1 Experiencing Electricity

I want you to get a taste for electricity—literally!—in the first experiment. This first chapter of the book will show you:

- How to understand and measure electricity and resistance
- How to handle and connect components without overloading, damaging, or destroying them

Even if you have some prior knowledge of electronics, you should try these experiments before you venture on to the rest of the book.

IN THIS CHAPTER

Maker Shed (www.makershed.com) *has put together a series of* Make: Electronics *companion kits. These include all of the tools and components used in book's experiments. This is a quick, simple, and cost-effective way of getting everything you need to complete the projects in this book.*

Shopping List: Experiments 1 Through 5

If you want to limit your number of shopping trips or online purchases, look ahead in the book for additional shopping lists, and combine them to make one bulk purchase.

In this first chapter, I will give you part numbers and sources for every tool and component that we'll be using. Subsequently, I won't expect you to need such specific information, because you will have gained experience searching for items on your own.

Tools

Small pliers

RadioShack 4.5-inch mini long-nose pliers, part number 64-0062, or Xcelite 4-inch mini long-nose pliers, model L4G.

Or similar. See Figures 1-1 through 1-3. Look for these tools in hardware stores and the sources listed in the preface. The brand is unimportant. After you use them for a while, you'll develop your own preferences. In particular, you have to decide whether you like spring-loaded handles. If you decide you don't, you'll need a second pair of pliers to pull the springs out of the first.

Wire cutters

RadioShack 4.5-inch mini diagonal cutters, part number 64-0061, or Stanley 7-inch model 84-108.

Or similar. Use them for cutting copper wire, not harder metals (Figure 1-4).

Figure 1-1. *Generic long-nosed pliers are your most fundamental tool for gripping, bending, and picking things up after you drop them.*

Figure 1-2. *Longer-nosed pliers: these are useful for reaching into tiny spaces.*

Figure 1-3. *Sharp-pointed pliers are designed for making jewelry, but are also useful for grabbing tiny components.*

Figure 1-4. *Wire cutters, sometimes known as side cutters, are essential.*

Multimeter

Extech model EX410 or BK Precision model 2704-B or Amprobe model 5XP-A.

Or similar. Because electricity is invisible, we need a tool to visualize the pressure and flow, and a meter is the only way. A cheap meter will be sufficient for your initial experiments. If you buy online, try to check customer reviews, because reliability may be a problem for cheap meters. You can shop around for retailers offering the best price. Don't forget to search on eBay.

The meter must be digital—don't get the old-fashioned analog kind with a needle that moves across a set of printed scales. This book assumes that you are looking at a digital display.

I suggest that you do not buy an autoranging meter. "Autoranging" sounds useful—for example, when you want to check a 9-volt battery, the meter figures out for itself that you are not trying to measure hundreds of volts, nor fractions of a volt. The trouble is that this can trick you into making errors. What if the battery is almost dead? Then you may be measuring a fraction of a volt without realizing it. The only indication will be an easily overlooked "m" for "millivolts" beside the large numerals of the meter display.

On a manual-ranging meter, you select the range, and if the source that you are measuring is outside of that range, the meter tells you that you made an error. I prefer this. I also get impatient with the time it takes for the autoranging feature to figure out the appropriate range each time I make a measurement. But it's a matter of personal preference. See Figures 1-5 through 1-7 for some examples of multimeters.

Figure 1-5. *You can see by the wear and tear that this is my own favorite meter. It has all the necessary basic features and can also measure capacitance (the F section, for Farads). It can also check transistors. You have to choose the ranges manually.*

Figure 1-6. *Mid-priced RadioShack meter, which has the basic features; however, the dual purpose for each dial position, selected with the SELECT button, may be confusing. This is an autoranging meter.*

Figure 1-7. *An autoranging meter from Extech offers basic functions, plus a temperature probe, which may be useful to check whether components such as power supplies are running unduly hot.*

Supplies

Batteries

9-volt battery. Quantity: 1.

AA batteries, 1.5 volts each. Quantity: 6.

The batteries should be disposable alkaline, the cheapest available, because we may destroy some of them. You should *absolutely not* use rechargeable batteries in Experiments 1 and 2.

Figure 1-8. *Snap connector for a 9-volt battery.*

Battery holders and connectors

Snap connector for 9-volt battery, with wires attached (Figure 1-8). Quantity: 1. RadioShack part number 270-325 or similar. Any snap connector that has wires attached will do.

Battery holder for single AA cell, with wires attached (Figure 1-9). Quantity: 1. RadioShack part number 270-401 or Mouser.com catalog number 12BH311A-GR, or similar; any single-battery holder that has thin wires attached will do.

Figure 1-9. *Single AA-sized battery carrier with wires.*

Figure 1-10. *Battery carrier for four AA cells, to be installed in series, delivering 6 volts.*

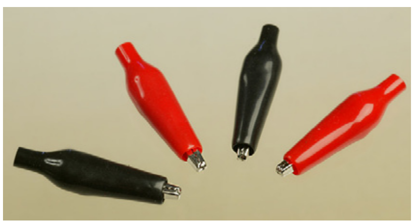


Figure 1-11. *Alligator clips inside vinyl sheaths, which reduce the chance of accidental short circuits.*

Figure 1-12. *A 3-amp fuse intended primarily for automotive use, shown here larger than actual size.*

Figure 1-13. *Potentiometers come in many shapes and sizes, with different lengths of shafts intended for different types of knobs. For our purposes, any style will do, but the larger-sized ones are easier to play with.*

Battery holder for four AA cells, with wires attached (Figure 1-10). Quantity: 1. All Electronics catalog number BH-342 or RadioShack part 270-391 or similar. Also, one battery carrier to hold two AA cells, from the same sources.

Alligator clips

Vinyl-insulated. Quantity: at least 6. All Electronics catalog number ALG-28 or RadioShack part number 270-1545 or similar (Figure 1-11).

Components

You may not know what some of these items are, or what they do. Just look for the part numbers and descriptions, and match them with the photographs shown here. Very quickly, in the learning by discovery process, all will be revealed.

Fuses

Automotive-style, mini-blade type, 3 amps. Quantity: 3. RadioShack part number 270-1089, or Bussmann part ATM-3, available from automotive parts suppliers such as AutoZone (Figure 1-12).

Or similar. A blade-type fuse is easier to grip with alligator clips than a round cartridge fuse.

Potentiometers

Panel-mount, single-turn, 2K linear, 0.1 watt minimum. Quantity: 2. Alpha part RV170F-10-15R1-B23 or BI Technologies part P160KNPD-2QC25B2K, from Mouser.com or other component suppliers (Figure 1-13).

Or similar. The "watt" rating tells you how much power this component can handle. You don't need more than 0.5 watts.

Resistors

Assortment 1/4-watt minimum, various values but must include 470 ohms, 1K, and 2K or 2.2K. Quantity: at least 100. RadioShack part number 271-312.

Or search eBay for "resistor assorted."

Light-emitting diodes (LEDs)

Any size or color (Figures 1-14 and 1-15). Quantity: 10. RadioShack part number 276-1622 or All Spectrum Electronics part K/LED1 from Mouser.com.

Or similar. Just about any LEDs will do for these first experiments.

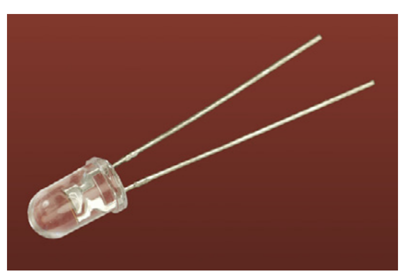


Figure 1-14. *Typical 5-mm diameter light-emitting diode (LED).*

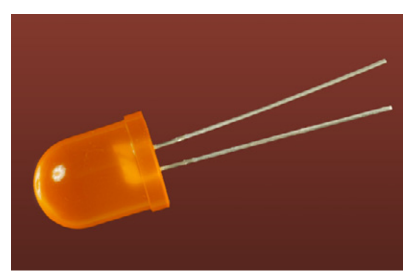


Figure 1-15. *Jumbo-sized LED (1 cm diameter) is not necessarily brighter or more expensive. For most of the experiments in this book, buy whatever LEDs you like the look of.*

Experiment 1: Taste the Power!

Can you taste electricity? Maybe not, but it feels as if you can.

You will need:

- 9-volt battery
- Snap connector for battery terminals
- Multimeter

No More Than 9 Volts

A 9-volt battery won't hurt you. But do not try this experiment with a higher-voltage battery or a larger battery that can deliver more current. Also, if you have metal braces on your teeth, be very careful not to touch them with the battery.

Procedure

Moisten your tongue and touch the tip of it to the metal terminals of a 9-volt battery. The sudden sharp tingle that you feel is caused by electricity flowing from one terminal of the battery (Figure 1-16), through the moisture on and in your tongue, to the other terminal. Because the skin of your tongue is very thin (it's actually a mucus membrane) and the nerves are close to the surface, you can feel the electricity very easily.

Now stick out your tongue, dry the tip of it very thoroughly with a tissue, and repeat the experiment without allowing your tongue to become moist again. You should feel less of a tingle.

What's happening here? We're going to need a meter to find out.

Figure 1-16. *Step 1 in the process of learning by discovery: the 9-volt tongue test.*

Tools

Setting up your meter

Check the instructions that came with the meter to find out whether you have to install a battery in it, or whether a battery is preinstalled.

Most meters have removable wires, known as *leads* (pronounced "leeds"). Most meters also have three sockets on the front, the leftmost one usually being reserved to measure high electrical currents (flows of electricity). We can ignore that one for now.

The leads will probably be black and red. The black wire plugs into a socket labeled "COM" or "Common." Plug the red one into the socket labeled "V" or "volts." See Figures 1-17 through 1-20.

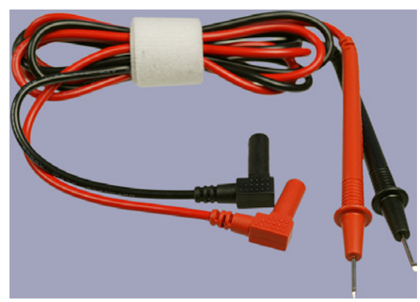


Figure 1-17. *The black lead plugs into the Common (COM) socket, and the red lead plugs into the red socket that's almost always on the righthand side of a multimeter.*

The other ends of the leads terminate in metal spikes known as *probes*, which you will be touching to components when you want to make electrical measurements. The probes detect electricity; they don't emit it in significant quantities. Therefore, they cannot hurt you unless you poke yourself with their sharp ends.

If your meter doesn't do autoranging, each position on the dial will have a number beside it. This number means "no higher than." For instance if you want to check a 6-volt battery, and one position on the voltage section of the dial is numbered 2 and the next position is numbered 20, position 2 means "no higher than 2 volts." You have to go to the next position, which means "no higher than 20 volts."

If you make a mistake and try to measure something inappropriate, the meter will show you an error message such as "E" or "L." Turn the dial and try again.

Figure 1-18

Figure 1-19

Figure 1-20. *To measure resistance and voltage, plug the black lead into the Common socket and the red lead into the Volts socket. Almost all meters have a separate socket where you must plug the red lead when you measure large currents in amps, but we'll be dealing with this later.*

FUNDAMENTALS

Ohms

We measure distance in miles or kilometers, mass in pounds or kilograms, temperature in Fahrenheit or Centigrade—and electrical resistance in ohms. The ohm is an international unit.

The Greek omega symbol (Ω) is used to indicate ohms, as shown in Figures 1-21 and 1-22. Letter K (or alternatively, KΩ) means a kilohm, which is 1,000 ohms. Letter M (or MΩ) means a megohm, which is 1,000,000 ohms.

Number of ohms	Usually expressed as	Abbreviated as
1,000 ohms	1 kilohm	1KΩ or 1K
10,000 ohms	10 kilohms	10KΩ or 10K
100,000 ohms	100 kilohms	100KΩ or 100K
1,000,000 ohms	1 megohm	1MΩ or 1M
10,000,000 ohms	10 megohms	10MΩ or 10M

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.

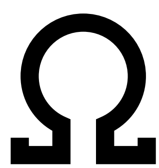


Figure 1-21. *The omega symbol is used internationally to indicate resistance on ohms.*

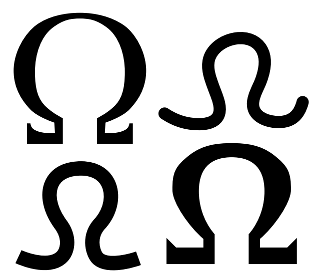


Figure 1-22. *You'll find it printed or written in a wide variety of styles.*

Procedure

We're going to use the meter to discover the electrical resistance of your tongue. First, set your meter to measure resistance. If it has autoranging, look to see whether it is displaying a K, meaning kilohms, or M, meaning megohms. If you have to set the range manually, begin with no less than 100,000 ohms (100K). See Figures 1-23 through 1-25.

Touch the probes to your tongue, about an inch apart. Note the reading, which should be around 50K. Now put aside the probes, stick out your tongue, and use a tissue to dry it very carefully and thoroughly. Without allowing your tongue to become moist again, repeat the test, and the reading should be higher. Finally, press the probes against the skin of your hand or arm: you may get no reading at all, until you moisten your skin.

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.

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 inside it. Think of the cells inside a battery as being like two water tanks—one of them full, the other empty. If they are connected with a pipe, water flows between them until their levels are equal. Figure 1-26 may help you 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).

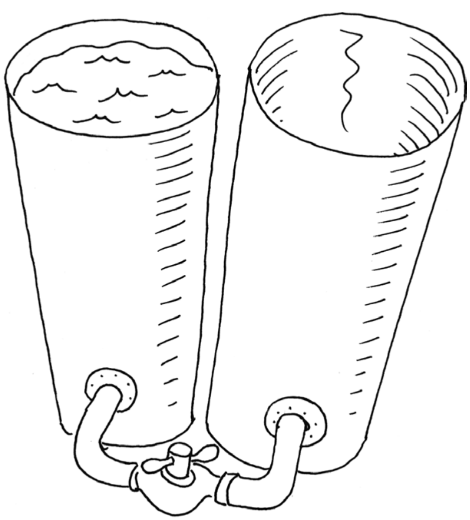


Figure 1-26. *Think of the cells in a battery as being like two cylinders: one full of water, the other empty. Open a connection between the cylinders, and the water will flow until the levels are equal on both sides. The less resistance in the connection, the faster the flow will be.*

Figure 1-23

Figure 1-24

Figure 1-25. *To measure ohms, turn the dial to the ohm (omega) symbol. On an autoranging meter, you can then press the Range button repeatedly to display different ranges of resistance, or simply touch the probes to a resistance and wait for the meter to choose a range automatically. A manual meter requires you to select the range with the dial (you should set it to 100K or higher, to measure skin resistance). If you don't get a meaningful reading, try a different range.*

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).

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

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, as 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.

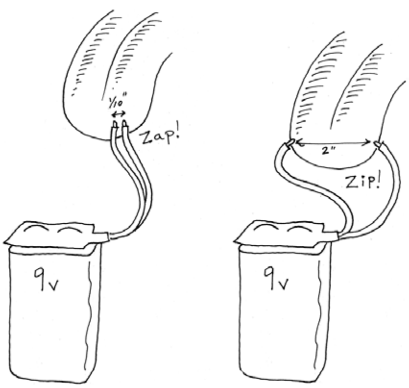


Figure 1-28. *Modifying the tongue test to show that a shorter distance, with lower resistance, allows greater flow of electricity, and a bigger zap.*

Further Investigation

Attach the snap-on terminal cap (shown earlier in Figure 1-8) to the 9-volt battery. Take the two wires that are attached to the cap and hold them so that the bare ends are just a few millimeters apart. Touch them to your tongue. Now separate the ends of the wires by a couple of inches, and touch them to your tongue again. (See Figure 1-28.) Notice any difference?

Use your meter to measure the electrical resistance of your tongue, this time varying the distance between the two probes. When electricity travels through a shorter distance, it encounters less total resistance. As a result, the current (the flow of electricity per second) increases. You can try a similar experiment on your arm, as shown in Figure 1-29.

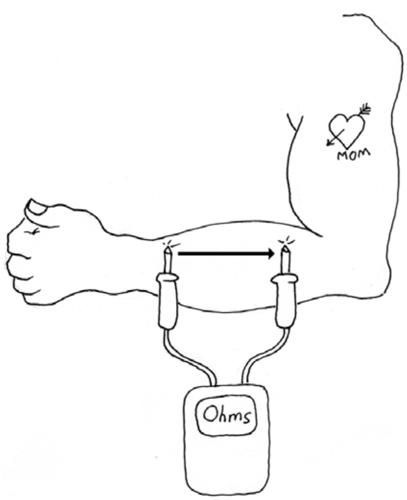


Figure 1-29. *Moisten your skin before trying to measure its resistance. You should find that the resistance goes up as you move the meter probes farther apart. The resistance is proportional to the distance.*

Use your meter to test the electrical resistance of water. Dissolve some salt in the water, and test it again. Now try measuring the resistance of distilled water (in a clean glass).

The world around you is full of materials that conduct electricity with varying amounts of resistance.

Cleanup and Recycling

Your battery should not have been damaged or significantly discharged by this experiment. You'll be able to use it again.

Remember to switch off your meter before putting it away.

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 direct connection between the two sides of a power source.

Short Circuits

Short circuits can be dangerous. Do not 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 (Figure 1-30).

Lithium batteries are also dangerous. Never short-circuit a lithium battery: it can catch fire and burn you (Figure 1-31).

Use only an alkaline battery in this experiment, and only a single AA cell (Figure 1-32). You should also wear safety glasses in case you happen to have a defective battery.

Figure 1-30. *Anyone who has dropped an adjustable wrench across the bare terminals of a car battery will tell you that short circuits can be dramatic at a "mere" 12 volts, if the battery is big enough.*

Figure 1-31. *The low internal resistance of lithium batteries (which are often used in laptop computers) allows high currents to flow, with unexpected results. Never fool around with lithium batteries!*

Figure 1-32. *Shorting out an alkaline battery can be safe if you follow the directions precisely. Even so, the battery is liable to become too hot to touch comfortably. Don't try this with any type of rechargeable battery.*

You will need:

- 1.5-volt AA battery
- Single-battery carrier
- 3-amp fuse
- Safety glasses (regular eyeglasses or sunglasses will do)
- Alligator clip (small or large)

Procedure

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

Put the battery into a battery holder that's designed for a single battery and has two thin insulated wires emerging from it, as shown in Figure 1-32. Do not use any other kind of battery holder.

Use an alligator clip to connect the bare ends of the wires, as shown in Figure 1-32. There will be no spark, because you are using only 1.5 volts. Wait one minute, and you'll find that the wires are getting hot. Wait another minute, and the battery, too, will be hot.

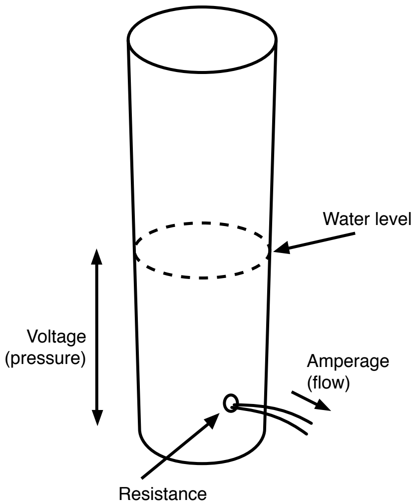


Figure 1-33. *Think of voltage as pressure, and amperes as flow.*

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.

Chemical reactions inside the battery create electrical pressure. The correct name for this pressure is *voltage*, which is measured in volts and is named after Alessandro Volta, an electrical pioneer.

Going back to the water analogy: the height of the water in a tank is proportionate to the pressure of the water, and comparable to voltage. Figure 1-33 may help you to visualize this.

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

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 used a lower voltage. How can we explain this?

The electrical resistance of your tongue is very high, which reduces the flow of electrons. The resistance of a wire is very low, so if there's only a wire connecting the two terminals of the battery, more current will pass through it, creating more heat. If all other factors remain constant:

- Lower resistance allows more current to flow (Figure 1-34).
- The heat generated by electricity is proportional to the amount of electricity (the current) that flows.

Here are some other basic concepts:

- The flow of electricity per second is measured in amperes, or amps.
- The pressure of electricity, measured in volts, causes the flow.
- The resistance to the flow is measured in ohms.
- A higher resistance restricts the current.
- A higher voltage overcomes resistance and increases the current.

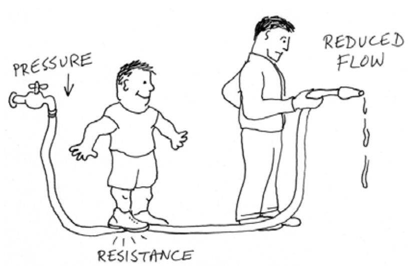


Figure 1-34. *Larger resistance results in smaller flow—but if you increase the pressure, it may overcome the resistance and increase the flow.*

If you're wondering exactly how much current flows between the terminals of a battery when you short it out, that's a difficult question to answer. If you try to use your multimeter to measure it, you're liable to blow the fuse inside the meter. Still, you can use your very own 3-amp fuse, which we can sacrifice because it didn't cost very much.

First inspect the fuse very carefully, using a magnifying glass if you have one. You should see a tiny S-shape in the transparent window at the center of the fuse. That S is a thin section of metal that melts easily.

Remove the battery that you short-circuited. It is no longer useful for anything, and should be recycled if possible. Put a fresh battery into the battery carrier, connect the fuse as shown in Figure 1-35, and take another look. You should see a break in the center of the S shape, where the metal melted almost instantly. Figure 1-36 shows the fuse before you connected it, and Figure 1-37 depicts a blown fuse. 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.

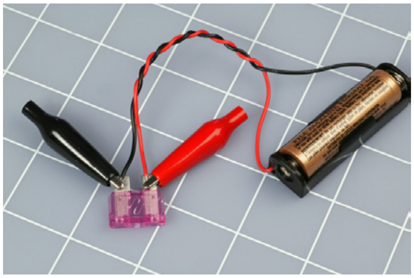


Figure 1-35. *When you attach both wires to the fuse, the little S-shaped element inside will melt almost instantly.*

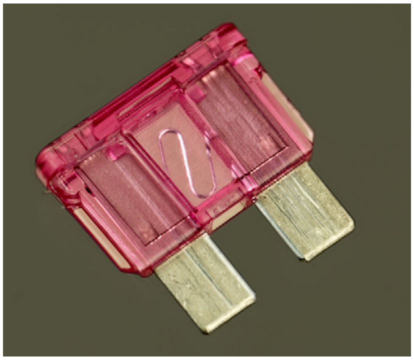


Figure 1-36. *A 3-amp fuse, before its element was melted by a single 1.5-volt battery.*

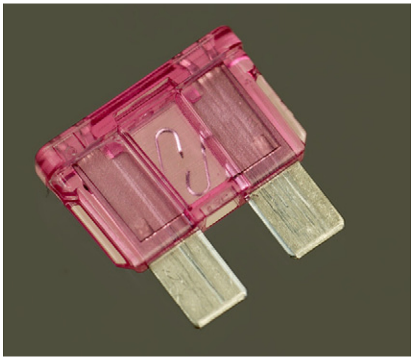


Figure 1-37. *The same fuse after being melted by electric current.*

FUNDAMENTALS

Volt basics

Electrical pressure is measured in volts. The volt is an international unit. A millivolt is 1/1,000 of a volt.

Number of volts	Usually expressed as	Abbreviated as
0.001 volts	1 millivolt	1 mV
0.01 volts	10 millivolts	10 mV
0.1 volts	100 millivolts	100 mV
1 volt	1,000 millivolts	1V

Ampere basics

We measure electrical flow in amperes, or amps. The ampere is an international unit, often referred to as an "amp." A milliamp is 1/1,000 of an ampere.

Number of amperes	Usually expressed as	Abbreviated as
0.001 amps	1 milliamp	1 mA
0.01 amps	10 milliamps	10 mA
0.1 amps	100 milliamps	100 mA
1 amp	1,000 milliamps	1A

BACKGROUND

Inventor of the battery

Alessandro Volta (Figure 1-38) 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 became interested 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.

Figure 1-38. *Alessandro Volta discovered that chemical reactions can create electricity.*

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, in one direction.

The flow of current that you get from the "hot" wire in a power outlet in your home is very different. It changes from positive to negative 60 times each second (in many foreign countries and Europe, 50 times per second). This is known as *alternating current*, or AC, which is more like the pulsatile flow you get from a power washer.

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 an American power outlet are shown in Figure 1-39. A few other nations, such as Japan, also use American-style outlets.

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.

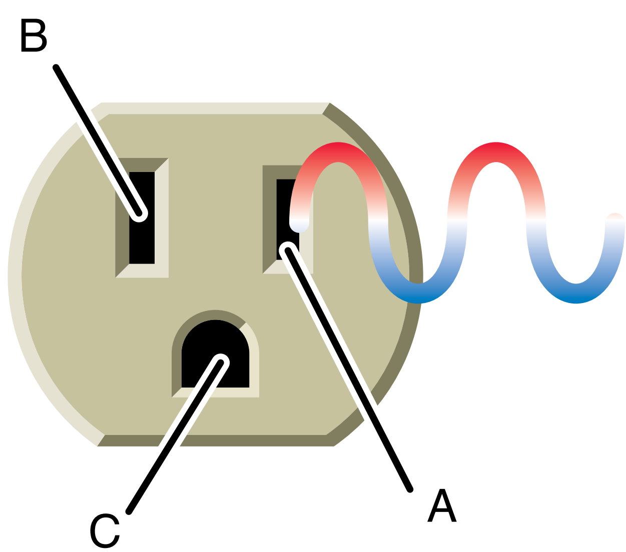


Figure 1-39. *This style of power outlet is found in North America, South America, Japan, and some other nations. European outlets look different, but the principle remains the same. Socket A is the "live" side of the outlet, supplying voltage that alternates between positive and negative, relative to socket B, which is called 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.*

Cleanup and Recycling

The first AA battery that you shorted out is probably damaged beyond repair. You should dispose of 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.) You'll have to 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 holder also can be reused later.

Experiment 3: Your First Circuit

Now it's time to make electricity do something that's at least slightly useful. For this purpose, you'll use components known as resistors, and a light-emitting diode, or LED.

You will need:

- 1.5-volt AA batteries. Quantity: 4.
- Four-battery holder. Quantity: 1.
- Resistors: 470Ω, 1K, and either 2K or 2.2K (the 2.2K value happens to be more common than 2K, but either will do in this experiment). Quantity: 1 of each resistor.
- An LED, any type. Quantity: 1.
- Alligator clips. Quantity: 3.

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, the value is measured in ohms.

If you bought a bargain-basement assortment package of resistors, you may find nothing that tells you their values. That's OK; we can find out easily enough. In fact, even if they are clearly labeled, I want you to check their values yourself. You can do it in two ways:

- Use your multimeter. This is excellent practice in learning to interpret the numbers that it displays.
- Learn the color codes that are printed on most resistors. See the following section, "Fundamentals: Decoding resistors," for instructions.

After you check them, it's a good idea to sort them into labeled compartments in a little plastic parts box. Personally, I like the boxes sold at the Michaels chain of crafts stores, but you can find them from many sources.

BACKGROUND

Father of electromagnetism

Born in 1775 in France, André-Marie Ampère (Figure 1-40) 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 1-40. *Andre-Marie Ampere 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.*

FUNDAMENTALS

Decoding resistors

Some resistors have their value clearly stated on them in microscopic print that you can read with a magnifying glass. Most, however, are color-coded with stripes. The code works like this: first, ignore the color of the body of the resistor. Second, look for a silver or gold stripe. If you find it, turn the resistor so that the stripe is on the righthand side. Silver means that the value of the resistor is accurate within 10%, while gold means that the value is accurate within 5%. If you don't find a silver or gold stripe, turn the resistor so that the stripes are clustered at the left end. You should now find yourself looking at three colored stripes on the left. Some resistors have more stripes, but we'll deal with those in a moment. See Figures 1-41 and 1-42.

Figure 1-41. *Some modern resistors have their values printed on them, although you may need a magnifier to read them. This 15K resistor is less than half an inch long.*

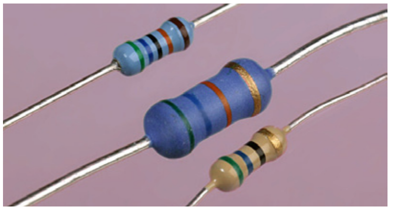


Figure 1-42. *From top to bottom, these resistor values are 56,000 ohms (56K), 5,600 ohms (5.6K), and 560 ohms. The size tells you how much power the resistor can handle; it has nothing to do with the resistance. The smaller components are rated at 1/4 watt; the larger one in the center can handle 1 watt of power.*

Starting from the left, the first and second stripes are coded according to this table:

Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

The third stripe has a different meaning: It tells you how many zeros to add, like this:

Black	-	No zeros
Brown	0	1 zero
Red	00	2 zeros
Orange	000	3 zeros
Yellow	0000	4 zeros
Green	00000	5 zeros
Blue	000000	6 zeros
Violet	0000000	7 zeros
Gray	00000000	8 zeros
White	000000000	9 zeros

FUNDAMENTALS

Decoding resistors (continued)

Note that the color-coding is consistent, so that green, for instance, means either a value of 5 (for the first two stripes) or 5 zeros (for the third stripe). Also, the sequence of colors is the same as their sequence in a rainbow.

So, a resistor colored brown-red-green would have a value of 1-2 and five zeros, making 1,200,000 ohms, or 1.2MΩ. A resistor colored orange-orange-orange would have a value of 3-3 and three zeros, making 33,000 ohms, or 33KΩ. A resistor colored brown-black-red would have a value of 1-0 and two additional zeros, or 1KΩ. Figure 1-43 shows some other examples.

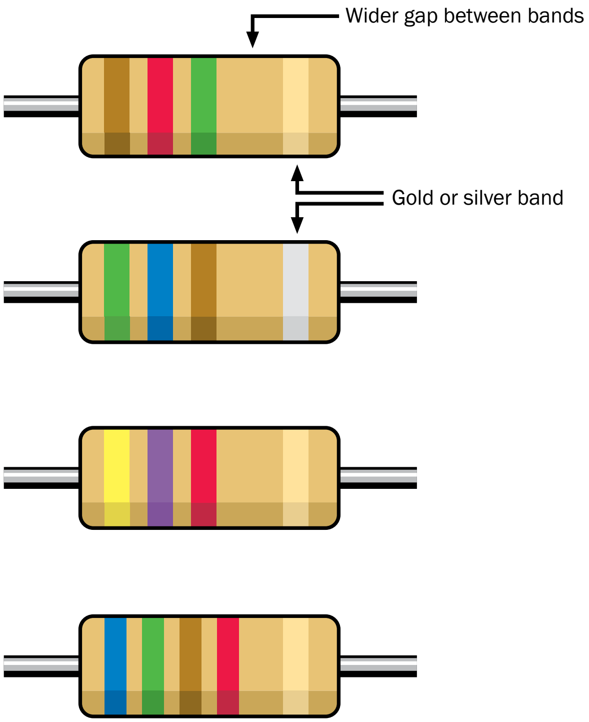


Figure 1-43. *To read the value of a resistor, first turn it so that the silver or gold stripe is on the right, or the other stripes are clustered on the left. From top to bottom: The first resistor has a value of 1-2 and five zeros, or 1,200,000, which is 1.2MΩ. The second is 5-6 and one zero, or 560Ω. The third is 4-7 and two zeros, or 4,700, which is 4.7KΩ. The last is 6-5-1 and two zeros, or 65,100Ω, which is 65.1KΩ.*

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 the resistor to be calibrated to a finer tolerance.

Confusing? Absolutely. That's why it's easier to 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. As long as you're within 5% of the claimed value, it doesn't matter for our purposes.

Lighting an LED

Now take a look at one of your LEDs. An old-fashioned lightbulb wastes a lot of power by converting it into heat. LEDs are much smarter: they convert almost all their power into light, and they last almost indefinitely—as long as 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 protruding from the LED must receive a *more positive* voltage than the shorter wire.
- The voltage difference between the long wire and the short wire must not exceed the limit stated by the manufacturer.
- The current passing through the LED must not exceed the limit stated by the manufacturer.

What happens if you break these rules? Well, we're going to find out!

Make sure you are using fresh batteries. You can check by setting your multimeter to measure volts DC, and touching the probes to the terminals of each battery. You should find that each of them generates a pressure of at least 1.5 volts. If they read slightly higher than this, it's normal. A battery starts out above its rated voltage, and delivers progressively less as you use it. Batteries also lose some voltage while they are sitting on the shelf doing nothing.

Load your battery holder (taking care that the batteries are the right way around, with the negative ends pressing against the springs in the carrier). Use your meter to check the voltage on the wires coming out of the battery carrier. You should have at least 6 volts.

Now select a 2KΩ resistor. Remember, "2KΩ" means "2,000 ohms." If it has colored stripes, they should be red-black-red, meaning 2-0 and two more zeros. Because 2.2K resistors are more common than 2K resistors, you can substitute one of them if necessary. It will be colored red-red-red.

Wire it into the circuit as shown in Figures 1-44 and 1-45, making the connections with alligator clips. You should see the LED glow very dimly.

Now swap out your 2K resistor and substitute a 1K resistor, which will have brown-black-red stripes, meaning 1-0 and two more zeros. The LED should glow more brightly.

Swap out the 1K resistor and substitute a 470Ω resistor, which will have yellow-violet-brown stripes, meaning 4-7 and one more zero. The LED should be brighter still.

This may seem very elementary, but it makes an important point. The resistor blocks a percentage of the voltage in the circuit. Think of it as being like a kink or constriction in a flexible hose. A higher-value resistor blocks more voltage, leaving less for the LED.

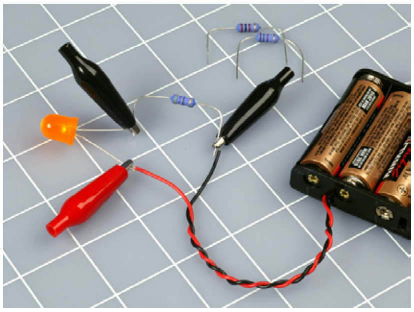


Figure 1-44. *The setup for Experiment 3, showing resistors of 470Ω, 1KΩ, and 2KΩ. Apply alligator clips where shown, to make a secure contact, and try each of the resistors one at a time at the same point in the circuit, while watching the LED.*

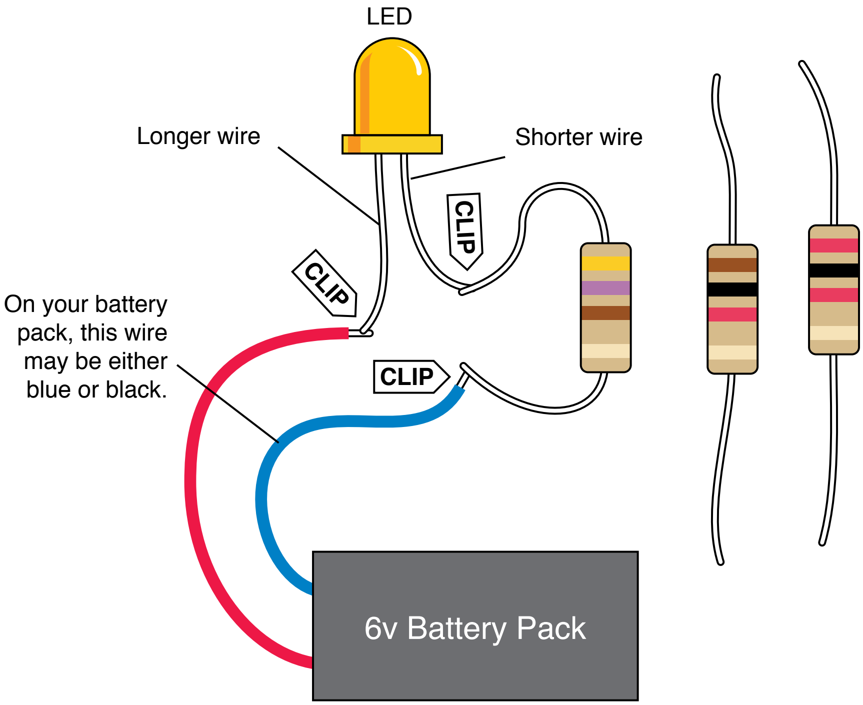


Figure 1-45. *Here's how it actually looks, using a large LED. If you start with the highest value resistor, the LED will glow very dimly as you complete the circuit. The resistor drops most of the voltage, leaving the LED with insufficient current to make it shine brightly.*

Cleanup and Recycling

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

Experiment 4: Varying the Voltage

Potentiometers come in various shapes and sizes, but they all do the same thing: they allow you to vary voltage and current by varying resistance. 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 data sheet.

You will need the same batteries, battery carrier, alligator clips, and LED from the last experiment, plus:

- Potentiometer, 2KΩ linear. Quantity: 2. (See Figure 1-46.) Full-sized potentiometers that look like this are becoming less common, as miniature versions are taking their place. I'd like you to use a large one, though, because it's so much easier to work with.
- One extra LED.
- Multimeter.

Look Inside Your Potentiometer

The first thing I want you to do is find out how a potentiometer works. This means you'll have to open it, which is why your shopping list required you to buy two of them, in case you can't put the first one back together again.

Most potentiometers are held together with little metal tabs. You should be able to grab hold of the tabs with your wire cutters or pliers, and bend them up and outward. If you do this, the potentiometer should open up as shown in Figures 1-47 and 1-48.

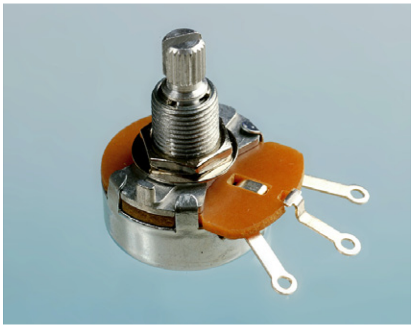


Figure 1-46

Figure 1-47

Figure 1-48. *To open the potentiometer, first pry up the four little metal tabs around the edge (you can see one sticking out at the left and another one sticking out at the right in Figure 1-47). Inside is a coil of wire around a flat plastic band, and a pair of springy contacts (the wiper), which conduct electricity to or from any point in the coil when you turn the shaft.*

Depending whether you have a really cheap potentiometer or a slightly more high-class version, you may find a circular track of conductive plastic or a loop of coiled wire. Either way, the principle is the same. The wire or the plastic possesses some resistance (a total of 2K in this instance), and as you turn the shaft of the potentiometer, a wiper rubs against the resistance, giving you a shortcut to any point from the center terminal.

You can try to put it back together, but if it doesn't work, use your backup potentiometer instead.

To test your potentiometer, set your meter to measure resistance (ohms) and touch the probes while turning the potentiometer shaft to and fro, as shown in Figure 1-49.

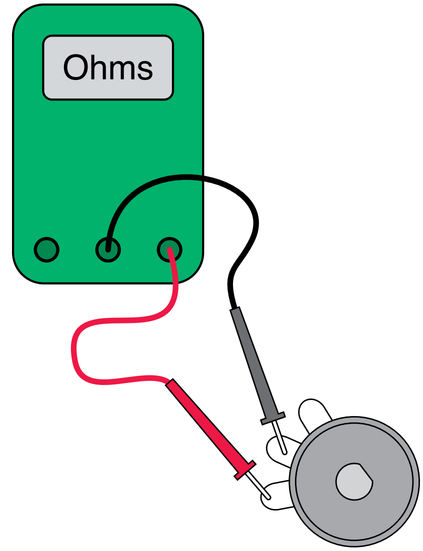


Figure 1-49. *Measure the resistance between these two terminals of the potentiometer while you turn its shaft to and fro.*

Dimming Your LED

Begin with the potentiometer turned all the way counterclockwise, otherwise you'll burn out the LED before we even get started. (A very, very small number of potentiometers increase and decrease resistance in the opposite way to which I'm describing here, but as long as your potentiometer looks like the one in Figure 1-48 after you open it up, my description should be accurate.)

Now connect everything as shown in Figures 1-50 and 1-51, taking care that you don't allow the metal parts of any of the alligator clips to touch each other. Now turn up the potentiometer *very* slowly. You'll notice the LED glowing brighter, and brighter, and brighter—until, oops, it goes dark. You see how easy it is to destroy modern electronics? Throw away that LED. It will never glow again. Substitute a new LED, and we'll be more careful this time.

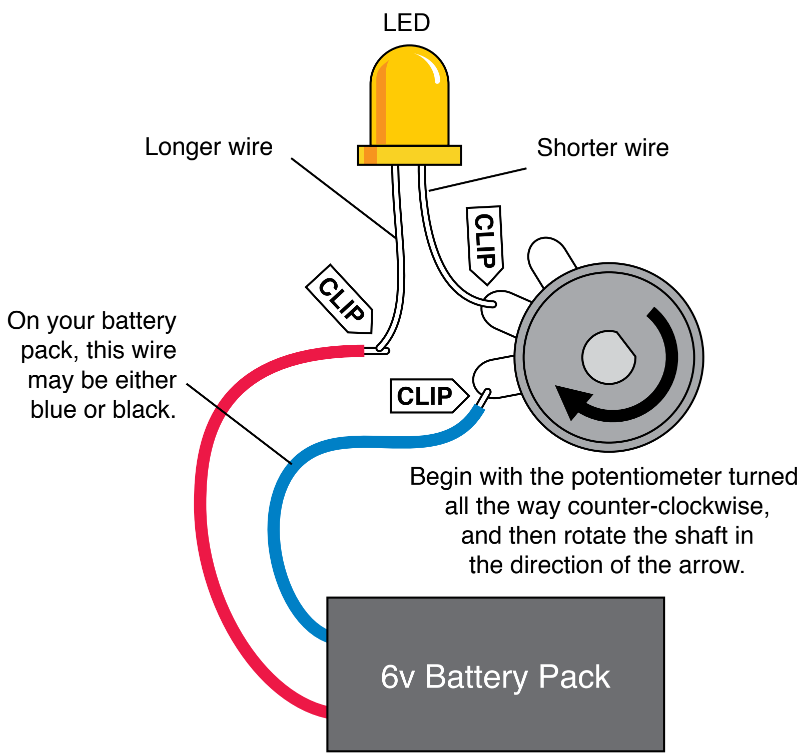


Figure 1-50. *The setup for Experiment 4. Rotating the shaft of the 2K potentiometer varies its resistance from 0 to 2,000Ω. This resistance restricts the current that can flow through the LED, and also changes the voltage across the LED.*

Figure 1-51. *The LED in this photo is dark because I turned the potentiometer up just a little bit too far.*

Figure 1-52

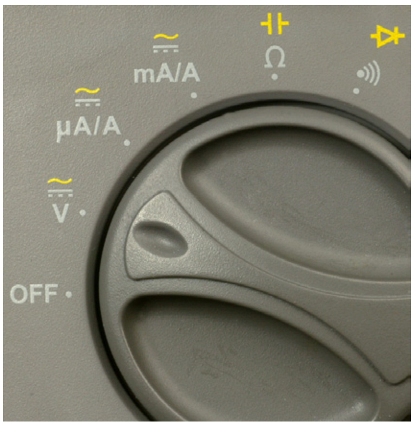


Figure 1-53

Figure 1-54. *Each meter has a different way to measure volts DC. The manually adjusted meter (top) requires you to move a slider switch to "DC" and then choose the highest voltage you want to measure: In this case, the selected voltage is 20 (because 2 would be too low). Using the autoranging RadioShack meter, you set it to "V" and the meter will figure out which range to use.*

While the batteries are connected to the circuit, set your meter to measure *volts DC* as shown in Figures 1-52 through 1-54. Now touch the probes either side of the LED. Try to hold the probes in place while you turn the potentiometer up a little, and down a little. You should see the voltage pressure around the LED changing accordingly. We call this the *potential difference* between the two wires of the LED.

If you were using a miniature old-fashioned lightbulb instead of an LED, you'd see the potential difference varying much more, because a lightbulb behaves like a "pure" resistor, whereas an LED self-adjusts to some extent, modifying its resistance as the voltage pressure changes.

Now touch the probes to the two terminals of the potentiometer that we're using, so that you can measure the potential difference between them. The potentiometer and the LED share the total available voltage, so when the potential difference (the voltage drop) around the potentiometer goes up, the potential difference around the LED goes down, and vice versa. See Figures 1-55 through 1-57. A few things to keep in mind:

- If you add the voltage drops across the devices in the circuit, the total is the same as the voltage supplied by the batteries.
- You measure voltage relatively, between two points in a circuit.
- Apply your meter like a stethoscope, without disturbing or breaking the connections in the circuit.

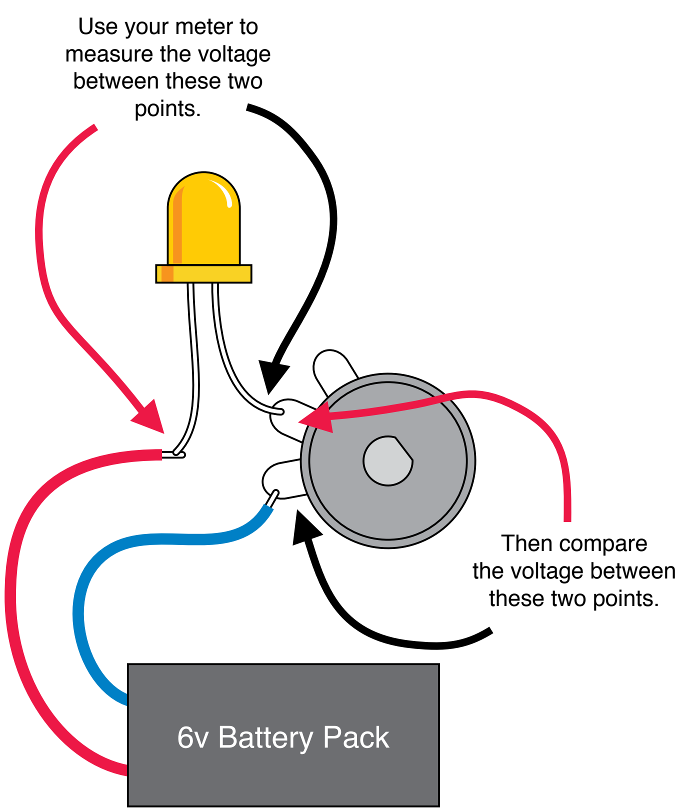


Figure 1-55. *How to measure voltage in a simple circuit.*

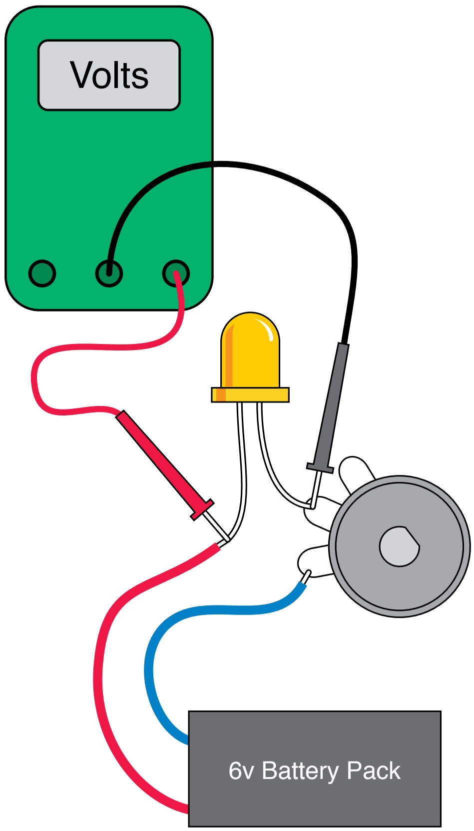


Figure 1-56. *The meter shows how much voltage the LED takes.*

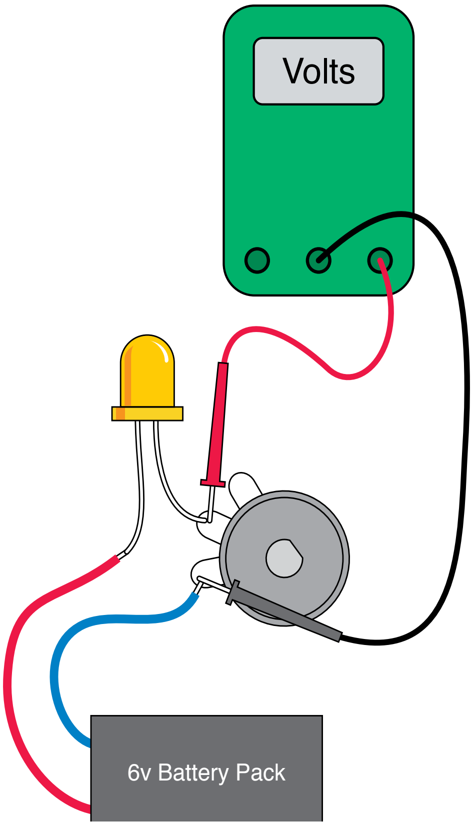


Figure 1-57. *The meter shows how much voltage the potentiometer takes.*

Checking the Flow

Now I want you to make a different measurement. I want you to measure the flow, or current, in the circuit, using your meter set to mA (milliamps). Remember, to measure current:

- You can only measure current when it passes *through* the meter.
- You have to insert your meter into the circuit.
- Too much current will blow the fuse inside your meter.

Make sure you set your meter to measure mA, not volts, before you try this. Some meters require you to move one of your leads to a different socket on the meter, to measure mA. See Figures 1-58 through 1-61.

Figure 1-58. *Any meter will blow its internal fuse if you try to make it measure too high an amperage. In our circuit, this is not a risk as long as you keep the potentiometer in the middle of its range. Choose "mA" for milliamps and remember that the meter displays numbers that mean thousandths of an amp.*

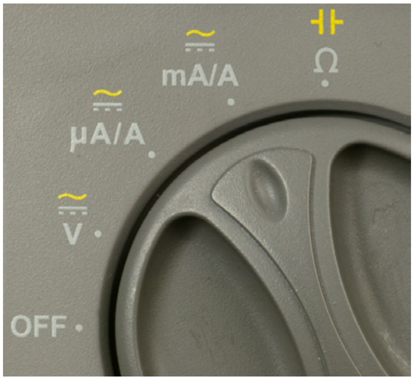


Figure 1-59

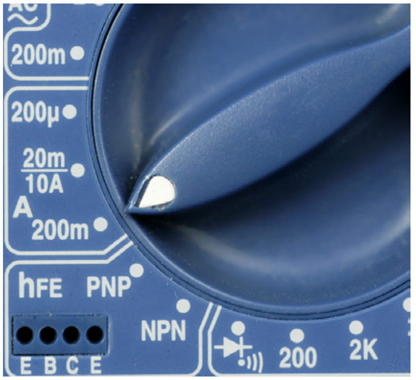


Figure 1-60

Figure 1-61. *A manual meter such as the one here may require you to shift the red lead to a different socket, to measure milliamps. Most modern meters don't require this until you are measuring higher currents.*

Insert your meter into the circuit, as shown in Figure 1-62. Don't turn the potentiometer more than halfway up. The resistance in the potentiometer will protect your meter, as well as the LED. If the meter gets too much current, you'll find yourself replacing its internal fuse.

As you adjust the potentiometer up and down a little, you should find that the varying resistance in the circuit changes the flow of current—the amperage. This is why the LED burned out in the previous experiment: too much current made it hot, and the heat melts it inside, just like the fuse in the previous experiment. *A higher resistance limits the flow of current, or amperage.*

Now insert the meter in another part of the circuit, as shown in Figure 1-63. As you turn the potentiometer up and down, you should get exactly the same results as with the configuration in Figure 1-62. This is because the current is the same at all points in a similar circuit. *It has to be, because the flow of electrons has no place else to go.*

It's time now to nail this down with some numbers. Here's one last thing to try. Set aside the LED and substitute a 1KΩ resistor, as shown in Figure 1-64. The total resistance in the circuit is now 1KΩ plus whatever the resistance the potentiometer provides, depending how you set it. (The meter also has some resistance, but it's so low, we can ignore it.)

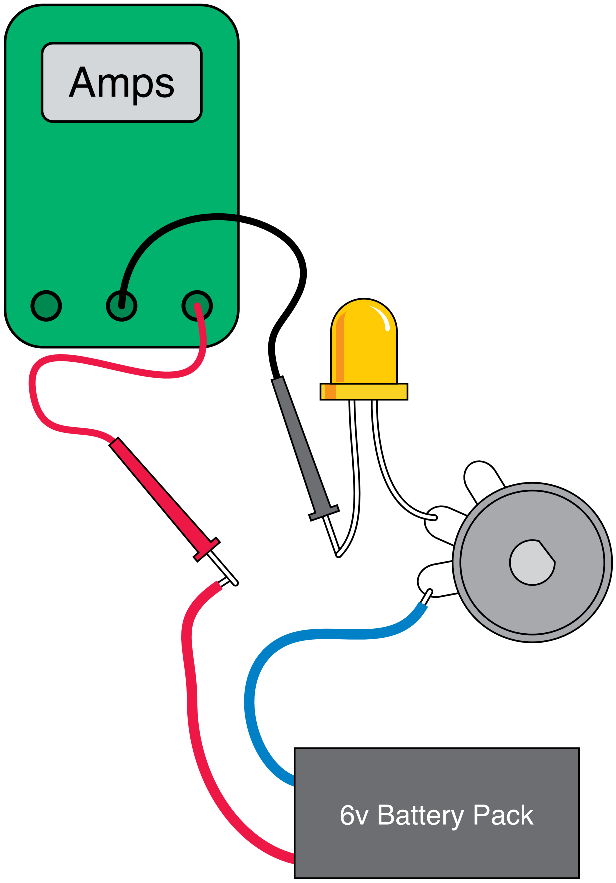


Figure 1-62. *To measure amps, as illustrated here and in Figure 1-63, the current has to pass through the meter. When you increase the resistance, you restrict the current flow, and the lower flow makes the LED glow less brightly.*

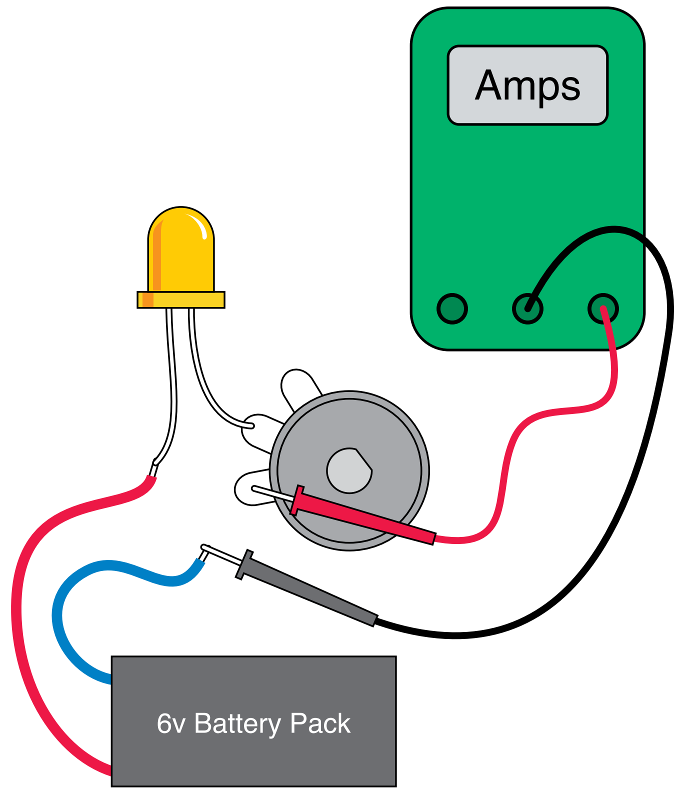


Figure 1-63

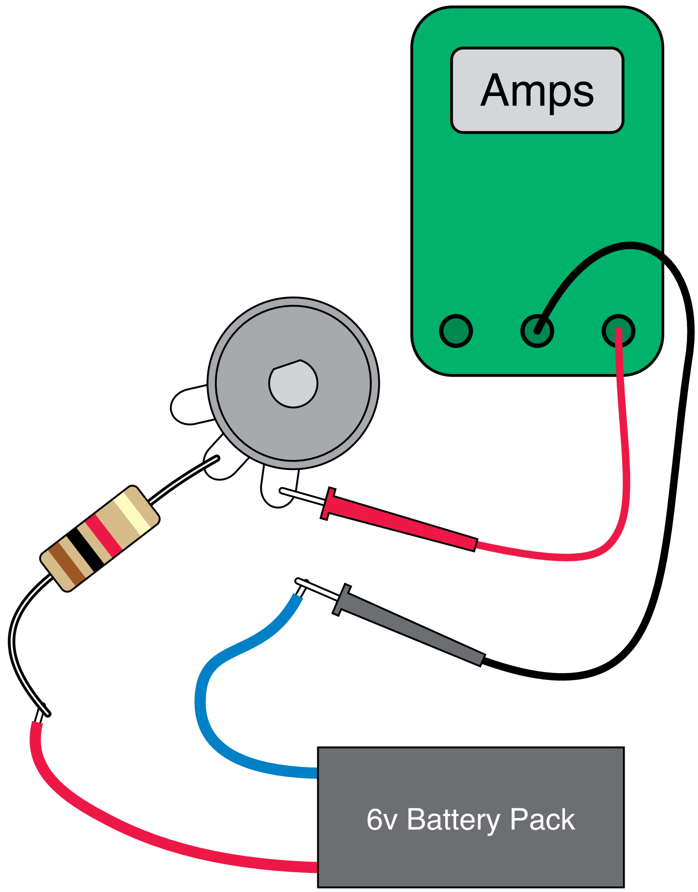


Figure 1-84. *If you substitute a resistor instead of the LED, you can confirm that the current flowing through the circuit varies with the total resistance in the circuit, if the voltage stays the same.*

Turn the potentiometer all the way counterclockwise, and you have a total of 3K resistance in the circuit. Your meter should show about 2 mA flowing. Now turn the potentiometer halfway, and you have about 2K total resistance. You should see about 3 mA flowing. Turn the potentiometer all the way clockwise, so there's a total of 1K, and you should see 6 mA flowing. You may notice that if we multiply the resistance by the amperage, we get 6 each time—which just happens to be the voltage being applied to the circuit. See the following table.

Total resistance	Current	Voltage
(KΩ)	(mA)	(Volts)
3	2	6
2	3	6
1	6	6

In fact, we could say:

voltage = kilohms × milliamps

But wait a minute: 1K is 1,000 ohms, and 1mA is 1/1,000 of an amp. Therefore, our formula should really look like this:

voltage = (ohms × 1,000) × (amps/1,000)

The two factors of 1,000 cancel out, so we get this:

volts = ohms × amps

This is known as Ohm's Law. See the section, "Fundamentals: Ohm's Law," on the following page.

FUNDAMENTALS

Series and parallel

Before we go any further, you should know how resistance in a circuit increases when you put resistors in series or in parallel. Figures 1-65 through 1-67 illustrate this. Remember:

- Resistors in series are oriented so that one follows the other.
- Resistors in parallel are oriented side by side.

When you put two equal-valued resistors in series, you double the total resistance, because electricity has to pass through two barriers in succession.

When you put two equal-valued resistors in parallel, you divide the total resistance by two, because you're giving the electricity two paths which it can take, instead of one.

In reality we don't normally need to put resistors in parallel, but we often put other types of components in parallel. Lightbulbs in your house, for instance, are all wired that way. So, it's useful to understand that resistance in a circuit goes down if you keep adding components in parallel.

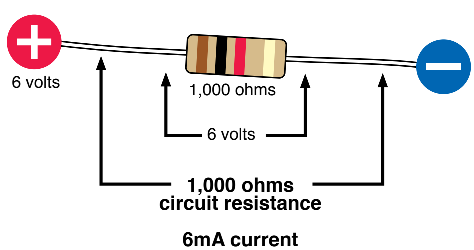


Figure 1-65. *One resistor takes the entire voltage, and according to Ohm's Law, it draws v/R = 6/1,000 = 0.006 amps = 6mA of current.*

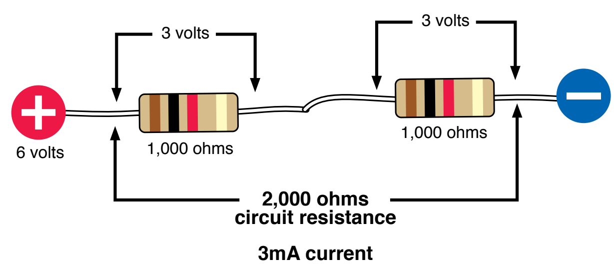


Figure 1-66. *When two resistors are in series, the electricity has to pass through one to reach the other, and therefore each of them takes half the voltage. Total resistance is now 2,000 ohms, and according to Ohm's Law, the circuit draws v/R = 6/2,000 = 0.003 amps = 3mA of current.*

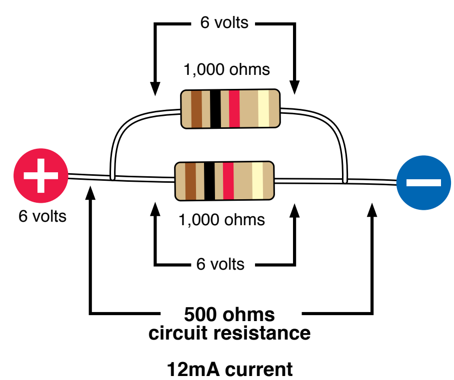


Figure 1-67. *When two resistors are in parallel, each is exposed to the full voltage, so each of them takes 6 volts. The electricity can now flow through both at once, so the total resistance of the circuit is half as much as before. According to Ohm's Law, the circuit draws v/R = 6/500 = 0.012 amps = 12mA of current.*

FUNDAMENTALS

Ohm's Law

For reasons I'll explain in a moment, amps are normally abbreviated with the letter I. V stands for volts and R stands for resistance in ohms (because the omega symbol, Ω, is not easily generated from most keyboards). Using these symbols, you can write Ohm's Law in three different ways:

$V = I \times R$

$I = V/R$

$R = V/I$

Remember, V is a *difference* in voltage between two points in a simple circuit, R is the resistance in ohms *between* the same two points, and I is the current in amps flowing *through* the circuit between the two points.

Letter I is used because originally current was measured by its *inductance*, meaning the ability to induce magnetic effects. It would be much less confusing to use A for amps, but unfortunately it's too late for that to happen.

Using Ohm's Law

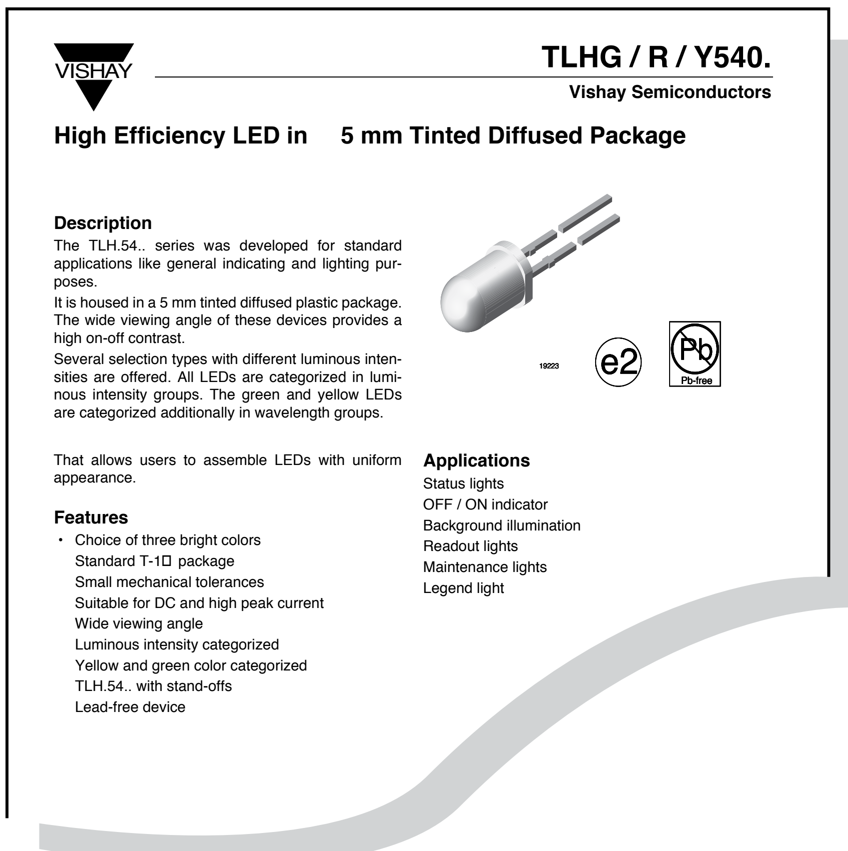
Ohm's Law is extremely useful. For example, it helps us to figure out whether a component can be used safely in a circuit. Instead of stressing the component until we burn it out, we can predict whether it will work.

For instance, the first time you turned the potentiometer, you didn't really know how far you could go until the LED burned out. Wouldn't it be useful to know precisely what resistance to put in series with an LED, to protect it adequately while providing as much light as possible?

How to Read a Data Sheet

Like most information, the answer to this question is available online.

Here's how you find a manufacturer's data sheet (Figure 1-68). First, find the component that you're interested in from a mail-order source. Next, Google the part number and manufacturer's name. Usually the data sheet will pop up as the first hit. A source such as *Mouser.com* makes it even easier by giving you a direct link to manufacturers' data sheets for many products.



VISHAY

TLHG / R / Y540.

Vishay Semiconductors

High Efficiency LED in 5 mm Tinted Diffused Package

Description

The TLH.54.. series was developed for standard applications like general indicating and lighting purposes.

It is housed in a 5 mm tinted diffused plastic package. The wide viewing angle of these devices provides a high on-off contrast.

Several selection types with different luminous intensities are offered. All LEDs are categorized in luminous intensity groups. The green and yellow LEDs are categorized additionally in wavelength groups.

That allows users to assemble LEDs with uniform appearance.

Features

- Choice of three bright colors
- Standard T-1□ package
- Small mechanical tolerances
- Suitable for DC and high peak current
- Wide viewing angle
- Luminous intensity categorized
- Yellow and green color categorized
- TLH.54.. with stand-offs
- Lead-free device

Applications

Status lights
OFF / ON indicator
Background illumination
Readout lights
Maintenance lights
Legend light

Figure 1-68. *The beginning of a typical data sheet, which includes all relevant specifications for the product, freely available online.*

BACKGROUND

How much voltage does a wire consume?

Normally, we can ignore the resistance in electric wires, such as the little leads of wire that stick out of resistors, because it's trivial. However, if you try to force large amounts of current through long lengths of thin wire, the resistance of the wire can become important.

How important? Once again, we can use Ohm's Law to find out.

Suppose that a very long piece of wire has a resistance of 0.2Ω. And we want to run 15 amps through it. How much voltage will the wire steal from the circuit, because of its resistance?

Once again, you begin by writing down what you know:

$R = 0.2$

$I = 15$

We want to know V, the potential difference, for the wire, so we use the version of Ohm's Law that places V on the left side:

$V = I \times R$

Now plug in the values:

$V = 15 \times 0.2 = 3$ volts

Three volts is not a big deal if you have a high-voltage power supply, but if you are using a 12-volt car battery, this length of wire will take one-quarter of the available voltage.

Now you know why the wiring in automobiles is relatively thick—to reduce its resistance well below 0.2Ω. See Figure 1-69.

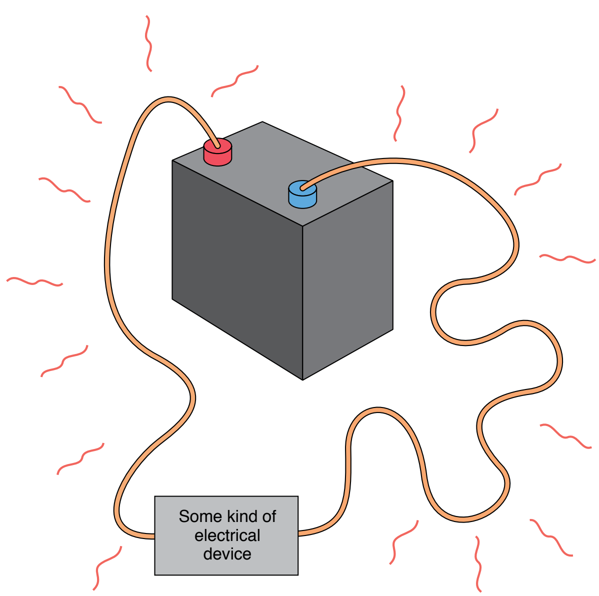


Figure 1-69. *When a 12-volt car battery runs some kind of electrical device through a long piece of thin wire, the resistance of the wire steals some of the voltage and dissipates it as heat.*

BACKGROUND

The origins of wattage

James Watt (Figure 1-70) is known as the inventor of the steam engine. Born in 1736 in Scotland, he set up a small workshop in the University of Glasgow, where he struggled to perfect an efficient design for using steam to move a piston in a cylinder. Financial problems and the primitive state of the art of metal working delayed practical applications until 1776.

Despite difficulties in obtaining patents (which could only be granted by an act of parliament in those times), Watt and his business partner eventually made a lot of money from his innovations. Although he predated the pioneers in electricity, in 1889 (70 years after his death), his name was assigned to the basic unit of electric power that can be defined by multiplying amperes by volts. See the Fundamentals section, "Watt Basics," on page 31.

Figure 1-70. *James Watt's development of steam power enabled the industrial revolution. After his death, he was honored by having his name applied to the basic unit of power in electricity.*

Here's an example. Suppose I want a red LED, such as the Vishay part TLHR5400, which has become such a common item that I can buy them individually for 9 cents apiece. I click the link to the data sheet maintained by the manufacturer, Vishay Semiconductor. Almost immediately I have a PDF page on my screen. This data sheet is for TLHR, TLHG, and TLHY types of LED, which are red, green, and yellow respectively, as suggested by the R, G, and Y in the product codes. I scroll down and look at the "Optical and Electrical Characteristics" section. It tells me that under conditions of drawing a current of 20 mA, the LED will enjoy a "Typ," meaning, typical, "forward voltage" of 2 volts. The "Max," meaning maximum, is 3 volts.

Let's look at one other data sheet, as not all of them are written the same way. I'll choose a different LED, the Kingbright part WP7113SGC. Click on the link to the manufacturer's site, and I find on the second page of the data sheet a typical forward voltage of 2.2, maximum 2.5, and a maximum forward current of 25 mA. I also find some additional information: a maximum reverse voltage of 5 and maximum reverse current of 10 uA (that's microamps, which are 1,000 times smaller than milliamps). This tells us that you should avoid applying excessive voltage to the LED the wrong way around. If you exceed the reverse voltage, you risk burning out the LED. Always observe polarity!

Kingbright also warns us how much heat the LED can stand: 260° C (500° F) for a few seconds. This is useful information, as we'll be putting aside our alligator clips and using hot molten solder to connect electrical parts in the near future. Because we have already destroyed a battery, a fuse, and an LED in just four experiments, maybe you won't be surprised when I tell you that we will destroy at least a couple more components as we test their limits with a soldering iron.

Anyway, now we know what an LED wants, we can figure out how to supply it. If you have any difficulties dealing with decimals, check the Fundamentals section "Decimals," on the next page, before continuing.

How Big a Resistor Does an LED Need?

Suppose that we use the Vishay LED. Remember its requirements from the data sheet? Maximum of 3 volts, and a safe current of 20mA.

I'm going to limit it to 2.5 volts, to be on the safe side. We have 6 volts of battery power. Subtract 2.5 from 6 and we get 3.5. So we need a resistor that will take 3.5 volts from the circuit, leaving 2.5 for the LED.

The current flow is the same at all places in a simple circuit. If we want a maximum of 20mA to flow through the LED, the same amount of current will be flowing through the resistor.

Now we can write down what we know about the resistor in the circuit. Note that we have to convert all units to volts, amps, and ohms, so that 20mA should be written as 0.02 amps:

V = 3.5 (the potential drop across the resistor)
I = 0.02 (the current flowing through the resistor)

We want to know R, the resistance. So, we use the version of Ohm's Law that puts R on the left side:

$R = V/I$

Now plug in the values:

$R = 3.5/0.02$

Run this through your pocket calculator if you find decimals confusing. The answer is:

$R = 175\Omega$

It so happens that 175Ω isn't a standard value. You may have to settle for 180 or 220Ω, but that's close enough.

Evidently the 470Ω resistor that you used in Experiment 3 was a very conservative choice. I suggested it because I said originally that you could use any LED at all. I figured that no matter which one you picked, it should be safe with 470Ω to protect it.

Cleanup and Recycling

The dead LED can be thrown away. Everything else is reusable.

FUNDAMENTALS

Decimals

Legendary British politician Sir Winston Churchill is famous for complaining about "those damned dots." He was referring to decimal points. Because Churchill was Chancellor of the Exchequer at the time, and thus in charge of all government expenditures, his difficulty with decimals was a bit of a problem. Still, he muddled through in time-honored British fashion, and so can you.

You can also use a pocket calculator—or follow two basic rules.

Doing multiplication: move the decimal points

Suppose you want to multiply 0.03 by 0.002:

1. Move the decimal points to the ends of both the numbers. In this case, you have to move the decimal points by a total of 5 places to get 3 and 2.
2. Do the multiplication of the whole numbers you have created and note the result. In this case, 3 x 2 = 6.
3. Move the decimal point back again by the same number of places you counted in step 1. In this case, you get 0.00006.

Doing division: cancel the zeros

Suppose you need to divide 0.006 by 0.0002:

1. Shift the decimal points to the right, in both the numbers, by the same number of steps, until both the numbers are greater than 1. In this case, shift the point four steps in each number, so you get 60 divided by 2.
2. Do the division. The result in this case is 30.

THEORY

Doing the math on your tongue

I'm going to go back to the question I asked in the previous experiment: why didn't your tongue get hot?

Now that you know Ohm's Law, you can figure out the answer in numbers. Let's suppose the battery delivered its rated 9 volts, and your tongue had a resistance of 50K, which is 50,000 ohms. Write down what you know:

$V = 9$

$R = 50{,}000$

We want to know the current, I, so we use the version of Ohm's Law that puts this on the left:

$I = V/R$

Plug in the numbers:

$I = 9/50{,}000 = 0.00018$ amps

Move the decimal point three places to convert to milliamps:

$I = 0.18$ mA

That's a tiny current that will not produce much heat at 9 volts.

What about when you shorted out the battery? How much current made the wires get hot? Well, suppose the wires had a resistance of 0.1 ohms (probably it's less, but I'll start with 0.1 as a guess). Write down what we know:

$V = 1.5$

$R = 0.1$

Once again we're trying to find I, the current, so we use:

$I = V/R$

Plug in the numbers:

$I = 1.5/0.1 = 15$ amps

That's 100,000 times the current that may have passed through your tongue, which would have generated much more heat, even though the voltage was lower.

Could that tiny little battery really pump out 15 amps? Remember that the battery got hot, as well as the wire. This tells us that the electrons may have met some resistance inside the battery, as well as in the wire. (Otherwise, where else did the heat come from?) Normally we can forget about the internal resistance of a battery, because it's so low. But at high currents, it becomes a factor.

I was reluctant to short-circuit the battery through a meter, to try to measure the current. My meter will fry if the current is greater than 10A. However I did try putting other fuses into the circuit, to see whether they would blow. When I tried a 10A fuse, it did not melt. Therefore, for the brand of battery I used, I'm fairly sure that the current in the short circuit was under 10A, but I know it was over 3A, because the 3A fuse blew right away.

The internal resistance of the 1.5-volt battery prevented the current in the short circuit from getting too high. This is why I cautioned against using a larger battery (especially a car battery). Larger batteries have a much lower internal resistance, allowing dangerously high currents which generate explosive amounts of heat. A car battery is designed to deliver literally hundreds of amps when it turns a starter motor. That's quite enough current to melt wires and cause nasty burns. In fact, you can weld metal using a car battery.

Lithium batteries also have low internal resistance, making them very dangerous when they're shorted out. High current can be just as dangerous as high voltage.

FUNDAMENTALS

Watt basics

So far I haven't mentioned a unit that everyone is familiar with: watts.

A watt is a unit of power, and when power is applied over a period of time, it performs work. Engineers have their own definition of work—they say that work is done when a person, an animal, or a machine pushes something to overcome mechanical resistance. Examples would be a steam engine pulling a train on a level track (overcoming friction and air resistance) or a person walking upstairs (overcoming the force of gravity).

When electrons push their way through a circuit, they are overcoming a kind of resistance, and so they are doing work, which can be measured in watts per second. The definition of a watt is easy:

watts = volts × amps

Or, using the symbols customarily assigned, these three formulas all mean the same thing:

$W = V \times I$

$V = W/I$

$I = W/V$

Watts can be preceded with an "m," for "milli," just like volts:

Number of watts	Usually expressed as	Abbreviated as
0.001 watts	1 milliwatt	1mW
0.01 watts	10 milliwatts	10 mW
0.1 watts	100 milliwatts	100 mW
1 watt	1,000 milliwatts	1W

Because power stations, solar installations, and wind farms deal with much larger numbers, you may also see references to kilowatts (using letter K) and megawatts (with a capital M, not to be confused with the lowercase m used to define milliwatts):

Number of watts	Usually expressed as	Abbreviated as
1,000 watts	1 kilowatt	1 KW
1,000,000 watts	1 megawatt	1 MW

Lightbulbs are calibrated in watts. So are stereo systems. The watt is named after James Watt, inventor of the steam engine. Incidentally, watts can be converted to horsepower, and vice versa.

THEORY

Power assessments

I mentioned earlier that resistors are commonly rated as being capable of dealing with 1/4 watt, 1/2 watt, 1 watt, and so on. I suggested that you should buy resistors of 1/4 watt or higher. How did I know this?

Go back to the LED circuit. Remember we wanted the resistor to drop the voltage by 3.5 volts, at a current of 20 mA. How many watts of power would this impose on the resistor?

Write down what you know:

$V = 3.5$ (the voltage drop imposed by the resistor)

$I = 20\text{mA} = 0.02$ amps (the current flowing through the resistor)

We want to know W, so we use this version of the formula:

$W = V \times I$

Plug in the values:

$W = 3.5 \times 0.02 = 0.07$ watts (the power being dissipated by the resistor)

Because 1/4 watt is 0.25 watts, obviously a 1/4 watt resistor will have about four times the necessary capacity. In fact you could have used a 1/8 watt resistor, but in future experiments we may need resistors that can handle 1/4 watt, and there's no penalty for using a resistor that is rated for more watts than will actually pass through it.

Experiment 5: Let's Make a Battery

Long ago, before web surfing, file sharing, or cell phones, kids were so horribly deprived that they tried to amuse themselves with kitchen-table experiments such as making a primitive battery by pushing a nail and a penny into a lemon. Hard to believe, perhaps, but true!

This is seriously old-school—but I want you to try it anyway, because anyone who wants to get a feel for electricity should see how easy it is to extract it from everyday objects around us. Plus, if you use enough lemons, you just *might* generate enough voltage to power an LED.

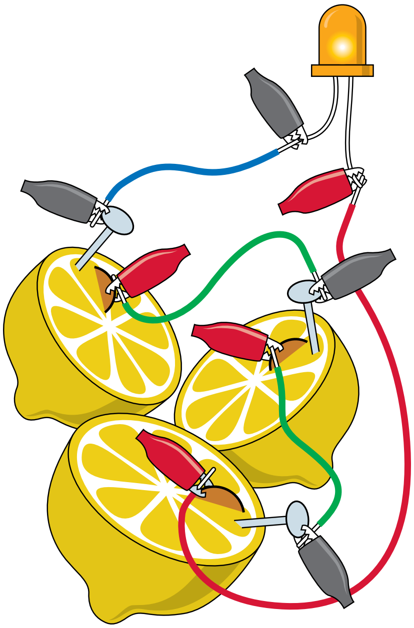


Figure 1-71. *A three-lemon battery. Don't be too disappointed if the LED fails to light up. The lemons have a high electrical resistance, so they can't deliver much current, especially through the relatively small surface area of the nails and the pennies. However, the lemon battery does generate voltage that you can measure with your meter.*

The basic components of a battery are two metal electrodes immersed in an electrolyte. I won't define these terms here (they're explained in the following section "Theory: The nature of electricity"). Right now all you need to know is that lemon juice will be your electrolyte, and copper and zinc will be your electrodes. A penny provides the necessary copper, as long as it is fairly new and shiny. Pennies aren't solid copper anymore, but they are still copper-plated, which is good enough.

To find some metallic zinc, you will have to make a trip to a hardware store, where you should ask for roofing nails. The nails are zinc-plated to prevent them from rusting. Small metal brackets or mending plates also are usually zinc-plated. They should have a slightly dull, silvery look. If they have a mirror-bright finish, they're more likely to be nickel-plated.

Cut a lemon in half, set your multimeter so that it can measure up to 2 volts DC, and hold one probe against a penny while you hold the other probe against a roofing nail (or other zinc-plated object). Now force the penny and the nail into the exposed juicy interior of the lemon, as close to each other as possible, but not actually touching. You should find that your meter detects between 0.8 volts and 1 volt.

You can experiment with different items and liquids to see which works best. Immersing your nail and penny in lemon juice that you have squeezed into a shot glass or egg cup may enhance the efficiency of your battery, although you'll have a harder time holding everything in place. Grapefruit juice and vinegar will work as substitutes for lemon juice.

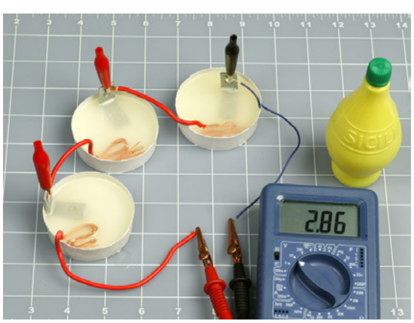


Figure 1-72. *Bottled lemon juice seems to work just as well as fresh lemon juice. I cut the bottoms off three paper cups, inserted a galvanized bracket into each, and used heavyweight stranded copper wire to make the positive electrodes*

To drive a typical LED, you need more than 1 volt. How to generate the extra electrical pressure? By putting batteries in series, of course. In other words, more lemons! (Or more shot glasses or egg cups.) You'll also need lengths of wire to connect multiple electrodes, and this may entail skipping ahead to Chapter 2, where I describe how to strip insulation from hookup wire. Figures 1-71 and 1-72 show the configuration.

If you set things up carefully, making sure than none of the electrodes are touching, you may be able to illuminate your LED with two or three lemon-juice batteries in series. (Some LEDs are more sensitive to very low currents than others. Later in the book I'll be talking about very-low-current LEDs. If you want your lemon-juice battery to have the best chance of working, you can search online for low-current LEDs and buy a couple.)

THEORY

The nature of electricity

To understand electricity, you have to start with some basic information about atoms. Each atom consists of a nucleus at the center, containing protons, which have a positive charge. The nucleus is surrounded by electrons, which carry a negative charge.

Breaking up the nucleus of an atom requires a lot of energy, and can also liberate a lot of energy—as happens in a nuclear explosion. But persuading a couple of electrons to leave an atom (or join an atom) takes very little energy. For instance, when zinc reacts chemically with an acid, it can liberate electrons. This is what happens at the zinc electrode of the chemical battery in Experiment 5.

The reaction soon stops, as electrons accumulate on the zinc electrode. They feel a mutual force of repulsion, yet they have nowhere to go. You can imagine them like a crowd of hostile people, each one wanting the others to leave, and refusing to allow new ones to join them, as shown in Figure 1-73.

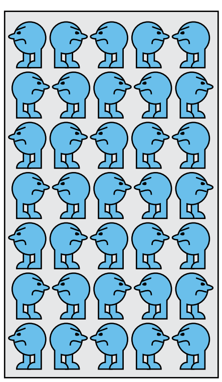


Figure 1-73. *Electrons on an electrode have a bad attitude known as mutual repulsion.*

Now consider what happens when a wire connects the zinc electrode, which has a surplus of electrons, to another electrode, made from a different material, that has a shortage of electrons. The electrons can pass through the wire very easily by jumping from one atom to the next, so they escape from the zinc electrode and run through the wire, propelled by their great desire to get away from each other. See Figure 1-74. This mutual force of propulsion is what creates an electrical current.

Now that the population of electrons on the zinc electrode has been reduced, the zinc-acid reaction can continue, replacing the missing electrons with new ones—which promptly imitate their predecessors and try to get away from each other by running away down the wire. The process continues until the zinc-acid reaction grinds to a halt, usually because it creates a layer of a compound such as zinc oxide, which won't react with acid and prevents the acid from reacting with the zinc underneath. (This is why your zinc electrode may have looked sooty when you pulled it out of the acidic electrolyte.)

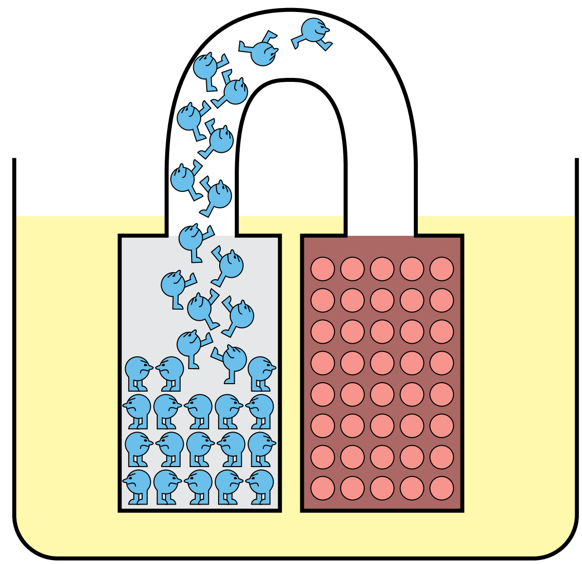


Figure 1-74. *As soon as we open up a pathway from a zinc electrode crowded with electrons to a copper electrode, which contains "holes" for the electrons, their mutual repulsion makes them try to escape from each other to their new home as quickly as possible.*

This description applies to a "primary battery," meaning one that is ready to generate electricity as soon as a connection between its terminals allows electrons to transfer from one electrode to the other. The amount of current that a primary battery can generate is determined by the speed at which chemical reactions inside the battery can liberate electrons. When the raw metal in the electrodes has all been used up in chemical reactions, the battery can't generate any more electricity and is dead. It cannot easily be recharged, because the chemical reactions are not easily reversible, and the electrodes may have oxidized.

In a rechargeable battery, also known as a secondary battery, a smarter choice of electrodes and electrolyte does allow the chemical reactions to be reversed.

How much current is being generated in your lemon battery? Set your meter to measure milliamps, and connect it between the nail and the penny. I measured about 2mA, but got 10mA when I used some #10 stranded copper wire instead of a penny and a large mending plate instead of a roofing nail, immersed in a cup of grapefruit juice. When a larger surface area of metal makes better contact with the electrolyte, you get a greater flow of current. (Don't ever connect your meter to measure amps directly between the terminals of a real battery. The current will be too high, and can blow the fuse inside your meter.)

What's the internal resistance of your lemon? Put aside the copper and zinc electrodes and insert your nickel-plated meter probes into the juice. I got a reading of around 30K when both probes were in the same segment of the lemon, but 40K or higher if the probes were in different segments. Is the resistance lower when you test liquid in a cup?

Here are a couple more questions that you may wish to investigate. For how long will your lemon battery generate electricity? And why do you think your zinc-plated electrode becomes discolored after it has been used for a while?

Electricity is generated in a battery by an exchange of ions, or free electrons, between metals. If you want to know more about this, check the section "Theory: The nature of electricity" on the previous page.

Cleanup and Recycling

The hardware that you immersed in lemons or lemon juice may be discolored, but it is reusable. Whether you eat the lemons is up to you.

BACKGROUND

Positive and negative

If electricity is a flow of electrons, which have a negative charge, why do people talk as if electricity flows from the positive terminal to the negative terminal of a battery?

The answer lies in a fundamental embarrassment in the history of research into electricity. For various reasons, when Benjamin Franklin was trying to understand the nature of electric current by studying phenomena such as lightning during thunderstorms, he believed he observed a flow of "electrical fluid" from positive to negative. He proposed this concept in 1747.

In fact, Franklin had made an unfortunate error that remained uncorrected until after physicist J. J. Thomson announced his discovery of the electron in 1897, 150 years later. Electricity actually flows from an area of greater negative charge, to some other location that is "less negative"—that is, "more positive." In other words, electricity is a flow of negatively charged particles. In a battery, they originate from the negative terminal and flow to the positive terminal.

You might think that when this fact was established, everyone should have discarded Franklin's idea of a flow from positive to negative. But when an electron moves through a wire, you can still think of an equal positive charge flowing in the opposite direction. When the electron leaves home, it takes a small negative charge with it; therefore, its home becomes a bit more positive. When the electron arrives at its destination, its negative charge makes the destination a bit less positive. This is pretty much what would happen if an imaginary positive particle traveled in the opposite direction. Moreover, all of the mathematics describing electrical behavior are still valid if you apply them to the imaginary flow of positive charges.

As a matter of tradition and convenience we still retain Ben Franklin's erroneous concept of flow from positive to negative, because it really makes no difference. In the symbols that represent components such as diodes and transistors, you will actually find arrows reminding you which way these components should be placed—and the arrows all point from positive to negative, even though that's not the way things really work at all! Ben Franklin would have been surprised to learn that although most lightning strikes occur when a negative charge in clouds discharges to neutralize a positive charge on the ground, some forms of lightning are actually a flow of electrons from the negatively charged surface of the earth, up to a positive charge in the clouds. That's right: someone who is "struck by lightning" may be hurt by *emitting* electrons rather than by receiving them, as shown in Figure 1-75.

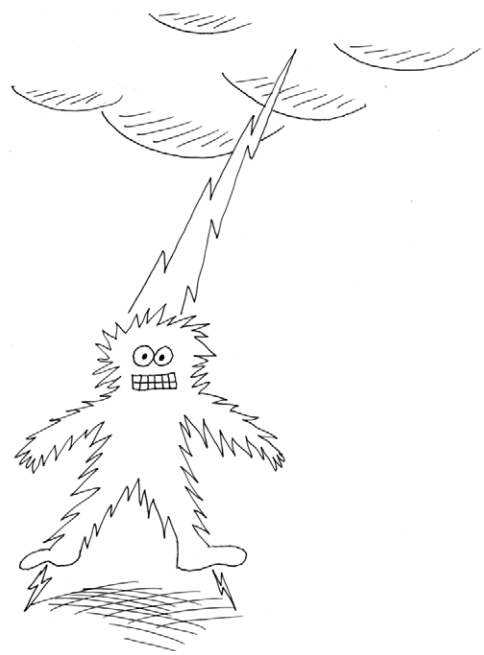


Figure 1-75. *In some weather conditions, the flow of electrons during a lightning strike can be from the ground, through your feet, out of the top of your head, and up to the clouds. Benjamin Franklin would have been surprised.*

THEORY

Basic measurements

Electrical potential is measured by adding up the charges on individual electrons. The basic unit is the *coulomb*, equal to the total charge on about 6,250,000,000,000,000,000 electrons.

If you know how many electrons pass through a piece of wire each second, this establishes the flow of electricity, which can be expressed in amperes. In fact 1 ampere can be defined as 1 coulomb per second. Thus:

1 ampere = 1 coulomb/second

= about 6.25 quintillion electrons/second

There's no way to "see" the number of electrons running through a conductor (Figure 1-76), but there are indirect ways of getting at this information. For instance, when an electron goes running through a wire, it creates a wave of electromagnetic force around it. This force can be measured, and we can calculate the amperage from that. The electric meter installed at your home by the utility company functions on this principle.

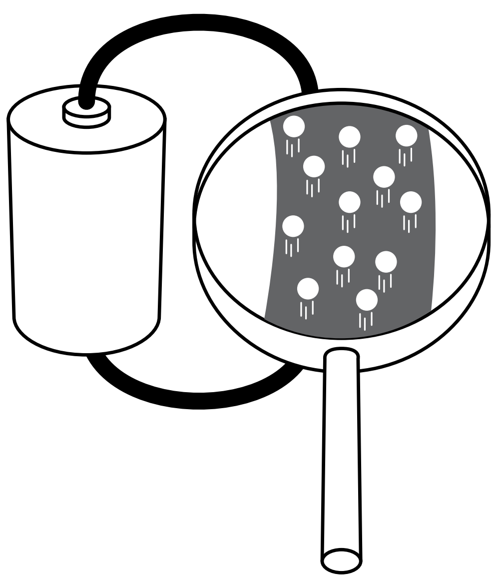


Figure 1-76. *If you could look inside an electric wire with a sufficiently powerful magnifying device, and the wire happened to be carrying 1 ampere of electron flow at the time, you might hope to see about 6.25 quintillion electrons speeding past each second.*

If electrons are just moving freely, they aren't doing any work. If you had a loop of wire of zero resistance, and you kick-started a flow of electrons somehow, they could just go buzzing around forever. (This is what happens inside a superconductor—almost.)

Under everyday conditions, even a copper wire has some resistance. The force that we need to push electrons through it is known as "voltage," and creates a flow that can create heat, as you saw when you shorted out a battery. (If the wire that you used had zero resistance, the electricity running through it would not have created any heat.) We can use the heat directly, as in an electric stove, or we can use the electrical energy in other ways—to run a motor, for instance. Either way, we are taking energy out of the electrons, to do some work.

One volt can be defined as the amount of pressure that you need to create a flow of 1 ampere, which does 1 watt of work. As previously defined, 1 watt = 1 volt × 1 ampere, but the definition actually originated the other way around:

1 volt = 1 watt/1 ampere

It's more meaningful this way, because a watt can be defined in nonelectrical terms. Just in case you're interested, we can work backward through the units of the metric system like this:

1 watt = 1 joule/second

1 joule = a force of 1 newton acting through 1 meter

1 newton = the force required to accelerate 1 kilogram by 1 meter per second, each second

On this basis, the electrical units can all be anchored with observations of mass, time, and the charge on electrons.

Practically Speaking

For practical purposes, an intuitive understanding of electricity can be more useful than the theory. Personally I like the water analogies that have been used for decades in guides to electricity. Figure 1-77 shows a tall tank half full of water, with a hole punched in it near the bottom. Think of the tank as being like a battery. The height of the water is comparable to voltage. The volume of flow through the hole, per second, is comparable to amperage. The smallness of the hole is comparable to resistance. See Figure 1-79 on the next page.

Where's the wattage in this picture? Suppose we place a little water wheel where it is hit by the flow from the hole. We can attach some machinery to the water wheel. Now the flow is doing some work. (Remember, wattage is a measurement of work.)

Maybe this looks as if we're getting something for nothing, extracting work from the water wheel without putting any energy back into the system. But remember, the water level in the tank is falling. As soon as I include some helpers hauling the waste water back up to the top of the tank (in Figure 1-78), you see that we have to put work in to get work out.

Similarly, a battery may seem to be giving power out without taking anything in, but the chemical reactions inside it are changing pure metals into metallic compounds, and the power we get out of a battery is enabled by this change of state. If it's a rechargeable battery, we have to push power back into it to reverse the chemical reactions.

Going back to the tank of water, suppose we can't get enough power out of it to turn the wheel. One answer could be to add more water. The height of the water will create more force. This would be the same as putting two batteries end to end, positive to negative, in series, to double the voltage. See Figure 1-80. As long as the resistance in the circuit remains the same, greater voltage will create more amperage, because amperage = voltage/resistance.

What if we want to run two wheels instead of one? We can punch a second hole in the tank, and the force (voltage) will be the same at each of them. However, the water level in the tank will drop twice as fast. Really, we'd do better to build a second tank, and here again the analogy with a battery is good. If you wire two batteries side by side, in parallel, you get the same voltage, but for twice as long. The two batteries may also be able to deliver more current than if you just used one. See Figure 1-81.

Summing up:

- Two batteries in series deliver twice the voltage.
- Two batteries in parallel can deliver twice the current.

All right, that's more than enough theory for now. In the next chapter, we'll continue with some experiments that will build on the foundations of knowledge about electricity, to take us gradually toward gadgets that can be fun and useful.

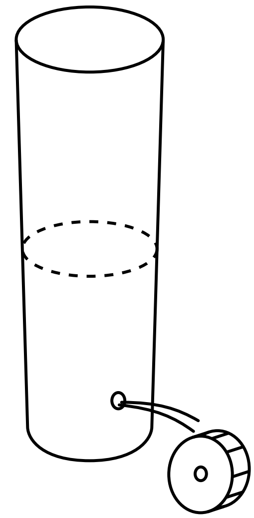


Figure 1-77. *If you want to get work out of a system...*

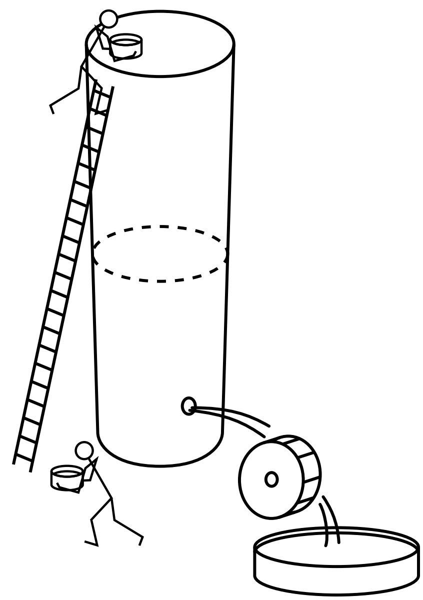


Figure 1-78. *. . . somehow or other you have to put work back into it.*

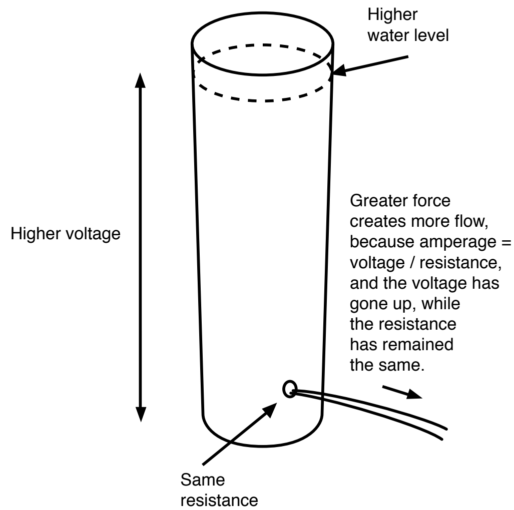


Figure 1-79. *Greater force generates more flow, as long as the resistance remains the same.*

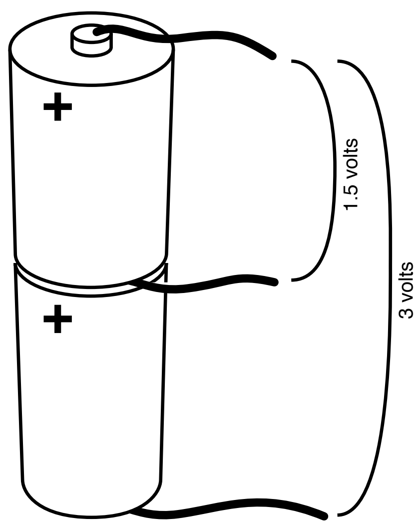


Figure 1-80. *When you place two equal batteries in series, you double the voltage.*

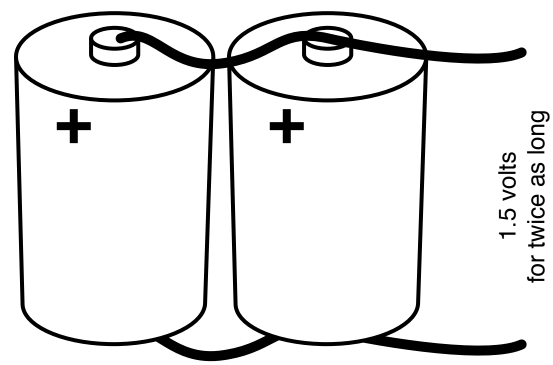


Figure 1-81. *Two equal batteries that are wired in parallel will deliver the same voltage for twice as long as one.*