Burn things out, mess things up—that's how you learn.

Make: Electronics

Second Edition

Charles Platt

A HANDS-ON PRIMER FOR THE NEW ELECTRONICS ENTHUSIAST

Learning by Discovery

SECOND EDITION

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by Charles Platt

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Dedication

To readers of the first edition of Make: Electronics who contributed many ideas and suggestions for this second edition. In particular: Jeremy Frank, Russ Sprouse, Darral Teeples, Andrew Shaw, Brian Good, Behram Patel, Brian Smith, Gary White, Tom Malone, Joe Everhart, Don Girvin, Marshall Magee, Albert Qin, Vida John, Mark Jones, Chris Silva, and Warren Smith. Several of them also volunteered to review the text for errors. Feedback from my readers continues to be an amazing resource.

Acknowledgments

I discovered electronics with my school friends. We were nerds before the word existed. Patrick Fagg, Hugh Levinson, Graham Rogers, and John Witty showed me some of the possibilities.

It was Mark Frauenfelder who nudged me back into the habit of making things. Gareth Branwyn facilitated Make: Electronics, and Brian Jepson enabled the sequel and this new edition. They are three of the best editors I have known, and they are also three of my favorite people. Most writers are not so fortunate.

I am also grateful to Dale Dougherty for starting something that I never imagined could become so significant, and for welcoming me as a participant.

Russ Sprouse and Anthony Golin built and tested the circuits. Technical fact checking was provided by Philipp Marek, Fredrik Jansson, and Steve Conklin. Don't blame them if there are still any errors in this book. It's much easier for me to make an error than it is for someone else to find it.

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What's New in the Second Edition

All of the text from the first edition of this book has been rewritten, and most of the photographs and schematics have been replaced.

Single-bus breadboards are now used throughout (as in *Make: More Electronics*) to reduce the risk of wiring errors. This change entailed rebuilding the circuits, but I believe it was worthwhile.

Diagrams showing component placement are now used instead of photographs of breadboarded circuits. I think the diagrams are clearer.

Internal views of breadboard connections have been redrawn to match the revisions noted above.

New photographs of tools and supplies have been included. For small items, I have used a ruled background to indicate the scale.

Where possible, I have substituted components that cost less. I have also reduced the range that you need to buy.

Three experiments have been completely revised:

- The Nice Dice project that used LS-series 74xx chips in the first edition now uses 74HCxx chips, to be consistent with the rest of the book and with modern usage.
- The project using a unijunction transistor has been replaced with an astable multivibrator circuit using two bipolar transistors.
- The section on microcontrollers now recognizes that the Arduino has become the most popular choice in the Maker community.

New Component Kits

Many of these improvements were suggested by my readers, and all of them have made this a better book. Unfortunately, the changes have created a compatibility problem: component kits that were marketed for the first edition are not compatible with the second edition.

To obtain kits that match this edition of the book, see Chapter 6 for instructions. Please be careful not to buy old kits that may still be offered for sale from third parties on eBay or Amazon. Some kits that were made by Radio Shack, in particular, are being resold by individuals. I regret that I have no control over this. Just be aware that if a kit doesn't refer specifically to the second edition of this book, it is probably not compatible.

Other Changes

In addition, two projects involving workshop fabrication using ABS plastic have been omitted, as many readers did not seem to find them useful.

All the page layouts have been changed to make them easily adaptable for handheld devices. The formatting is controlled by a plaintext markup language, so that future revisions will be simpler and quicker. We want the book to remain relevant and useful for many more years to come.

--Charles Platt, 2015

Preface: How to Have Fun with This Book

Everyone uses electronic devices, but most of us don't really know what goes on inside them.

You may feel that you don't need to know. You can drive a car without understanding the workings of an internal combustion engine, so why should you learn about electricity and electronics?

I think there are three reasons:

- By learning how technology works, you become better able to control your world instead of being controlled by it. When you run into problems, you can solve them instead of feeling frustrated by them.
- Learning about electronics can be fun, so long as you approach the process in the right way. It is also very affordable.
- Knowledge of electronics can enhance your value as an employee, or perhaps even lead to a whole new career.

Learning by Discovery

Most introductory guides begin by using definitions and theory to explain some fundamental concepts. Circuits are included to demonstrate what you have been told.

Science education in schools often follows a similar plan. I think of this as *learning by explanation*.

This book works the other way around. I want you to dive right in and start putting components together without necessarily knowing what to expect. As you see what happens, you will figure out what's going on. This is *Learning by Discovery*, which I believe is more fun, more interesting, and more memorable.

Working on an exploratory basis, you run the risk of making mistakes. But I don't see this as a bad thing, because mistakes are a valuable way to learn. I want you to burn things out and mess things up, to see for yourself the behavior and limitations of the parts that you are dealing with. The very low voltages used throughout this book may damage sensitive components, but will not damage you.

The key requirement of Learning by Discovery is that it has to be hands-on. You can derive some value from this book merely by reading it, but you will enjoy a much more valuable experience if you perform the experiments yourself.

Fortunately, the tools and components that you need are inexpensive. Hobby electronics should not cost significantly more than a recreation such as needlepoint, and you don't need a workshop. Everything can be done on a tabletop.

Will It Be Difficult?

I assume that you're beginning with no prior knowledge. Consequently, the first few experiments will be extremely simple, and you won't even use prototyping boards or a soldering iron.

I don't believe that the concepts will be hard to understand. Of course, if you want to study electronics more formally and do your own circuit design, that can be challenging. But in this book I have kept theory to a minimum, and the only math you'll need will be addition, subtraction, multiplication, and division. You may also find it helpful (but not absolutely necessary) if you can move decimal points from one position to another.

How This Book Is Organized

An introductory book can present information in two ways: in tutorials or in reference sections. I decided to use both of these methods.

You'll find the *tutorials* in sections headed as follows:

- Experiments
- What You Will Need
- Cautions

Experiments are the heart of the book, and they have been sequenced so that the knowledge you gain at the beginning can be applied to subsequent projects. I suggest that you perform the experiments in numerical order, skipping as few as possible.

You'll find *reference sections* under the following headings:

- Fundamentals
- Theory
- Background

I think the reference sections are important (otherwise, I would not have included them), but if you're impatient, you can dip into them at random or skip them and come back to them later.

If Something Doesn't Work

Usually there is only one way to build a circuit that works, while there are hundreds of ways to make mistakes that will prevent it from working. Therefore the odds are against you, unless you proceed in a really careful and methodical manner.

I know how frustrating it is when components just sit there doing nothing, but if you build a circuit that doesn't work, please begin by following the fault-tracing procedure that I have recommended (see "Fundamentals: Fault Tracing" on page 73). I will do my best to answer emails from readers who run into problems, but it's only fair for you to try to solve your problems first.

Writer–Reader Communication

There are three situations where you and I may want to communicate with each other.

- I may want to tell you if it turns out that the book contains a mistake which will prevent you from building a project successfully. I may also want to tell you if a parts kit, sold in association with the book, has something wrong with it. This is *me-informing-you* feedback.
- You may want to tell me if you think you found an error in the book, or in a parts kit. This is *you-informing-me* feedback.
- You may be having trouble making something work, and you don't know whether I made a mistake or you made a mistake. You would like some help. This is *you-asking-me* feedback.

I will explain how to deal with each of these situations.

Me Informing You

If you already registered with me in connection with *Make: More Electronics*, you don't need to register again for updates relating to *Make: Electronics*. But if you have not already registered, here's how it works.

I can't notify you if there's an error in the book or in a parts kit unless I have your contact information. Therefore I am asking you to send me your email address for the following purposes. Your email will not be used or abused for any other purpose.

- I will notify you if any significant errors are found in this book or in its successor, *Make: More Electronics*, and I will provide a workaround.
- I will notify you of any errors or problems relating to kits of components sold in association with this book or in *Make: More Electronics*.
- I will notify you if there is a completely new edition of this book, or of *Make: More Electronics*, or of my other books. These notifications will be very rare.

We've all seen registration cards that promise to enter you for a prize drawing. I'm going to offer you a much better deal. If you submit your email address, which may only be used for the three purposes listed above, I will send you an unpublished electronics project with complete construction plans as a two-page PDF. It will be fun, it will be unique, and it will be relatively easy. You won't be able to get this in any other way.

The reason I am encouraging you to participate is that if an error is found, and I have no way to tell you, and you discover it later on your own, you're likely to get annoyed. This will be bad for my reputation and the reputation of my work. It is very much in my interest to avoid a situation where you have a complaint.

- Simply send a blank email (or include some comments in it, if you like) to *make.electronics@gmail.com*. Please put REGISTER in the subject line.

You Informing Me

If you only want to notify me of an error that you have found, it's really better to use the "errata" system maintained by my publisher. The publisher uses the "errata" information to fix the error in updates of the book.

If you are sure that you found an error, please visit:

http://shop.oreilly.com/category/customer-service/faq-errata.do

The web page will tell you how to submit errata.

You Asking Me

My time is obviously limited, but if you attach a photograph of a project that doesn't work, I may have a suggestion. The photograph is essential.

You can use *make.electronics@gmail.com* for this purpose. Please put the word HELP in the subject line.

Going Public

There are dozens of forums online where you can discuss this book and mention any problems you are having, but please be aware of the power that you have as a reader, and use it fairly. A single negative review can create a bigger effect than you may realize. It can certainly outweigh half-a-dozen positive reviews.

The responses that I receive are generally very positive, but in a couple of cases people have been annoyed over small issues such as being unable to find a part online. I would have been happy to help these people if they had asked me.

I do read my reviews on Amazon about once each month, and will always provide a response if necessary.

Of course, if you simply don't like the way in which I have written this book, you should feel free to say so.

Going Further

After you work your way through this book, you will have grasped many of the basic principles in electronics. I like to think that if you want to know more, my own *Make: More Electronics* is the ideal next step. It is slightly more difficult, but uses the same "Learning by Discovery" method that I have used here. My intention is that you will end up with what I consider an "intermediate" understanding of electronics.

I am not qualified to write an "advanced" guide, and consequently I don't expect to create a third book with a title such as "Make: Even More Electronics."

If you want to know more electrical theory, *Practical Electronics for Inventors* by Paul Scherz is still the book that I recommend most often. You don't have to be an inventor to find it useful.

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To comment or ask technical questions about this book, send email to *bookquestions@oreilly.com*.

1 The Basics

Chapter One of this book contains Experiments 1 through 5.

In Experiment 1, I want you to get a taste for electricity—literally! You'll experience electric current and discover the nature of electrical resistance, not just in wires and components but in the world around you.

Experiments 2 through 5 will show you how to measure and understand the pressure and flow of electricity—and finally, how to generate electricity with everyday items on a tabletop.

Even if you have prior knowledge of electronics, I encourage you to try these experiments before venturing into subsequent parts of the book. They're fun, and they clarify some basic concepts.

Necessary Items for Chapter One

Each chapter of this book begins with pictures and descriptions of the tools, equipment, components, and supplies that will be required. After you have learned about them, you can flip to the back of the book where your buying options are summarized for quick reference.

- To buy tools and equipment, see "Buying Tools and Equipment" on page 324.
- For components, see "Components" on page 317.
- For supplies, see "Supplies" on page 316.
- If you prefer to get a prepackaged set of the components that you need, you have a choice of kits. See "Kits" on page 311 for more information.

I classify *tools and equipment* as items that should be useful indefinitely. They range from pliers to a multimeter. *Supplies*, such as wire and solder, will gradually be consumed in a variety of projects, but the quantities that I am recommending should be sufficient for all the experiments in the book. *Components* will be listed for individual projects, and will become part of those projects.

The Multimeter

Figure 1-1 *This kind of analog meter is inadequate for your purposes. You need a digital meter.*

I'm beginning my instructional overview of tools and equipment with the multimeter, because I consider it the most essential piece of equipment. It will tell you how much voltage exists between any two points in a circuit, or how much current is passing through the circuit. It will help you to find a wiring error, and can also evaluate a component to determine its electrical resistance—or its capacitance, which is the ability to store an electrical charge.

If you're starting with little or no knowledge, these terms may seem confusing, and you may feel that a multimeter looks complicated and difficult to use. This is not the case. It makes the learning process easier, because it reveals what you cannot see.

Before I discuss which meter to buy, I can tell you what not to buy. You don't want an old-school meter with a needle that moves across a scale, as shown in Figure 1-1. That is an *analog* meter.

You want a *digital* meter that displays values numerically—and to give you an idea of the equipment available, I have selected four examples.

Figure 1-2 shows the cheapest digital meter that I could find, costing less than a paperback novel or a six-pack of soda. It cannot measure very high resistances or very low voltages, its accuracy is poor, and it does not measure capacitance at all. However, if your budget is very tight, it will probably see you through the experiments in this book.

Figure 1-2 *The cheapest meter that I could find.*

The meter in Figure 1-3 offers more accuracy and more features. This meter, or one similar to it, is a good basic choice while you are learning electronics.

Figure 1-3 *Any meter similar to this one is a good basic choice.*

The example in Figure 1-4 is slightly more expensive but much better made. This particular model has been discontinued, but you can find many like it, probably costing two to three times as much as the NT brand in Figure 1-3. Extech is a well-established company trying to maintain its standards in the face of cut-price competitors.

Figure 1-4 *A better-made meter at a somewhat higher price.*

Figure 1-5 shows my personal preferred meter at the time of writing. It is physically rugged, has all the features I could want, and measures a wide range of values with extremely good accuracy. However, it costs more than twenty times as much as the lowest-priced, bargain-basement product. I regard it as a long-term investment.

Figure 1-5 *A high-quality product.*

How do you decide which meter to buy? Well, if you were learning to drive, you wouldn't necessarily need a high-priced car. Similarly, you don't need a high-priced meter while you are learning electronics. On the other hand, the absolute cheapest meter may have some drawbacks, such as an internal fuse that is not easily replaceable, or a rotary switch with contacts that wear out quickly. So here's a rule of thumb if you want something that I would regard as inexpensive but acceptable:

- Search eBay for the absolute cheapest model you can find, then double the price, and use that as your guideline.

Regardless of how much you spend, the following attributes and capabilities are important.

Ranging

A meter can measure so many values, it has to have a way to narrow the range. Some meters have *manual ranging*, meaning that you turn a dial to choose a ballpark for the quantity that interests you. A range could be from 2 to 20 volts, for instance.

Other meters have *autoranging*, which is more convenient, because you just connect the meter and wait for it to figure everything out. The key word, however, is "wait." Every time you make a measurement with an autoranging meter, you will wait a couple of seconds while it performs an internal evaluation. Personally I tend to be impatient, so I prefer manual meters.

Another problem with autoranging is that because you have not selected a range yourself, you must pay attention to little letters in the display where the meter is telling you which units it has decided to use. For example, the difference between a "K" or an "M" when measuring electrical resistance is a factor of 1,000. This leads me to my personal recommendation:

- I suggest you use a manual-ranging meter for your initial adventures. You'll have fewer chances to make errors, and it should cost slightly less.

A vendor's description of a meter should say whether it uses manual ranging or autoranging, but if not, you can tell by looking at a photograph of its selector dial. If you don't see any numbers around the dial, it's an autoranging meter. The meter in Figure 1-4 does autoranging. The others that I pictured do not.

Values

The dial will also reveal what types of measurements are possible. At the very least, you should expect:

Volts, amps, and ohms, often abbreviated with the letter V, the letter A, and the ohm symbol, which is the Greek letter omega, shown in Figure 1-6. You may not know what these attributes mean right now, but they are fundamental.

Your meter should also be capable of measuring milliamps (abbreviated *mA*) and millivolts (abbreviated *mV*). This may not be immediately clear from the dial on the meter, but will be listed in its specification.

Figure 1-6 *Three samples of the Greek symbol omega, used to represent electrical resistance.*

DC/AC, meaning direct current and alternating current. These options may be selected with a DC/AC pushbutton, or they may be chosen on the main selector dial. A pushbutton is probably more convenient.

Continuity testing. This useful feature enables you to check for bad connections or breaks in an electrical circuit. Ideally it should create an audible alert, in which case it will be represented symbolically with a little dot that has semicircular lines radiating from it, as shown in Figure 1-7.

Figure 1-7 *This symbol indicates the option to test a circuit for continuity, with audible feedback. It's a very useful feature.*

For a small additional sum, you should be able to buy a meter that makes the following measurements. In order of importance:

Capacitance. Capacitors are small components that are needed in the majority of electronic circuits. Because small ones usually don't have their values printed on them, the ability to measure their values can be important, especially if some of them get mixed up or (worse) fall on the floor. Very cheap meters usually cannot measure capacitance. When the feature exists, it is usually indicated with a letter F, meaning farads, which are the units of measurement. The abbreviation CAP may also be used.

Transistor testing, indicated by little holes labeled E, B, C, and E. You plug the transistor into the holes. This enables you to verify which way up the transistor should be placed in a circuit, or if you have burned it out.

Frequency, abbreviated Hz. This is unimportant in the experiments in this book, but may be useful if you go further.

Any features beyond these are not significant.

If you still feel unsure about which meter to buy, read ahead a little to get an idea of how you will be using a meter in Experiments 1, 2, 3, and 4.

Safety Glasses

For Experiment 2, you may want to use safety glasses. The cheapest plastic type is satisfactory for this little adventure, as the risk of a battery bursting is almost nonexistent, and probably would not occur with much force.

Regular eyeglasses would be an acceptable substitute, or you could view the experiment through a little piece of transparent plastic (for instance, you can cut out a piece of a water bottle).

Batteries and Connectors

Because batteries and connectors become part of a circuit, I am categorizing them as components. See "Other Components" on page 319 for details about ordering these parts.

Almost all the experiments in this book will use a power source of 9 volts. You can obtain this from a basic nine-volt battery sold in supermarkets and convenience stores. Later I'll suggest an upgrade to an AC adapter, but you don't need that right now.

For Experiment 2, you will need a couple of 1.5-volt AA batteries. These have to be the alkaline type. You must not perform this experiment with any kind of rechargeable battery.

To transfer the power from a battery into a circuit, you need a connector for the 9-volt battery, as shown in Figure 1-8, and a carrier for a single AA battery, as shown in Figure 1-9. One carrier will be enough, but I suggest you get at least three 9-volt connectors for future use.

Figure 1-8 *Connector to deliver power from a 9-volt battery.*

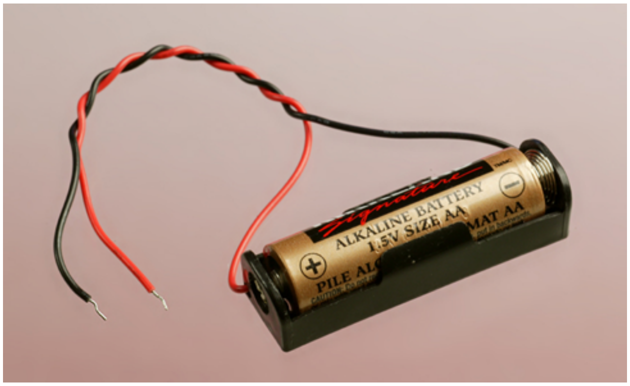

Figure 1-9 *You need a carrier like this for a single AA battery. Don't buy the type of carrier that holds two batteries (or three, or four).*

Test Leads

You will use test leads (pronounced "leeds") to connect components with each other in the first few experiments. The type of leads I mean are *double-ended*. Surely, any piece of wire has two ends, so why should it be called "double-ended"? The term usually means that each end is fitted with an *alligator clip* as shown in Figure 1-10. Each clip can make a connection by grabbing something and gripping it securely, freeing you to use your hands elsewhere.

You don't want the kind of test leads that have a plug at each end. Those are sometimes known as *jumper wires*.

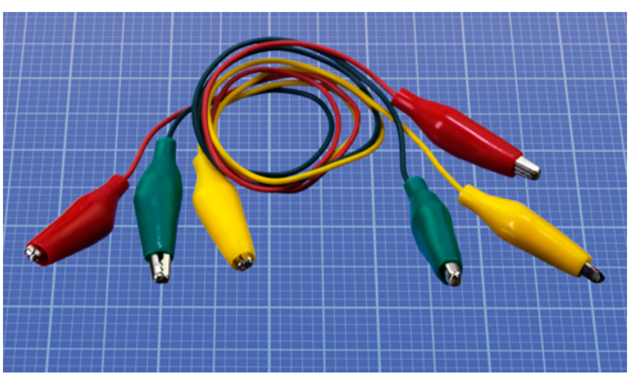

Figure 1-10 *Double-ended test leads with an alligator clip at each end.*

Test leads are classified as equipment for the purposes of this book. See "Buying Tools and Equipment" on page 324 for more information.

Potentiometer

A potentiometer functions like the volume control on an old-fashioned stereo. The kinds shown in Figure 1-11 are considered large by modern standards, but large is what you need, because you'll be gripping the terminals with the alligator clips on your test leads. A 1" diameter potentiometer is preferred. Its resistance should be listed as 1K. If you are buying your own, see "Other Components" on page 319 for details.

Figure 1-11 *Potentiometers of the general type required for your first experiments.*

Fuse

A fuse interrupts a circuit if too much electricity passes through it. Ideally you'll buy the type of 3-amp automotive fuse shown in Figure 1-12, which is easy to grip with test leads, and clearly reveals the element inside it. Automotive fuses are sold in a variety of physical sizes, but so long as you use one rated for 3 amps, the dimensions don't matter. Buy three to allow for destroying them intentionally or accidentally. If you don't want to use an auto parts supplier, a 2AG-size 3-amp glass cartridge fuse of the kind shown in Figure 1-13 will be available from electronics component suppliers, although it is not quite so easy to use.

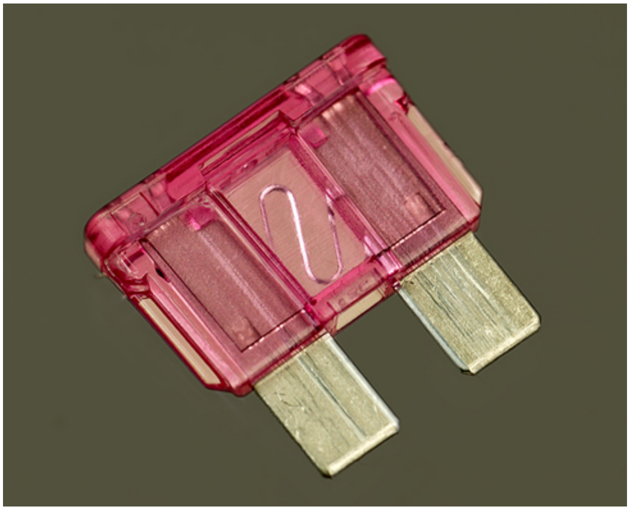

Figure 1-12 *This type of automotive fuse is easier to handle than the cartridge fuses used in electronics hardware.*

Figure 1-13 *You can use a cartridge fuse like this, although your alligator clips won't grip it so easily.*

Light-Emitting Diodes

More commonly known as *LEDs*, they come in various shapes and forms. The ones we will be using are properly known as *LED indicators*, and are often described as *standard through-hole LEDs* in catalogs. A sample in Figure 1-14 is 5mm in diameter, but 3mm is sometimes easier to fit into a circuit when space is limited. Either will do.

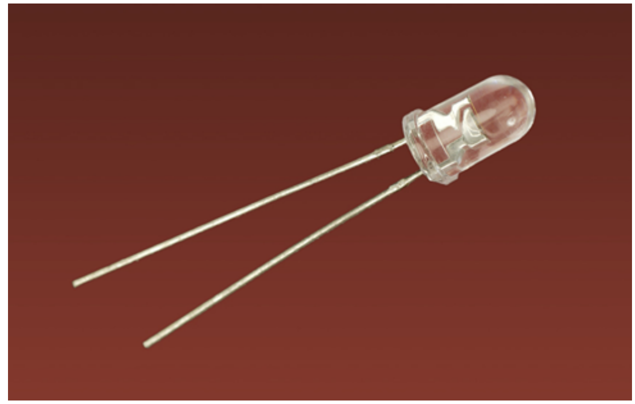

Figure 1-14 *A light-emitting diode (LED) approximately 5mm in diameter.*

Throughout this book I will refer to *generic LEDs*, by which I mean the cheapest ones that don't emit a high-intensity light and are commonly available in red, yellow, or green. They are often sold in bulk quantities, and are used in so many applications that I suggest you buy at least a dozen of each color.

Some generic LEDs are encapsulated in "water clear" plastic or resin, but emit a color when power is applied. Other LEDs are encapsulated in plastic or resin tinted with the same color that they will display. Either type is acceptable.

In a few experiments, *low-current LEDs* are preferred. They cost slightly more, but are more sensitive. For example, in Experiment 5, where you will generate a small amount of current with an improvised battery, you'll get better results with a low-current LED. See "Other Components" on page 319 for additional guidance, if you are not using components that were supplied in a kit.

Resistors

You'll need a variety of resistors to restrict the voltage and current in various parts of a circuit. They should look something like the ones in Figure 1-15. The color of the body of the resistor doesn't matter. Later I will explain how the colored stripes tell you the value of the component.

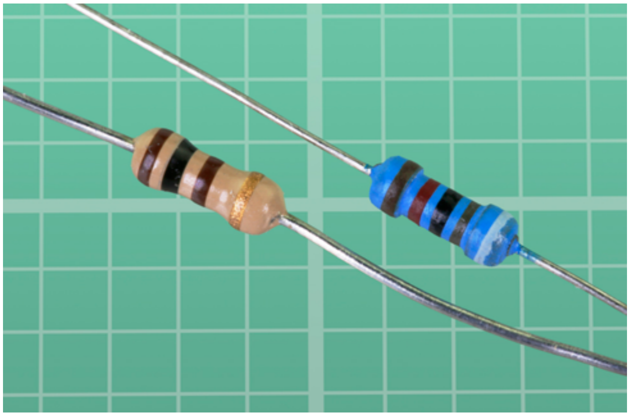

Figure 1-15 *Two resistors of the type you need, all rated for 1/4 watt.*

If you are buying your own resistors, they are so small and cheap, you would be foolish to select just the values listed in each experiment. Get a prepackaged selection in bulk from surplus or discount sources, or eBay. For more information about resistors, including a complete list of all the values used throughout this book, see "Components" on page 317.

You don't need any other components to take you through Experiments 1 through 5. So let's get started!

Experiment 1: Taste the Power!

Can you taste electricity? It feels as if you can.

What You Will Need

- 9-volt battery (1)
- Multimeter (1)

That's all!

Caution: No More than Nine Volts

This experiment should only use a 9-volt battery. *Do not* try it with a higher voltage, and *do not* use a bigger battery that can deliver more current. Also, if you have metal braces on your teeth, be careful not to touch them with the battery. Most important, never apply electric current from any size of battery through a break in your skin.

Procedure

Moisten your tongue and touch the tip of it to the metal terminals of a 9-volt battery, as shown in Figure 1-16. (Maybe your tongue isn't quite as big as the one in the picture. Mine certainly isn't. But this experiment will work regardless of how big or small your tongue may be.)

Figure 1-16 *An intrepid Maker tests the characteristics of an alkaline battery.*

Do you feel that tingle? Now set aside the battery, stick out your tongue, and dry the tip of it very thoroughly with a tissue. Touch the battery to your tongue again, and you should feel less of a tingle.

What's happening here? You can use a meter to find out.

Setting Up Your Meter

Does your meter have a battery preinstalled? Select any function with the dial, and wait to see if the display shows a number. If nothing is visible, you may have to open the meter and put in a battery before you can use it. To find out how to do this, check the instructions that came with the meter.

Meters are supplied with a red lead and a black lead. Each lead has a plug on one end, and a steel probe on the other end. You insert the plugs into the meter, then touch the probes on locations where you want to know what's going on. See Figure 1-17. The probes detect electricity; they don't emit it in significant quantities. When you are dealing with the small currents and voltages in the experiments in this book, the probes cannot hurt you (unless you poke yourself with their sharp ends).

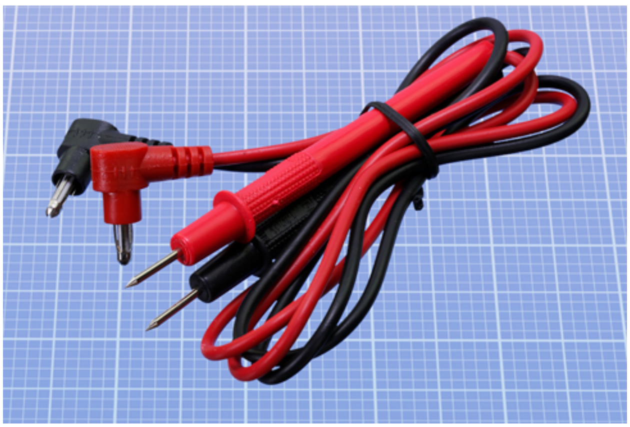

Figure 1-17 *Leads for a meter, terminating in metal probes.*

Most meters have three sockets, but some have four. See Figure 1-18, Figure 1-19, and Figure 1-20 for examples. Here are the general rules:

- One socket should be labelled COM. This is *common* to all your measurements. Plug the black lead into this socket, and leave it there.
- Another socket should be identified with the ohm (omega) symbol, and the letter V for volts. It can measure either resistance or voltage. Plug the red lead into this socket.
- The voltage/ohms socket may also be used for measuring small currents in mA (milliamps) . . . or you may see a separate socket for this, which will require you to move the red lead sometimes. We'll get to that later.
- An additional socket may be labelled 2A, 5A, 10A, 20A, or something similar, to indicate a maximum number of amps. This is used for measuring high currents. We won't be needing it for projects in this book.

Figure 1-18 *Note the labeling of sockets on this meter.*

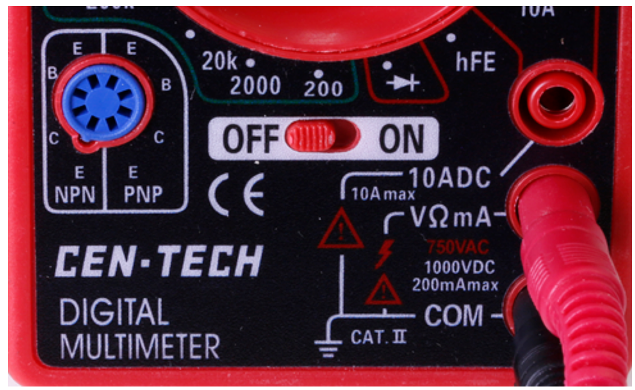

Figure 1-19 *Socket functions are split up differently on this meter.*

Figure 1-20 *Sockets on one more meter.*

Fundamentals: Ohms

You're going to evaluate the resistance of your tongue, in ohms. But what is an ohm?

We measure distance in miles or kilometers, mass in pounds or kilograms, and temperature in Fahrenheit or Centigrade. We measure electrical resistance in ohms, which is an international unit named after Georg Simon Ohm, who was an electrical pioneer.

The Greek omega symbol indicates ohms, but for resistances above 999 ohms the uppercase letter K is used, which means *kilohm*, equivalent to a thousand ohms. For example, a resistance of 1,500 ohms will be referred to as 1.5K.

Above 999,999 ohms, the uppercase letter M is used, meaning *megohm*, which is a million ohms. In everyday speech, a megohm is often referred to as a "meg." If someone is using a "two-point-two meg resistor," its value will be 2.2M.

A conversion table for ohms, kilohms, and megohms is shown in Figure 1-21.

Ohms	Kilohms	Megohms
1 Ω	0.001K	0.000001M
10 Ω	0.01K	0.00001M
100 Ω	0.1K	0.0001M
1,000 Ω	1K	0.001M
10,000 Ω	10K	0.01M
100,000 Ω	100K	0.1M
1,000,000 Ω	1,000K	1M

Figure 1-21 *Conversion table for the most common multiples of ohms.*

- In Europe, the letter R, K, or M is substituted for a decimal point, to reduce the risk of errors. Thus, 5K6 in a European circuit diagram means 5.6K, 6M8 means 6.8M, and 6R8 means 6.8 ohms. I won't be using the European style here, but you may find it in some circuit diagrams elsewhere.

A material that has very high resistance to electricity is known as an *insulator*. Most plastics, including the colored sheaths around wires, are insulators.

A material with very low resistance is a *conductor*. Metals such as copper, aluminum, silver, and gold are excellent conductors.

Measuring Your Tongue

Inspect the dial on the front of your meter, and you'll find at least one position identified with the ohm symbol. On an autoranging meter, turn the dial to point to the ohm symbol as shown in Figure 1-22, touch the probes *gently* to your tongue, and wait for the meter to choose a range automatically. Watch for the letter K in the numeric display. Never stick the probes *into* your tongue!

Figure 1-22 *On an autoranging meter, just turn the dial to the ohm (omega) symbol.*

On a manual meter, you must choose a range of values. For a tongue measurement, probably 200K (200,000 ohms) would be about right. Note that the numbers beside the dial are maximums, so 200K means "no more than 200,000 ohms" while 20K means "no more than 20,000 ohms." See the close-ups of the manual meters in Figure 1-23 and Figure 1-24.

Figure 1-23 *A manual meter requires you to select the range.*

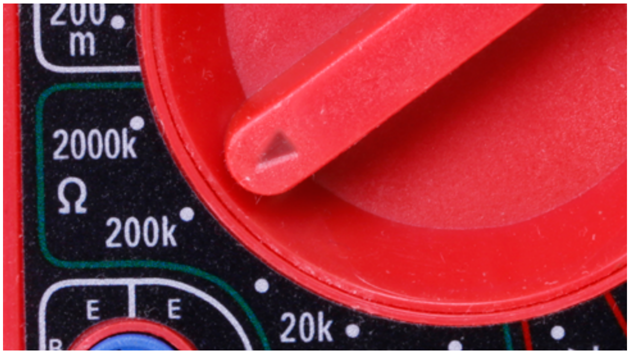

Figure 1-24 *A different manual meter dial, but the principle is the same.*

Touch the probes to your tongue about one inch apart. Note the meter reading, which should be around 50K. Put aside the probes, stick out your tongue, and use a tissue to dry it carefully and thoroughly, as you did before. Without allowing your tongue to become moist again, repeat the test, and the reading should be higher. Using a manual ranging meter, you may have to select a higher range to see a resistance value.

- When your skin is moist (for instance, if you perspire), its electrical resistance decreases. This principle is used in lie detectors, because someone who knowingly tells a lie, under conditions of stress, may tend to perspire.

Here's the conclusion that your test may suggest. A lower resistance allows more electric current to flow, and in your initial tongue test, more current created a bigger tingle.

Fundamentals: Inside a Battery

When you used a battery for the original tongue test, I didn't bother to mention how a battery works. Now is the time to rectify that omission.

A 9-volt battery contains chemicals that liberate *electrons* (particles of electricity), which want to flow from one terminal to the other as a result of a chemical reaction. Think of the cells inside a battery as being like two water tanks—one of them full, the other empty. If the tanks are connected with each other by a pipe and a valve, and you open the valve, water will flow between them until their levels are equal. Figure 1-25 may help you to visualize this. Similarly, when you open up an electrical pathway between the two sides of a battery, electrons flow between them, even if the pathway consists only of the moisture on your tongue.

Electrons flow more easily through some substances (such as a moist tongue) than others (such as a dry tongue).

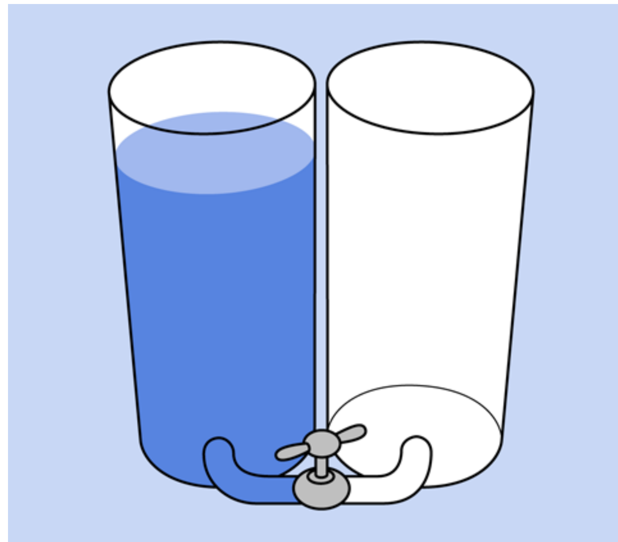

Figure 1-25 *You can think of a battery as being like a pair of interconnected water reservoirs.*

Further Investigation

The tongue test was not a very well-controlled experiment, because the distance between the probes might have varied a little between one trial and the next. Do you think that may be significant? Let's find out.

Hold the meter probes so that their tips are only 1/4" apart. Touch them to your moist tongue. Now separate the probes by 1" and try again. What readings do you get?

When electricity travels through a shorter distance, it encounters less resistance. As a result, the current will increase.

Try a similar experiment on your arm, as shown in Figure 1-26. You can vary the distance between the probes in fixed steps, such as 1/4", and note the resistance shown by your meter. Do you think that doubling the distance between the probes doubles the resistance shown by the meter? How can you prove or disprove this?

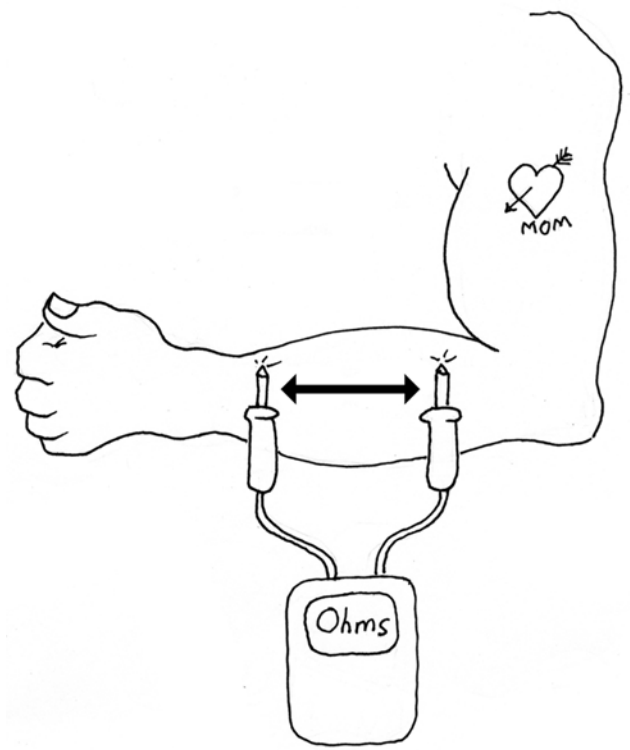

Figure 1-26 *Vary the distance between the probes, and note the reading on your meter.*

If the resistance is too high for your meter to measure, you will see an error message, such as L, instead of some numbers. Try moistening your skin, then repeat the test, and you should get a result. The only problem is, as the moisture on your skin evaporates, the resistance will change. You see how difficult it is to control all the factors in an experiment. The random factors are properly known as *uncontrolled variables*.

There is still one more variable that I haven't discussed, which is the amount of pressure between each probe and the skin. If you press harder, I suspect that the resistance will diminish. Can you prove this? How could you design an experiment to eliminate this variable?

If you're tired of measuring skin resistance, you can try dunking the probes into a glass of water. Then dissolve some salt in the water, and test it again. No doubt you've heard that water conducts electricity, but the full story is not so simple. Impurities in water play an important part.

What do you think will happen if you try to measure the resistance of water that contains no impurities at all? Your first step would be to obtain some pure water. So-called *purified water* usually has minerals added after it was purified, so, that's not what you want. Similarly, *spring water* is not totally pure. What you need is *distilled water*, also known as *deionized water*. This is often sold in supermarkets. I think you'll find that its resistance, per inch between the meter probes, is higher than the resistance of your tongue. Try it to find out.

Those are all the experiments relating to resistance that I can think of, right now. But I still have a little background information for you.

Background: The Man Who Discovered Resistance

Georg Simon Ohm, pictured in Figure 1-27, was born in Bavaria in 1787 and worked in obscurity for much of his life, studying the nature of electricity using metal wire that he had to make for himself (you couldn't truck on down to Home Depot for a spool of hookup wire back in the early 1800s).

Despite his limited resources and inadequate mathematical abilities, Ohm was able to demonstrate in 1827 that the electrical resistance of a conductor such as copper varied in inverse proportion with its area of cross-section, and the current flowing through it is proportional to the voltage applied to it, so long as temperature is held constant. Fourteen years later, the Royal Society in London finally recognized the significance of his contribution and awarded him the Copley Medal. Today, his discovery is known as Ohm's Law. I'll explain more about this in Experiment 4.

Figure 1-27 *Georg Simon Ohm, after being honored for his pioneering work, most of which he pursued in relative obscurity.*

Cleanup and Recycling

Your battery should not have been damaged or significantly discharged by this experiment. You can use it again.

Remember to switch off your meter before putting it away. Many meters will beep to remind you to switch them off if you don't use them for a while, but some don't. A meter consumes a very small amount of electricity while it is switched on, even when you are not using it to measure anything.

Experiment 2: Let's Abuse a Battery!

To get a better feeling for electrical power, you're going to do what most books tell you not to do. You're going to short out a battery. (A *short circuit* is a shortcut between two sides of a power source.)

Caution: Use a Small Battery

The experiment that I am going to describe is safe, but some short circuits can be dangerous. Never short out a power outlet in your home: there'll be a loud bang, a bright flash, and the wire or tool that you use will be partially melted, while flying particles of melted metal can burn you or blind you.

If you short out a car battery, the flow of current is so huge that the battery might even explode, drenching you in acid. Just ask the guy in Figure 1-28 (if he is able to answer).

Figure 1-28 *Dropping a wrench between the terminals of a car battery will be bad for your health. Short circuits can be dramatic, even at a "mere" 12 volts, if the battery is big enough.*

Lithium batteries are often found in power tools, laptop computers, and other portable devices. Never short-circuit a lithium battery: it can catch fire and burn you. Lithium batteries have been known to catch fire even if you don't short them out, as shown in Figure 1-29. After some early laptops self-destructed, lithium battery packs were modified to prevent this kind of thing. But short-circuiting them is still a very bad idea.

Figure 1-29 *Never fool around with lithium batteries.*

Use only an alkaline battery in this experiment, and only a single AA cell. You may also want to wear safety glasses in case you happen to have a defective battery.

What You Will Need

- 1.5-volt AA battery (2)
- Battery carrier (1)
- 3-amp fuse (2)
- Safety glasses (regular eyeglasses or sunglasses will do)
- Test leads with alligator clips at each end (2)

Generating Heat with Current

Use an alkaline battery. Do not use any kind of rechargeable battery.

Put the battery into a battery carrier that terminates in two thin wires, as shown in Figure 1-9. Twist the bare ends of the wires together, as shown in Figure 1-30. At first it seems that nothing happens. But wait one minute, and you'll find that the wires are getting hot. Wait another minute, and the battery, too, will be hot.

Figure 1-30 *Shorting out an alkaline battery can be safe if you follow the directions precisely.*

The heat is caused by electricity flowing through the wires and through the *electrolyte* (the conductive fluid) inside the battery. If you've ever used a hand pump to force air into a bicycle tire, you know that the pump gets warm. Electricity behaves in much the same way. You can imagine the electricity being composed of particles (electrons) that make the wire hot as they push through it. This isn't a perfect analogy, but it's close enough for our purposes.

Where do the electrons come from? Chemical reactions inside the battery liberate them, creating electrical pressure. The correct name for this pressure is *voltage*, which is measured in volts and is named after Alessandro Volta, another electrical pioneer.

Going back to the water analogy: the height of the water in a tank is proportional with the pressure of the water, and is similar to voltage. Figure 1-31 may help you to visualize this.

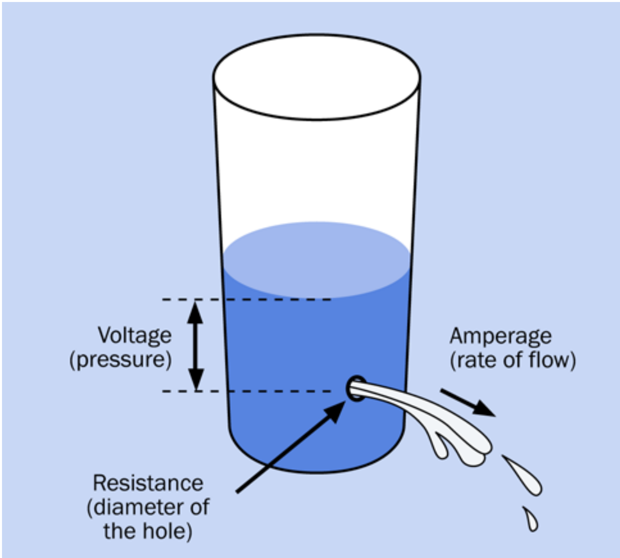

Figure 1-31 *The pressure in a source of water is analogous to the voltage in a source of electricity.*

But volts are only half of the story. When electrons flow through a wire, the amount of flow during a period of time is known as *amperage*, named after yet another electrical pioneer, André-Marie Ampère. That flow is also generally known as *current*. The current—the amperage—generates the heat.

- Think of voltage as pressure.
- Think of amperes as the rate of flow, properly known as current.

Background: Why Didn't Your Tongue Get Hot?

When you touched the 9-volt battery to your tongue, you felt a tingle, but no perceptible heat. When you shorted out a battery, you generated a noticeable amount of heat, even though you only used a 1.5-volt battery. How can you explain this?

Your meter showed you that the electrical resistance of your tongue is very high. This high resistance reduced the flow of electrons.

The resistance of a wire is very low, so if there's a wire connecting the two terminals of the battery, more current will pass through it than passed through your tongue, and it will create more heat. If all other factors remain constant:

- Lower resistance allows more current to flow.
- The heat generated by electricity is proportional with the amount of electricity (the current) passing through a conductor in a period of time. (This relationship is no longer exactly true if the resistance of the wire changes as the wire gets hot. But it remains approximately true.)

Here are some other basic concepts:

- The flow of electricity per second is measured in amperes, very commonly abbreviated as *amps*.
- The pressure of electricity that causes the flow is measured in *volts*.
- The resistance to the flow is measured in *ohms*.
- A higher resistance restricts the current.
- A higher voltage is better able to overcome resistance and increase the current.

The relationship between voltage, resistance, and amperage (pressure, resistance, and flow) is illustrated in Figure 1-32.

Figure 1-32 *Resistance blocks pressure and reduces flow—in water, and in electricity.*

Fundamentals: Volt Basics

The volt is an international unit, represented by an uppercase letter V. In the United States and much of Europe, AC power for domestic use is supplied at 110V, 115V, or 120V, with separate circuits for heavy-duty appliances delivering 220V, 230V, or 240V. Solid-state electronic components traditionally required DC power ranging from 5V to about 20V, although modern surface-mount devices may use less than 2V. Some components, such as a microphone, deliver voltage measured in millivolts, abbreviated mV, each millivolt being 1/1,000th of a volt. When electricity is distributed over long distances, it is measured in kilovolts, abbreviated kV. A few long-distance lines use megavolts. A conversion table for millivolts, volts, and kilovolts is shown in Figure 1-33.

Millivolts	Volts	Kilovolts
1mV	0.001V	0.000001kV
10mV	0.01V	0.00001kV
100mV	0.1V	0.0001kV
1,000mV	1V	0.001kV
10,000mV	10V	0.01kV
100,000mV	100V	0.1kV
1,000,000mV	1,000V	1kV

Figure 1-33 *Conversion table for the most common multiples of volts.*

Fundamentals: Ampere Basics

The ampere is an international unit, represented by an uppercase letter A. Household appliances may draw several amps, and a typical circuit breaker in the United States is rated for 20A. Electronic components often are rated in milliamps, abbreviated mA, each milliamp being 1/1,000th of an amp. Devices such as liquid-crystal displays may draw microamps, abbreviated μA, each microamp being 1/1,000th of a milliamp. A conversion table for amps, milliamps, and microamps is shown in Figure 1-34.

Microamps	Milliamps	Amps
1μA	0.001mA	0.000001A
10μA	0.01mA	0.00001A
100μA	0.1mA	0.0001A
1,000μA	1mA	0.001A
10,000μA	10mA	0.01A
100,000μA	100mA	0.1A
1,000,000μA	1,000mA	1A

Figure 1-34 *Conversion table for the most common multiples of amps.*

How to Blow a Fuse

Exactly how much current flowed through the wires of the battery carrier, when you shorted out the battery? Could we have measured it?

Not easily, because if you try to use your multimeter to measure high current, you may blow the fuse inside the meter. So set aside the meter, and we'll use your 3-amp fuse, which we can sacrifice because it didn't cost very much.

First inspect the fuse, using a magnifying glass, if you have one. In an automotive fuse, you should see a tiny S-shape in the transparent window at the center. That S is a thin section of metal that melts easily. You saw it in Figure 1-12. In a glass cartridge fuse, there's a thin piece of wire that serves the same purpose.

Remove the 1.5-volt battery from its carrier. The battery is no longer useful for anything, and should be recycled if possible. Separate the two wires that you twisted together, and use two test leads to connect the carrier with a fuse, as shown in Figure 1-35 or Figure 1-36. Watch the fuse as you insert a new battery in the carrier. A break should occur in the center of the fuse element, where the metal melted. Figure 1-37 and Figure 1-38 show what I mean.

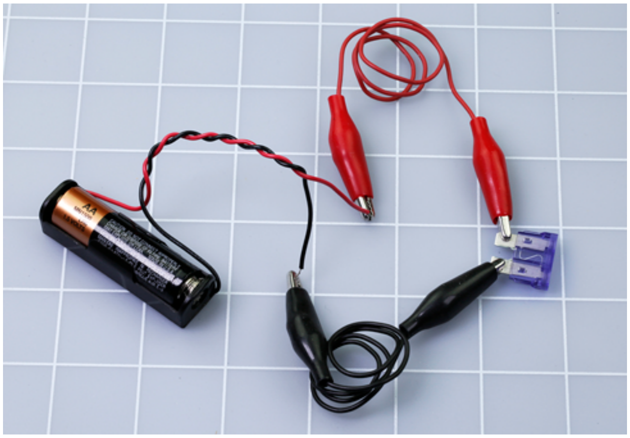

Figure 1-35 *How to short out an automotive fuse.*

Some 3-amp fuses blow more easily than others, even though they all have the same rating. If you think your fuse has not been affected, try applying the wires from the battery to it directly, instead of passing the current through the test leads. If you are not using a fresh AA battery, you may have to wait a few seconds for the fuse to respond. If all else fails, you can apply a C cell or a D cell, which have the same voltage as an AA battery but can deliver more current. But this shouldn't be necessary.

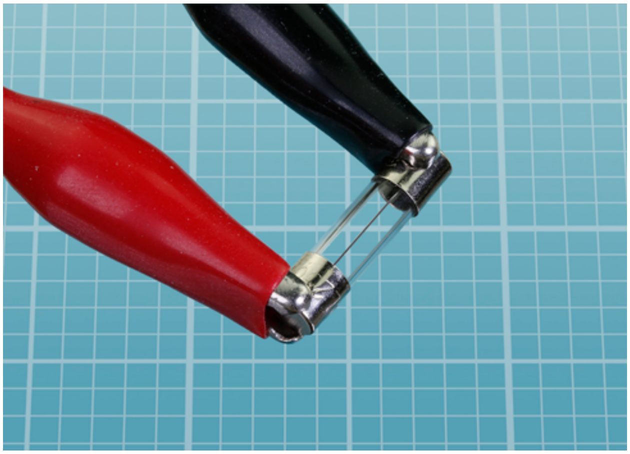

Figure 1-36 *How to apply your test leads to a small cartridge fuse.*

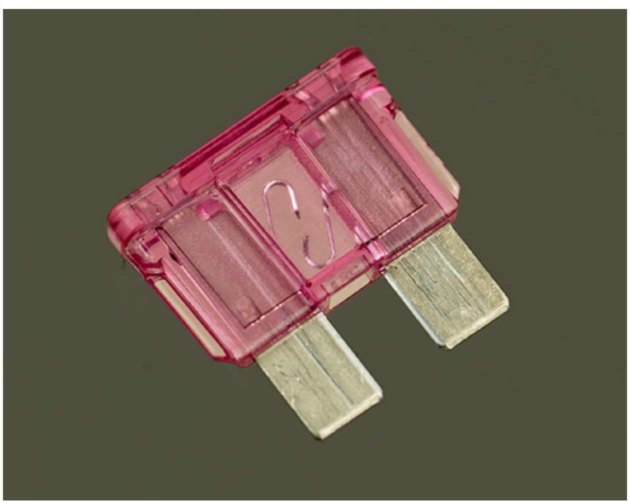

Figure 1-37 *Note the break in the element.*

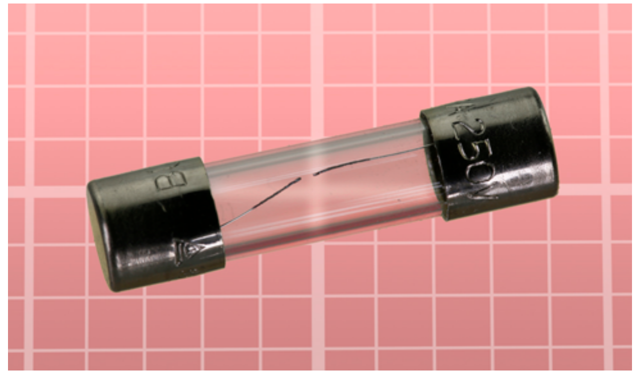

Figure 1-38 *In a shorted cartridge fuse, a similar break appears.*

This is how a fuse works: it melts to protect the rest of the circuit. That tiny break inside the fuse stops any more current from flowing.

Fundamentals: Direct and Alternating Current

The flow of current that you get from a battery is known as *direct current*, or DC. Like the flow of water from a faucet, it is a steady stream that flows in one direction.

The flow of current that you get from the power outlet in your home is very different. The "live" side of the outlet changes from positive to negative, relative to the "neutral" side, at a rate of 60 times each second (in many foreign countries, including Europe, 50 times per second). This is known as *alternating current*, or AC, which is more like the pulsing flow you get when you use a power washer to wash a car.

Alternating current is essential for some purposes, such as cranking up voltage so that electricity can be distributed over long distances. AC is also useful in motors and domestic appliances. The parts of a power outlet are shown in Figure 1-39. This style of outlet is found in North America, South America, Japan, and some other nations. European outlets look different, but the principle remains the same.

In the figure, socket A is the "hot" or "live" side of the outlet, supplying voltage that alternates between positive and negative relative to socket B, which is the "neutral" side. If an appliance develops a fault such as an internal loose wire, it should protect you by sinking the voltage through socket C, the ground.

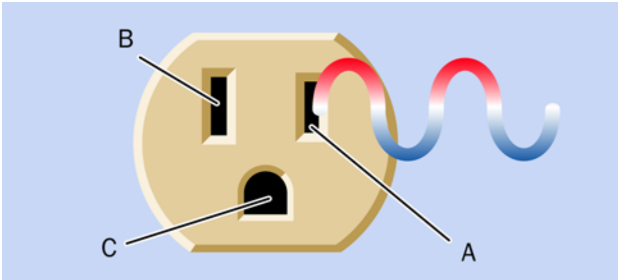

Figure 1-39 *The parts of a power outlet.*

In the United States, the outlet shown in the diagram is rated for 110 to 120 volts. Other configurations of outlet are used for higher voltages, but they still have live, neutral, and ground wires—with the exception of three-phase outlets, which are used primarily in industry.

For most of this book I'm going to be talking about DC, for two reasons: first, most simple electronic circuits are powered with DC, and second, the way it behaves is much easier to understand.

- I won't bother to mention repeatedly that I'm dealing with DC. Just assume that everything is DC unless otherwise noted.

Background: Inventor of the Battery

Alessandro Volta, shown in Figure 1-40, was born in Italy in 1745, long before science was broken up into specialties. After studying chemistry (he discovered methane in 1776) he became a professor of physics and developed an interest in the so-called galvanic response, whereby a frog's leg will twitch in response to a jolt of static electricity.

Using a wine glass full of salt water, Volta demonstrated that the chemical reaction between two electrodes (one made of copper, the other of zinc) will generate a steady electric current. In 1800, he refined his apparatus by stacking plates of copper and zinc, separated by cardboard soaked in salt and water. This "voltaic pile" was the first electric battery in Western civilization.

Figure 1-40 *Alessandro Volta discovered that chemical reactions can create electricity.*

Background: Father of Electromagnetism

Born in 1775 in France, André-Marie Ampère (shown in Figure 1-41) was a mathematical prodigy who became a science teacher, despite being largely self-educated in his father's library. His best-known work was to derive a theory of electromagnetism in 1820, describing the way that an electric current generates a magnetic field. He also built the first instrument to measure the flow of electricity (now known as a *galvanometer*), and discovered the element fluorine.

Figure 1-41 *André-Marie Ampère found that an electric current running through a wire creates a magnetic field around it. He used this principle to make the first reliable measurements of what came to be known as amperage.*

Cleanup and Recycling

You can dispose of the battery that you damaged when you shorted it. Putting batteries in the trash is not a great idea, because they contain heavy metals that should be kept out of the ecosystem. Your state or town may include batteries in a local recycling scheme. (California requires that almost all batteries be recycled.) Check your local regulations for details.

The blown fuse is of no further use, and can be thrown away.

The second battery, which was protected by the fuse, should still be OK.

The battery carrier can be reused later.

Experiment 3: Your First Circuit

Now it's time to make electricity do something more useful. To achieve this, you'll be experimenting with components known as resistors, and a light-emitting diode, or LED.

What You Will Need

- 9-volt battery (1)
- Resistors: 470 ohm (1), 1K (1), 2.2K (1)
- Generic LED (1)
- Test leads with alligator clips at each end (3)
- Multimeter (1)

Setup

It's time to get acquainted with the most fundamental component we'll be using in electronic circuits: the humble resistor. As its name implies, it resists the flow of electricity. As you might expect, its value is measured in ohms.

If you bought a bargain-basement assortment of resistors, they may be delivered to you in unmarked bags. No problem; we can determine their values easily enough. In fact, even if the packages are clearly labeled, I want you to check the resistors as we go along, because it's easy to get them mixed up. You have two alternatives:

- Use your multimeter, after setting it to measure ohms.
- Learn the color codes that are printed on most resistors. I'll explain them immediately below.

After you check the values of resistors, it's a good idea to sort them into labeled compartments in little plastic parts boxes. Personally, I like the boxes sold at the Michael's chain of crafts stores in the United States, but there are many alternatives. You can also use miniature plastic bags, which you can find by searching eBay for:

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plastic bags parts
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Fundamentals: Decoding Resistors

Some resistors have a value clearly stated on them in microscopic print that you can read with a magnifying glass, as shown in Figure 1-42.

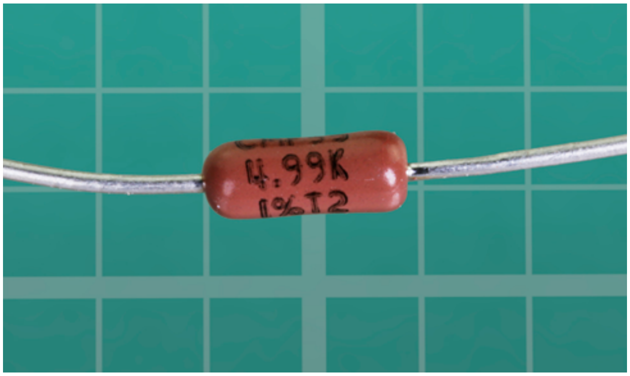

Figure 1-42 *Only a minority of resistors have their values printed on them.*

However, most resistors are color-coded with stripes. Figure 1-43 shows the coding scheme.

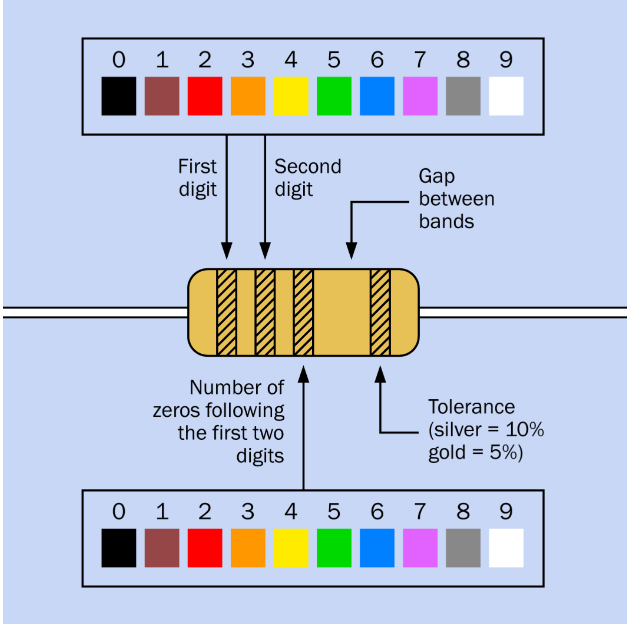

Figure 1-43 *The coding scheme that shows the value of a resistor. Some resistors have four stripes on the left instead of three, as explained in the text.*

Figure 1-44 shows you some examples. From top to bottom: 1,500,000 ohms (1.5M) at 10% tolerance, 560 ohms at 5%, 4,700 ohms (4.7K) at 10%, and 65,500 ohms (65.5K) at 5%.

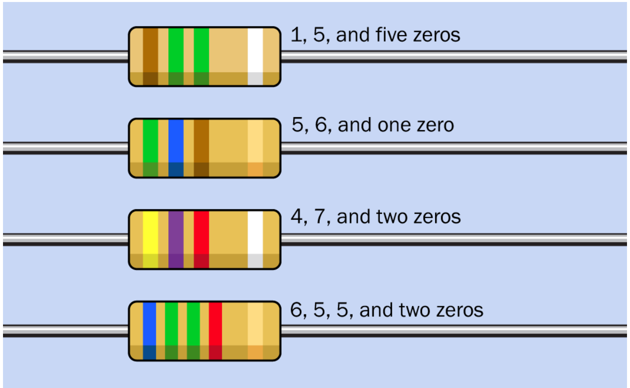

Figure 1-44 *Four examples of color-coded resistors.*

The code can be summarized in words like this:

- Ignore the color of the body of the resistor. (The exception to this rule would be a white resistor that may be fireproof or fused, and must be replaced with the same type. But you are unlikely to encounter one of these.)
- Look for a silver or gold stripe. If you find it, turn the resistor so that the stripe is on the right-hand side. Silver means that the value of the resistor is accurate within 10%, while gold means that the value is accurate within 5%. This is known as the *tolerance* of the resistor.
- If you don't find a silver or gold stripe, turn the resistor so that the colored stripes are clustered at the left end. Usually there are three of them. If there are four, I'll deal with those in a moment.
- The colors of the first two stripes, from left to right, tell you the first two digits in the value of the resistor. The color of the third stripe from the left tells you how many zeros follow the two numbers. The color values are shown in Figure 1-43.

If you run across a resistor with four stripes instead of three, the first *three* stripes are digits and the *fourth* stripe is the number of zeros. The third numeric stripe allows a resistor to have an intermediate value.

Confusing? Well, you can still use your meter to check the values. Just be aware that the meter reading may be slightly different from the claimed value of the resistor. This can happen because your meter isn't absolutely accurate, or because the resistor is not absolutely accurate, or both. Small variations don't matter in the projects in this book.

Lighting an LED

Now take a look at one of your generic LEDs. Old-fashioned lightbulbs used to waste power by converting a lot of the power into heat. LEDs are much smarter: they convert almost all their power into light, and they last almost indefinitely—provided you treat them right!

An LED is quite fussy about the amount of power it gets, and the way it gets it. Always follow these rules:

- The *longer* wire sticking out of the LED must receive a *more positive* voltage relative to the shorter wire.
- The positive voltage difference that you apply between the long wire and the short wire must not exceed the limit stated by the manufacturer. This is known as the *forward voltage*.
- The current passing into the LED through the long wire and out through the short wire must not exceed the limit stated by the manufacturer. This is known as the *forward current*.

What happens if you break these rules? You'll see for yourself in Experiment 4.

Make sure you have a fresh 9-volt battery. You could use a connector with the battery, as shown in Figure 1-8, but I think it's easier just to clip a couple of test leads directly to the battery terminals, as in Figure 1-45.

Select a 2.2K resistor. Remember, 2.2K means 2,200 ohms. Why is it 2,200 and not a nice round amount such as 2,000? I'll explain that shortly. See "Background: Puzzling Numbers" on page 21 if you want to know right now.

The colored stripes on your 2.2K resistor should be red-red-red, meaning 2 followed by another 2 and two more zeros. You will also need a 1K resistor (brown-black-red) and a 470-ohm resistor (yellow-violet-brown), so have them ready.

Wire the 2.2K resistor into the circuit shown in Figure 1-45. Make sure you get the battery the right way around, with its positive terminal on the right.

- The "plus" symbol always means "positive."
- The "minus" symbol always means "negative."

Be sure that the long lead of the LED is on the right, and be careful that none of the alligator clips touches each other. You should see the LED glow dimly.

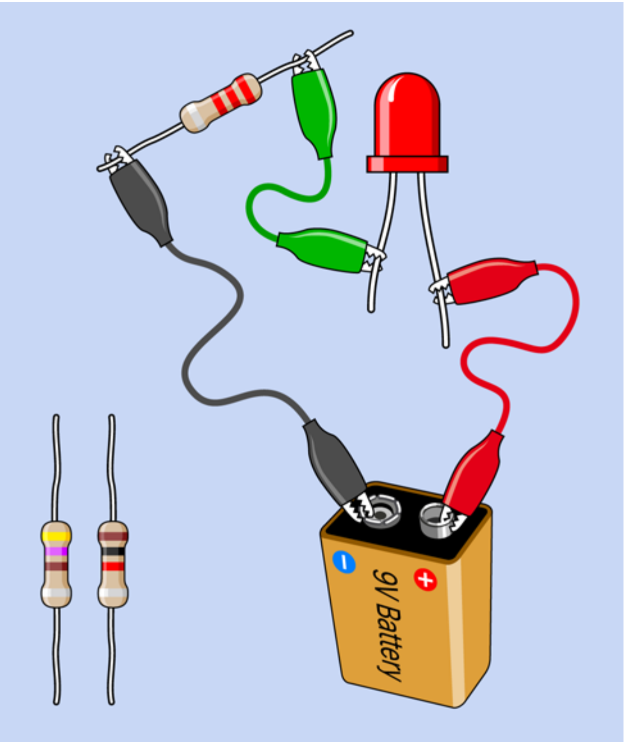

Figure 1-45 *Your first circuit, to light an LED.*

Now swap out your 2.2K resistor and substitute the 1K resistor. The LED should glow more brightly.

Swap out the 1K resistor and substitute a 470-ohm resistor, and the LED should be brighter still.

This may seem obvious, but it makes an important point. The resistor blocks a percentage of the current in the circuit. A higher-value resistor blocks more current, leaving less for the LED.

Checking a Resistor

I mentioned that you can use your meter to check the value of a resistor. This is really very easy. The procedure is shown in Figure 1-46. First, don't forget to set your meter to ohms. Disconnect the resistor from any other components, and apply the probes of your meter. If you have a manual-ranging meter, you must set the meter to a higher value than you expect to find. Otherwise, you'll get an error message.

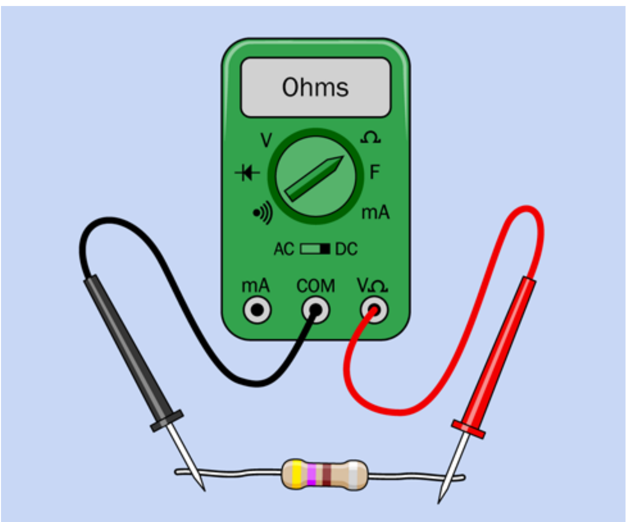

Figure 1-46 *Testing the value of a resistor.*

One thing to bear in mind is that you will get a more accurate reading if you press the probes firmly against the leads of the resistor. Don't hold the resistors and probes between your fingers—you don't want to measure the resistance of your body along with the resistance of the resistor. Place the resistor on an insulating surface, such as a nonmetallic desktop. Hold the probes by their plastic handles, and press down hard with the metal tips.

Alternatively, you can use a couple of test leads. Clip one end of each lead to each end of the resistor, and clip the other ends of the leads to the meter probes. Now you can do hands-free resistor testing, which is much easier.

Background: Puzzling Numbers

After you check a few resistors (or shop for them online) you'll notice that the same pairs of digits keep recurring. In thousands of ohms, we often find 1.0K, 1.5K, 2.2K, 3.3K, 4.7K, and 6.8K. In tens of thousands, we find 10K, 15K, 22K, 33K, 47K, and 68K.

The pairs of digits are known as *multipliers*, because you can multiply them by 1, or 1,000, or 10,000, or 100, or 10 to get basic resistor values in ohms.

There is a logical reason for this. Long ago, many resistors had an accuracy of plus-or-minus 20%, and therefore a 1.0K resistor could have an actual resistance as high as 1 + 20% = 1.2K while a 1.5K resistor could have a resistance as low as 1.5 – 20% = 1.2K. Therefore, it was pointless to have any values between 1K and 1.5K. Similarly, a 68 ohm resistor could have a value as high as 68 + 20% = just over 80 ohms, while a 100 ohm resistor could have a value as low as 100 – 20% = 80 ohms; so, it was unnecessary to have a value between 68 and 100.

In the top row of the table in Figure 1-47, the white numbers were the original multipliers for resistors. These numbers are still the most widely used today, even though modern resistor values are plus-or-minus 10% or better.

If you include the numbers in black type with the numbers in white type, you get all the possible multipliers for 10% resistors. If you then include the values in blue type, you have all the possible multipliers for 5% resistors.

1.0	1.5	2.2	3.3	4.7	6.8
1.1	1.6	2.4	3.6	5.1	7.5
1.2	1.8	2.7	3.9	5.6	8.2
1.3	2.0	3.0	4.3	6.2	9.1

Figure 1-47 *Traditional multipliers for resistor and capacitor values. See text for details.*

I have only used the original six multipliers for the projects in this book, to minimize the range of resistors that you will require. If accuracy is important (in Experiment 19, for example, where a circuit measures the speed of your reflexes) you can use a potentiometer to fine-tune the output—as I will show you in the very next experiment.

Cleanup and Recycling

You'll use the battery and the LED in the next experiment. The resistors can be reused in the future.

Experiment 4: Variable Resistance

You can vary the resistance in a circuit by inserting a *potentiometer*, which will control the current. The potentiometer in this experiment will enable you to learn more about voltage, amperage, and the relationship between them. You'll also learn how to read a manufacturer's datasheet.

What You Will Need

- 9-volt battery (1)
- Resistors: 470 ohms (1) and 1K (1)
- Generic LEDs (2)
- Test leads with alligator clips at each end (4)
- Potentiometer, 1K linear (2)
- Multimeter (1)

Look Inside Your Potentiometer

The first thing I want you to do is see for yourself how a potentiometer works, and the best way to accomplish this is to open it. This is why I asked you to acquire two potentiometers for this experiment—in case you can't put the first one back together again.

Some readers of the first edition of this book complained that it's wasteful to risk destroying a potentiometer by prying it open. But almost any learning experience consumes some resources, from pens and paper to whiteboard markers. If you really don't want to risk the future of your potentiometer, you can leave it untouched while you study the photographs that follow.

Most potentiometers are held together with little metal tabs. You need to bend the tabs upward. One way to do this is to slide in a knife and use it as a lever. Another way is to use a screwdriver—or maybe some pliers. I haven't specified any tools for this experiment, because I am hoping you already have a knife, or a screwdriver, or pliers in your home.

Figure 1-48 shows the tabs circled in red. (A fourth one is hidden behind the shaft of the component.) Figure 1-49 shows the tabs bent upward and outward.

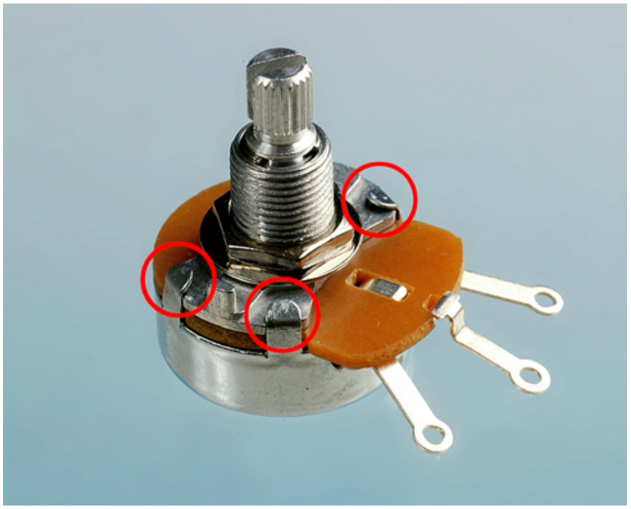

Figure 1-48 *The tabs that hold a potentiometer together.*

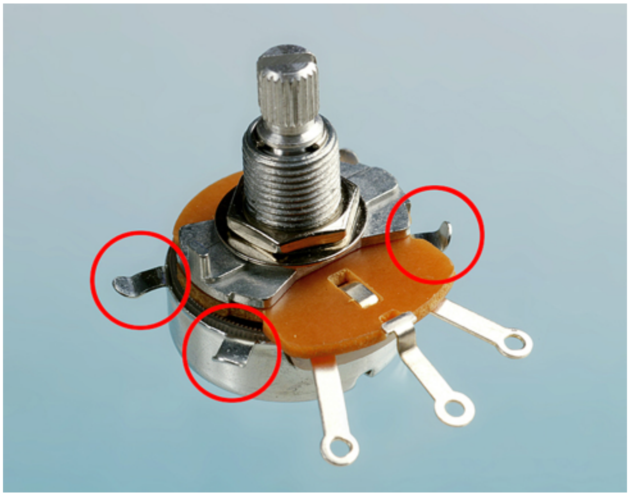

Figure 1-49 *The tabs have been bent upward and outward.*

After you have pried up the tabs, very carefully pull up on the shaft while holding the body of the potentiometer in your other hand. It should come apart as shown in Figure 1-50.

Figure 1-50 *The wiper of the potentiometer is circled.*

Inside the shell you will find a circular *track*. Depending on whether you have a really cheap potentiometer or a slightly more high-class version, the track will be made of conductive plastic or will have thin wire wrapped around it, as shown in the photograph. Either way, the principle is the same. The wire or the plastic possesses some resistance (a total of 1,000 ohms in a 1K potentiometer), and as you turn the shaft, a *wiper* rubs against the resistance, giving you a shortcut to any point from the center terminal. The wiper is circled red in Figure 1-50.

You can probably put it back together, but if necessary, use your backup potentiometer.

Testing the Potentiometer

Set your meter to measure resistance (at least 1K, on a manual-ranging meter) and touch the probes to the two adjacent terminals shown in Figure 1-51. You should find that when you turn the shaft of the potentiometer clockwise (seen from above), the resistance diminishes to almost zero. When you turn the shaft counterclockwise, the resistance increases to about 1K. Now keep the black probe where it is, and touch the red probe on the opposite terminal. The behavior of the potentiometer will be reversed.

Do you think, maybe, the middle terminal connects with the wiper inside the potentiometer? Do you think the other two terminals connect with the ends of the track?

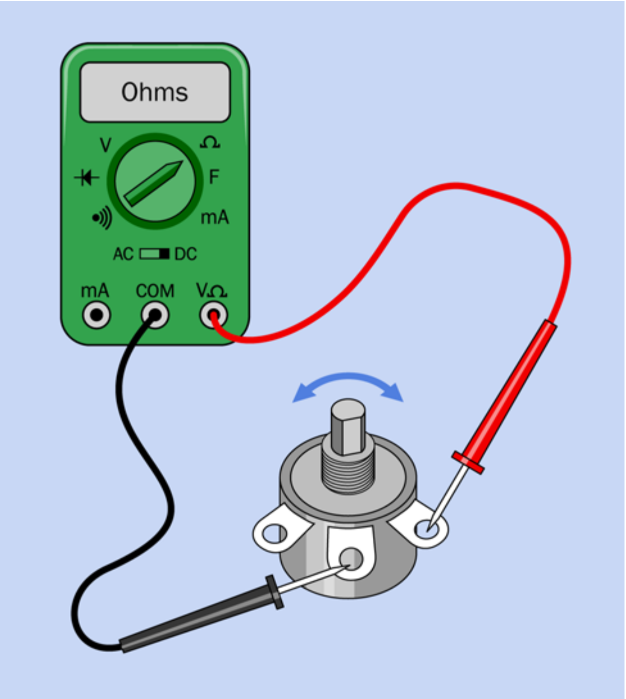

Figure 1-51 *Procedure for testing the behavior of a potentiometer.*

If you move the red probe to where the black probe is, and move the black probe to where the red probe was, the resistance between them will not change. It's the same in both directions. Unlike an LED, which has to be connected the right way around, a potentiometer has *no polarity*.

Caution: Don't Add Power

Don't apply power to a circuit while trying to measure resistance. Your meter uses a small amount of voltage from its internal battery when you are measuring resistance. You don't want that voltage to fight with voltage that you are applying from a battery.

Caution: Destructive Experiment Ahead

I have performed the next procedure many times uneventfully, but one reader reports that his LED fractured. You may wish to use safety glasses, if you want to be cautious. Regular eyeglasses will be acceptable.

Dimming Your LED

Now you can use the potentiometer to control the brightness of your LED. Connect everything exactly as shown in Figure 1-52. Make sure the two alligator clips are on the terminals shown. You are now using a variable resistance (the potentiometer) where the fixed resistor was in Experiment 3 (see Figure 1-45).

Begin with the shaft turned all the way *counterclockwise* (seen from above), otherwise you'll burn out the LED before we even get started. Now turn the shaft clockwise, very slowly, as shown by the blue arrow. You'll notice the LED glowing brighter, and brighter, and brighter—until, oops, it just went dark! You see how easy it is to destroy modern electronics? When I titled this procedure "Dimming your LED," you probably didn't realize I was talking about dimming it permanently.

Set aside that LED. I'm sorry to say, it will never glow again.

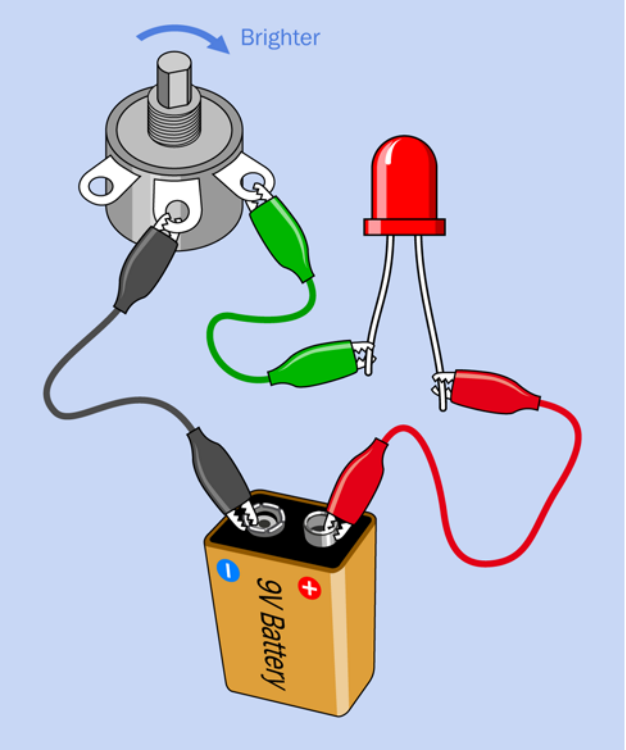

Figure 1-52 *Adjusting the brightness of an LED with a potentiometer.*

Substitute a new LED, and this time, let's protect it. Add a 470-ohm resistor, as shown in Figure 1-53. Electricity now passes through the 470-ohm resistor as well as the potentiometer, so that the LED will be protected even if the potentiometer's resistance diminishes to zero. You can turn the shaft of the potentiometer without worrying about destroying anything.

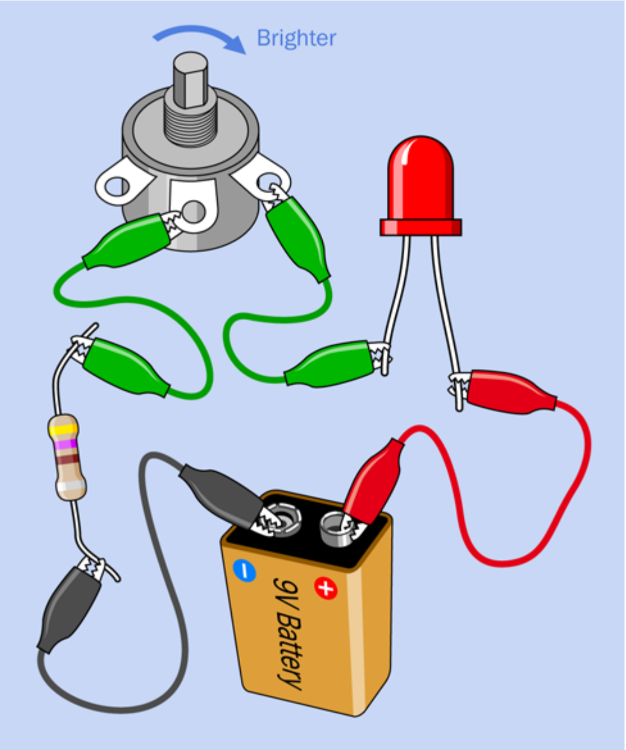

Figure 1-53 *Protecting the LED.*

The lesson that I hope you have learned is that an LED is too sensitive to be connected directly with a 9-volt battery. It must always be protected by some extra resistance in the circuit.

Could you power an LED directly from a single 1.5-volt battery? Try it. You may get a dim glow, but 1.5 volts is below the *threshold* for the LED. Let's find out how much voltage an LED needs.

Measuring Potential Difference

While the battery is connected in the circuit, set the dial of your meter to measure volts DC. You can leave the red lead plugged into the meter where it was before, because the socket for measuring volts is the same as the socket for measuring ohms.

If your meter uses manual ranging, set the voltage higher then 9 volts. Remember, the numbers beside the dial on the meter are the maximum in each range.