The graph in Figure 2-91 gives a rough idea of how the charge on the capacitor changes.

- A capacitor does block direct current (DC).
- The same capacitor will allow a brief fluctuation to pass through, regardless of which way the current is flowing.
- The capacitor then accumulates a charge, as I described at the beginning of this experiment.

This leads to an important conclusion. Because alternating current (AC) is a rapid series of relatively negative and relatively positive pulses, a capacitor will allow them through.

The size of the capacitor will be important. When you substituted smaller values, you saw that they would only respond briefly. A smaller capacitor will pass high-frequency fluctuations, but will block low-frequency fluctuations—and this behavior is useful in many applications, including audio. You'll see this for yourself in Experiment 29. Bear in mind that audio signals are a form of alternating current, because they fluctuate rapidly.

When a capacitor is positioned in a circuit to pass AC while blocking DC, we call it a *coupling capacitor*. It can allow a signal to travel from one part of a circuit to another, while blocking their DC voltages, which can be completely different. I'll be using this concept when we get to Experiment 11.

Experiment 10: Transistor Switching

Now that you've seen the behavior of capacitors, I'm going to move on to another fundamental component: the transistor. After you learn how that works, you'll see how capacitors and transistors can be used together.

What You Will Need

- Breadboard, hookup wire, wire cutters, wire strippers, multimeter
- Transistor, 2N2222 (1)
- 9-volt battery and connector (1)
- Resistors: 470 ohms (2), 1M (1)
- Trimmer potentiometer, 500K (1)
- Generic LED (1)

The Finger Test

I'm going to be using the 2N2222 transistor, which is the most widely used semiconductor of all time (it was introduced by Motorola in 1962 and has been in production ever since, in one form or another).

Because Motorola's patents on the 2N2222 ran out long ago, any company can manufacture their own version of it. Some versions are packaged in a little piece of plastic, while others are enclosed in a little metal "can." I showed these two versions in Figure 2-23. For our purposes, either will do. However, note the warning that I included previously about part numbers (see "Essentials: Transistors" on page 49). Some 2N2222s are not the same as others, and you need to use the right type.

Plug your transistor into your breadboard with an LED and a 470-ohm resistor, as shown in Figure 2-93. Make sure that the longer lead on your LED is facing to the left, as indicated by the + sign. Also, check that the transistor has its flat side facing to the right. In the unlikely event that you are using a transistor in a metal can, the tab sticking out from the can should point down and to the left.

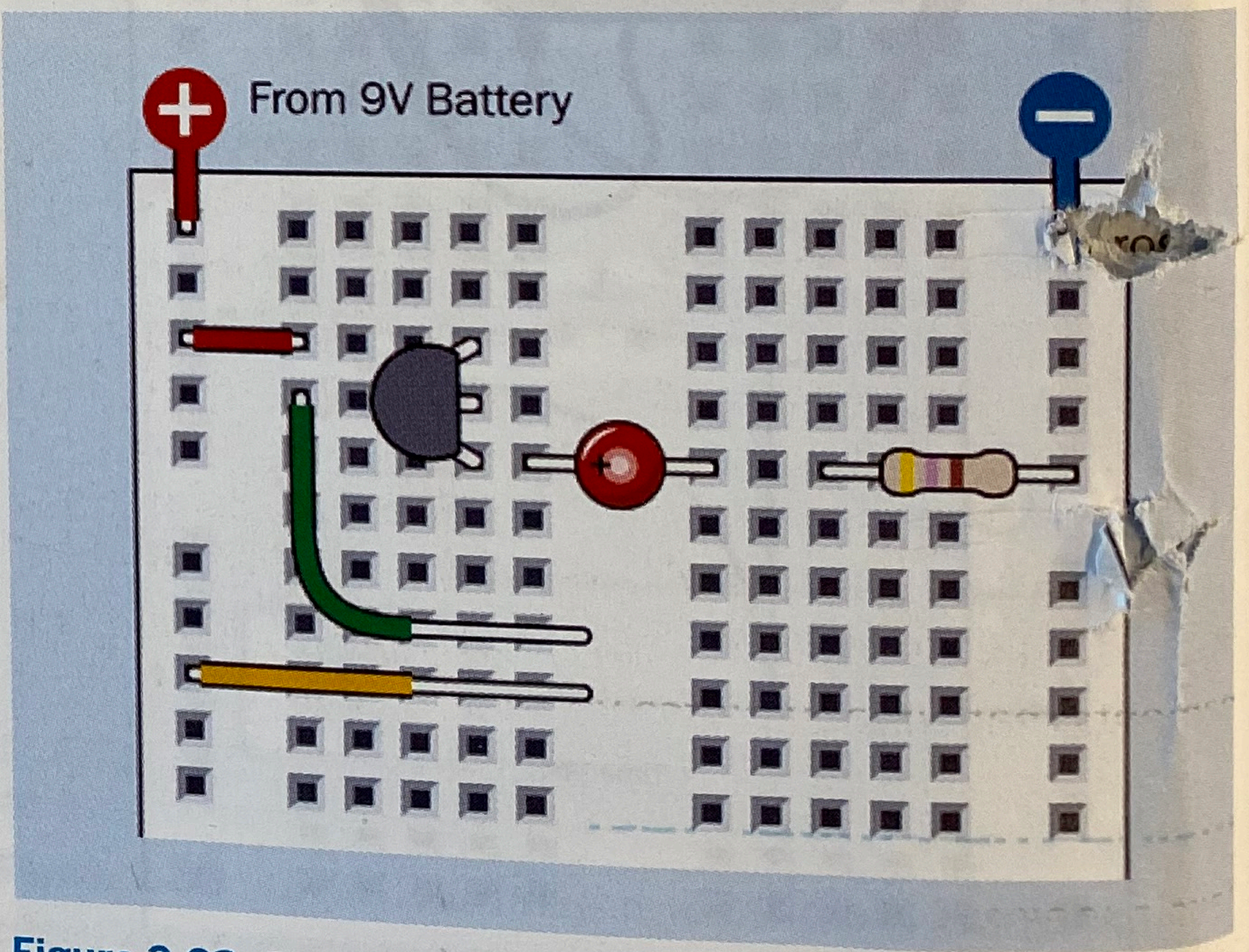

Figure 2-93 *Breadboard setup for your first transistor test.*

Notice that the wires that I have shown as green and orange have had some extra insulation removed. If you are using precut jumpers, you'll have to bend out one end of each, so that they rest flat on the breadboard.

Now for the fun part. Press your finger to the exposed metal of the green and orange jumpers as shown in Figure 2-94, while you watch the LED. If nothing happens, moisten your finger slightly and try again. The harder you press, the brighter the LED becomes. The transistor is amplifying the tiny amount of current flowing through your finger.

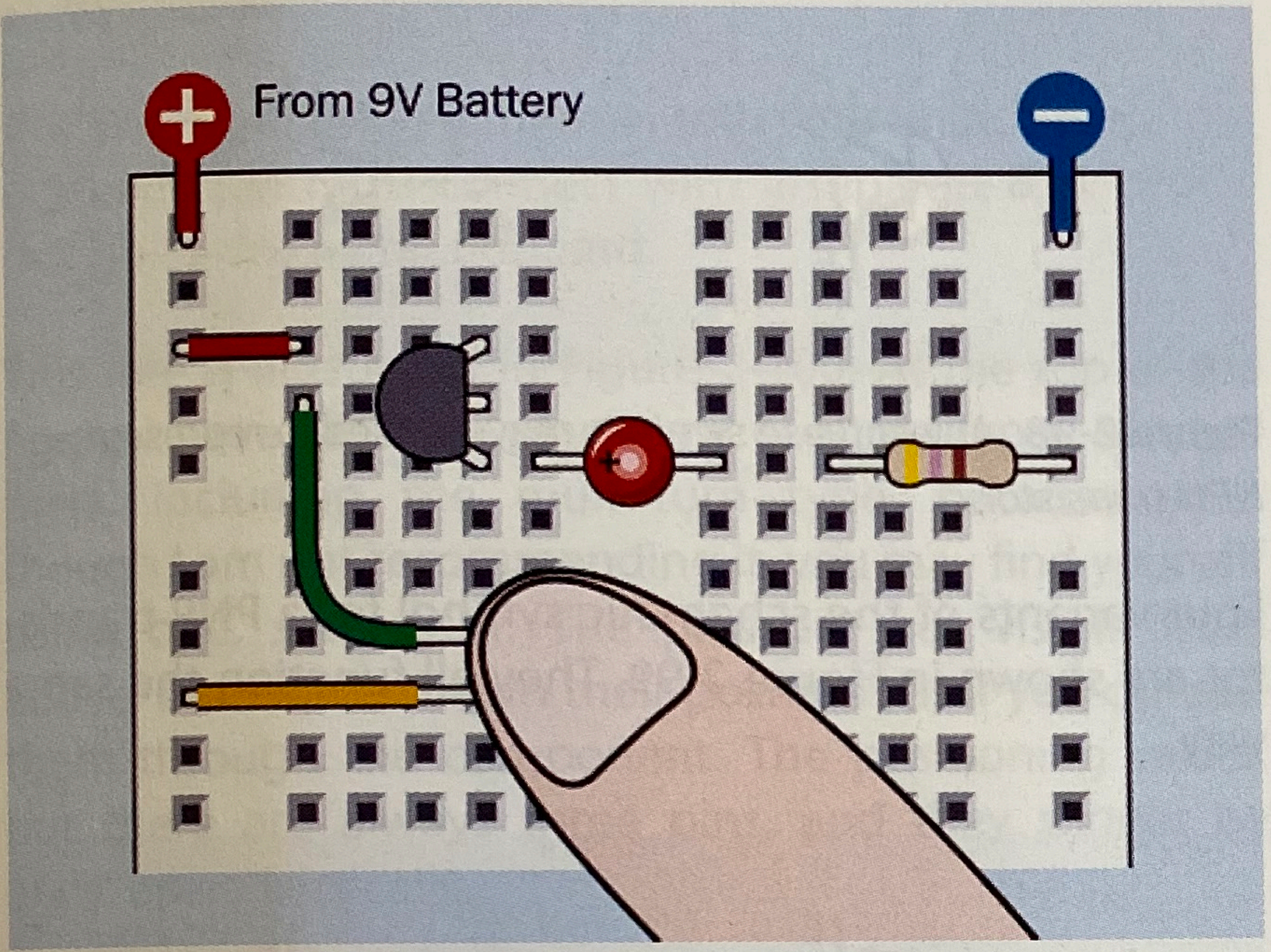

Figure 2-94 *Adding your finger makes the experiment work.*

Caution: Never Use Two Hands

The fingertip switching demo is safe if the electricity only passes through your finger. You won't even feel it, because it's 9 volts DC from a small battery. But it's not a good idea to put the finger of one hand on one wire, and the finger of your other hand on the other wire. This would allow the electricity to pass through your body. Although there is no chance of hurting yourself in this circuit because the current is so small, you should *never get into the habit of allowing electricity to run through you from one hand to the other*. Also, when touching the wires, *don't allow them to penetrate your skin*. This also means that you shouldn't apply voltage to any body ornaments that already pierce your skin.

Inside the Finger Test

Take a look at Figure 2-95, which reveals the connectors inside the breadboard, omitting the ones that are not connected in this experiment. Notice that the bottom lead of the transistor is connected through the breadboard to the LED, and then through the 470-ohm resistor to the negative bus. So, enough current flowed out of the transistor to light the LED.

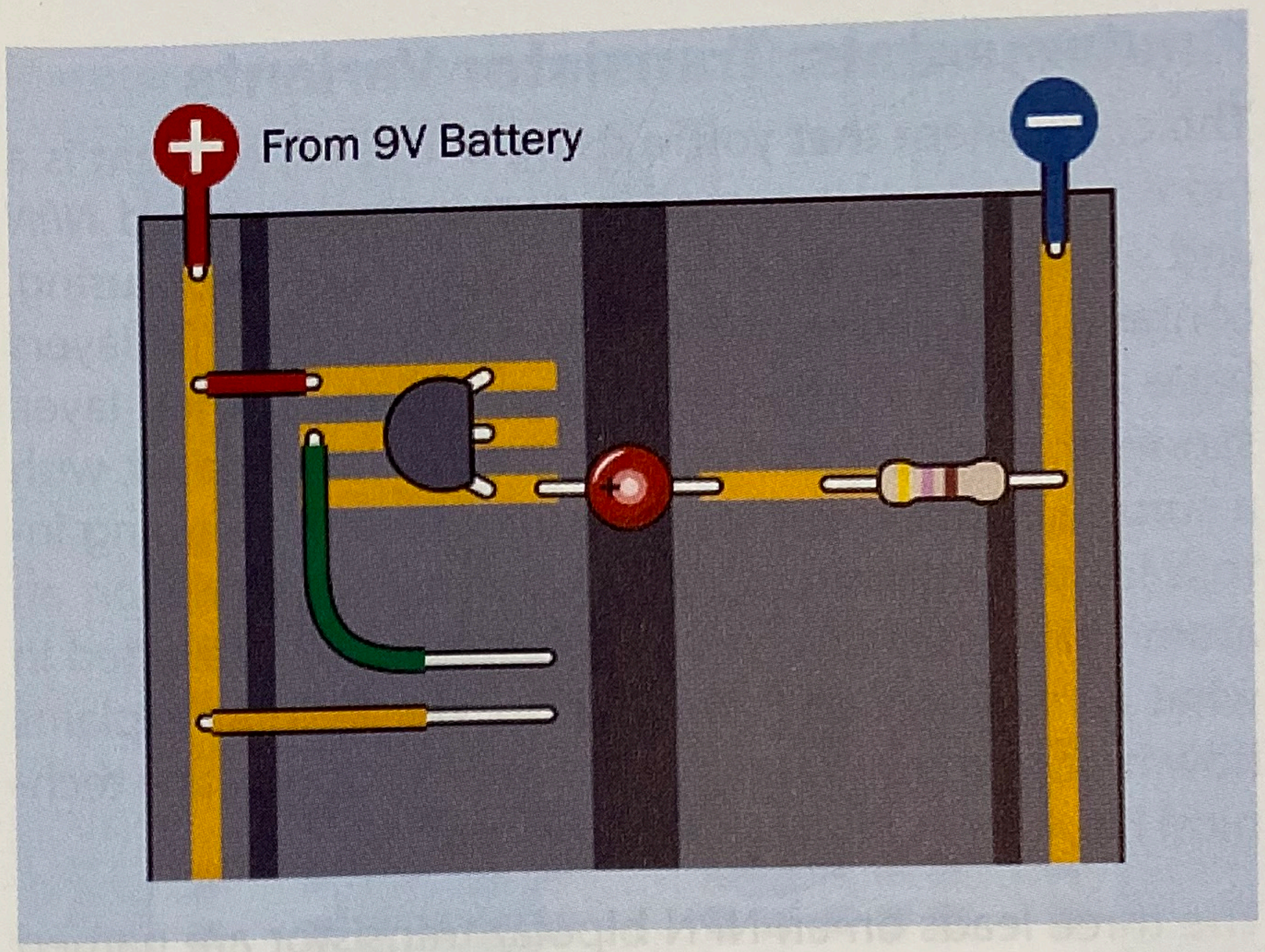

Figure 2-95 *X-ray view of the breadboard from the previous figure.*

Where did this current come from? Well, some electricity flowed in through the skin of your finger, to the center lead of the transistor. But this wasn't enough to light an LED.

There's only one other explanation. The transistor has a third lead, at the top, which is connected to the positive bus. Electricity entered the transistor through this lead. And then, somehow, this flow of current was controlled by the smaller amount of current that flowed through your finger into the center lead of the transistor.

This principle is illustrated in Figure 2-96.

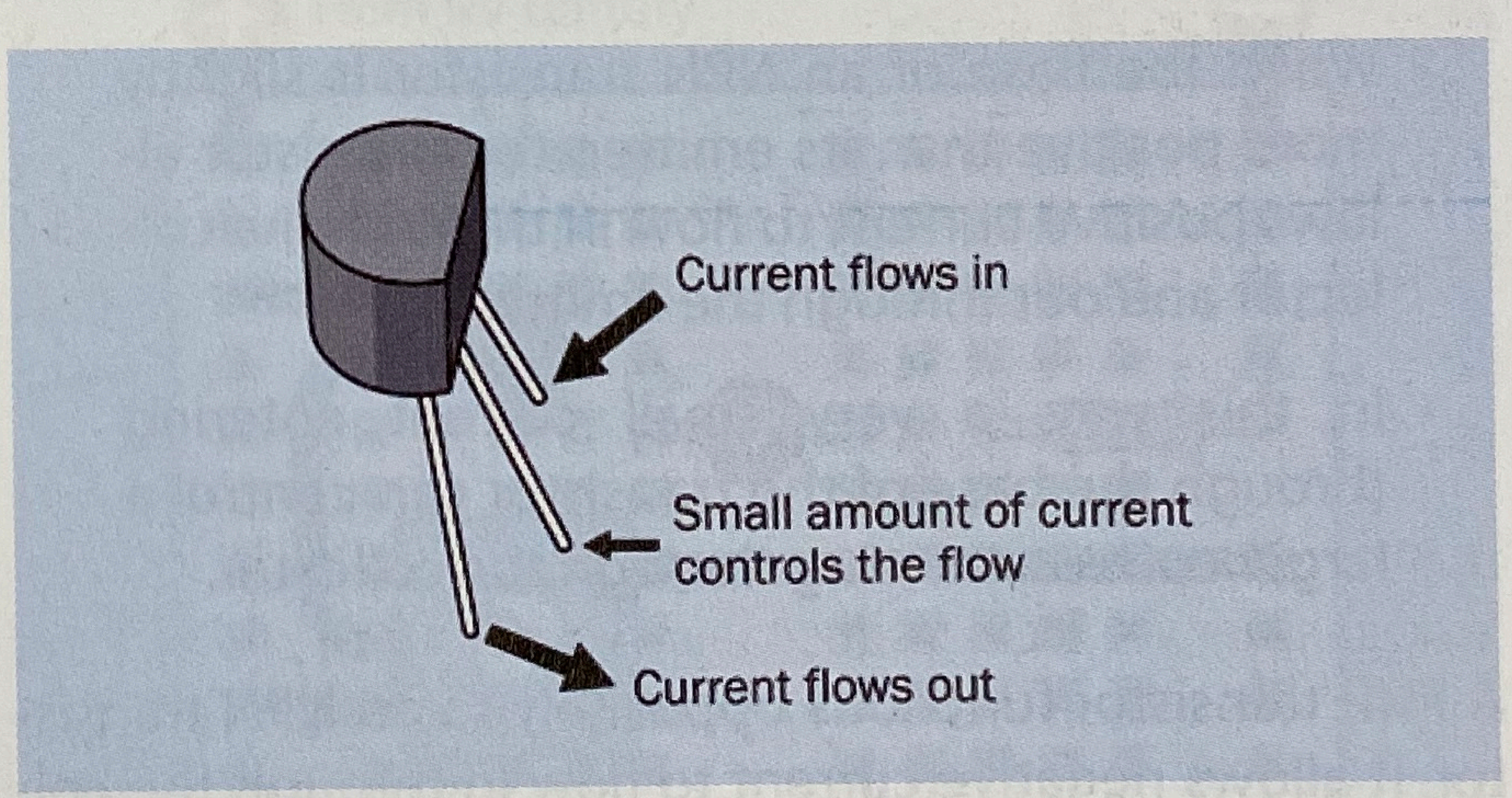

Figure 2-96 *The basic function of an NPN transistor.*

Incidentally, this phenomenon is very different from the behavior of the capacitor that you saw in the previous experiment. A capacitor just passed a quick pulse of electricity. A transistor controls a steady flow.

Fundamentals: Transistor Variants

The component that you're using in this experiment is a *NPN bipolar transistor*. It comes in two variants named *NPN* and *PNP*. The NPN type, which you have been using, contains three layers of silicon, of which two "N" layers have a surplus of negative charge carriers. A third layer, sandwiched between the other two, is the "P" layer, with a surplus of positive charge carriers. I won't be going into a lot of detail about how the transistor works on an atomic level, because in this book I'm more interested in what a transistor does than in the theory that explains how it does it. You can find that information in any technical book, or in many sources online.

The three leads on an NPN bipolar transistor are named the collector, base, and emitter, as shown in Figure 2-97.

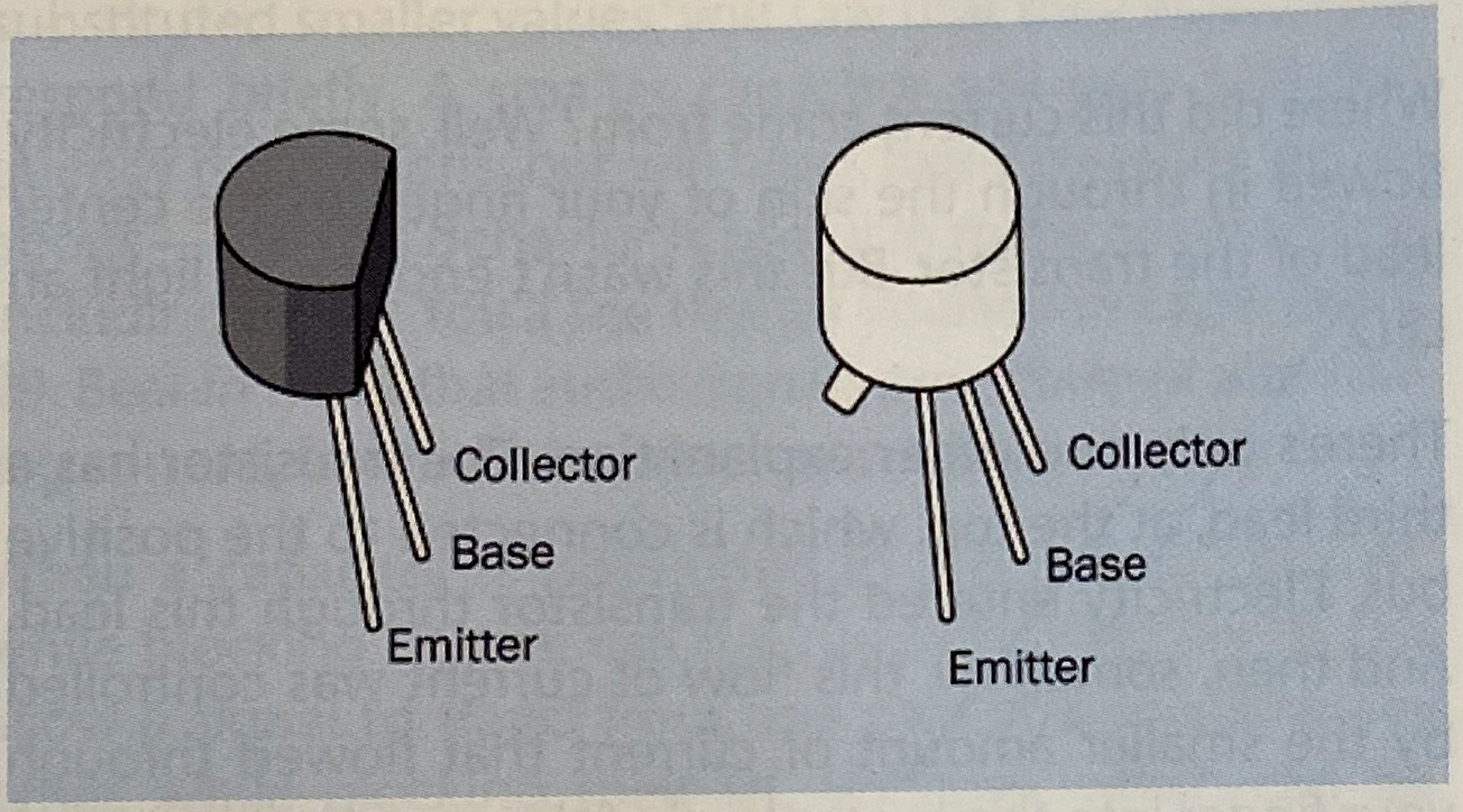

Figure 2-97 *The names of the three leads of an NPN bipolar transistor, supplied in a plastic body (left) and metal can (right).*

- When the base of an NPN transistor is slightly more positive than its emitter, the transistor allows positive current to flow in through the collector and out through the emitter.
- In this way, a very small current entering through the base of the transistor can control a larger current entering through the collector.

A PNP transistor functions oppositely to an NPN transistor. It allows negative current to flow in through the collector and out through the emitter when the base is slightly more negative than the emitter. PNP transistors are sometimes more convenient in a circuit, but are less commonly used. I will not be using them in *Make: Electronics*.

Four variants of the schematic symbol for an NPN transistor are shown in Figure 2-98. They all function the same way. The letters C, B, and E remind you that these connections are for the collector, base, and emitter.

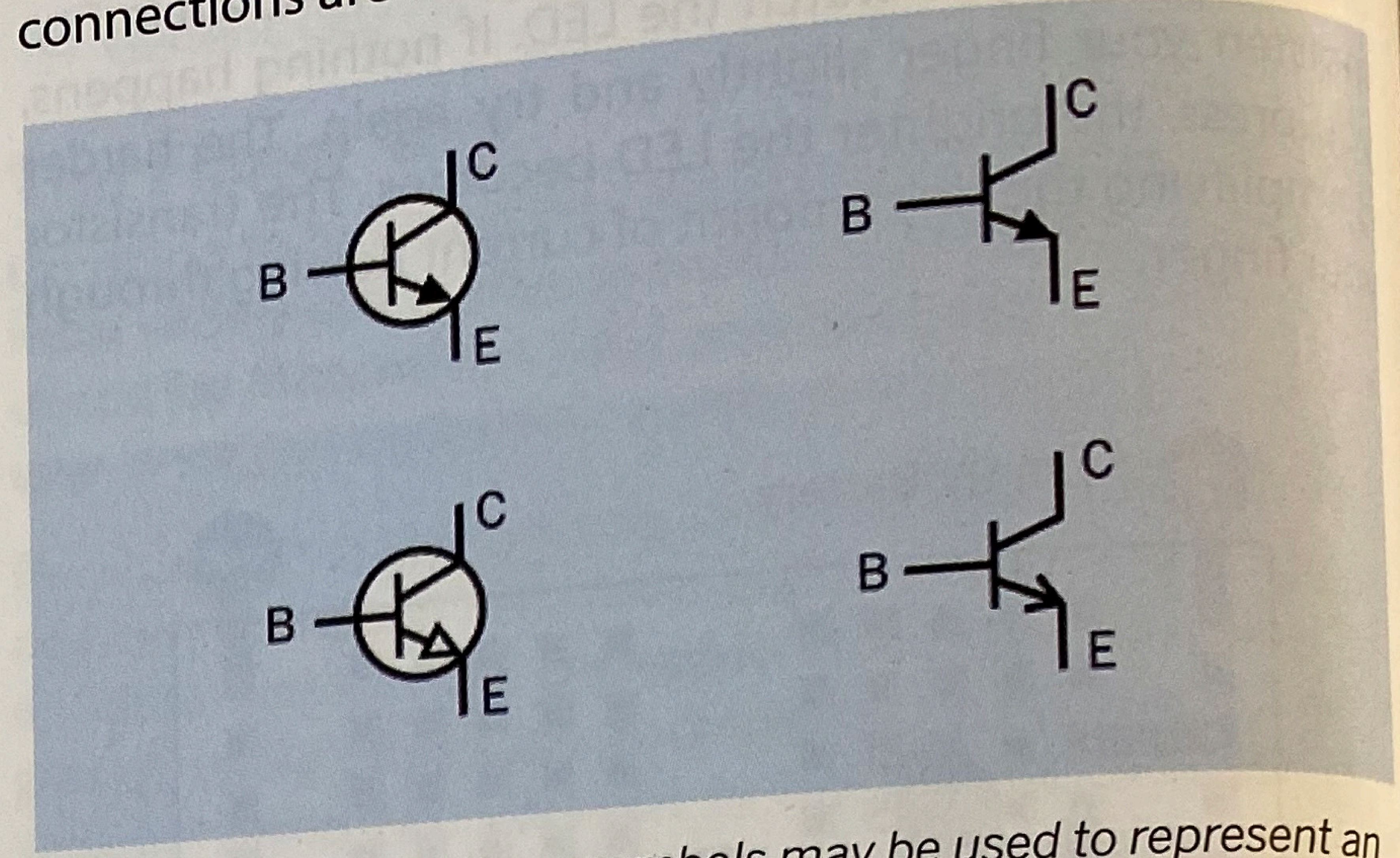

Figure 2-98 *Any of these symbols may be used to represent an NPN transistor.*

Four variants of the schematic symbol for a PNP transistor are shown in Figure 2-99. They all function the same way.

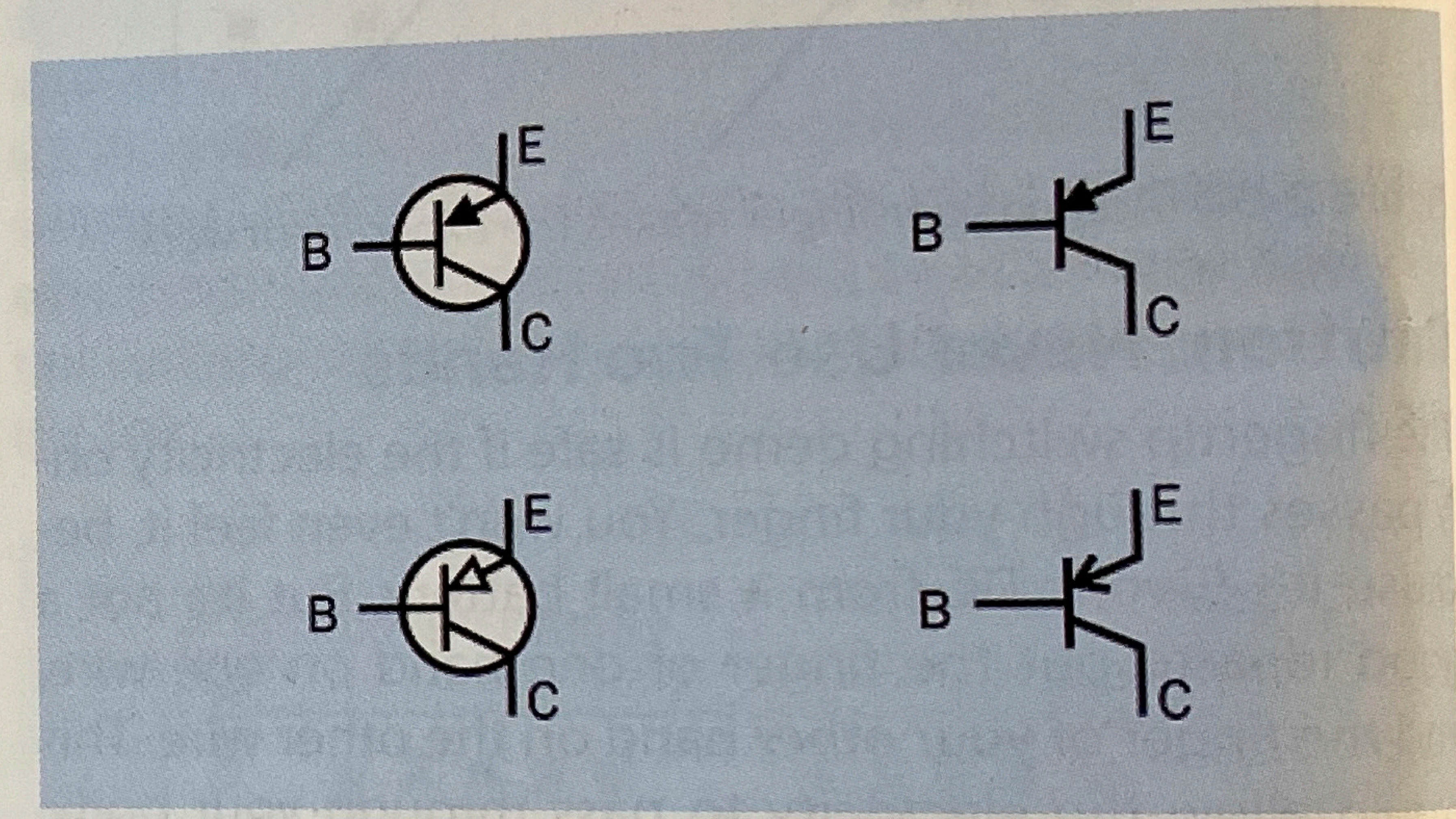

Figure 2-99 *Any of these symbols may be used to represent a PNP transistor.*

It's easy to get the symbols for PNP and NPN transistors mixed up, but there's a simple way to remind yourself which is which. The arrow in the NPN symbol points outward, never in. So, think of "NPN" as being short for "never pointing in."

Adding a Potentiometer

To learn more about the way in which a transistor works, we need a component that is a little more controllable than the tip of your finger. I think a potentiometer will do the job, but not the large type that you used previously. A *trimmer potentiometer* is what I have in mind, as pictured in Figure 2-22.

Even though they are dissimilar in shape and size, they all have three pins. These pins are functionally the same as the three tags that stick out of a large potentiometer of the kind that you used previously. The middle pin always connects with the wiper inside the trimmer, while the other two pins connect with each end of the resistive track inside it. Here is the basic rule that you must always follow:

- When you plug a trimmer into your breadboard, each pin must connect with a separate row of holes on the breadboard.

This rule is illustrated in Figure 2-100. At the top of the figure I have drawn a plan view of three types of trimmers, including the multi-turn type, because even though I am not recommending it, you may find yourself using one, some day. The pins are not visible from above, but I have shown their positions as if you can see them through the component. The positioning varies, but there are always three pins, and they should be 1/10″ apart vertically.

In the lower part of the figure, the two "Yes" examples will work because each pin connects with a different row of holes in the breadboard. The two "No" examples are unacceptable, because a pair of pins will be shorted together by a conductor inside the board.

Having dealt with the trimmer basics, I want you to add a 500K trimmer to your transistor circuit. This is shown in Figure 2-101. Connect the power and use a small screwdriver to rotate your trimmer all the way clockwise, and all the way counterclockwise. Notice that if you start with the LED completely dark, you have to turn the screw on the trimmer a little way before the LED begins to glow.

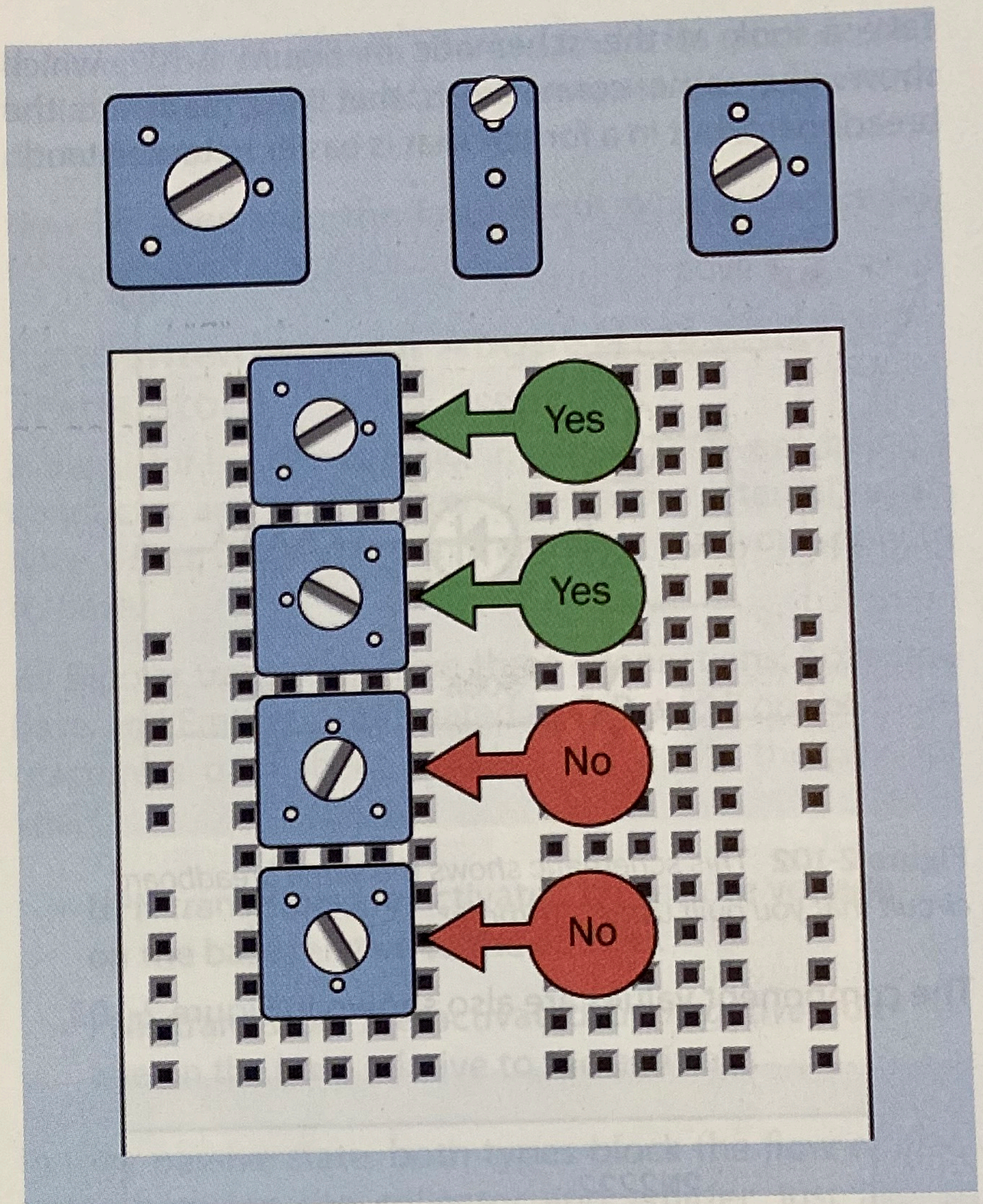

Figure 2-100 *Three types of trimmers, and the correct orientation of their pins.*

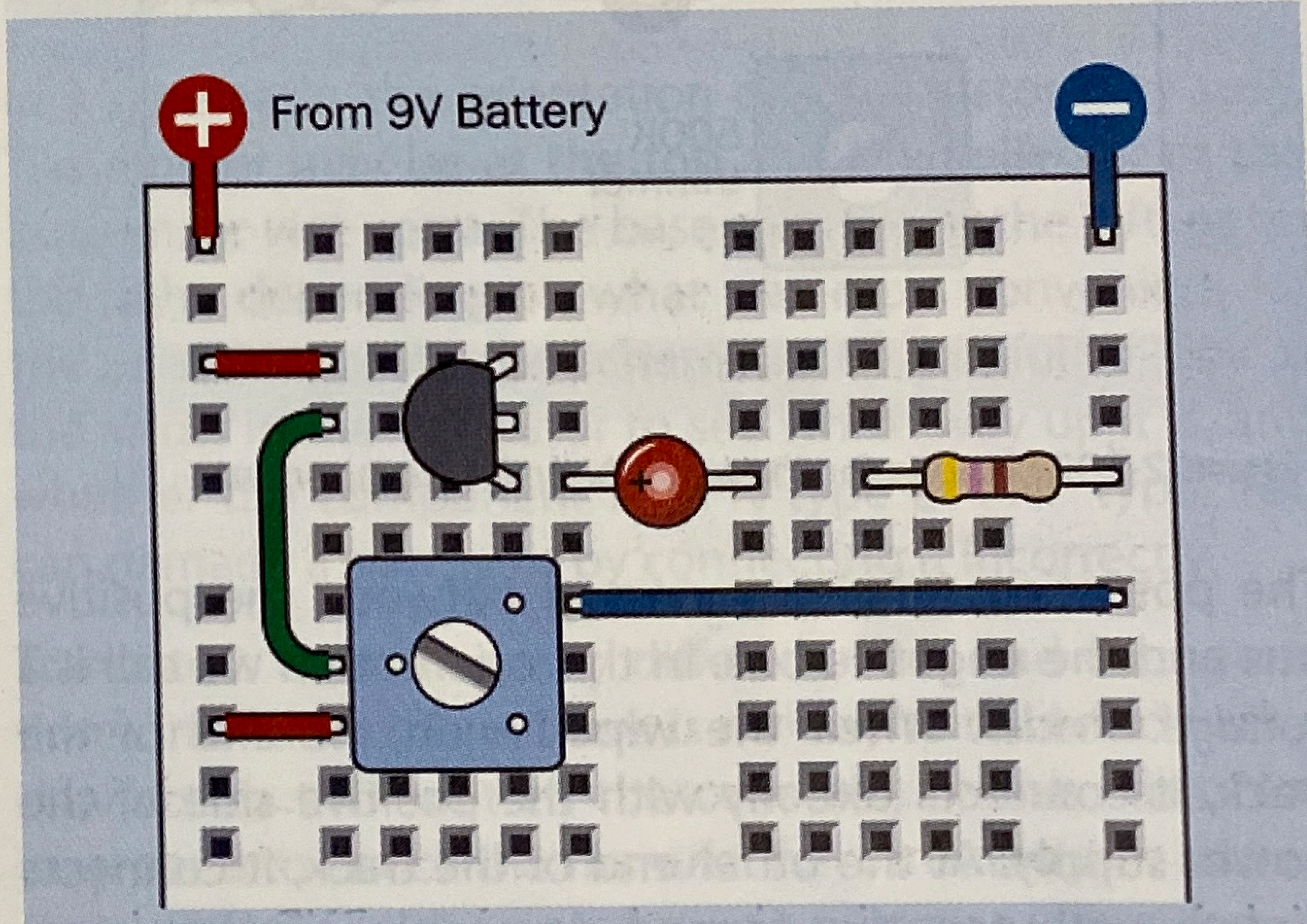

Figure 2-101 *The previous circuit now has a trimmer potentiometer so that you can control the transistor more precisely than was possible with your finger.*

Take a look at the schematic in Figure 2-102, which shows the same connections that you made on the breadboard, but in a format that is easier to understand.

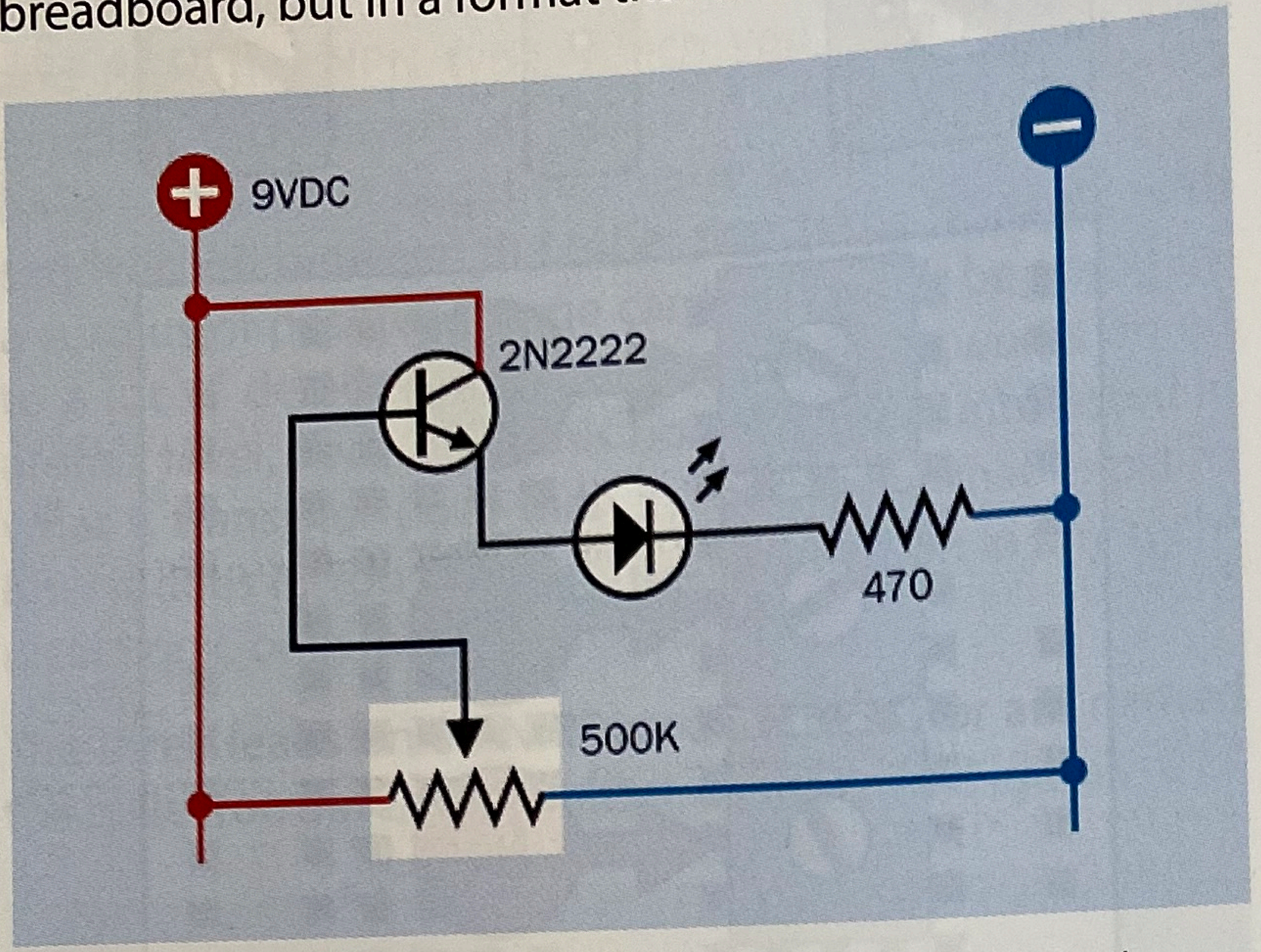

Figure 2-102 *This schematic shows the same breadboard circuit that you built using a trimmer.*

The component values are also shown in Figure 2-103.

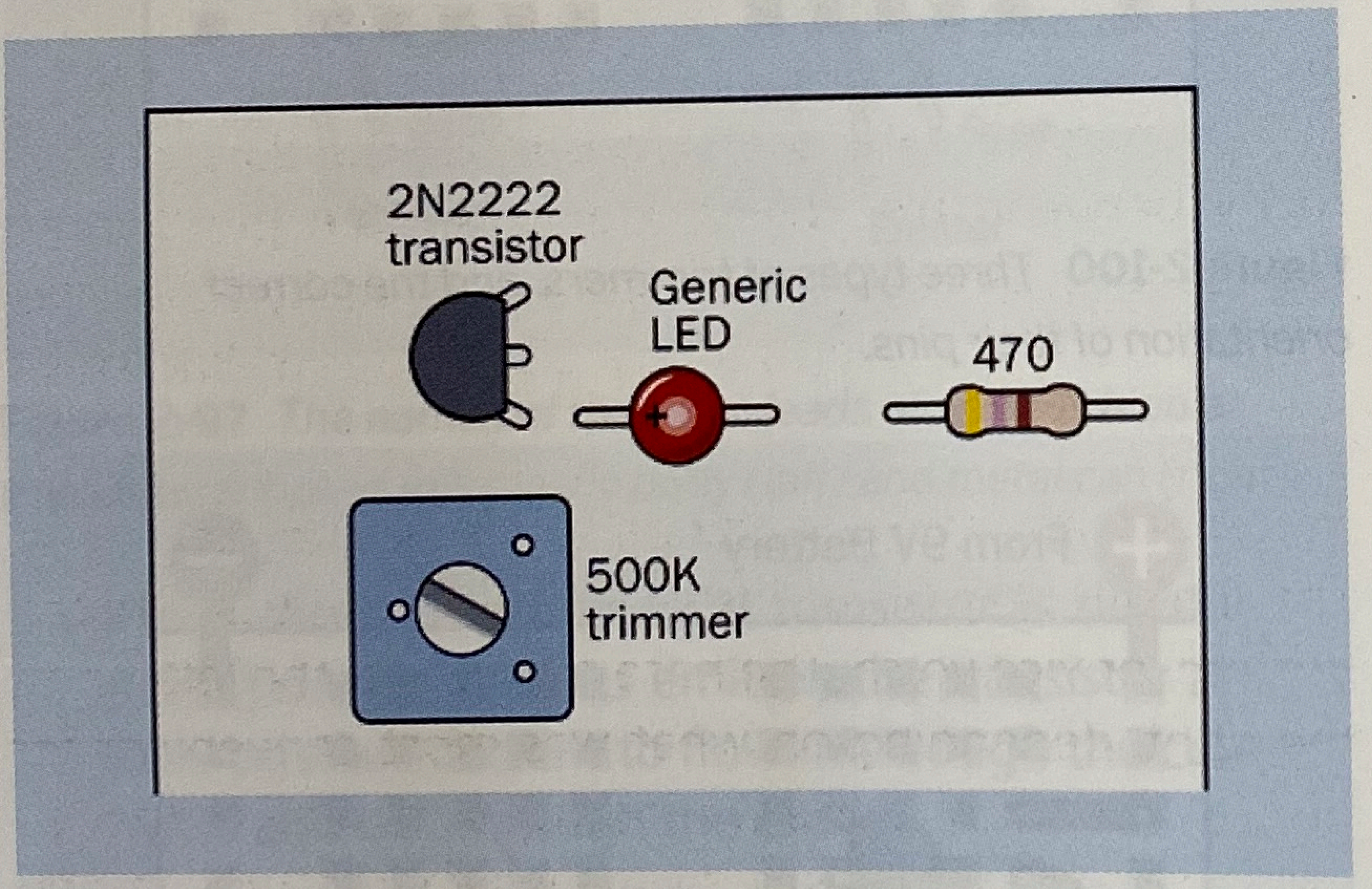

Figure 2-103 *Values for the breadboarded components.*

The potentiometer is connected between the positive bus and the negative bus. In this orientation we call it a *voltage divider*. When the wiper is at one end of the track, it connects directly with the positive side of the power supply. At the other end of the track, it connects directly with negative ground. At positions in between, it divides the voltage. Potentiometers are often used in this way, to provide a full range of voltages.

I mentioned that the LED didn't light up when you first started moving the wiper of the potentiometer from negative to positive. Is this just because the LED isn't getting enough power? Not exactly. The bipolar transistor deducts some of the power as its fee for providing a service. It won't respond unless the voltage at its base is higher than the voltage at its emitter (usually by around 0.7V). In this mode, the transistor is *positively biased*.

The general concept is illustrated in Figure 2-104.

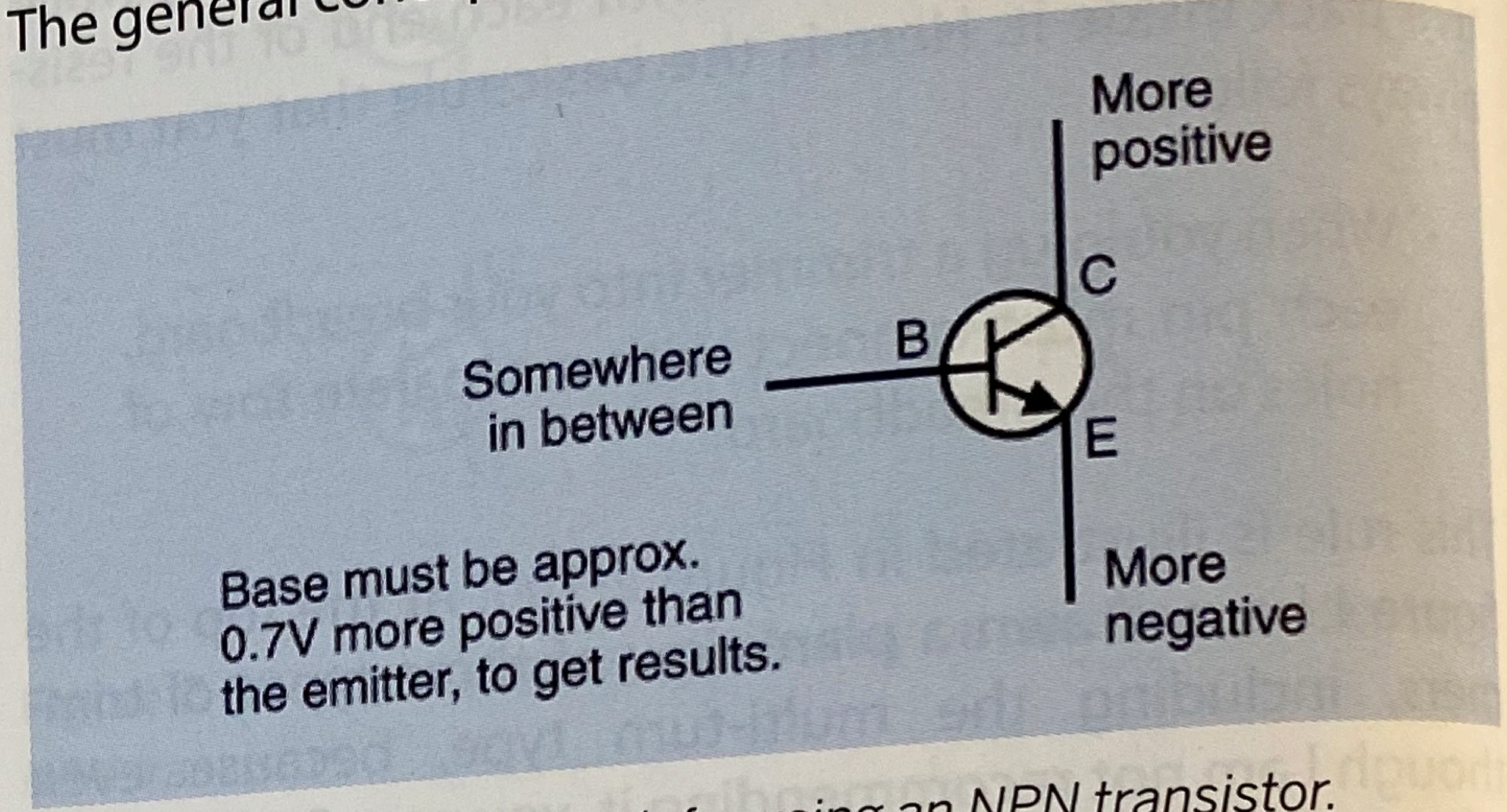

Figure 2-104 *Rule of thumb for using an NPN transistor.*

Voltage and Current

You've seen that the voltage at the base of a bipolar transistor controls the output from the transistor. Does that mean the transistor is amplifying the voltage?

You can discover this for yourself. Take your meter, set it to measure volts, and use a test lead to anchor the negative probe to the negative bus on the breadboard, as shown in Figure 2-105. Touch the red probe to the emitter pin of the transistor, make a note of the voltage, and move the probe to the base pin. I guarantee that the voltage at the emitter will be lower than the voltage on the base.

Readjust the trimmer to a different position, and try again. Regardless of how you change the voltage on the base pin, the emitter pin will always be lower.

Could this be because the 470-ohm resistor doesn't provide much resistance between the emitter of the transistor and the negative bus? Could it be pulling the voltage down?

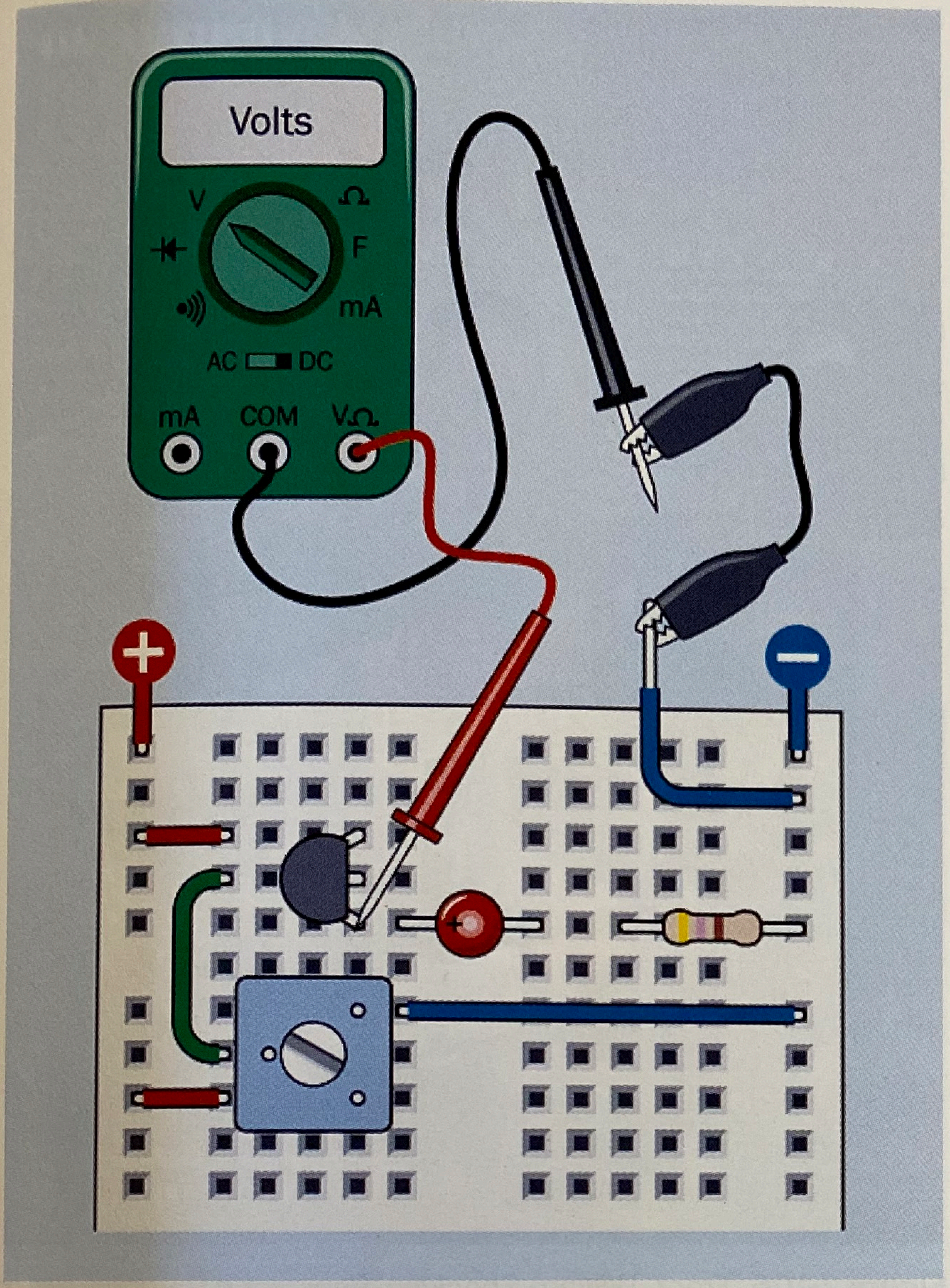

Figure 2-105 *Testing to discover if a transistor amplifies voltage.*

Let's find out. Remove the LED and the 470-ohm resistor, and substitute a 1M resistor between the emitter of the transistor and negative ground. It won't make much difference. The voltage on the emitter will still be lower than the voltage on the base.

If you have the patience to test the *current* into the base and out of the emitter, you would find something very different. This would entail setting your meter to measure milliamps and inserting it into the circuit in each location. Remember, current must pass *through* the meter to be measurable.

But I'll tell you what you would find. This particular transistor amplifies the current entering its base by a factor of more than 200:1. This is called the *beta value* of a transistor, and leads me to a fundamental fact:

- A bipolar transistor amplifies current, not voltage.

In *Make: More Electronics* you can find a lot more on this topic. I'm keeping it brief, here, because this is an introductory book.

Now I'll summarize the facts about bipolar transistors, for your future reference.

Fundamentals: All About NPN and PNP Transistors

A transistor is a *semiconductor*, midway between being a conductor and an insulator. Its effective internal resistance varies, depending on the power that you apply to its base.

All bipolar transistors have three connections: Collector, Base, and Emitter, abbreviated as C, B, and E on the manufacturer's data sheet, which will identify the pins for you.

- NPN transistors are activated by *positive* voltage on the base relative to the emitter.
- PNP transistors are activated by *negative* voltage on the base relative to the emitter.

In their passive state, both types block the flow of electricity between the collector and emitter, just like an SPST relay in which the contacts are normally open. (Actually a transistor allows a tiny bit of current known as *leakage*.)

In a schematic, the orientation of a transistor may vary. The emitter may be at the top and the collector at the bottom, or vice versa. The base may be on the left, or on the right, depending on what was most convenient for the person drawing the schematic. Be careful to look at the arrow in the transistor to see which way up it is, and whether the component is NPN type or PNP type. You can damage a transistor by connecting it incorrectly.

Transistors come in many different sizes and configurations. In a lot of them, there is no way to tell which wires connect to the emitter, the collector, or the base. You may need to check the manufacturer's datasheet to find out.

If you forget which lead is which, many multimeters have a function that will identify the emitter, collector, and base for you. Typically there are four holes labeled E, B, C, and E. When you have the emitter lead of your transistor inserted in either of the holes marked E, the base lead in B, and the collector lead in C, the meter will display the beta value of the transistor. In any other orientation, the meter reading will be unstable, or blank, or zero, or much lower than it should be (almost always below 50, and usually below 5).

Caution: Fragile Component!

Transistors are easily damaged, and the damage will be permanent.

- Never apply a power supply directly between any two pins of a transistor. You can burn it out with too much current.
- Always limit the current flowing between the collector and the emitter of a transistor by using another component such as a resistor, in the same way you would protect an LED.
- Don't apply voltage in reverse orientation. The collector of an NPN transistor should always be more positive than the base, which should be more positive than the emitter.

Background: Transistor Origins

Although some historians trace the origins of the transistor back to the invention of diodes (which allow electricity to flow in one direction while preventing reversal of the flow), the first practical and fully functional transistor was developed at Bell Laboratories in 1948 by John Bardeen, William Shockley, and Walter Brattain.

Shockley was the leader of the team, and had the foresight to see how potentially important a solid-state switch could be. Bardeen was the theorist, and Brattain actually made it work. This was a hugely productive collaboration—until it succeeded. At that point, Shockley started maneuvering to have the transistor patented exclusively under his own name. When he notified his collaborators, they were naturally unhappy about this.

A widely circulated publicity photograph didn't help, in that it showed Shockley sitting at the center in front of a microscope, as if he had done the hands-on work, while the other two stood behind him, implying that they had played a lesser role. A copy of this picture appeared on the cover of *Electronics* magazine (see Figure 2-106). In fact Shockley, as the supervisor, was seldom present in the laboratory where the real work was done.

Figure 2-106 *Front, William Shockley. Rear, John Bardeen. Right, Walter Brattain. For their collaboration in development of the world's first working transistor in 1948, they shared a Nobel prize in 1956.*

The productive collaboration quickly disintegrated. Brattain asked to be transferred to a different lab at AT&T. Bardeen moved to the University of Illinois to pursue theoretical physics. Shockley eventually left Bell Labs and founded Shockley Semiconductor in what was later to become Silicon Valley, but his ambitions outstripped the capabilities of the technology of his time. His company never manufactured a profitable product.

Eight of Shockley's coworkers in his company eventually betrayed him by quitting and establishing their own business, Fairchild Semiconductor, which became hugely successful as a manufacturer of transistors and, later, integrated circuit chips.

Fundamentals: Transistors and Relays

One limitation of NPN and PNP transistors is that they require power to perform their function, unlike a relay, which can be passively on or off without any power input at all.

Relays also offer more switching options. Different versions can be normally open, normally closed, or can latch in either position. A relay can contain a double-throw switch, which gives you a choice of two "on" positions. It can also contain a double-pole switch, which makes (or breaks) two entirely separate connections. Single-transistor devices cannot provide the double-throw or double-pole features, although you can design more complex circuits that emulate this behavior.

A table comparing the attributes of transistors and relays appears in Figure 2-107.

	Transistor	Relay
Long-term reliability	Excellent	Limited
Can switch in DP or DT mode	No	Yes
Can switch large currents	Limited	Yes
Can switch alternating current	Usually not	Yes
Triggerable by alternating current	Usually not	Optional
Suitable for miniaturization	Excellent	Very limited
Able to switch at very high speed	Yes	No
Price advantage for high voltage/current	No	Yes
Price advantage for low voltage/current	Yes	No
Current leakage when nonconducting	Yes	No

Figure 2-107 *Principal attributes of relays and transistors, compared.*

The decision to use a relay or a transistor will depend on each particular application.

So much for the theory. Now what can we do with a transistor that's fun, or useful, or both? We can do Experiment 11!

Experiment 11: Light and Sound

It is time now for your first project that has a function and a purpose. It will culminate with an ultra-simple sound synthesizer.

What You Will Need

- Breadboard, hookup wire, wire cutters, wire strippers, multimeter
- 9-volt battery and connector (1)
- Resistors: 470 (2), 1K (1), 4.7K (4), 100K (2), 220K (2), 470K (4)
- Capacitors: 0.01µF (2), 0.1µF (2), 0.33µF (2), 1µF (1), 3.3µF (2), 33µF (1), 100µF (1), 220µF (1)
- Transistors: 2N2222 (6)
- Generic LED (1)
- Loudspeaker, 8-ohm, 1" or (preferably) 2" (1)

Fluctuations

Figure 2-108 shows the new circuit that I'd like you to create on your breadboard. There's not a lot of room among the components, so you may find that it's easier to install them using your pliers instead of your fingers. Count the holes in the board carefully, and double-check to make sure that everything is in exactly the right place.

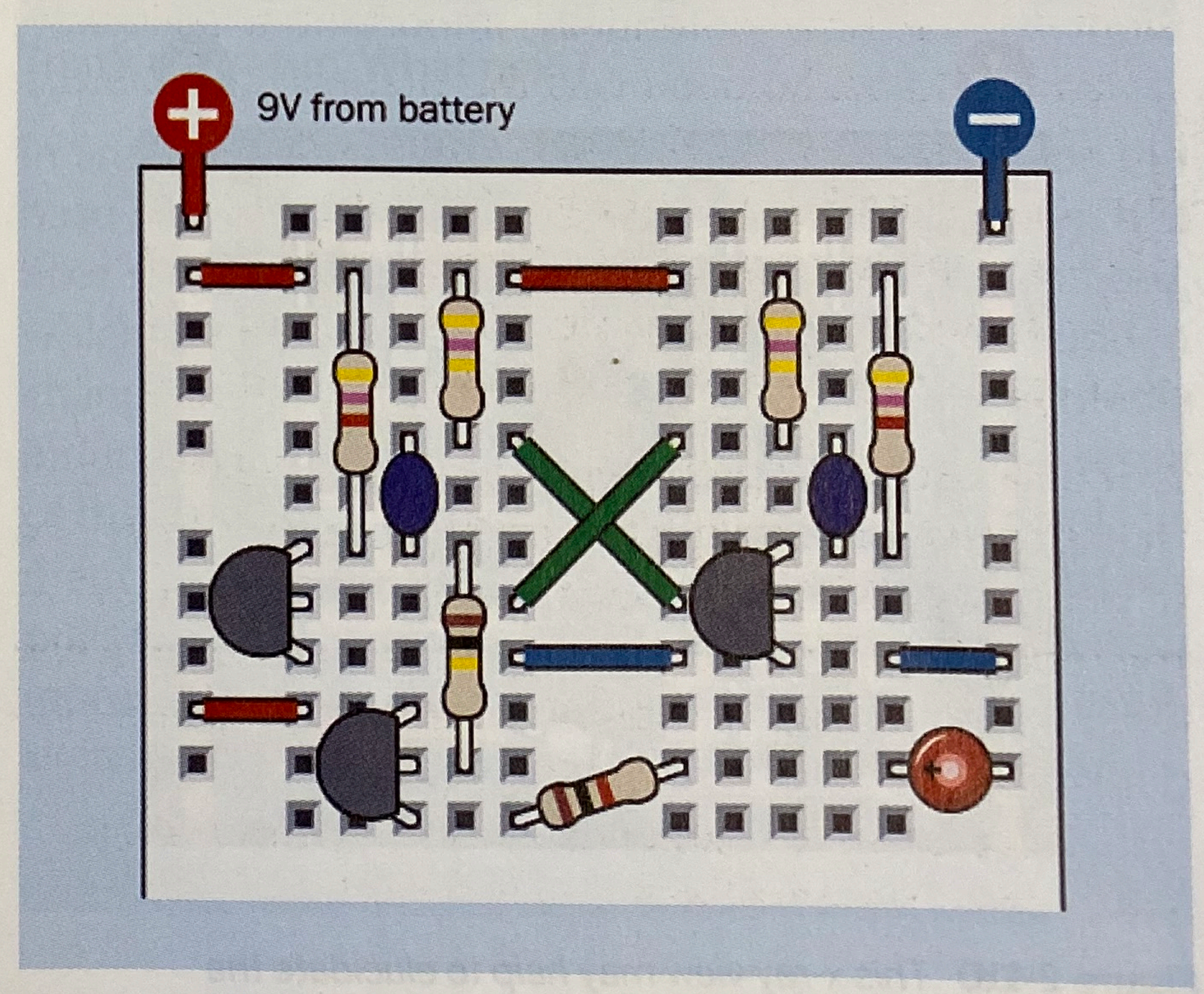

Figure 2-108 *Breadboard layout for an oscillator circuit.*