

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.

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Third Edition

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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.<sup>1</sup> 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.<sup>2</sup> Voltage is also called

<sup>1</sup> 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.

<sup>2</sup> 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.

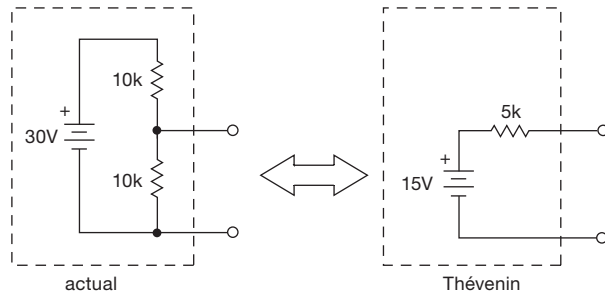


Figure 1.13. Voltage divider example.

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).<sup>15</sup> 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.”<sup>16</sup>

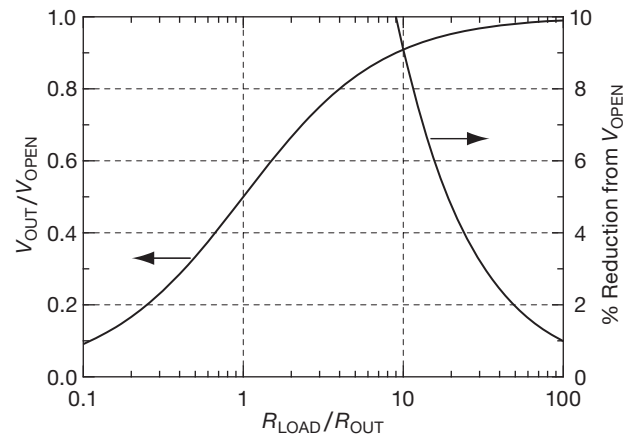


Figure 1.14. To minimize the attenuation of a signal source below its open-circuit voltage, keep the load resistance large compared with the output resistance.

## 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  $R_{\text{load}}=0$  or  $R_{\text{load}}=\infty$  results in zero power transferred, because  $R_{\text{load}}=0$  means that  $V_{\text{load}}=0$  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  $I_{\text{load}}=0$ , so that again  $P_{\text{load}}=0$ . There has to be a maximum in between.

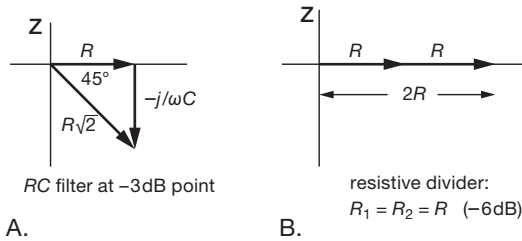
**Exercise 1.11.** Show that  $R_{\text{load}} = R_{\text{source}}$  maximizes the power in the load for a given source resistance. Note: skip this exercise if you don’t know calculus, and take it on faith that the answer is true.

At 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.

<sup>16</sup> The urge to anthropomorphize runs deep in the engineering and scientific community, despite warnings like “don’t anthropomorphize computers ... they don’t like it.”

<sup>15</sup> 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 ra-

i.e.,  $f = 1/2\pi RC$ , and shows that the ratio of output voltage to input voltage is  $1/\sqrt{2}$ , i.e.,  $-3$  dB.



**Figure 1.105.** Phasor diagram for lowpass filter at 3 dB point.

The angle between the vectors gives the phase shift from input to output. At the 3 dB point, for instance, the output amplitude equals the input amplitude divided by the square root of 2, and it leads by  $45^\circ$  in phase. This graphical method makes it easy to read off amplitude and phase relationships in *RLC* circuits. You can use it, for example, to get the response of the highpass filter that we previously derived algebraically.

**Exercise 1.32.** Use a phasor diagram to derive the response of an *RC* high-pass filter:  $V_{\text{out}} = V_{\text{in}}R/\sqrt{R^2 + (1/\omega^2 C^2)}$ .

**Exercise 1.33.** At what frequency does an *RC* lowpass filter attenuate by 6 dB (output voltage equal to half the input voltage)? What is the phase shift at that frequency?

**Exercise 1.34.** Use a phasor diagram to obtain the lowpass filter response previously derived algebraically.

In the next chapter (§2.2.8) we'll see a nice example of phasor diagrams in connection with a constant-amplitude phase-shifting circuit.

### 1.7.13 “Poles” and decibels per octave

Look again at the response of the *RC* lowpass filter (Figures 1.103 and 1.104). Far to the right of the “knee” the output amplitude is dropping proportional to  $1/f$ . In one octave (as in music, one octave is twice the frequency) the output amplitude will drop to half, or  $-6$  dB; so a simple *RC* filter has a 6 dB/octave falloff. You can make filters with several *RC* sections; then you get 12 dB/octave (two *RC* sections), 18 dB/octave (three sections), and so on. This is the usual way of describing how a filter behaves beyond the cutoff. Another popular way is to say a “three-pole filter,” for instance, meaning a filter with three *RC* sections (or one that behaves like one). (The word “pole” derives from a method of analysis that is beyond the scope of this book and that involves complex

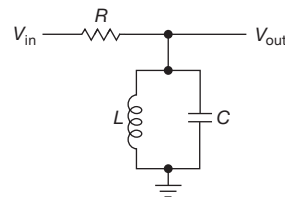
transfer functions in the complex frequency plane, known by engineers as the “*s*-plane.” This is discussed in the advanced volume, in Chapter 1*x*.)

A caution on multistage filters: you can't simply cascade several identical filter sections in order to get a frequency response that is the concatenation of the individual responses. The reason is that each stage will load the previous one significantly (since they're identical), changing the overall response. Remember that the response function we derived for the simple *RC* filters was based on a zero-impedance driving source and an infinite-impedance load. One solution is to make each successive filter section have much higher impedance than the preceding one. A better solution involves active circuits like transistor or operational amplifier (op-amp) interstage “buffers,” or active filters. These subjects will be treated in Chapters 2–4, 6, and 13.

### 1.7.14 Resonant circuits

When capacitors are combined with inductors or are used in special circuits called active filters, it is possible to make circuits that have very sharp frequency characteristics (e.g., a large peak in the response at a particular frequency), compared with the gradual characteristics of the *RC* filters we've seen so far. These circuits find applications in various audio and RF devices. Let's now take a quick look at *LC* circuits (there will be more on them, and active filters, in Chapter 6 and in Appendix E).

#### A. Parallel and series *LC* circuits



**Figure 1.106.** *LC* resonant circuit: bandpass filter.

First, consider the circuit shown in Figure 1.106. The impedance of the *LC* combination at frequency  $f$  is just

$$\begin{aligned}\frac{1}{Z_{LC}} &= \frac{1}{Z_L} + \frac{1}{Z_C} = \frac{1}{j\omega L} - \frac{\omega C}{j} \\ &= j\left(\omega C - \frac{1}{\omega L}\right),\end{aligned}$$

i.e.,

$$Z_{LC} = \frac{j}{(1/\omega L) - \omega C}.$$

# BIPOLAR TRANSISTORS

## CHAPTER 2

### 2.1 Introduction

The transistor is our most important example of an “active” component, a device that can amplify, producing an output signal with more power in it than the input signal. The additional power comes from an external source of power (the power supply, to be exact). Note that *voltage* amplification isn’t what matters, since, for example, a step-up transformer, a “passive” component just like a resistor or capacitor, has voltage gain but no power gain.<sup>1</sup> Devices with power gain are distinguishable by their ability to make oscillators, by feeding some output signal back into the input.

It is interesting to note that the property of power amplification seemed very important to the inventors of the transistor. Almost the first thing they did to convince themselves that they had really invented something was to power a loudspeaker from a transistor, observing that the output signal sounded louder than the input signal.

The transistor is the essential ingredient of every electronic circuit, from the simplest amplifier or oscillator to the most elaborate digital computer. Integrated circuits (ICs), which have largely replaced circuits constructed from discrete transistors, are themselves merely arrays of transistors and other components built from a single chip of semiconductor material.

A good understanding of transistors is very important, even if most of your circuits are made from ICs, because you need to understand the input and output properties of the IC in order to connect it to the rest of your circuit and to the outside world. In addition, the transistor is the single most powerful resource for interfacing, whether between ICs and other circuitry or between one subcircuit and another. Finally, there are frequent (some might say too frequent) situations in which the right IC just doesn’t exist, and you have to rely on discrete transistor circuitry to do the job. As you will see, transistors have an excitement all their own. Learning how they work can be great fun.

<sup>1</sup> It is even possible to achieve modest voltage gain in a circuit comprising only resistors and capacitors. To explore this idea, surprising even to seasoned engineers, look at Appendix J on SPICE.

There are two major species of transistors: in this chapter we will learn about bipolar junction transistors (BJTs), which historically came first with their Nobel Prize-winning invention in 1947 at Bell Laboratories. The next chapter deals with “field-effect” transistors (FETs), the now-dominant species in digital electronics. To give the coarsest comparison, BJTs excel in accuracy and low noise, whereas FETs excel in low power, high impedance, and high-current switching; there is, of course, much more to this complex subject.

Our treatment of bipolar transistors is going to be quite different from that of many other books. It is common practice to use the *h*-parameter model and equivalent circuit. In our opinion that is unnecessarily complicated and unintuitive. Not only does circuit behavior tend to be revealed to you as something that drops out of elaborate equations, rather than deriving from a clear understanding in your own mind as to how the circuit functions; you also have the tendency to lose sight of which parameters of transistor behavior you can count on and, more important, which ones can vary over large ranges.

In this chapter we will instead build up a very simple introductory transistor model and immediately work out some circuits with it. Its limitations will soon become apparent; then we will expand the model to include the respected Ebers–Moll conventions. With the Ebers–Moll equations and a simple three-terminal model, you will have a good understanding of transistors; you won’t need to do a lot of calculations, and your designs will be first rate. In particular, they will be largely independent of the poorly controlled transistor parameters such as current gain.

Some important engineering notation should be mentioned. Voltage at a transistor terminal (relative to ground) is indicated by a single subscript (C, B, or E):  $V_C$  is the collector voltage, for instance. Voltage between two terminals is indicated by a double subscript:  $V_{BE}$  is the base-to-emitter voltage drop, for instance. If the same letter is repeated, that means a power-supply voltage:  $V_{CC}$  is the (positive) power-supply voltage associated with the collector,