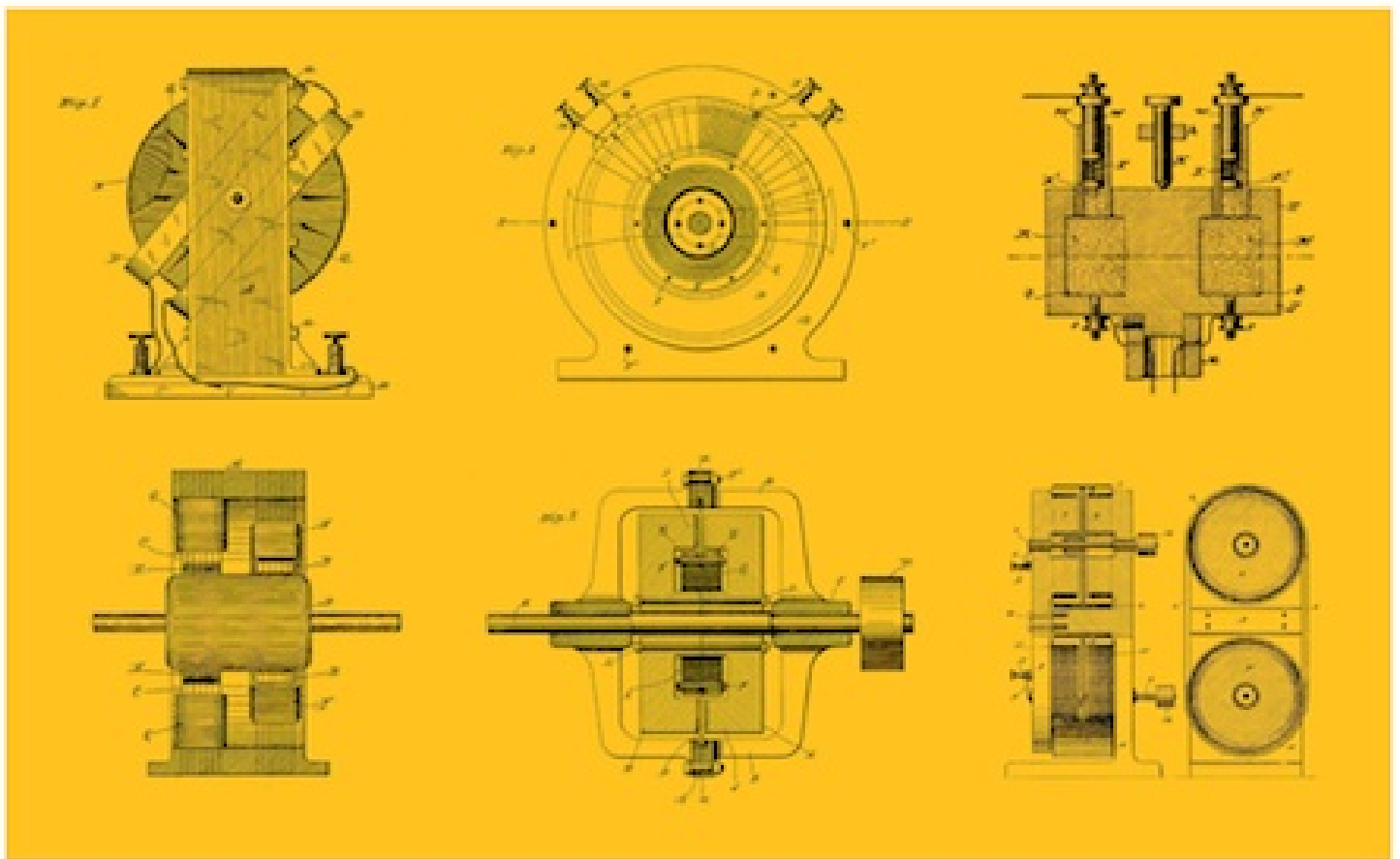


J. M. Hughes

Practical Electronics

Components and Techniques



Practical Electronics: Components and Techniques

John M. Hughes

Practical Electronics: Components and Techniques

by John M. Hughes

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Printed in the United States of America.

Published by O'Reilly Media, Inc., 1005 Gravenstein Highway North, Sebastopol, CA 95472.

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- Editors: Brian Sawyer and Mike Loukides
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- Interior Designer: David Futato
- Cover Designer: Ellie Volckhausen
- Illustrators: John M. Hughes and Rebecca Demarest
- March 2015: First Edition

Revision History for the First Edition

- 2015-03-10: First Release

See <http://oreilly.com/catalog/errata.csp?isbn=9781449373078> for release details.

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978-1-449-37307-8

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Preface

So, how much electronics do you need to know to be able to create something interesting, or creative, or modify something that already exists? Well, that depends on where you start in the creative process. It also depends on your willingness to seek out new knowledge and acquire new skills as you go along.

The primary purpose of this book is to give you a reference for some of the more arcane (and possibly mundane) but essential aspects of electronics. These include things you would typically learn on the job and from years of experience, such as how to read the datasheet for an electronic component, determining how many things can be connected to an interface pin on a microcontroller, how to assemble various types of connectors, how to minimize noise and interference on a signal interface circuit, how to determine the resolution of an analog-to-digital converter, how various types of serial and network interfaces work, and how to use open source tools for schematic capture and PCB layout. And, of course, we will also cover the tools used in electronics work and how they are used, and we'll examine what's available in terms of test equipment beyond the garden-variety digital multimeter.

We'll start off with an introduction to the underlying physics of electricity that dispenses with the water-flowing-in-a-pipe analogy and gets right to the heart of the matter with a look at how atoms pass electrons around. We'll then examine the basic concepts of voltage and current. For those readers who might need or want a more detailed discussion of basic electrical theory, it can be found in [Appendix A](#).

I should point out that this book is not intended to be an in-depth tutorial on electronics theory. There are already many excellent books on that topic, and to repeat that here would just be a pointless exercise in killing trees. So, while there is some introductory material to set the stage, so to speak, the primary intent of this book is to provide you with a reference for topics that aren't usually covered in an electronics text or a step-by-step project book.

With this book, perhaps one or two of the suggested reference works in [Appendix C](#), and your own enthusiasm and ambition, you should be able to create that gadget or system you've been wanting to build and have it work as you intended. And remember, it's not the end of the world if you accidentally convert an electronic component into charcoal. It happens all the time; it's called *learning*.

Who This Book Is For

This book is for anyone with a desire to build an electronic device of some sort, but, to the maximum extent possible, I have made no assumptions about your skill level. What I *have* assumed is that you might not be familiar with the hardware, components, tools, and techniques that are used in electronics, or perhaps you already know something about electronics but could use some help with some of the more arcane aspects of the craft.

With this book as a workbench reference and guide to more detailed sources of information, you should be able to get started on building a nifty gadget and avoid some (hopefully, most) of the pitfalls that await the unwary. I've made the assumption that you will follow the pointers given to learn more about the various topics this book covers, and it covers a lot. It's simply not possible to cover all the topics presented in this book at more than just a surface level; the resulting tome would be huge. In lieu of a lot of details, I've tried to provide enough information to give you a basic understanding of the topics and a foundation to build upon.

So, if you've been thinking about something you'd like to build but aren't sure how to go about it, or you already know a fair amount about electronics but perhaps need some help putting it all together, then this book is for you.

How This Book Is Organized

Each chapter is devoted to a specific topic, ranging from hardware (screws, nuts, and bolts) to tools, and from switches, relays, and passive components to active solid-state parts. Each chapter is designed to allow you to easily find a specific subject and get quick answers to your questions:

Chapter 1: Electrons in Motion

The first chapter provides a high-level “top-of-the-waves” look at electronics, using the notion of electrons in motion as the key to concepts such as voltage, current, and power.

Chapter 2: Fasteners and Adhesives

Often overlooked or taken for granted, fasteners and fastening methods are essential to a successful project. The choice of fasteners can also have a major effect on the aesthetics of a project, so getting the right parts for the job can make the difference between elegant and clunky.

Chapter 3: Tools

This chapter describes the basic tools needed to work with electronics (diagonal cutters, flush cutters, pliers, screwdrivers, etc.), along with some tools not commonly discussed in other texts, including things like crimp tools, rotary tools, step drills, professional grade soldering stations, and magnifiers and microscopes for surface-mount work.

Chapter 4: Tool Techniques

Short sections for each tool discuss its uses and applications, including the correct use of sockets, wrenches, and screwdrivers; how to solder various component types, including surface-mounted components; and how to correctly size the holes needed to mount components like switches, lamps, or printed circuit boards in a chassis or panel.

Chapter 5: Power Sources

An overview of power supplies for both DC and AC current, ranging from batteries to Variac-type devices, this chapter gives special attention to inexpensive DC power supplies in the form of plug-in modules (so-called *wall warts*). It also presents a discussion of fuses and circuit breakers and offers guidance on how to select an appropriate rating for these essential protection devices.

Chapter 6: Switches

This chapter is a survey of the types of switches available and where they are typically used. This covers conventional switches, such as toggles and panel-mount pushbuttons, along with other types, such as PCB-mounted pushbuttons and membrane-type switches.

Chapter 7: Connectors and Wiring

In electronics, almost everything connects to something, somewhere. This chapter describes the various types of connectors available, where they are commonly used, and how to assemble some

of the more common types, such as DB-9, DB-25, high-density terminal blocks, and the 0.1-inch grid pin connectors found on Arduino, Raspberry Pi, and BeagleBone boards. It also covers related topics, such as soldering, crimping, and insulation displacement (IDC) techniques for connector assembly. This chapter deals mostly with those connectors that a typical human being can easily assemble without resorting to a microscope and tweezers, or a special tool that costs hundreds of dollars.

Chapter 8: Passive Components

Passive components are the framework on which circuits are built. This chapter describes commonly encountered passive components such as resistors, capacitors, and inductors, including both through-hole and surface-mounted types. It also describes how to read component markings and how to understand component ratings for power, temperature, and tolerance.

Chapter 9: Active Components

This chapter covers various types of active components, from diodes to ICs, with photos and package outline drawings to illustrate the various types. It also discusses key points to bear in mind when working with active components, such as static sensitivity, heat damage from soldering, and some of the package types available for surface-mount components.

Chapter 10: Relays

Relays might be an old technology, but they are still essential in electronics. This chapter covers the various types of relays available and their typical applications. It describes types ranging from low-current, TTL-compatible reed relays to high-power types used to control AC current. It also covers techniques for controlling a relay from a low-voltage circuit.

Chapter 11: Logic

Along with a condensed description of basic logic components (OR, NOR, AND, NAND, etc.), logic families (TTL, CMOS), and some examples of combinatorial logic circuits, this chapter also presents an introduction to microprocessors and microcontrollers, in terms of what is currently available and what you might need or encounter in your own activities.

Chapter 12: Discrete Control Interfaces

This chapter covers the basics of using a discrete signal (a single logic I/O port) to control things in the physical world. It also includes a discussion on the use of buffers, using both individual transistors and ICs, along with a discussion of current sink and sourcing considerations.

Chapter 13: Analog Interfaces

This chapter describes the basics of analog interfaces, both input and output, and includes discussions on resolution, speed, and the effects of quantization. It also covers aspects of analog I/O, such as voltage range, buffering, and circuit design considerations to reduce noise and

improve performance.

Chapter 14: Data Communication Interfaces

Topics include common interfaces, from board-level SPI and I²C to RS-232, RS-485, USB, and Ethernet. This chapter also covers wireless interfaces, such as generic 2.45 GHz devices, 802.11 wireless networking, ZigBee, and Bluetooth. Serial and parallel, the two primary interface families, are introduced, followed by a discussion of synchronous and asynchronous modes of operation. The remainder of the chapter is organized into sections that cover each topic with a high-level technical discussion, and representative component part numbers are provided where applicable.

Chapter 15: Printed Circuit Boards

This chapter is an overview of PCB design and layout, with a focus on technique rather than specific tools. The chapter starts off with an introduction to PCB technology and concepts, including circuit board substrate materials and circuit trace (or track, if you will) pattern etching and plating techniques. An example from a real project is used to demonstrate the basic steps involved in creating a double-sided PCB layout. The chapter wraps up with a collection of general guidelines and tips.

Chapter 16: Packaging

A guide to the various options available for physically housing electronics, this chapter includes a discussion of plastic versus metal, sources for chassis components, and the use of unconventional enclosures to create unique packaging prototypes. Examples are given for commercial off-the-shelf packages in the form of small plastic enclosures, metal enclosures using both aluminum and steel sheet metal, extruded aluminum packages, and heavy-gauge kits for more demanding applications.

Chapter 17: Test Equipment

A short tour of inexpensive test equipment, this chapter starts with the ubiquitous digital multimeter and moves on to oscilloscopes, signal generators, and logic analyzers. The examples include readily available, low-cost devices such as single- and dual-channel pocket digital oscilloscopes from China, and a multi-waveform signal generator module for the Arduino. The intent is to give you some suggestions that don't involve breaking the bank to purchase high-end test equipment (not that there's anything wrong with high-end gear—it's generally excellent; it just happens to be rather expensive).

Appendix A: Essential Electronics and AC Circuits

For anyone interested, or anyone who could benefit from it for their projects, this appendix presents a terse, high-level overview of basic electronics theory beyond what [Chapter 1](#) provides. Topics covered include capacitance, series and parallel resistor and capacitor circuits, basic AC circuit theory, inductance, noise, impedance, and grounding techniques.

Appendix B: Schematics

This appendix defines the basics of schematic drawings, with examples of commonly encountered symbols. Light on text but heavy on graphics, this appendix is intended to be a place where you can quickly find the definition for a particular symbol. It also describes some available open source tools for creating schematic diagrams.

Glossary

The glossary provides definitions of many key terms and acronyms used in this book.

Appendix C: Bibliography

This appendix provides a bibliography of the suggested reference texts presented throughout the book, organized by topic.

Appendix D: Resources

This appendix includes URLs for electronics distributors, sources for mechanical components, and vendors of surplus components of various types, as well as a brief discussion of buying electronic components and other items from vendors on eBay, with some guidance and caveats.

Appendix E: Components Lists

This appendix lists most all of the IC components and modules mentioned in this book. While this collection is by no means comprehensive, it does contain enough representative parts from each category to provide a solid starting point for a new design.

Conventions Used in This Book

The following typographical conventions are used in this book:

Italic

Indicates new terms, URLs, email addresses, filenames, and file extensions.

Constant width

Used for program listings, as well as within paragraphs to refer to program elements such as variable or function names, databases, data types, environment variables, statements, and keywords.

Constant width bold

Shows commands or other text that should be typed literally by the user.

Constant width italic

Shows text that should be replaced with user-supplied values or by values determined by context.

This element signifies a tip or suggestion.

This element indicates a warning or caution.

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Acknowledgments

This book would not have been possible without the enduring patience and support of my family. In particular, I would like to acknowledge the photography and organizational assistance of my daughter Seren, who put up with my fussiness and took yet another picture of something or other in the light tent for me when I didn't like the pose or lighting of the first (or second, or third) attempt. And, of course, my lovely wife, Carol, who would bring me things to eat in my shop and fret about me losing sleep.

Special thanks to Mike Westerfield for his technical review and input. It's always good to have more than one pair of eyes on the details, and Mike pointed out some rough spots that needed some editing and clarification. The end result is a better book, and it just goes to show why review is a crucial part of any development process.

The feedback from readers of the early release has been invaluable. Special thanks to those who suggested additions for the bibliography in Appendix D (you know who you are) and for the many helpful comments and constructive criticisms.

I would also like to thank the editorial staff at O'Reilly for the opportunity to work with them once again, especially Brian Sawyer for his willingness to put up with me in general, Mike Loukides for giving me this opportunity to write another book for O'Reilly, and the Atlas team for responding to my technical issues in a timely and helpful manner.

Chapter 1. Electrons in Motion

The field of electrical theory and electronics is huge, and it can be somewhat daunting at first. In reality, you don't need to know all the little theoretical details to get things up and running. But to give your efforts a better chance at success, it is a good idea to understand the basics of what electricity is and how, in general terms, it works. So that's what we're going to look at here.

The main intent of this chapter is twofold. First, I want to dispense with the old “water-flowing-in-a-pipe” analogy that has been used in the past to describe the flow of electrons in a conductor; it's not very accurate and can lead to some erroneous assumptions. There is, I believe, a better way to visualize what is going on, but it does require a basic understanding of what an atom is and how its component parts work to create electric charge and, ultimately, electric current. It might sound rather like something from the realm of physics (and, to be honest, it is, along with chemistry), but once you understand these concepts, things like fluorescent lights, neon signs, lightning, arc welders, plasma cutting torches, heating elements, and the electronic components you might want to use in a project will become easier to understand. The old water-flowing-in-a-pipe model doesn't really scale very well, nor does it translate easily to anything other than, well, water flowing through a pipe.

Second, I'd like to build on this atom-based model to introduce some basic concepts that will come up later as you work on your own projects. By the end of this chapter, you should have a good idea of what the terms *voltage*, *current*, and *power* mean and how to calculate these values. If you need more details on a lower level, you'll find them in [Appendix A](#), including overviews of serial and parallel circuits, and basic AC circuit concepts. Of course, numerous excellent texts are readily available on the subject, and I encourage you to seek them out if you would like to dig deeper into the theory of electronics.

If you are already familiar with the basic concepts of electronics, feel free to skip this chapter. Just don't forget to take advantage of [Appendix A](#) and the suggested references in [Appendix C](#) if you run into a need for further details somewhere along the line.

Atoms and Electrons

In common everyday usage, the term *electricity* is used to refer to the stuff that one finds inside a computer, in a wall outlet, in the wires strung between poles beside the street, or at the terminals of a battery. But just what *is* this stuff, really?

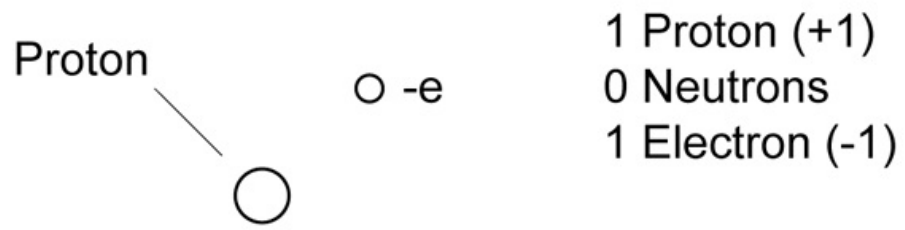
Electricity is the physical manifestation of the movement of *electrons*, little specks of subatomic matter that carry a negative electrical charge. As we know, all matter is composed of *atoms*. Each atom has a nucleus at its core with a net positive charge. Each atom also has one or more negative electrons bound to it, each one whipping around the positively charged nucleus in a quantum frenzy.

It is not uncommon to hear of the “orbit” of an electron about the nucleus, but this isn't entirely accurate, at least not in the classical sense of the term *orbit*. An electron doesn't orbit the nucleus of an atom in the way a planet orbits a star or a satellite orbits the earth, but it's a close enough

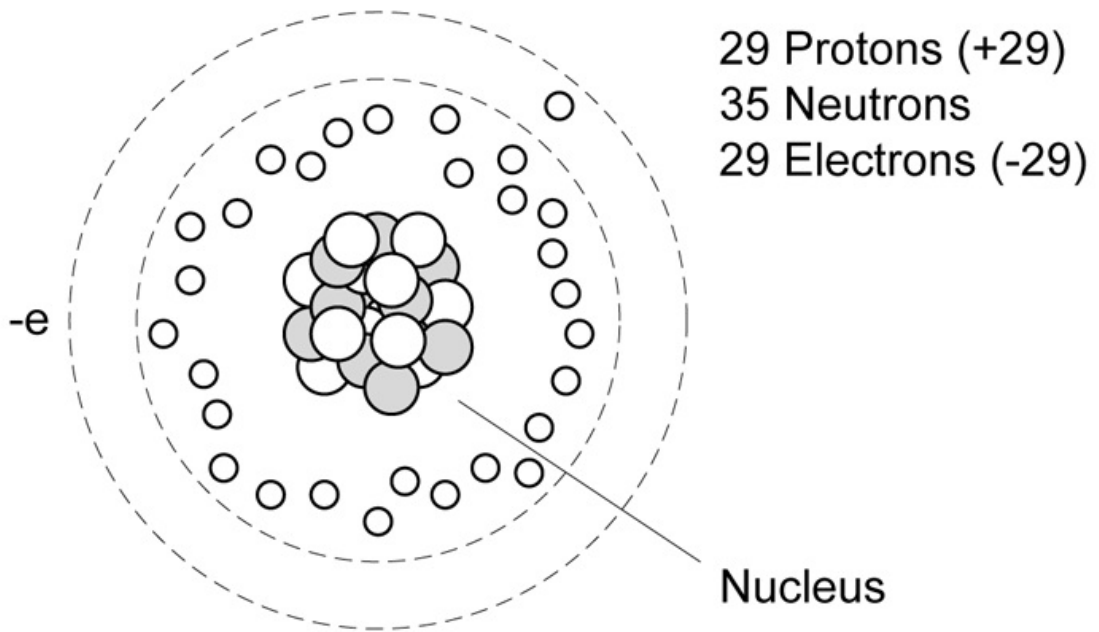
approximation for our purposes.

In reality, it's more like layers of clouds wrapped around the nucleus, with the electrons being somewhere in the layers of the cloud. One way to think of it is as a probability cloud, with a high probability that the electron is somewhere in a particular layer. Due to the quirks of quantum physics we can't directly determine where an electron is located in space at any given time without breaking things, but we can infer where it is by indirect measurements. Yes, it's a bit mind-numbing, so we won't delve any deeper into it here. If you want to know more of the details, I would suggest a good modern chemistry or physics textbook, or for a more lightweight introduction, you might want to check out the "Mr. Tompkins" series of books by the late theoretical physicist George Gamow.

The nucleus of most atoms is made up of two basic particles: *protons* and *neutrons*, with the exception of the hydrogen atom, which has only a single positive proton as its nucleus. A nucleus may have many protons, depending on what type of atom it happens to be (iron, silicon, oxygen, etc.). Each proton has a positive charge (called a *unit charge*). Most atoms also have a collection of neutrons, which have about the same mass as a proton but no charge (you might think of them as ballast for the atom's nucleus). **Figure 1-1** shows schematic representations of a hydrogen atom and a copper atom.



Hydrogen



Copper

Figure 1-1. Hydrogen and copper atoms

The +1 unit charges of the protons in the nucleus will cancel out the -1 unit charges of the electrons, and the atom will be electrically neutral, which is the state that atoms want to be in. If an atom is missing an electron, it will have a net positive charge, and an extra electron will give it a net negative charge.

The electrons of an atom are arranged into what are called *orbital shells* (the clouds mentioned earlier), with an outermost shell called the *valence shell*. Conventional theory states that each shell has a unique energy level and each can hold a specific number of electrons. The outermost shell typically determines the chemical and conductive properties of an atom, in terms of how easily it can release or receive an electron. Some elements, such as metals, have what is considered to be an “incomplete” valence shell. Incomplete, in this sense, means that the shell contains fewer than the maximum possible number of electrons, and the element is chemically reactive and able to exchange electrons with other atoms. It is, of course, more complex than that, but a better definition is way beyond the scope of this book.

For example, notice that the copper atom in [Figure 1-1](#) has 29 electrons and one is shown outside of the main group of 28 (which would be arranged in a set of shells around the nucleus, not shown here for clarity). The lone outermost electron is copper’s valence electron. Because the valence shell of copper is incomplete, this electron isn’t very tightly bound, so copper doesn’t put up too much of a fuss about passing it around. In other words, copper is a relatively good conductor.

An element such as sulfur, on the other hand, has a complete outer shell and does not willingly give up any electrons. Sulfur is rated as one of the least conductive elements, so it’s a good insulator. Silver tops the list as the most conductive element, which explains why it’s considered useful in electronics. Copper is next, followed by gold. Still, other elements are somewhat ambivalent about conducting electrons, but will do so under certain conditions. These are called *semiconductors*, and they are the key to modern electronics.

This should be a sufficient model for our purposes, so we won’t pry any further into the inner secrets of atomic structure. What we’re really interested in here is what happens when atoms do pass electrons around, and why they would do that to begin with.

Electric Charge and Current

Electricity involves two fundamental phenomena: electric charge and electric current. *Electric charge* is a basic characteristic of matter and is the result of something having too many electrons (negative charge), or too few electrons (positive charge) with regard to what it would otherwise need to be electrically neutral. An atom with a negative or positive charge is sometimes called an *ion*.

A basic characteristic of electric charges is that charges of the same kind repel one another, and opposite charges attract. This is why electrons and protons are bound together in an atom, although under most conditions they can’t directly combine with each other because of some other fundamental characteristics of atomic particles (the exceptional cases are a certain type of radioactive decay and inside a stellar supernova). The important thing to remember is that a negative charge will repel electrons, and a positive charge will attract them.

Electric charge, in and of itself, is interesting but not particularly useful from an electronics perspective. For our purposes, really interesting things begin to happen only when charges are moving. The movement of electrons through a circuit of some kind is called *electric current*, or *current flow*, and it is also what happens when the static charge you build up walking across a carpet on a cold, dry day is transferred to a doorknob. This is, in effect, the current (flow) moving between a high potential

(you) to a lower potential (the doorknob), much like water flows down a waterfall or a rock falls down the side of a hill. The otherwise uninteresting static charge suddenly becomes very interesting (or at least it should get your attention). When a charge is not in motion, it is called the *potential*, and yes, we can make an analogy between electrical potential and mechanical potential energy, as you'll see shortly.

Current flow arises when the atoms that make up the conductors and components of electrical circuit transfer electrons from one to another. Electrons move toward things that are positive, so if you have a small light bulb attached to a battery with some wires (sometimes also known as a *flashlight*), the electrons move out of the negative terminal of the battery, through the light bulb, and return back into the positive terminal. Along the way, they cause the filament in the lamp to get white-hot and glow.

Figure 1-2, a simplified diagram of some copper atoms in a wire, shows one way to visualize the current flow. When an electron is introduced into one end of the wire, it causes the first atom to become negatively charged. It now has too many electrons. Assuming a continuous source of electrons, the new electron cannot exit the way it came in, so it moves to the next available neutral atom. This atom is now negative and has a surplus electron. In order to become neutral again (the preferred state of an atom), it then passes an extra electron to the next (neutral) atom, and so on, until an electron appears at the other end of the wire. So long as there is a source of electrons under pressure connected to the wire and a return path for the electrons back to the source, current will flow. The pressure is called *voltage*, which **“Current Flow in a Basic Circuit”** will discuss in more detail.

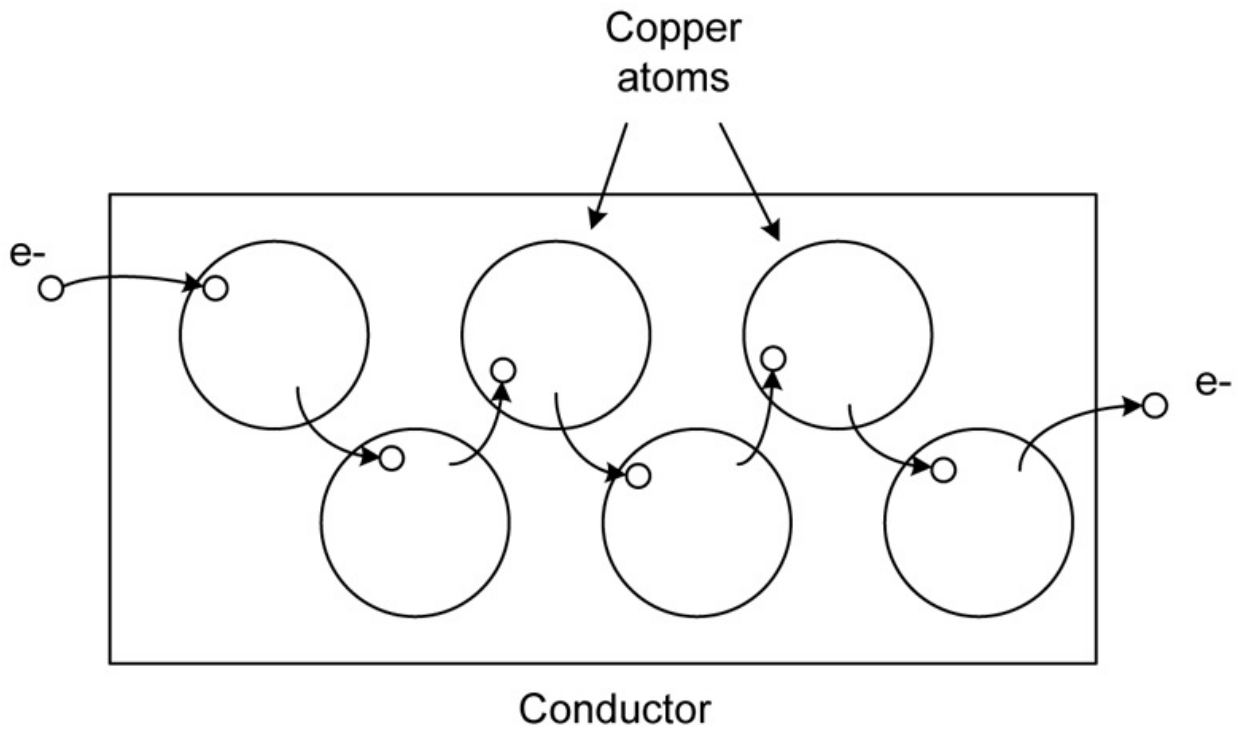


Figure 1-2. Electrons moving in a wire

Figure 1-3 shows another way to think about current. In this case, we have a tube (a conductor) filled end to end with marbles (electrons).

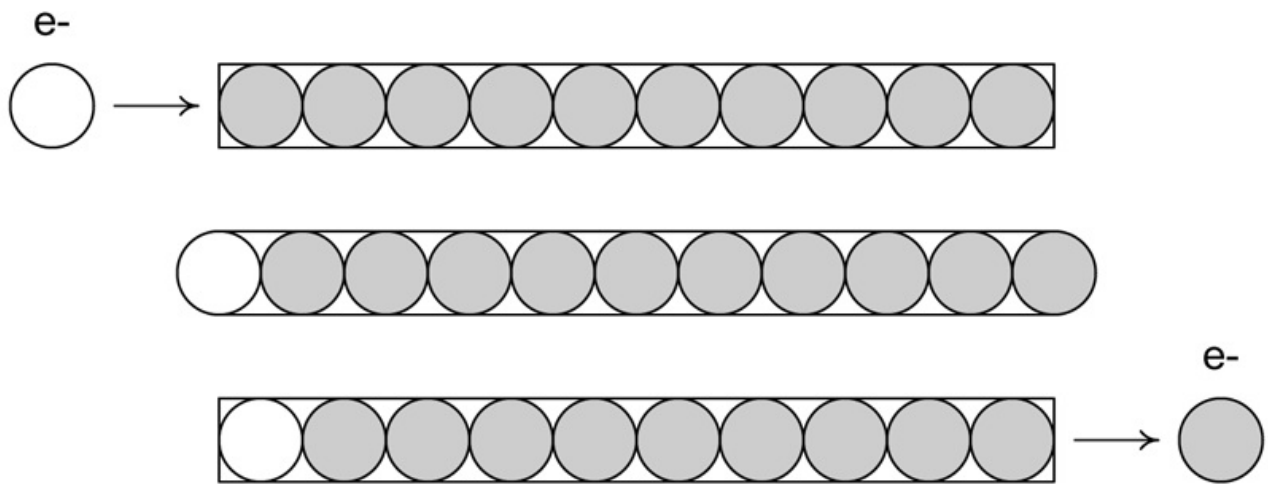


Figure 1-3. Modeling electrons with marbles in a tube

When we push a marble into one end of the tube in [Figure 1-3](#), a marble falls out the opposite end. The net number of marbles in the tube remains the same. Note that the electrons put into one end of a conductor are not necessarily the ones that come out the other end, as you can see from [Figures 1-2](#) and [1-3](#). In fact, if the conductor is long enough, the electrons introduced at one end might not be the ones that appear at the other end, but electrons would appear, and you would still be able to measure electron movement in the conductor.

Current Flow in a Basic Circuit

Electricity flows when a closed circuit allows for the electrons to move from a high potential to a lower potential in a closed loop. Stated another way, current flow requires a source of electrons with force to move them, as well as a return point for the electrons.

Electric current flow (a physical phenomenon) is characterized by four fundamental quantities: voltage, current, resistance, and power. We'll use the simple circuit shown in [Figure 1-4](#) as our baseline for the following discussion. Notice that the circuit is shown both in picture and schematic form. For more about schematic symbols, refer to [Appendix B](#).

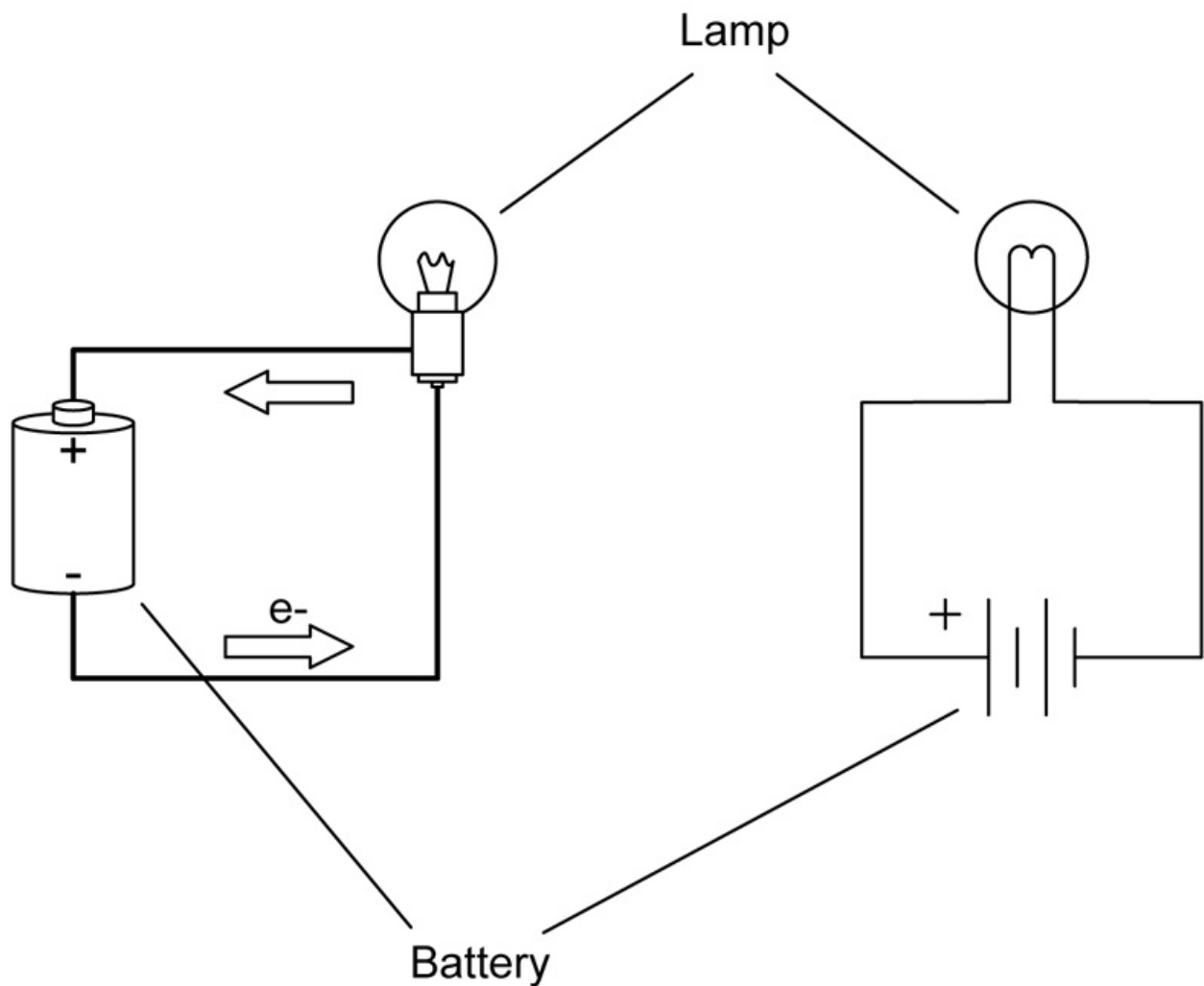


Figure 1-4. A simple DC circuit

A few words about the term *current* are in order here. The word has more than one meaning in electronics, which can be confusing at first. In one sense, current refers to the flow of electrons through a conductor of some kind. It is a reference to the movement of charge carried by the electron. In the other sense, current refers to the number of electrons moving through the conductor. In this sense, it specifies the volume of electrons moving past some point in the circuit at some point in time. In other words, the measurement of current is the determination of the quantity of electrons in motion.

One way to think about current is to remember that it cannot be measured without movement, so when you see or hear the word *current*, it is usually referring to movement. To make the distinction clear, the term *current flow* is often used to mean movement of electrical charges. Static charges, even if just at the terminals of a common battery, have no current flow and hence no measurable current.

Current that flows in only one direction, as in **Figure 1-4**, is called *direct current* (DC). A common battery produces DC, as does the DC power supply in a typical computer system. Current that changes direction repeatedly is called *alternating current* (AC). AC is what comes out of a household wall socket (in the US, for example). It is also the type of current that drives the loudspeakers in a stereo.

system. The rate at which the current changes direction is called the *frequency* and is measured in cycles per second in units of Hertz (abbreviated Hz). So, a 60 Hz signal is made up of a current flow changing direction 60 times per second. When AC is used to drive a loudspeaker, a signal with a frequency of 440 Hz will be A above middle C to our ears.

By convention, DC is described as flowing from positive to ground (negative), whereas in reality, electrons flow from the negative terminal to the positive terminal of the power source. In [Figure 1-4](#), the arrows show the electron flow. Basically, the discrepancy stems from an erroneous assumption made by Benjamin Franklin, who thought that electrons had a positive charge and flowed from positive to negative terminals. He guessed wrong, but we ended up with a convention that was already well ingrained by the time physicists figured out what was really going on. Hence we have conventional current flow and electron current flow. Although you should be aware of this discrepancy, from this point onward, we'll use conventional current flow, since that is what most of the electronics industry uses.

A *volt* (V) is the unit of measurement used for electric potential difference, electric potential, and electromotive force. When the term *voltage* is used, it usually refers to the electric potential difference between two points. In other words, we say that a static charge has a value of some number of volts (potential), but there is a certain amount of voltage between two points in a circuit (potential difference).

Voltage can be visualized as a type of pressure, or driving force (although it is not actually a force in mechanical sense). This is the electromotive force (emf) produced by a battery or a generator of some type, and the emf can drive a current through a circuit. And even though it may not look like a generator, a power supply (like the one that plugs into the wall socket to charge a cell phone) is really nothing more than a converter for the output of a generator at a power plant somewhere.

Another way to think of voltage is as the electric potential difference between two points in an electric field. It is similar to the difference in the potential energy of a cannonball at the top of a ladder as opposed to one at the top of a tall tower. Both cannonballs exist in the earth's gravitational field, they both have potential energy, and it took some work to get them both into position. When they are released, the cannonball on the top of the tower will have more energy when it hits the ground than the cannonball dropped from the top of the ladder, because it had a larger potential energy due to its position.

These two descriptions of voltage are really just opposite sides of the same coin. In order to create a potential difference between two points, work must be done. When that energy is lost or used, there is a potential drop. When the cannonball hits the ground, all of the energy put into getting it into position against the pull of gravity is used to make a nice dent in the ground.

The main point here to remember is that a high voltage has more available electrical energy (pressure) than a low voltage. This is why you don't get much more than a barely visible spark when you short out a common 9-volt battery with a piece of wire, but lightning, at around 10,000,000 volts (or more!) is able to arc all the way between a cloud and the ground in a brilliant flash. The lightning has more voltage and hence a larger potential difference, so it is able to overcome the insulating effects of the intervening air.

Whereas voltage can be viewed as electrical pressure, current is the measure of the quantity, or

volume, of electrons moving through a circuit at some given point. Remember that the term *current* can have two different meanings: electron movement (flow) and the volume of the electron flow. In electronics, the word *current* usually means the quantity of electrons flowing through a conductor at specific point at a single instant in time. In this case, it refers to a physical quantity and is measured in units of amperes (abbreviated as A).

Now that we've looked at voltage and current, we can examine some of the things that happen while charge is in motion (current flow) at some particular voltage. No matter how good a conventional conductor happens to be, it will never pass electrons without some resistance to the current flow (superconductors get around this, but we're not going to deal with that topic here). *Resistance* is the measure of how much the current flow is impeded in a circuit, and it is measured in units of ohms, named after German physicist Georg Simon Ohm. "**Resistance**" has more details about the physical properties of resistance, but for now, let's consider how resistance interacts with current flow.

You might think of resistance as an analog of mechanical friction (but the analogy isn't perfect). When current flows through a resistance, some of the voltage potential difference is converted to heat and there will be a voltage drop across the resistor. How much heat is generated is a function of how much current is flowing through the resistance and the amount of the voltage drop. We'll look at this more closely in "**Power**".

You can also think of resistance as the degree of "stickiness" that an atom's valence shell electrons will exhibit. Atoms that can give up or accept electrons easily will have low resistance, whereas those that want to hold onto their electrons will exhibit higher resistance (and, of course, those that don't readily give up electrons under normal conditions are good insulators).

Carbon, for example, will conduct electricity, but not as easily as copper. Carbon is a popular material for fabricating the components called resistors used in electronic circuits. **Chapter 8** covers passive components, such as resistors.

Ohm's Law

As you may have already surmised, there is a fundamental relationship between voltage, current, and resistance. This is the famous equation called *Ohm's law*. It looks like this:

$$E = IR$$

where E is voltage (in volts), I is current (in amperes), and R is resistance (in ohms).

This simple equation is fundamental to electronics, and indeed it is often the only equation that you really need to get things going. In **Figure 1-4**, the circuit has only two components: a battery and a lamp. The lamp comprises what is called the *load* in the circuit, and it exhibits a resistance to current flow. Incandescent lamps have a resistance that varies according to temperature, but for our purposes we'll assume that the lamp has a resistance of 2 ohms when it is glowing brightly.

The battery is 1.5 volts, and for the purposes of this example, we'll assume that it is capable of delivering a maximum current of 2,000 milliamps (or mA) for one hour at its rated output voltage. This is the battery's total rated capacity, which is usually around 2,000 mAh (milliamp-hour) for a typical alkaline AA type battery. A *milli* is one-thousandth of something, so 2,000 mA is the same as

amps of current.

Applying Ohm's law, we can find the amount of current the lamp will draw from the battery by solving for I :

$$I = E/R$$

or:

$$I = 1.5/2$$

$$I = 0.75 \text{ A}$$

Here, the value for I can also be written as 750 mA (milliamperes). If you want to know how long the battery will last, you can divide its capacity by the current in the circuit:

$$2/0.75 = 2.67 \text{ hours (approximately)}$$

Power

In the simple circuit shown in **Figure 1-4**, the flow of electrons through the filament in the lamp causes it to heat up to the point where it glows brightly (between 1,600 to 2,800 degrees C or so). The filament in the lamp gets hot because it has resistance, so current flows less easily through the filament than it does through the wires in the circuit.

Power is the rate of doing work per unit of time, and is measured in watts. One watt is defined as the use or generation of 1 joule of energy per second. In an electrical circuit, a watt can also be defined as 1 ampere of current moving through a resistance at 1 volt of potential, and when charges move from high voltage to a low voltage (a potential difference) across a resistive device, the energy in the potential is converted to some other form, such as heat or mechanical energy.

We can calculate power (P) in a DC circuit by multiplying the voltage by the current:

$$P = EI$$

In the case of the simple flashlight circuit, the power expended to force the current through the filament is expressed as heat, and subsequently as light when the filament gets hot enough to glow. If you want to know how much power the light bulb in our circuit is consuming, simply multiply the voltage across the bulb by the current:

$$P = 1.5 \times 0.75$$

$$P = 1.125 \text{ watts, or } 1.125\text{W}$$

Let's compare this power value with the rating for a common incandescent light bulb with a 100W rating. An old-style 100W light bulb operating at 110 VAC (volts AC, typical household voltage in the US) will use:

$$I = PE$$

$$I = 100/110$$

$$I = 0.9\text{A}$$

Amazing! The large light bulb consumes only a bit more current than the tiny light bulb connected to

a battery! How can this be?

The difference lies in the voltage supplied to the light bulbs and their internal resistance. Now that you have an estimate of the amount of current flowing through a 100W bulb, you could easily work out what its internal resistance might be. You should also be able to see why leaving lights on (or using old-style light bulbs at all) is wasteful. The current adds up, and each watt of power costs money.

Resistance

Now let's look at the phenomenon of resistance more closely, since it is such a fundamental aspect of electronics. Formally stated, 1 ohm is equal to the resistance between two points of a conductor when a potential of 1 volt produces a current of 1 ampere. This is, of course, the relationship defined by Ohm's law, discussed in "Ohm's Law".

Resistance is a key factor in electric circuits, which is why it is one of the three variables in the Ohm's law equation. As stated earlier, every circuit has some amount of resistance, except for things like exotic superconductors. Even the wires connecting a battery to a device have some intrinsic resistance.

Switches have internal resistance, as do connectors and even the copper traces on a printed circuit board (PCB). **Figure 1-5** illustrates this by showing a simple DC circuit and its resistance equivalent.

You might notice in **Figure 1-5** that even the battery has some internal resistance. **Appendix A** discusses series and parallel resistances, and how to calculate their values, but the point here is to show how nothing is free in the world of circuits. Resistance is everywhere, as far as electrons are concerned.

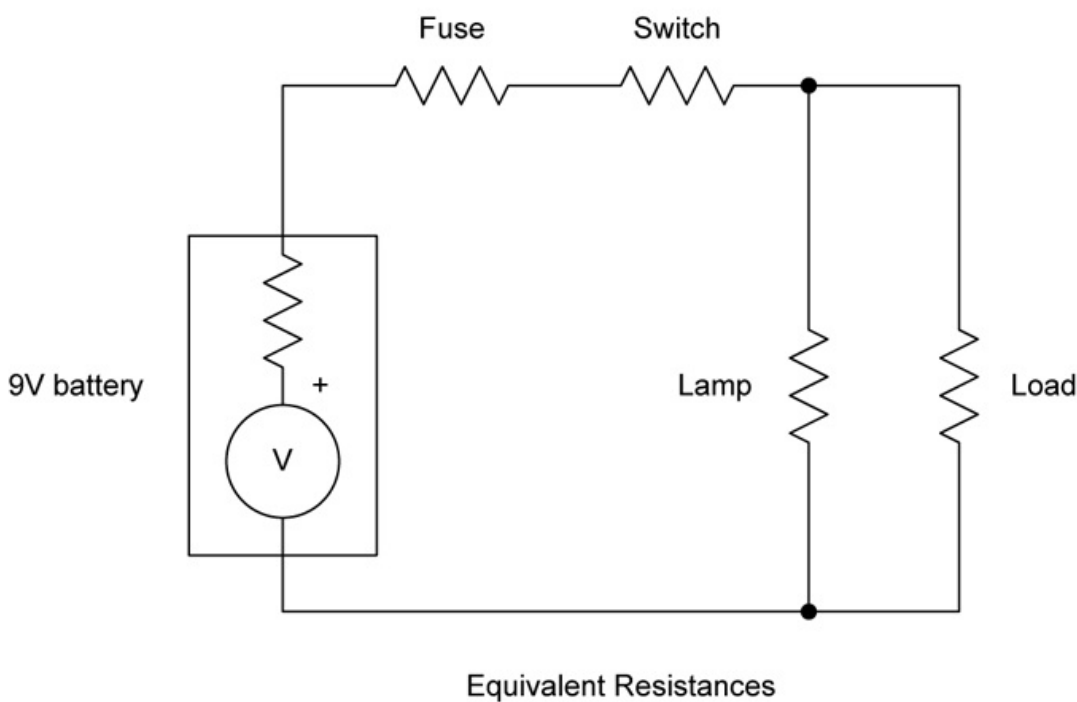
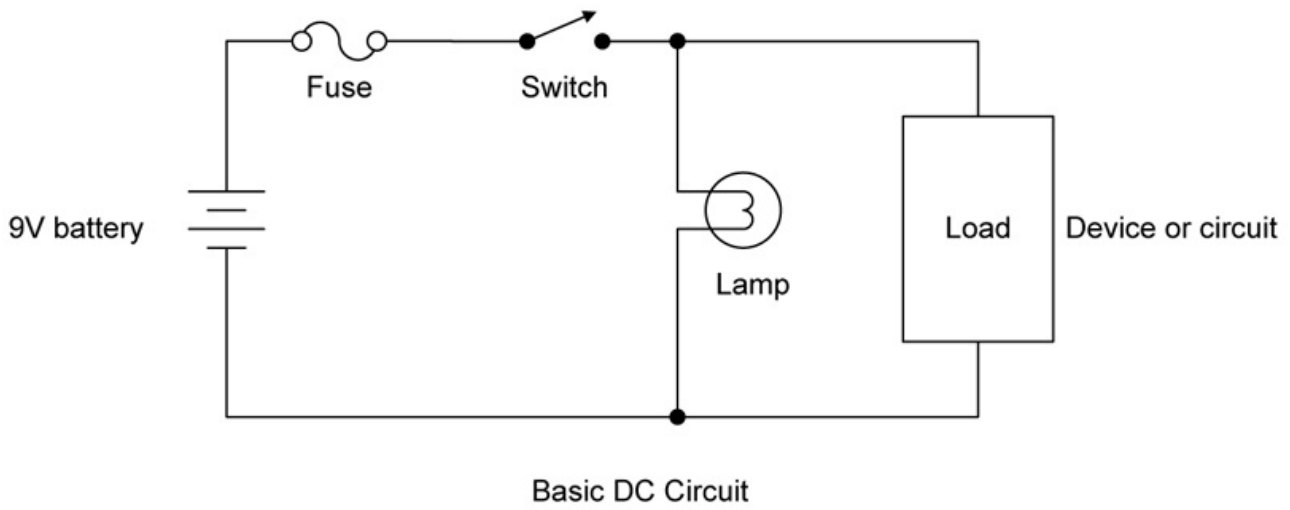


Figure 1-5. Circuit resistance example

Normally, this intrinsic resistance is ignored, as it tends to be small and doesn't really impact the overall operation of a device. However, if the device is a low-current one intended to run for a long time without the battery being changed, then it starts to become something to consider. Resistance to current flow means that energy is being expended pushing electrons through the resistive element, and that energy is dissipated as heat. Unless you are intentionally using a resistance as a heater (which is what electrical heating elements do), it is being wasted.

In electronics, the passive components called *resistors* are probably the most commonly used parts. Resistors come in a range of values and power ratings, from ultra-tiny little flecks for surface-mount use to huge devices used in diesel-electric locomotives to dissipate excess energy created during dynamic braking. [Figure 1-6](#) shows a typical 1/4-watt carbon composition resistor. See [Chapter 8](#) for

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