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.

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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

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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.

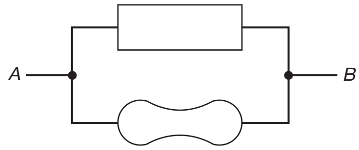

Figure 1.1. Parallel connection.

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) × (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.

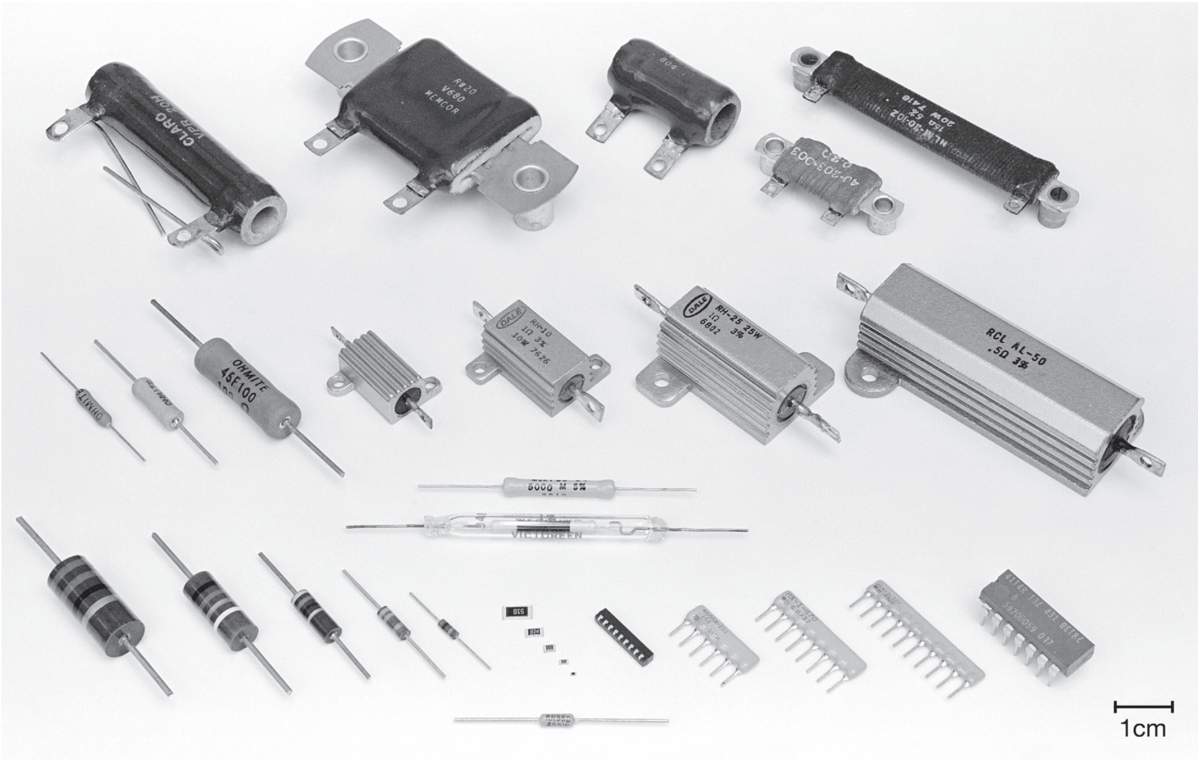

Figure 1.2. A selection of common resistor types. Top row, left to right (wirewound ceramic power resistors): 20W vitreous enamel with leads, 20W with mounting studs, 30W vitreous enamel, 5W and 20W with mounting studs. Middle row (wirewound power resistors): 1W, 3W, and 5W axial ceramic; 5W, 10W, 25W, 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.

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

[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.

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.

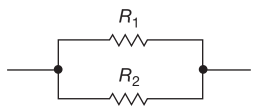

Figure 1.5. Resistors in parallel.

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

$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots} \qquad (1.5)$$

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 $V_{out}=(\sum V_iG_i)/\sum G_i$, 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.

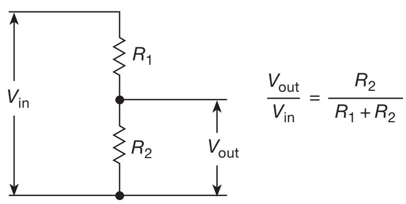

Figure 1.6. Voltage divider. An applied voltage V_{in} results in a (smaller) output voltage V_{out}.

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

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

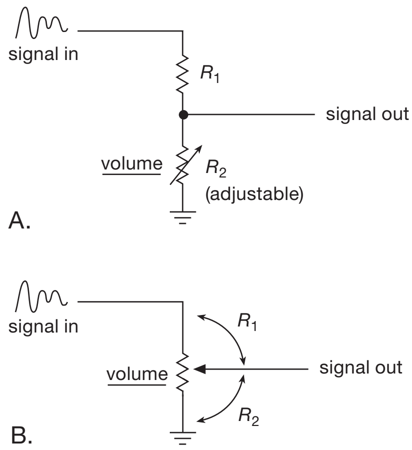

Figure 1.7. An adjustable voltage divider can be made from a fixed and variable resistor, or from a potentiometer. In some contemporary circuits you'll find instead a long series chain of equal-value resistors, with an arrangement of electronic switches that lets you choose any one of the junctions as 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