in parallel have resistance

$$R = \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \cdots} \tag{1.5}$$

Beginners tend to get carried away with complicated algebra in designing or trying to understand electronics. Now is the time to begin learning intuition and shortcuts. Here are a couple of good tricks:

Shortcut #1 A large resistor in series (parallel) with a small resistor has the resistance of the larger (smaller) one, roughly. So you can "trim" the value of a resistor up or down by connecting a second resistor in series or parallel: to trim *up*, choose an available resistor value below the target value, then add a (much smaller) series resistor to make up the difference; to trim *down*, choose an available resistor value above the target value, then connect a (much larger) resistor in parallel. For the latter you can approximate with proportions – to lower the value of a resistor by 1%, say, put a resistor 100 times as large in parallel.[10]

Shortcut #2 Suppose you want the resistance of 5k in parallel with 10k. If you think of the 5k as two 10k's in parallel, then the whole circuit is like three 10k's in parallel. Because the resistance of *n* equal resistors in parallel is 1/*n*th the resistance of the individual resistors, the answer in this case is 10k/3, or 3.33k. This trick is handy because it allows you to analyze circuits quickly in your head, without distractions. We want to encourage mental designing, or at least "back-of-the-envelope" designing, for idea brainstorming.

Some more home-grown philosophy: there is a tendency among beginners to want to compute resistor values and other circuit component values to many significant places, particularly with calculators and computers that readily oblige. There are two reasons you should try to avoid falling into this habit: (a) the components themselves are of finite precision (resistors typically have tolerances of ±5% or ±1%; for capacitors it's typically ±10% or ±5%; and the parameters that characterize transistors, say, frequently are known only to a factor of 2); (b) one mark of a good circuit design is insensitivity of the finished circuit to precise values of the components (there are exceptions, of course). You'll also learn circuit intuition more quickly if you get into the habit of doing approximate calculations in your head, rather than watching meaningless numbers pop up on a calculator display. We believe strongly that reliance on formulas and equations early in your electronic circuit education is a fine way to prevent you from understanding what's really going on.

In trying to develop intuition about resistance, some people find it helpful to think about *conductance*, $G = 1/R$. The current through a device of conductance G bridging a voltage V is then given by $I = GV$ (Ohm's law). A small resistance is a large conductance, with correspondingly large current under the influence of an applied voltage. Viewed in this light, the formula for parallel resistors is obvious: when several resistors or conducting paths are connected across the same voltage, the total current is the sum of the individual currents. Therefore the net conductance is simply the sum of the individual conductances, $G = G_1 + G_2 + G_3 + \cdots$, which is the same as the formula for parallel resistors derived earlier.

Engineers are fond of defining reciprocal units, and they have designated as the unit of conductance the siemens (S= $1/\Omega$), also known as the mho (that's ohm spelled backward, given the symbol ℧). Although the concept of conductance is helpful in developing intuition, it is not used widely;[11] most people prefer to talk about resistance instead.

C. Power in resistors

The power dissipated by a resistor (or any other device) is $P = IV$. Using Ohm's law, you can get the equivalent forms $P = I^2R$ and $P = V^2/R$.

Exercise 1.5. Show that it is not possible to exceed the power rating of a 1/4 watt resistor of resistance greater than 1k, no matter how you connect it, in a circuit operating from a 15 volt battery.

Exercise 1.6. Optional exercise: New York City requires about 10^{10} watts of electrical power, at 115 volts[12] (this is plausible: 10 million people averaging 1 kilowatt each). A heavy power cable might be an inch in diameter. Let's calculate what will happen if we try to supply the power through a cable 1 foot in diameter made of pure copper. Its resistance is 0.05 $\mu\Omega$ (5×10^{-8} ohms) per foot. Calculate (a) the power lost per foot from "I^2R losses," (b) the length of cable over which you will lose all 10^{10} watts, and (c) how hot the cable will get, if you know the physics involved ($\sigma = 6 \times 10^{-12}$W/K^4 cm^2). If you have done your computations correctly, the result should seem preposterous. What is the solution to this puzzle?

---

[10] With an error, in this case, of just 0.01%.

[11] Although the elegant *Millman's theorem* has its admirers: it says that the output voltage from a set of resistors (call them R_i) that are driven from a set of corresponding input voltages (V_i) and connected together at the output is $V_{\text{out}}=(\sum V_iG_i)/\sum G_i$, where the G_i are the conductances (G_i=$1/R_i$).

[12] Although the "official" line voltage is 120 V ±5%, you'll sometimes see 110 V, 115 V, or 117 V. This loose language is OK (and we use it in this book), because (a) the median voltage at the wall plug is 3 to 5 volts lower, when powering stuff; and (b) the *minimum* wall-plug voltage is 110 V. See ANSI standard C84.1.

D. Input and output

Nearly all electronic circuits accept some sort of applied *input* (usually a voltage) and produce some sort of corresponding *output* (which again is often a voltage). For example, an audio amplifier might produce a (varying) output voltage that is 100 times as large as a (similarly varying) input voltage. When describing such an amplifier, we imagine measuring the output voltage for a given applied input voltage. Engineers speak of the *transfer function* **H**, the ratio of (measured) output divided by (applied) input; for the audio amplifier above, **H** is simply a constant (**H** = 100). We'll get to amplifiers soon enough, in the next chapter. However, with only resistors we can already look at a very important circuit fragment, the *voltage divider* (which you might call a "de-amplifier").

1.2.3 Voltage dividers

We now come to the subject of the voltage divider, one of the most widespread electronic circuit fragments. Show us any real-life circuit and we'll show you half a dozen voltage dividers. To put it very simply, a voltage divider is a circuit that, given a certain voltage input, produces a predictable fraction of the input voltage as the output voltage. The simplest voltage divider is shown in Figure 1.6.

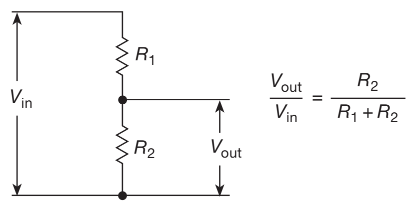

Figure 1.6. Voltage divider. An applied voltage V_{in} results in a (smaller) output voltage V_{out}.

An important word of explanation: when engineers draw a circuit like this, it's generally assumed that the V_{in} on the left is a voltage that you are applying to the circuit, and that the V_{out} on the right is the resulting output voltage (produced by the circuit) that you are measuring (or at least are interested in). You are supposed to know all this (a) because of the convention that signals generally flow from left to right, (b) from the suggestive names ("in," "out") of the signals, and (c) from familiarity with circuits like this. This may be confusing at first, but with time it becomes easy.

What is V_{out}? Well, the current (same everywhere, assuming no "load" on the output; i.e., nothing connected across the output) is

$$I = \frac{V_{in}}{R_1 + R_2}.$$

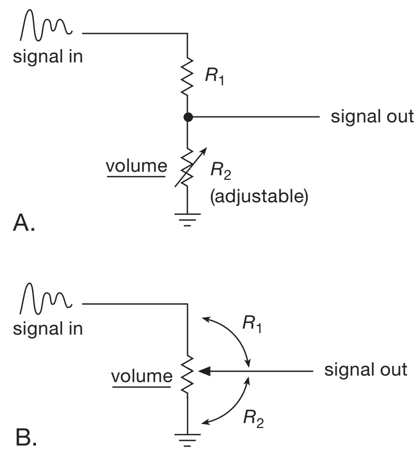

Figure 1.7. An adjustable voltage divider can be made from a fixed and variable resistor, or from a potentiometer. In some contemporary circuits you'll find instead a long series chain of equal-value resistors, with an arrangement of electronic switches that lets you choose any one of the junctions as the output; this sounds much more complicated – but it has the advantage that you can adjust the voltage ratio *electrically* (rather than mechanically).

(We've used the definition of resistance and the series law.) Then, for R_2,

$$V_{out} = IR_2 = \frac{R_2}{R_1 + R_2} V_{in}. \tag{1.6}$$

Note that the output voltage is always less than (or equal to) the input voltage; that's why it's called a divider. You could get amplification (more output than input) if one of the resistances were negative. This isn't as crazy as it sounds; it is possible to make devices with negative "incremental" resistances (e.g., the component known as a *tunnel diode*) or even true negative resistances (e.g., the negative-impedance converter that we will talk about later in the book, §6.2.4B). However, these applications are rather specialized and need not concern you now.

Voltage dividers are often used in circuits to generate a particular voltage from a larger fixed (or varying) voltage. For instance, if V_{in} is a varying voltage and R_2 is an adjustable resistor (Figure 1.7A), you have a "volume control"; more simply, the combination R_1R_2 can be made from a single variable resistor, or *potentiometer* (Figure 1.7B). This and similar applications are common, and potentiometers come in a variety of styles, some of which are shown in Figure 1.8.

The humble voltage divider is even more useful, though, as a way of *thinking* about a circuit: the input voltage and upper resistance might represent the output of an amplifier, say, and the lower resistance might represent the input of

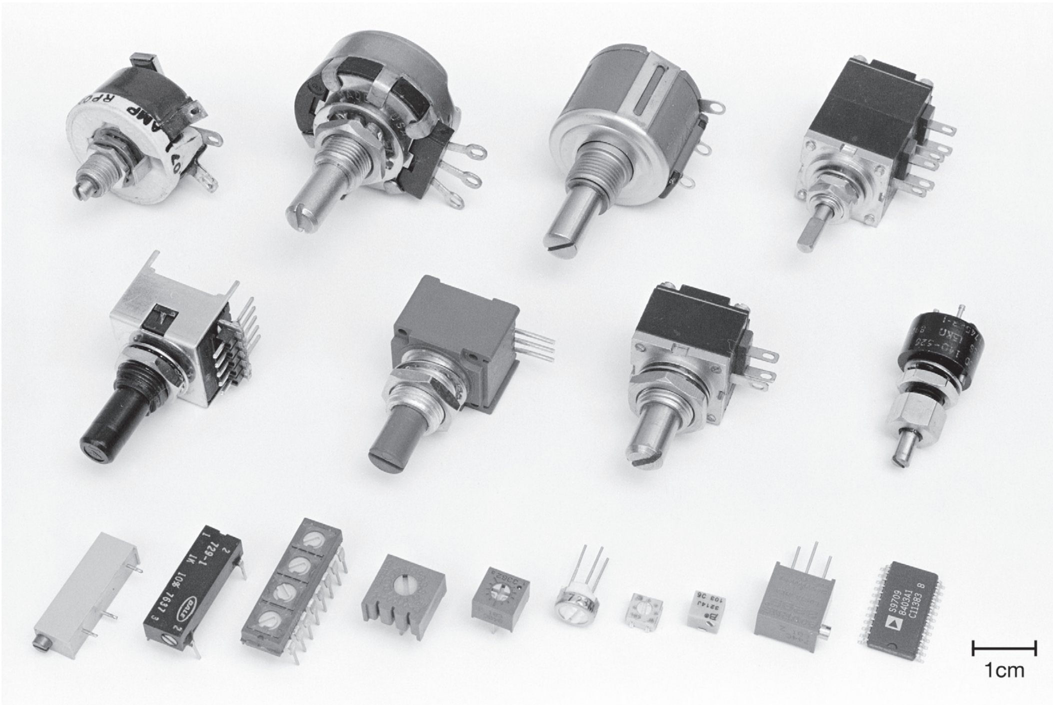

Figure 1.8. Most of the common potentiometer styles are shown here. Top row, left to right (panel mount): power wirewound, "type AB" 2W carbon composition, 10-turn wirewound/plastic hybrid, ganged dual pot. Middle row (panel mount): optical encoder (continuous rotation, 128 cycles per turn), single-turn cermet, single-turn carbon, screw-adjust single-turn locking. Front row (board-mount trimmers): multiturn side-adjust (two styles), quad single-turn, 3/8″ (9.5 mm) square single-turn, 1/4″ (6.4 mm) square single-turn, 1/4″ (6.4 mm) round single-turn, 4 mm square single-turn surface mount, 4 mm square multiturn surface mount, 3/8″ (9.5 mm) square multiturn, quad nonvolatile 256-step integrated pot (E^{2}POT) in 24-pin small-outline IC.

the following stage. In this case the voltage-divider equation tells you how much signal gets to the input of that last stage. This will all become clearer after you know about a remarkable fact (Thévenin's theorem) that will be discussed later. First, though, a short aside on voltage sources and current sources.

1.2.4 Voltage sources and current sources

A perfect *voltage source* is a two-terminal "black box" that maintains a fixed voltage drop across its terminals, regardless of load resistance. This means, for instance, that it must supply a current $I = V/R$ when a resistance R is attached to its terminals. A real voltage source can supply only a finite maximum current, and in addition it generally behaves like a perfect voltage source with a small resistance in series. Obviously, the smaller this series resistance, the better. For example, a standard 9 volt alkaline battery behaves approximately like a perfect 9 volt voltage source in series with a 3 Ω resistor, and it can provide a maximum current (when shorted) of 3 amps (which, however, will kill the battery in a few minutes). A voltage source "likes" an open-circuit load and "hates" a short-circuit load, for obvious reasons. (The meaning of "open circuit" and "short circuit" sometimes confuse the beginner: an open circuit has nothing connected to it, whereas a short circuit is a piece of wire bridging the output.) The symbols used to indicate a voltage source are shown in Figure 1.9.

A perfect *current source* is a two-terminal black box that maintains a constant current through the external circuit, regardless of load resistance or applied voltage. To do this it must be capable of supplying any necessary voltage across its terminals. Real current sources (a much-neglected subject in most textbooks) have a limit to the voltage they can provide (called the *output-voltage compliance,* or just *compliance*), and in addition they do not provide absolutely constant output current. A current source "likes" a short-circuit load and "hates" an open-circuit load. The symbols used to indicate a current source are shown in Figure 1.10.

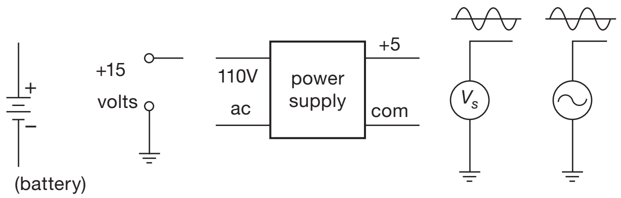

Figure 1.9. Voltage sources can be either steady (dc) or varying (ac).

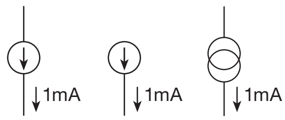

Figure 1.10. Current-source symbols.

A battery is a real-life approximation to a voltage source (there is no analog for a current source). A standard D-size flashlight cell, for instance, has a terminal voltage of 1.5 V, an equivalent series resistance of about 0.25 Ω, and a total energy capacity of about 10,000 watt–seconds (its characteristics gradually deteriorate with use; at the end of its life, the voltage may be about 1.0 V, with an internal series resistance of several ohms). It is easy to construct voltage sources with far better characteristics, as you will learn when we come to the subject of feedback; this is a major topic of Chapter 9. Except in the important class of devices intended for portability, the use of batteries in electronic devices is rare.

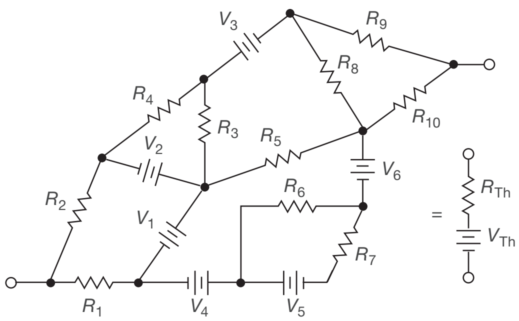

Figure 1.11. The Thévenin equivalent circuit.

1.2.5 Thévenin equivalent circuit

Thévenin's theorem states[12] that any two-terminal network of resistors and voltage sources is equivalent to a single resistor R in series with a single voltage source V. This is remarkable. Any mess of batteries and resistors can be mimicked with one battery and one resistor (Figure 1.11). (Incidentally, there's another theorem, Norton's theorem, that says you can do the same thing with a current source in parallel with a resistor.)

How do you figure out the Thévenin equivalent R_{Th} and V_{Th} for a given circuit? Easy! V_{Th} is the open-circuit voltage of the Thévenin equivalent circuit; so if the two circuits behave identically, it must also be the open-circuit voltage of the given circuit (which you get by calculation, if you know what the circuit is, or by measurement, if you don't). Then you find R_{Th} by noting that the short-circuit current of the equivalent circuit is $V_{\text{Th}}/R_{\text{Th}}$. In other words,

$$\begin{aligned} V_{\text{Th}} &= V\ (\text{open circuit}), \\ R_{\text{Th}} &= \frac{V\ (\text{open circuit})}{I\ (\text{short circuit})}. \end{aligned} \tag{1.7}$$

Let's apply this method to the voltage divider, which must have a Thévenin equivalent:

1. The open-circuit voltage is
$$V = V_{\text{in}}\frac{R_2}{R_1+R_2}.$$
2. The short-circuit current is
$$V_{\text{in}}/R_1.$$

So the Thévenin equivalent circuit is a voltage source,

$$V_{\text{Th}} = V_{\text{in}}\frac{R_2}{R_1+R_2}, \tag{1.8}$$

in series with a resistor,

$$R_{\text{Th}} = \frac{R_1R_2}{R_1+R_2}. \tag{1.9}$$

(It is not a coincidence that this happens to be the parallel resistance of R_1 and R_2. The reason will become clear later.)

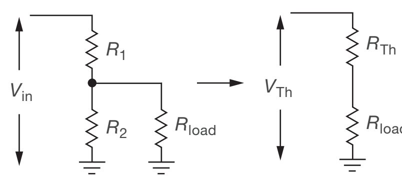

Figure 1.12. Thévenin equivalent of a voltage divider.

From this example it is easy to see that a voltage divider is not a very good battery, in the sense that its output voltage drops severely when a load is attached. As an example, consider Exercise 1.10. You now know everything you need to know to calculate exactly how much the output will

[12] We provide a proof, for those who are interested, in Appendix D.

MULTIMETERS

There are numerous instruments that let you measure voltages and currents in a circuit. The oscilloscope is the most versatile; it lets you "see" voltages versus time at one or more points in a circuit. Logic probes and logic analyzers are special-purpose instruments for troubleshooting digital circuits. The simple multimeter provides a good way to measure voltage, current, and resistance, often with good precision; however, it responds slowly, and thus it cannot replace the oscilloscope where changing voltages are of interest. Multimeters are of two varieties: those that indicate measurements on a conventional scale with a moving pointer, and those that use a digital display.

The traditional (and now largely obsolete) VOM (volt-ohm-milliammeter) multimeter uses a meter movement that measures current (typically 50 μA full scale). (See a less-design-oriented electronics book for pretty pictures of the innards of meter movements; for our purposes, it suffices to say that it uses coils and magnets.) To measure *voltage*, the VOM puts a resistor in series with the basic movement. For instance, one kind of VOM will generate a 1 V (full-scale) range by putting a 20k resistor in series with the standard 50 μA movement; higher voltage ranges use correspondingly larger resistors. Such a VOM is specified as 20,000 Ω/V, meaning that it looks like a resistor whose value is 20k multiplied by the full-scale voltage of the particular range selected. Full scale on any voltage range is 1/20,000 amps, or 50 μA. It should be clear that one of these voltmeters disturbs a circuit less on a higher range, since it looks like a higher resistance (think of the voltmeter as the lower leg of a voltage divider, with the Thévenin resistance of the circuit you are measuring as the upper resistor). Ideally, a voltmeter should have infinite input resistance.

Most contemporary multimeters use electronic amplification and have an input resistance of 10 MΩ to 1000 MΩ when measuring voltage; they display their results digitally, and are known collectively as digital multimeters (DMMs). A word of caution: sometimes the input resistance of these meters is very high on the most sensitive ranges, dropping to a lower resistance for the higher ranges. For instance, you might typically have an input resistance of 10^9 Ω on the 0.2 V and 2 V ranges, and 10^7 Ω on all higher ranges. Read the specifications carefully! However, for most circuit measurements these high input resistances will produce negligible loading effects. In any case, it is easy to calculate how serious the effect is by using the voltage-divider equation. Typically, multimeters provide voltage ranges from a volt (or less) to a kilovolt (or more), full scale.

A multimeter usually includes *current*-measuring capability, with a set of switchable ranges. Ideally, a current-measuring meter should have zero resistance[13] in order not to disturb the circuit under test, since it must be put in series with the circuit. In practice, you tolerate a few tenths of a volt drop (sometimes called "voltage burden") with both VOMs and digital multimeters. For either kind of meter, selecting a current range puts a small resistor across the meter's input terminals, typically of resistance value to create a voltage drop of 0.1 V to 0.25 V for the chosen full-scale current; the voltage drop is then converted to a corresponding current indication.[14] Typically, multimeters provide current ranges from 50 μA (or less) to an amp (or more), full scale.

Multimeters also have one or more batteries in them to power the resistance measurement. By supplying a small current and measuring the voltage drop, they measure resistance, with several ranges to cover values from 1 Ω (or less) to 10 MΩ (or more).

Important: don't try to measure "the current of a voltage source," by sticking the meter across the wall plug; the same applies for ohms. This is a leading cause of blown-out meters.

Exercise 1.7. What will a 20,000 Ω/V meter read, on its 1 V scale, when attached to a 1 V source with an internal resistance of 10k? What will it read when attached to a 10k–10k voltage divider driven by a "stiff" (zero source resistance) 1 V source?

Exercise 1.8. A 50 μA meter movement has an internal resistance of 5k. What shunt resistance is needed to convert it to a 0–1 A meter? What series resistance will convert it to a 0–10 V meter?

Exercise 1.9. The very high internal resistance of *digital* multimeters, in their voltage-measuring ranges, can be used to measure extremely low *currents* (even though the DMM may not offer a low current range explicitly). Suppose, for example, you want to measure the small current that flows through a 1000 MΩ "leakage" resistance (that term is used to describe a small current that ideally should be absent entirely, for example through the insulation of an underground cable). You have available a standard DMM, whose 2 V dc range has 10 MΩ internal resistance, and you have available a dc source of +10 V. How can you use what you've got to measure accurately the leakage resistance?

drop for a given load resistance: use the Thévenin equivalent circuit, attach a load, and calculate the new output, noting that the new circuit is nothing but a voltage divider (Figure 1.12).

Exercise 1.10. For the circuit shown in Figure 1.12, with V_{in}=30 V and $R_1 = R_2 = $ 10k, find (a) the output voltage with no load attached (the open-circuit voltage); (b) the output voltage with a 10k load (treat as a voltage divider, with R_2 and R_{load} combined into a single resistor); (c) the Thévenin equivalent circuit; (d) the same as in part (b), but using the Thévenin equivalent circuit [again, you wind up with a voltage divider; the answer should agree with the result in part (b)]; (e) the power dissipated in each of the resistors.

A. Equivalent source resistance and circuit loading

As we have just seen, a voltage divider powered from some fixed voltage is equivalent to some smaller voltage source

[13] This is the opposite of an ideal voltage-measuring meter, which should present infinite resistance across its input terminals.

[14] A special class of current meters known as *electrometers* operate with very small voltage burdens (as little at 0.1 mV) by using the technique of feedback, something we'll learn about in Chapters 2 and 4.

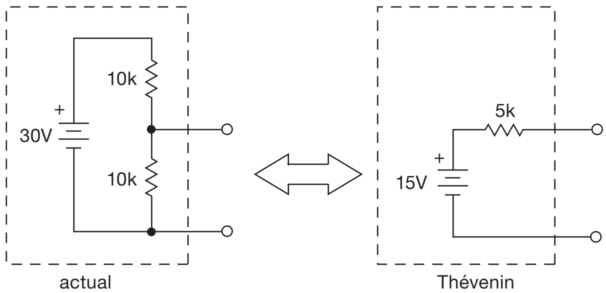

Figure 1.13. Voltage divider example.

in series with a resistor. For example, the output terminals of a 10k–10k voltage divider driven by a perfect 30 volt battery are precisely equivalent to a perfect 15 volt battery in series with a 5k resistor (Figure 1.13). Attaching a load resistor causes the voltage divider's output to drop, owing to the finite *source resistance* (Thévenin equivalent resistance of the voltage divider output, viewed as a source of voltage). This is often undesirable. One solution to the problem of making a stiff voltage source ("stiff" is used in this context to describe something that doesn't bend under load) might be to use much smaller resistors in a voltage divider. Occasionally this brute-force approach is useful. However, it is usually best to construct a voltage source, or power supply, as it's commonly called, using active components like transistors or operational amplifiers, which we will treat in Chapters 2–4. In this way you can easily make a voltage source with internal (Thévenin equivalent) resistance as small as milliohms (thousandths of an ohm), without the large currents and dissipation of power characteristic of a low-resistance voltage divider delivering the same performance. In addition, with an active power supply it is easy to make the output voltage adjustable. These topics are treated extensively in Chapter 9.

The concept of equivalent internal resistance applies to all sorts of sources, not just batteries and voltage dividers. Signal sources (e.g., oscillators, amplifiers, and sensing devices) all have an equivalent internal resistance. Attaching a load whose resistance is less than or even comparable to the internal resistance will reduce the output considerably. This undesirable reduction of the open-circuit voltage (or signal) by the load is called "circuit loading." Therefore you should strive to make $R_{\text{load}} \gg R_{\text{internal}}$, because a high-resistance load has little attenuating effect on the source (Figure 1.14).[15] We will see numerous circuit examples in the chapters ahead. This high-resistance condition ideally characterizes measuring instruments such as voltmeters and oscilloscopes.

A word on language: you frequently hear things like "the resistance looking into the voltage divider" or "the output sees a load of so-and-so many ohms," as if circuits had eyes. It's OK (in fact, it's a rather good way of keeping straight which resistance you're talking about) to say what part of the circuit is doing the "looking."[16]

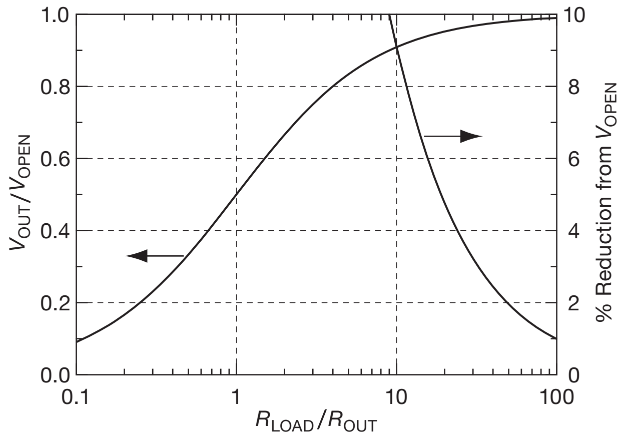

Figure 1.14. To minimize the attenuation of a signal source below its open-circuit voltage, keep the load resistance large compared with the output resistance.

B. Power transfer

Here is an interesting problem: what load resistance will result in maximum power being transferred to the load for a given source resistance? (The terms *source resistance, internal resistance*, and *Thévenin equivalent resistance* all mean the same thing.) It is easy to see that either R_{load}=0 or $R_{\text{load}}=\infty$ results in zero power transferred, because R_{load}=0 means that V_{load}=0 and $I_{\text{load}}=V_{\text{source}}/R_{\text{source}}$, so that $P_{\text{load}}=V_{\text{load}}I_{\text{load}}$=0. But $R_{\text{load}}=\infty$ means that $V_{\text{load}}=V_{\text{source}}$ and I_{load}=0, so that again P_{load}=0. There has to be a maximum in between.

Exercise 1.11. Show that $R_{\text{load}} = R_{\text{source}}$ maximizes the power in the load for a given source resistance. Note: skip this exercise if you don't know calculus, and take it on faith that the answer is true.

[15] There are two important exceptions to this general principle: (1) a current source has a high (ideally infinite) internal resistance and should drive a load of relatively low load resistance; (2) when dealing with radio frequencies and transmission lines, you must "match impedances" (i.e., set $R_{\text{load}}=R_{\text{internal}}$) in order to prevent reflection and loss of power. See Appendix H on transmission lines.

[16] The urge to anthropomorphize runs deep in the engineering and scientific community, despite warnings like "don't anthropomorphize computers … they don't like it."

Lest this example leave the wrong impression, we would like to emphasize again that circuits are ordinarily designed so that the load resistance is much greater than the source resistance of the signal that drives the load.

1.2.6 Small-signal resistance

We often deal with electronic devices for which I is not proportional to V; in such cases there's not much point in talking about resistance, since the ratio V/I will depend on V, rather than being a nice constant, independent of V. For these devices it is sometimes useful to know instead the *slope* of the V–I curve, in other words, the ratio of a small change in applied voltage to the resulting change in current through the device, $\Delta V/\Delta I$ (or dV/dI). This quantity has the units of resistance (ohms) and substitutes for resistance in many calculations. It is called the small-signal resistance, incremental resistance, or dynamic resistance.

A. Zener diodes

As an example, consider the *zener diode*, which has the I–V curve shown in Figure 1.15. Zeners are used to create a constant voltage inside a circuit somewhere, simply done by providing them with a (roughly constant) current derived from a higher voltage within the circuit.[17] For example, the zener diode in Figure 1.15 will convert an applied current in the range shown to a corresponding (but fractionally narrower) range of voltages. It is important to know how the resulting zener voltage will change with applied current; this is a measure of its "regulation" against changes in the driving current provided to it. Included in the specifications of a zener will be its dynamic resistance, given at a certain current. For example, a zener might have a dynamic resistance of $10\,\Omega$ at 10 mA, at its specified zener voltage of 5 V. Using the definition of dynamic resistance, we find that a 10% change in applied current will therefore result in a change in voltage of

$$\Delta V = R_{\text{dyn}}\Delta I = 10 \times 0.1 \times 0.01 = 10\,\text{mV}$$

or

$$\Delta V/V = 0.002 = 0.2\%,$$

thus demonstrating good voltage-regulating ability. In this sort of application you frequently get the zener current through a resistor from a higher voltage available somewhere in the circuit, as in Figure 1.16.

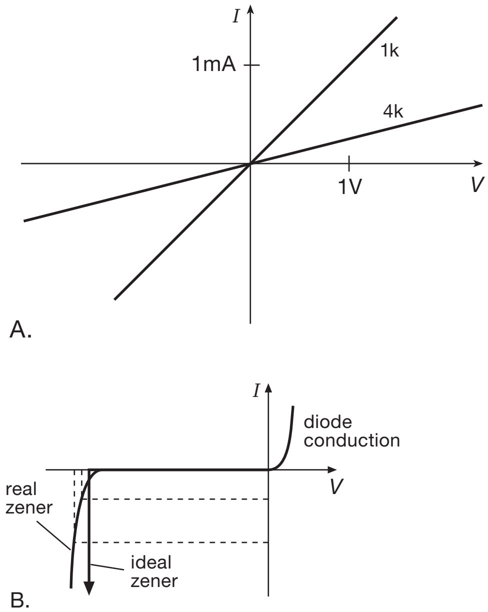

Figure 1.15. *I–V* curves: A. Resistor (linear). B. Zener diode (nonlinear).

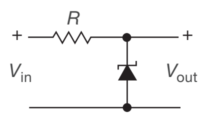

Figure 1.16. Zener regulator.

Then,

$$I = \frac{V_{\text{in}} - V_{\text{out}}}{R}$$

and

$$\Delta I = \frac{\Delta V_{\text{in}} - \Delta V_{\text{out}}}{R},$$

so

$$\Delta V_{\text{out}} = R_{\text{dyn}}\Delta I = \frac{R_{\text{dyn}}}{R}(\Delta V_{\text{in}} - \Delta V_{\text{out}})$$

and finally

$$\Delta V_{\text{out}} = \frac{R_{\text{dyn}}}{R + R_{\text{dyn}}}\Delta V_{\text{in}}.$$

Aha – the voltage-divider equation, again! Thus, for *changes* in voltage, the circuit behaves like a voltage divider, with the zener replaced by a resistor equal to its dynamic resistance at the operating current. This is the

[17] Zeners belong to the more general class of *diodes* and *rectifiers*, important devices that we'll see later in the chapter (§1.6), and indeed throughout the book. The ideal diode (or rectifier) acts as a perfect conductor for current flow in one direction, and a perfect insulator for current flow in the reverse direction; it is a "one-way valve" for current.

utility of incremental resistance. For instance, suppose in the preceding circuit we have an input voltage ranging between 15 and 20 V, and we use a 1N4733 (5.1 V, 1W zener diode) in order to generate a stable 5.1 V power supply. We choose $R = 300\,\Omega$, for a maximum zener current of 50 mA: (20 V−5.1 V)/300 Ω. We can now estimate the output-voltage regulation (variation in output voltage), knowing that this particular zener has a specified maximum dynamic resistance of 7.0 Ω at 50 mA. The zener current varies from 50 mA to 33 mA over the input-voltage range; this 17 mA change in current then produces a voltage change at the output of $\Delta V = R_{\mathrm{dyn}}\Delta I$, or 0.12 V.

It's a useful fact, when dealing with zener diodes, that the dynamic resistance of a zener diode varies roughly in inverse proportion to current. It's worth knowing, also, that there are ICs designed to substitute for zener diodes; these "two-terminal voltage references" have superior performance – much lower dynamic resistance (less than 1 Ω, even at currents as small as 0.1 mA; that's a thousand times better than the zener we just used), and excellent temperature stability (better than 0.01%/C). We will see more of zeners and voltage references in §§2.2.4 and 9.10.

In real life, a zener will provide better regulation if driven by a current source, which has, by definition, $R_{\mathrm{incr}}=\infty$ (the same current, regardless of voltage). But current sources are more complex, and therefore in practice we often resort to the humble resistor. When thinking about zeners, it's worth remembering that low-voltage units (e.g., 3.3 V) behave rather poorly, in terms of constancy of voltage versus current (Figure 1.17); if you think you need a low voltage zener, use a two-terminal reference instead (§9.10).

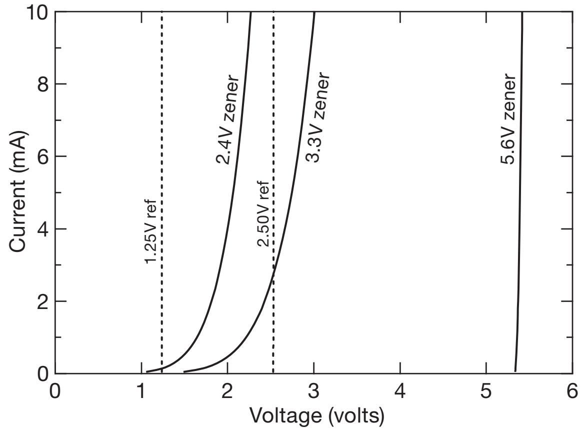

Figure 1.17. Low-voltage zeners are pretty dismal, as seen in these measured *I* vs. *V* curves (for three members of the 1N5221–67 series), particularly in contrast to the excellent measured performance of a pair of "IC voltage references" (LM385Z-1.2 and LM385Z-2.5, see §9.10 and Table 9.7). However, zener diodes in the neighborhood of 6 V (such as the 5.6 V 1N5232B or 6.2 V 1N5234B) exhibit admirably steep curves, and are useful parts.

1.2.7 An example: "It's too hot!"

Some people like to turn the thermostat way up, annoying other people who like their houses cool. Here's a little gadget (Figure 1.18) that lets folks of the latter persuasion know when to complain – it lights up a red light-emitting diode (LED) indicator when the room is warmer than 30°C (86°F). It also shows how to use the humble voltage divider (and even humbler Ohm's law), and how to deal with an LED, which behaves like a zener diode (and is sometimes used as such).

The triangular symbol is a *comparator*, a handy device (discussed in §12.3) that switches its output according to the relative voltages at its two input terminals. The temperature sensing device is R_4, which decreases in resistance by about 4%/°C, and which is 10kΩ at 25°C. So we've made it the lower leg of a voltage divider (R_3R_4), whose output is compared with the temperature-insensitive divider R_1R_2. When it's hotter than 30°C, point "X" is at a lower voltage than point "Y," so the comparator pulls its output to ground.

At the output there's an LED, which behaves electrically like a 1.6 V zener diode; and when current is flowing, it lights up. Its lower terminal is then at 5 V−1.6 V, or +3.4 V. So we've added a series resistor, sized to allow 5 mA when the comparator output is at ground: R_5=3.4 V/5 mA, or 680 Ω.

If you wanted to, you could make the setpoint adjustable by replacing R_2 with a 5k pot in series with a 5k fixed resistor. We'll see later that it's also a good idea to add some *hysteresis*, to encourage the comparator to be decisive. Note that this circuit is insensitive to the exact power-supply voltage because it compares *ratios*. Ratiometric techniques are good; we'll see them again later.

1.3 Signals

A later section in this chapter will deal with capacitors, devices whose properties depend on the way the voltages and currents in a circuit are *changing*. Our analysis of dc circuits so far (Ohm's law, Thévenin equivalent circuits, etc.) still holds, even if the voltages and currents are changing in time. But for a proper understanding of alternating-current (ac) circuits, it is useful to have in mind certain common

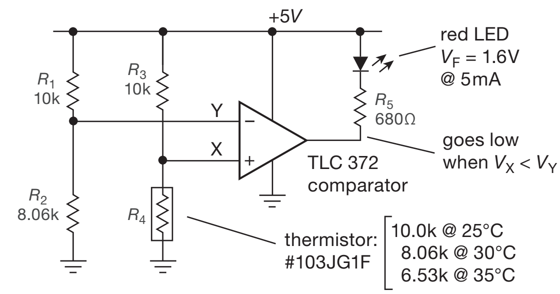

Figure 1.18. The LED lights up when it's hotter than 30°C. The comparator (which we'll see later, in Chapters 4 and 12) pulls its output to ground when the voltage at "X" is less than the voltage at "Y." R_4 is a thermistor, which is a resistor with a deliberate negative temperature coefficient; that is, its resistance decreases with increasing temperature – by about 4%/°C.

types of *signals*, voltages that change in time in a particular way.

1.3.1 Sinusoidal signals

Sinusoidal signals are the most popular signals around; they're what you get out of the wall plug. If someone says something like "take a 10 μV signal at 1 MHz," they mean a sinewave. Mathematically, what you have is a voltage described by

$$V = A \sin 2\pi f t \tag{1.10}$$

where A is called the amplitude and f is the frequency in hertz (cycles per second). A sinewave looks like the wave shown in Figure 1.19. Sometimes it is important to know the value of the signal at some arbitrary time $t = 0$, in which case you may see a *phase* ϕ in the expression:

$$V = A \sin(2\pi f t + \phi).$$

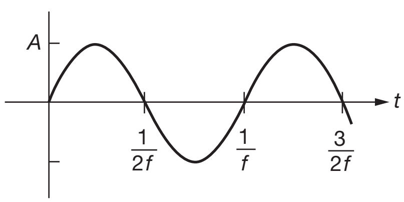

Figure 1.19. Sinewave of amplitude A and frequency f.

The other variation on this simple theme is the use of *angular frequency*, which looks like this:

$$V = A \sin \omega t.$$

Here ω is the angular frequency, measured in radians per second. Just remember the important relation $\omega = 2\pi f$ and you won't go wrong.

The great merit of sinewaves (and the cause of their perennial popularity) is the fact that they are the solutions to certain linear differential equations that happen to describe many phenomena in nature as well as the properties of linear circuits. A linear circuit has the property that its output, when driven by the sum of two input signals, equals the sum of its individual outputs when driven by each input signal in turn; i.e., if $\mathcal{O}(A)$ represents the output when driven by signal A, then a circuit is linear if $\mathcal{O}(A+B) = \mathcal{O}(A) + \mathcal{O}(B)$. A linear circuit driven by a sinewave always responds with a sinewave, although in general the phase and amplitude are changed. No other periodic signal can make this statement. It is standard practice, in fact, to describe the behavior of a circuit by its *frequency response*, by which we mean the way the circuit alters the amplitude of an applied sinewave as a function of frequency. A stereo amplifier, for instance, should be characterized by a "flat" frequency response over the range 20 Hz to 20 kHz, at least.

The sinewave frequencies we usually deal with range from a few hertz to a few tens of megahertz. Lower frequencies, down to 0.0001 Hz or lower, can be generated with carefully built circuits, if needed. Higher frequencies, up to say 2000 MHz (2 GHz) and above, can be generated, but they require special transmission-line techniques. Above that, you're dealing with microwaves, for which conventional wired circuits with lumped-circuit elements become impractical, and exotic waveguides or "striplines" are used instead.

1.3.2 Signal amplitudes and decibels

In addition to its amplitude, there are several other ways to characterize the magnitude of a sinewave or any other signal. You sometimes see it specified by *peak-to-peak amplitude* (pp amplitude), which is just what you would guess, namely, twice the amplitude. The other method is to give the *root-mean-square amplitude* (rms amplitude), which is $V_{\text{rms}} = (1/\sqrt{2})A = 0.707A$ (this is for sinewaves only; the ratio of pp to rms will be different for other waveforms). Odd as it may seem, this is the usual method, because rms voltage is what's used to compute power. The nominal voltage across the terminals of a wall socket (in the United States) is 120 volts rms, 60 Hz. The *amplitude* is 170 volts (339 volts pp).[18]

[18] Occasionally you'll encounter devices (e.g., mechanical moving-pointer meters) that respond to the *average* magnitude of an ac signal.

A. Decibels

How do you compare the relative amplitudes of two signals? You could say, for instance, that signal X is twice as large as signal Y. That's fine, and useful for many purposes. But because we often deal with ratios as large as a million, it is better to use a logarithmic measure, and for this we present the decibel (it's one-tenth as large as something called a bel, which no one ever uses). By definition, the ratio of two signals, in decibels (dB), is

$$\mathrm{dB} = 10\log_{10}\frac{P_2}{P_1}, \tag{1.11}$$

where P_1 and P_2 represent the *power* in the two signals. We are often dealing with signal *amplitudes*, however, in which case we can express the ratio of two signals having the same waveform as

$$\mathrm{dB} = 20\log_{10}\frac{A_2}{A_1}, \tag{1.12}$$

where A_1 and A_2 are the two signal amplitudes. So, for instance, one signal of twice the amplitude of another is $+6$ dB relative to it, since $\log_{10} 2 = 0.3010$. A signal 10 times as large is $+20$ dB; a signal one-tenth as large is -20 dB.

Although decibels are ordinarily used to specify the ratio of two signals, they are sometimes used as an absolute measure of amplitude. What is happening is that you are assuming some reference signal level and expressing any other level in decibels relative to it. There are several standard levels (which are unstated, but understood) that are used in this way; the most common references are (a) 0 dBV (1 V rms); (b) 0 dBm (the voltage corresponding to 1 mW into some assumed load impedance, which for radiofrequencies is usually 50 Ω, but for audio is often 600 Ω; the corresponding 0 dBm amplitudes, when loaded by those impedances, are then 0.22 V rms and 0.78 V rms); and (c) the small noise voltage generated by a resistor at room temperature (this surprising fact is discussed in §8.1.1). In addition to these, there are reference amplitudes used for measurements in other fields of engineering and science. For instance, in acoustics, 0 dB SPL (sound pressure level) is a wave whose rms pressure is 20 μPa (that's 2×10^{-10} atm); in audio communications, levels can be stated in dBrnC (relative noise reference weighted in frequency by "curve C"). When stating amplitudes this way, it is best to be specific about the 0 dB reference amplitude; say something like "an amplitude of 27 decibels relative to 1 V rms," or abbreviate "27 dB re 1 V rms," or define a term like "dBV."[19]

Exercise 1.12. Determine the voltage and power ratios for a pair of signals with the following decibel ratios: (a) 3 dB, (b) 6 dB, (c) 10 dB, (d) 20 dB.

Exercise 1.13. We might call this amusing exercise "Desert Island dBs": in the table below we've started entering some values for power ratios corresponding to the first dozen integral dBs, using the results for parts (a) and (c) of the last exercise. Your job is to complete the table, without recourse to a calculator. A possibly helpful hint: starting at 10 dB, go down the table in steps of 3 dB, then up in a step of 10 dB, then down again. Finally, get rid of yucky numbers like 3.125 (and its near relatives) by noticing that it's charmingly close to π.

dB	ratio (P/P_0)
0	1
1	
2	
3	2
4	
5	
6	4
7	
8	
9	8
10	10
11	

1.3.3 Other signals

A. Ramp

The ramp is a signal that looks like the one shown in Figure 1.20A. It is simply a voltage rising (or falling) at a constant rate. That can't go on forever, of course, even in science fiction movies. It is sometimes approximated by a finite ramp (Figure 1.20B) or by a periodic ramp (known as a *sawtooth*, Figure 1.20C).

B. Triangle

The triangle wave is a close cousin of the ramp; it is simply a symmetrical ramp (Figure 1.21).

C. Noise

Signals of interest are often mixed with *noise*; this is a catch-all phrase that usually applies to random noise of thermal origin. Noise voltages can be specified by their

For a sinewave the relationship is $V_{\mathrm{avg}}=V_{\mathrm{rms}}/1.11$. However, such meters are usually calibrated so that they indicate the rms sinewave amplitude. For signals other than sinewaves their indication is in error; be sure to use a "true rms" meter if you want the right answer.

[19] One of the authors, when asked by his nontechnical spouse how much we spent on that big plasma screen, replied "36 dB\$."

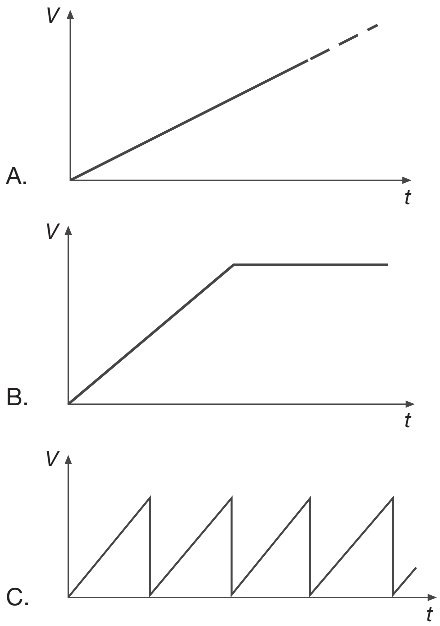

Figure 1.20. A: Voltage-ramp waveform. B: Ramp with limit. C: Sawtooth wave.

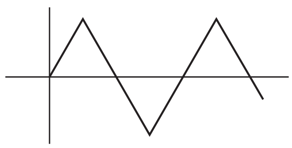

Figure 1.21. Triangle wave.

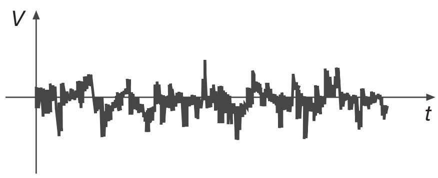

Figure 1.22. Noise.

frequency spectrum (power per hertz) or by their amplitude distribution. One of the most common kind of noise is *band-limited white Gaussian noise*, which means a signal with equal power per hertz in some band of frequencies and that exhibits a Gaussian (bell-shaped) distribution of amplitudes when many instantaneous measurements of its amplitude are made. This kind of noise is generated by a resistor (Johnson noise or Nyquist noise), and it plagues sensitive measurements of all kinds. On an oscilloscope it appears as shown in Figure 1.22. We will discuss noise and low-noise techniques in considerable detail in Chapter 8.

D. Square wave

A square wave is a signal that varies in time as shown in Figure 1.23. Like the sinewave, it is characterized by amplitude and frequency (and perhaps phase). A linear circuit driven by a square wave rarely responds with a square wave. For a square wave, the peak amplitude and the rms amplitude are the same.

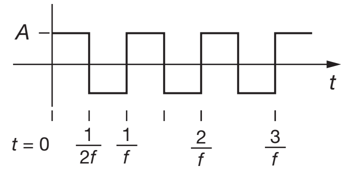

Figure 1.23. Square wave.

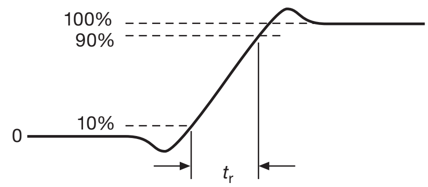

Figure 1.24. Rise time of a step waveform.

The edges of a square wave are not perfectly square; in typical electronic circuits the *rise time* t_r ranges from a few nanoseconds to a few microseconds. Figure 1.24 shows the sort of thing usually seen. The rise time is conventionally defined as the time required for the signal to go from 10% to 90% of its total transition.

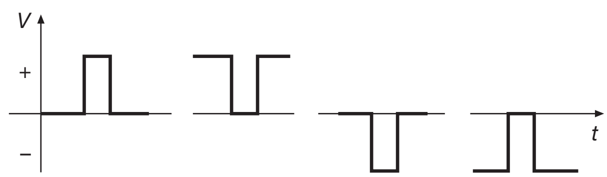

Figure 1.25. Positive- and negative-going pulses of both polarities.

E. Pulses

A pulse is a signal that looks like the objects shown in Figure 1.25. It is defined by amplitude and pulse width. You can generate a train of periodic (equally spaced) pulses, in which case you can talk about the frequency, or pulse repetition rate, and the "duty cycle," the ratio of pulse width to repetition period (duty cycle ranges from zero to 100%). Pulses can have positive or negative polarity; in addition, they can be "positive-going" or "negative-going." For instance, the second pulse in Figure 1.25 is a negative-going pulse of positive polarity.

F. Steps and spikes

Steps and spikes are signals that are talked about a lot but are not so often used. They provide a nice way of describing what happens in a circuit. If you could draw them, they would look something like the example in Figure 1.26. The step function is part of a square wave; the spike is simply a jump of vanishingly short duration.

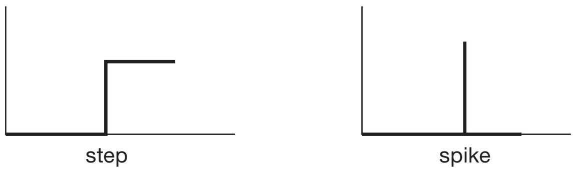

Figure 1.26. Steps and spikes.

1.3.4 Logic levels

Pulses and square waves are used extensively in digital electronics, in which predefined voltage levels represent one of two possible states present at any point in the circuit. These states are called simply HIGH and LOW, and correspond to the 1 (true) and 0 (false) states of Boolean logic (the algebra that describes such two-state systems).

Precise voltages are not necessary in digital electronics. You need only to distinguish which of the two possible states is present. Each digital logic family therefore specifies legal HIGH and LOW states. For example, the "74LVC" digital logic family runs from a single +3.3 V supply, with output levels that are typically 0 V (LOW) and 3.3 V (HIGH), and an input decision threshold of 1.5 V. However, actual outputs can be as much as 0.4 V away from ground or from +3.3 V without malfunction. We'll have much more to say about logic levels in Chapters 10 through 12.

1.3.5 Signal sources

Often the source of a signal is some part of the circuit you are working on. But for test purposes a flexible signal source is invaluable. They come in three flavors: signal generators, pulse generators, and function generators.

A. Signal generators

Signal generators are sinewave oscillators, usually equipped to give a wide range of frequency coverage, with provision for precise control of amplitude (using a resistive divider network called an *attenuator*). Some units let you *modulate* (i.e., vary in time) the output amplitude ("AM" for "amplitude modulated") or frequency ("FM" for "frequency modulated"). A variation on this theme is the *sweep generator*, a signal generator that can sweep its output frequency repeatedly over some range. These are handy for testing circuits whose properties vary with frequency in a particular way, e.g., "tuned circuits" or filters. Nowadays these devices, as well as most test instruments, are available in configurations that allow you to program the frequency, amplitude, etc., from a computer or other digital instrument.

For many signal generators the signal source is a *frequency synthesizer*, a device that generates sinewaves whose frequencies can be set precisely. The frequency is set digitally, often to eight significant figures or more, and is internally synthesized from a precise standard (a stand-alone quartz-crystal oscillator or rubidium frequency standard, or a GPS-derived oscillator) by digital methods we will discuss later (§13.13.6). Typical of synthesizers is the programmable SG384 from Stanford Research Systems, with a frequency range of 1 μHz to 4 GHz, an amplitude range of -110 dBm to $+16.5$ dBm (0.7 μV to 1.5 V, rms), and various modulation modes such as AM, FM, and ΦM; it costs about $4,600. You can get synthesized sweep generators, and you can get synthesizers that produce other waveforms (see *Function Generators*, below). If your requirement is for no-nonsense accurate frequency generation, you can't beat a synthesizer.

B. Pulse generators

Pulse generators make only pulses, but what pulses! Pulse width, repetition rate, amplitude, polarity, rise time, etc., may all be adjustable. The fastest ones go up to gigahertz pulse rates. In addition, many units allow you to generate pulse pairs, with settable spacing and repetition rate, or even programmable patterns (they are sometimes called pattern generators). Most contemporary pulse generators are provided with logic-level outputs for easy connection to digital circuitry. As with signal generators, these come in the programmable variety.

C. Function generators

In many ways function generators are the most flexible signal sources of all. You can make sine, triangle, and square waves over an enormous frequency range (0.01 Hz to 30 MHz is typical), with control of amplitude and dc offset (a constant-dc voltage added to the signal). Many of them have provision for frequency sweeping, often in