This material was taken from "Make: Electronics" by Charles Platt

Cleanup and Recycling

T Skip this Cleanup and Recycling Section and begin with Experiment 3 below. ir. 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.

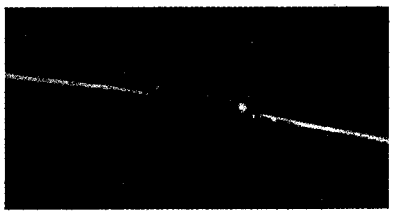

Figure 1-41. *Some modern resistors have their values printed on them, although you may need a magnifier to read them. This 15K resistor is less than half an inch long.*

The surface mount resistors in our toys had their resistance printed on them.

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.

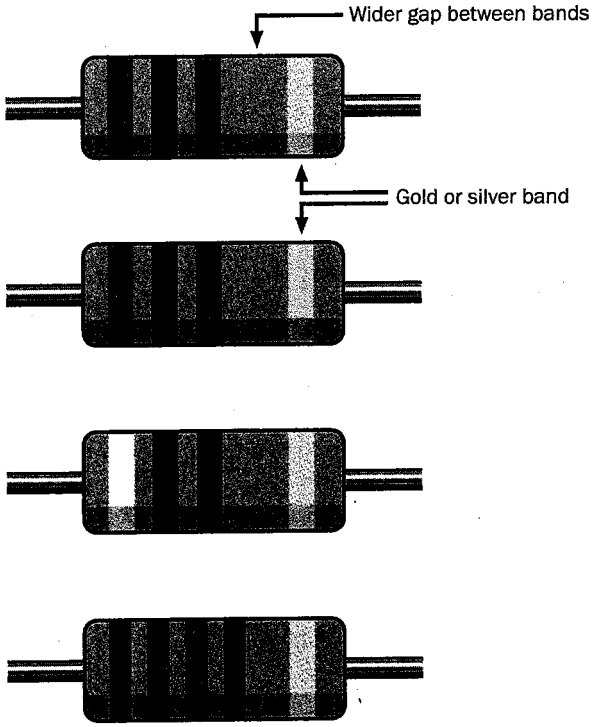

Figure 1-43. *To read the value of a resistor, first turn it so that the silver or gold stripe is on the right, or the other stripes are clustered on the left. From top to bottom: The first resistor has a value of 1-2 and five zeros, or 1,200,000, which is 1.2MΩ. The second is 5-6 and one zero, or 560Ω.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

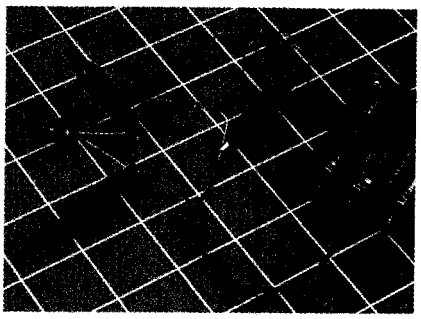

Figure 1-44. *The setup for Experiment 3, showing resistors of 470Ω, 1KΩ, and 2KΩ. Apply alligator clips where shown, to make a secure contact, and try each of the resistors one at a time at the same point in the circuit, while watching the LED.*

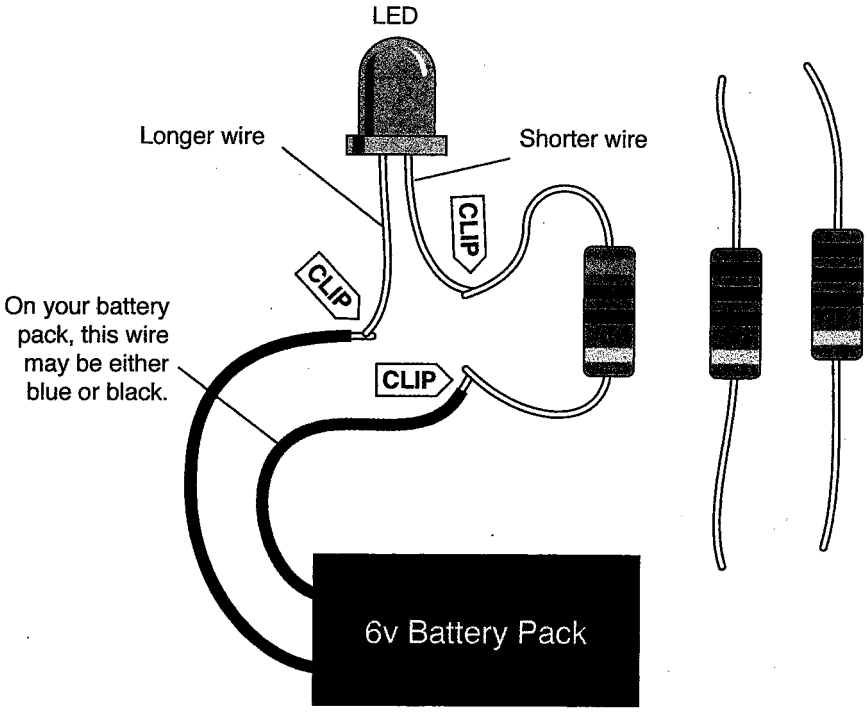

Figure 1-45. *Here's how it actually looks, using a large LED. If you start with the highest value resistor, the LED will glow very dimly as you complete the circuit. The resistor drops most of the voltage, leaving the LED with insufficient current to make it shine brightly.*

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:

Get only 1 potentiometer and don't worry about it's rating. Our potentiometers will provide more than 2K Ohms max resistance.

- 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.

Do NOT open your potentiometer.

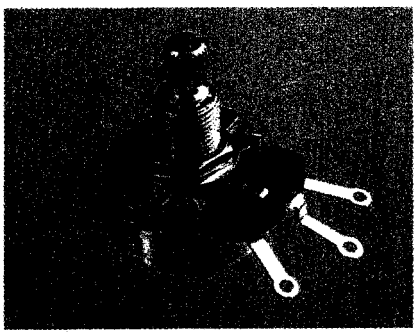

Figure 1-46

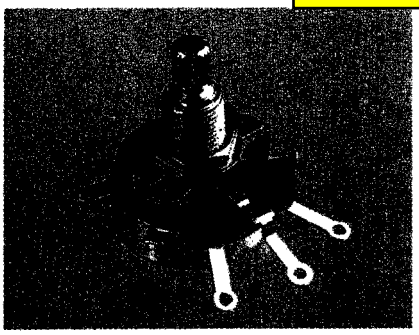

Figure 1-47

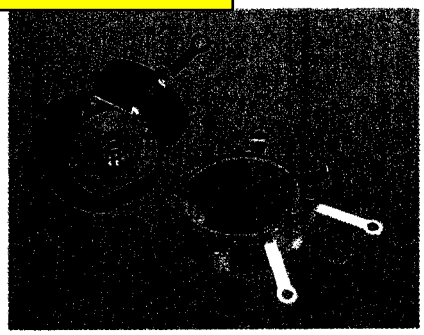

Figure 1-48. *To open the potentiometer, first pry up the four little metal tabs around the edge (you can see one sticking out at the left and another one sticking out at the right in Figure 1-47). Inside is a coil of wire around a flat plastic band, and a pair of springy contacts (the wiper), which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

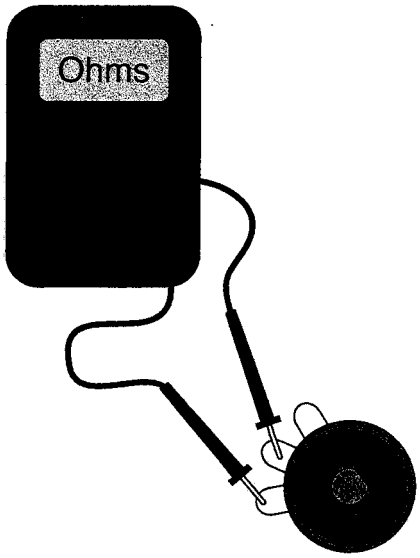

Figure 1-49. *Measure the resistance between these two terminals of the potentiometer while you turn its shaft to and fro.*

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.

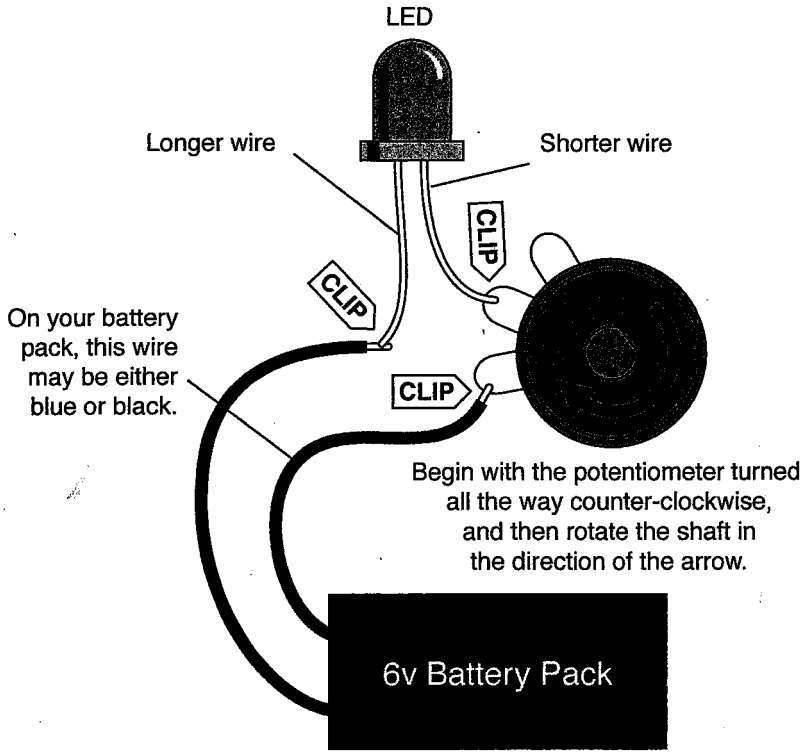

Figure 1-50. *The setup for Experiment 4. Rotating the shaft of the 2K potentiometer varies its resistance from 0 to 2,000Ω. This resistance protects the LED from the full 6 volts of the battery.*

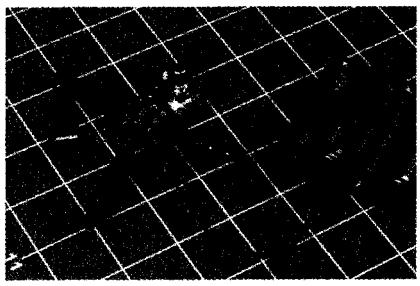

Figure 1-51. *The LED in this photo is dark because I turned the potentiometer up just a little bit too far.*

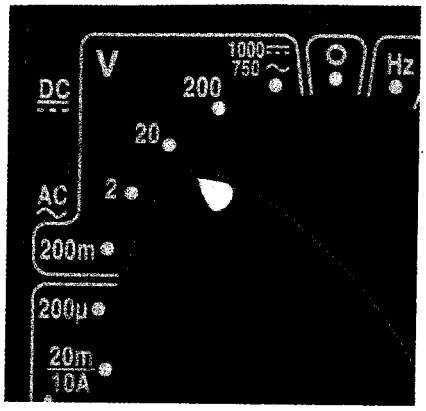

Figure 1-52

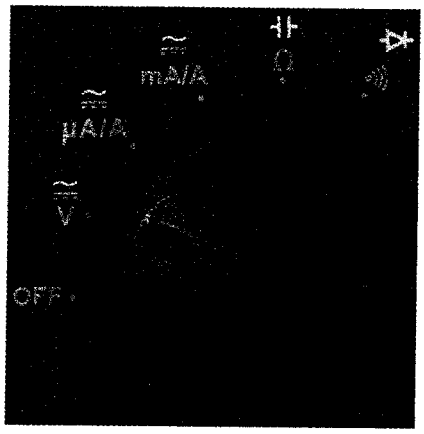

Figure 1-53

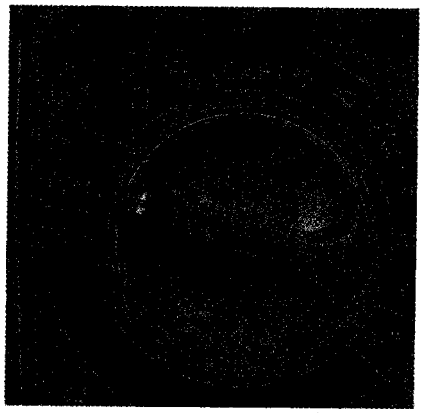

Figure 1-54. *Each meter has a different way to measure volts DC. The manually adjusted meter (top) requires you to move a slider switch to "DC" and then choose the highest voltage you want to measure: In this case, the selected voltage is 20 (because 2 would be too low). Using the autoranging RadioShack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

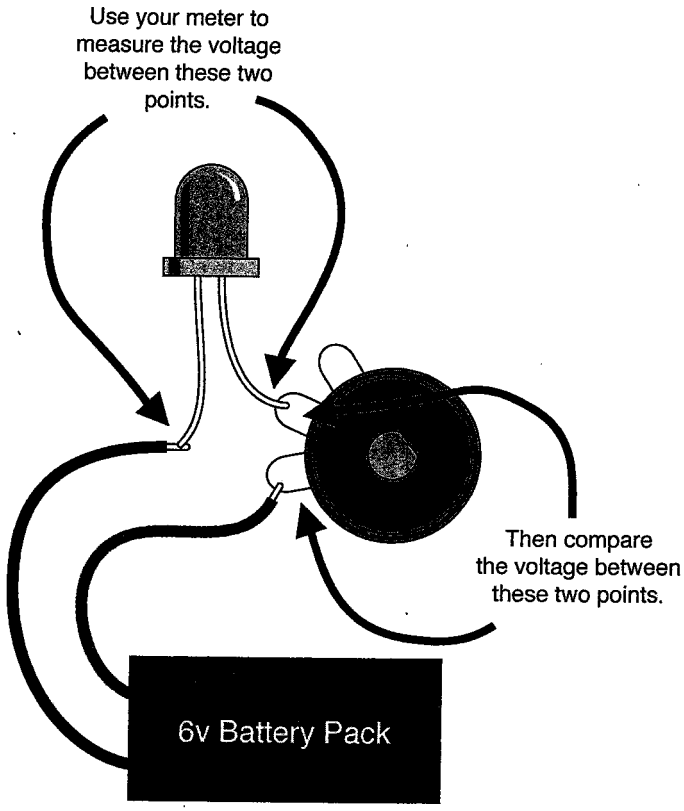

Figure 1-55. *How to measure voltage in a simple circuit.*

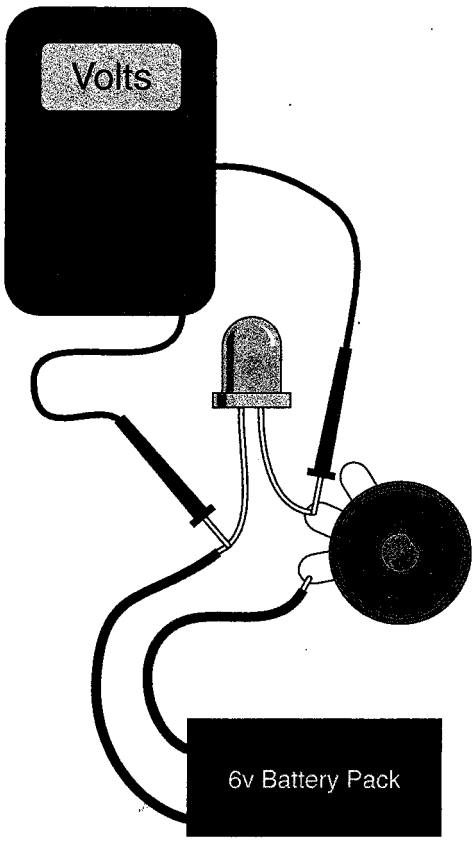

Figure 1-56. *The meter shows how much voltage the LED takes.*

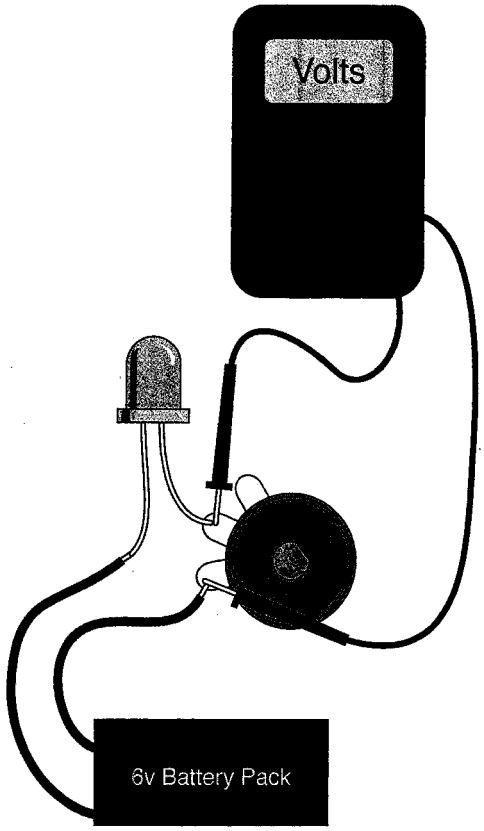

Figure 1-57. *The meter shows how much voltage the potentiometer takes.*

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.

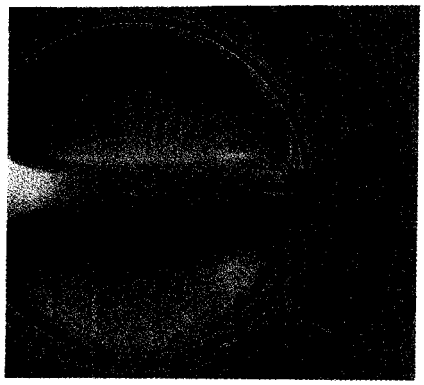

Figure 1-58. *Any meter will blow its internal fuse if you try to make it measure too high an amperage. In our circuit, this is not a risk as long as you keep the potentiometer in the middle of its range. Choose "mA" for milliamps and remember that the meter displays numbers that mean thousandths of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

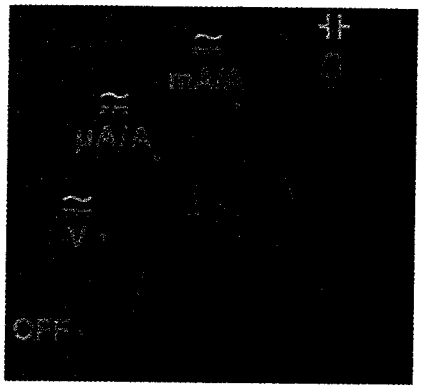

Figure 1-59

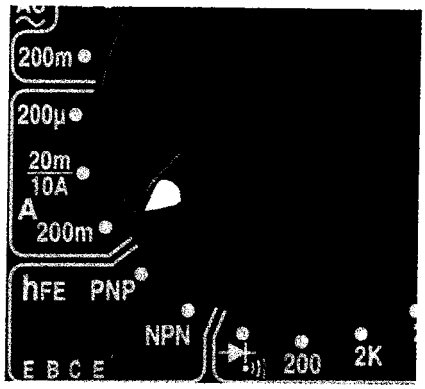

Figure 1-60

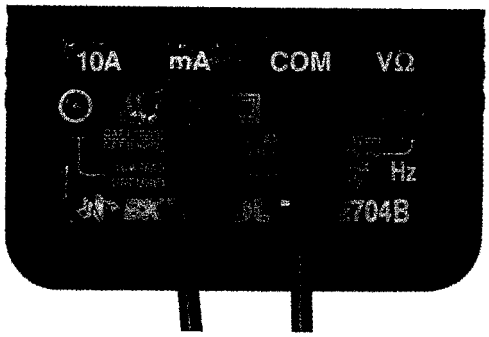

Figure 1-61. *A manual meter such as the one here may require you to shift the red lead to a different socket, to measure milliamps. Most modern meters don't require this until you are measuring higher currents.*

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.*

We did not do the fuse experiment.

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 1-64. 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.)

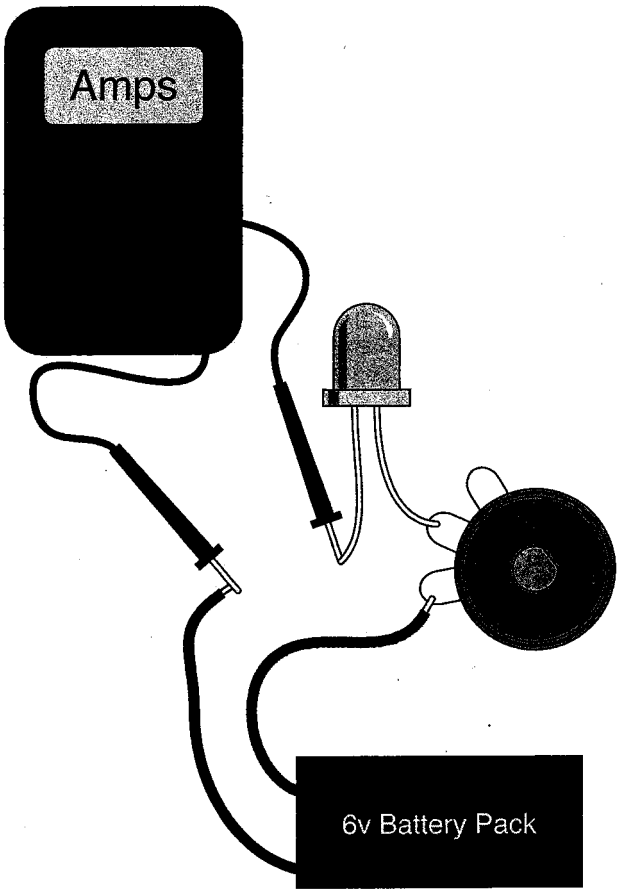

Figure 1-62. *To measure amps, as illustrated here and in Figure 1-63, the current has to pass through the meter. When you increase the resistance, you restrict the current flow, and the lower flow makes the LED glow less brightly.*

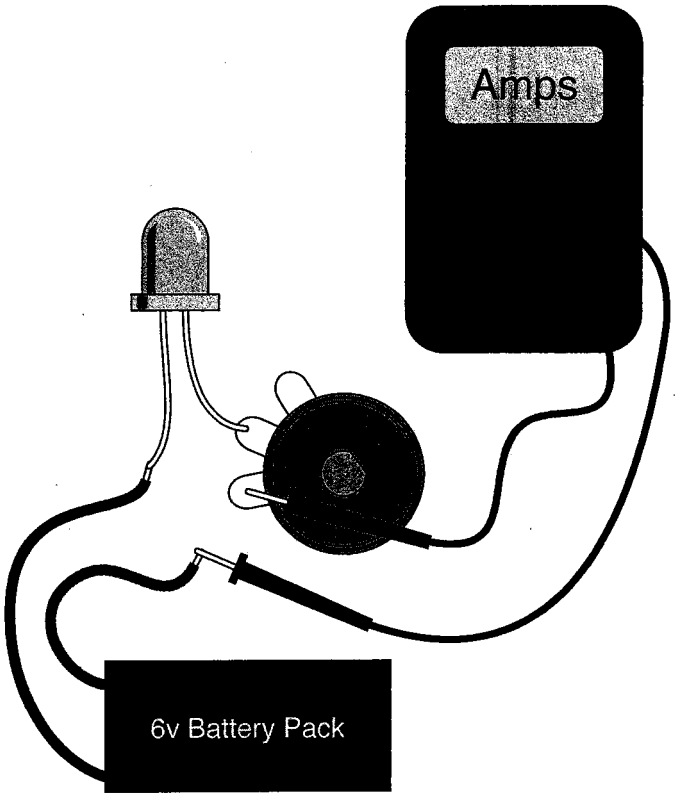

Figure 1-63

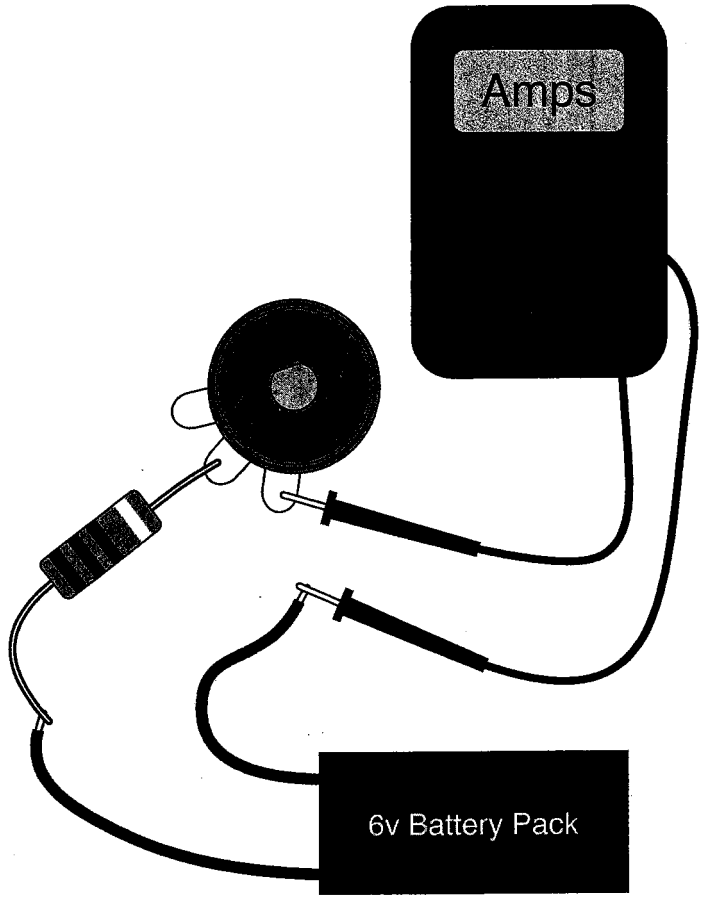

Figure 1-84. *If you substitute a resistor instead of the LED, you can confirm that the current flowing through the circuit varies with the total resistance in the circuit, if the voltage stays the same.*

Because our potentiometers have a larger max resistance than those specified in the exercise, your resistance values will be different.

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.

Fill in this table using measured values for resistance, voltage, and current.

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

Read this section.

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.

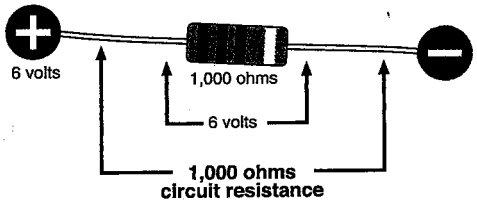

Figure 1-65. *One resistor takes the entire voltage, and according to Ohm's Law, it draws v/R = 6/1,000 = 0.006 amps = 6mA of current.*

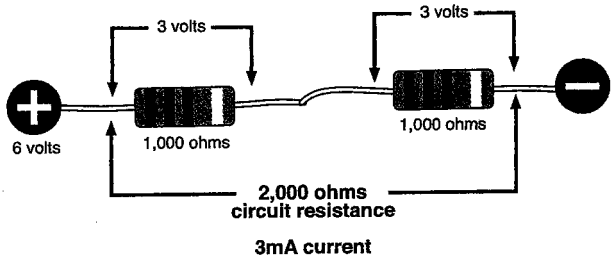

Figure 1-66. *When two resistors are in series, the electricity has to pass through one to reach the other, and therefore each of them takes half the voltage. Total resistance is now 2,000 ohms, and according to Ohm's Law, the circuit draws v/R = 6/2,000 = 0.003 amps = 3mA of current.*

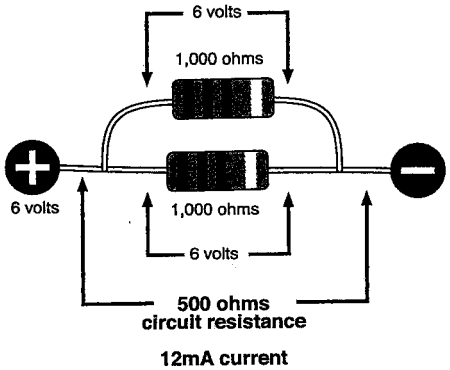

Figure 1-67. *When two resistors are in parallel, each is exposed to the full voltage, so each of them takes 6 volts. The electricity can now flow through both at once, so the total resistance of the circuit is half as much as before. According to Ohm's Law, the circuit draws v/R = 6/500 = 0.012 amps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