You may want to bookmark this list of fault-tracing procedures and come back to it later if something doesn't work.

Background: Michael Faraday and Capacitors

As previously noted, the farad is named after Michael Faraday. He was an English chemist and physicist who lived from 1791 to 1867. See Figure 2-78.

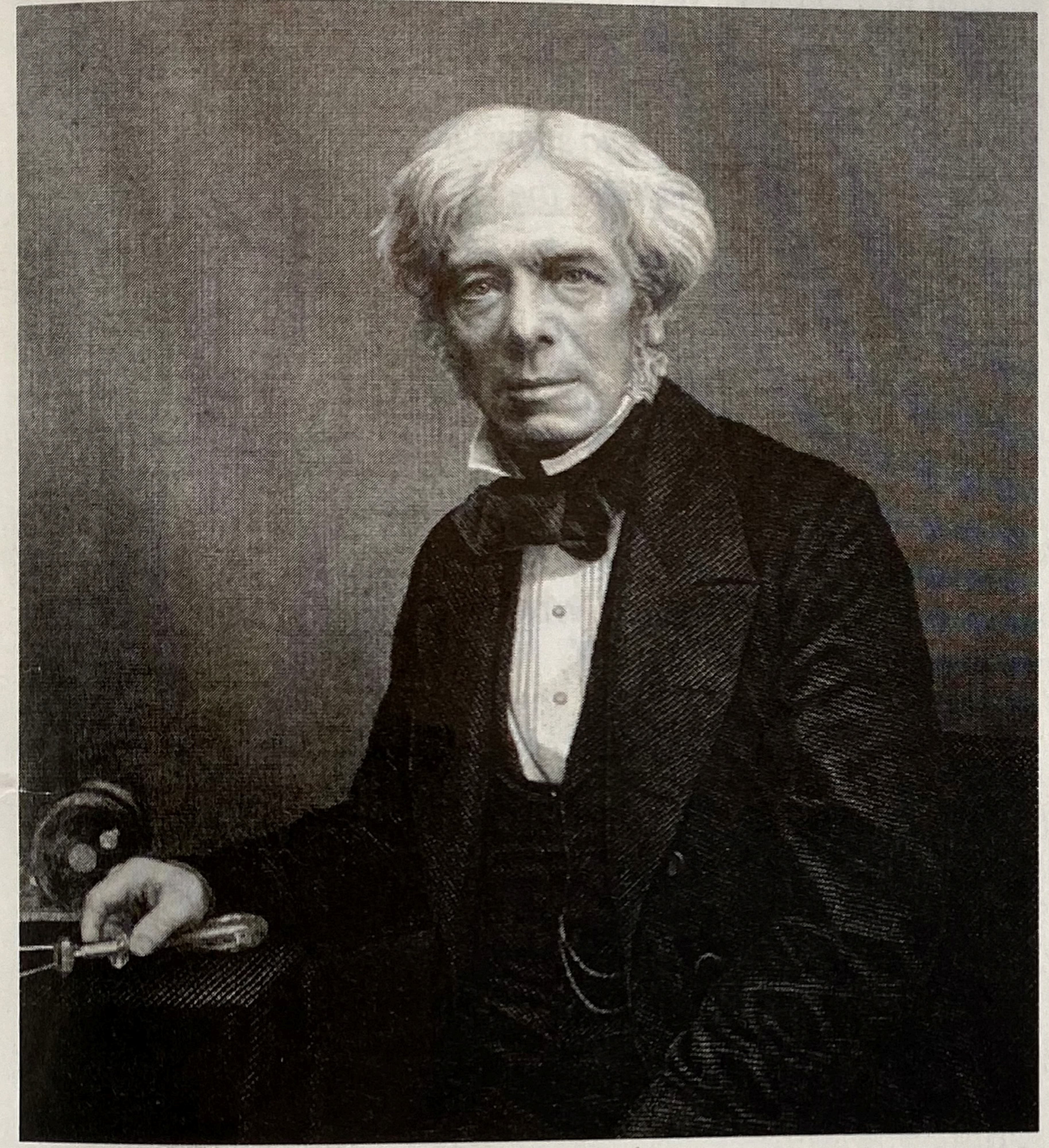

Figure 2-78 *Michael Faraday, after whom the farad is named.*

Although Faraday was relatively uneducated and had little knowledge of mathematics, he had an opportunity to read a wide variety of books while working for seven years as a bookbinder's apprentice, and thus was able to educate himself. Also, he lived at a time when relatively simple experiments could reveal fundamental properties of electricity. He made major discoveries including electromagnetic induction, which led to the development of electric motors. He also discovered that magnetism could affect rays of light.

His work earned him numerous honors, and his picture was printed on English bank notes denominated in 20 pounds sterling, from 1991 through 2001.

Experiment 9: Time and Capacitors

Electrons travel almost at the speed of light, yet we can use them to measure time in seconds, minutes, or even hours. This experiment will show you how.

What You Will Need

- Breadboard, hookup wire, wire cutters, wire strippers, test leads, multimeter
- 9-volt battery and connector (1)
- Tactile switches (2)
- Generic LED (1) 20mA, 2V
- Resistors: 470 ohms, 1K, 10K (one of each) ✓
- Capacitors: 0.1µF, 1µF, 10µF, 100µF, 1,000µF (one of each) ≥16 V

ceramic ca
longest
electrolytic

Charging a Capacitor

First set your meter to measure volts DC, and measure the voltage of a 9-volt battery with your meter. If it's less than 9.2V, you need a newer battery for this particular experiment.

Install two tactile switches, a 1K resistor, and a 1,000µF capacitor on your breadboard as shown in Figure 2-79. Use a couple of test leads to connect your meter so that you can measure the voltage across the leads of the capacitor while keeping your hands free.

Snap a connector on your battery, and plug the wires into the breadboard to provide the 9VDC supply on the two buses of the breadboard, with positive on the left, as shown in the figure.

If the meter measures more than 0.1V, discharge the capacitor by pressing button B, which shorts together the two sides of the capacitor.

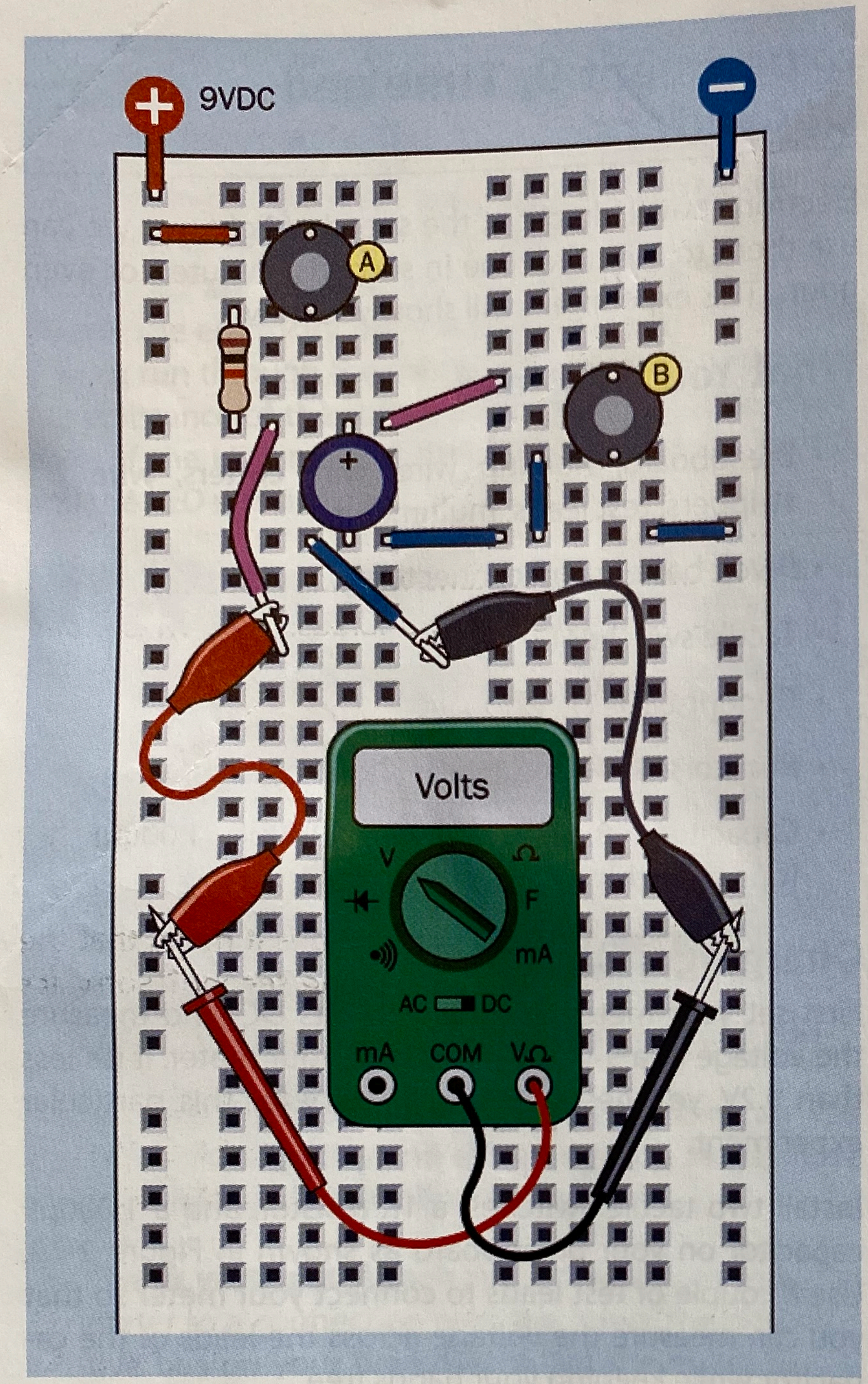

Figure 2-79 *A simple setup for timing the charging of a capacitor. The capacitor is 1,000µF and the resistor is 1K.*

A schematic in Figure 2-80 shows the same circuit, and may help you to see what's going on.

Now hold down button A while you use a watch, a clock, or a smartphone to count how many seconds the capacitor takes to charge to 9.0V. If you have an autoranging meter, it should automatically switch from measuring millivolts, at first, to measuring volts as the charge increases. When I performed this experiment, the meter took almost six seconds.

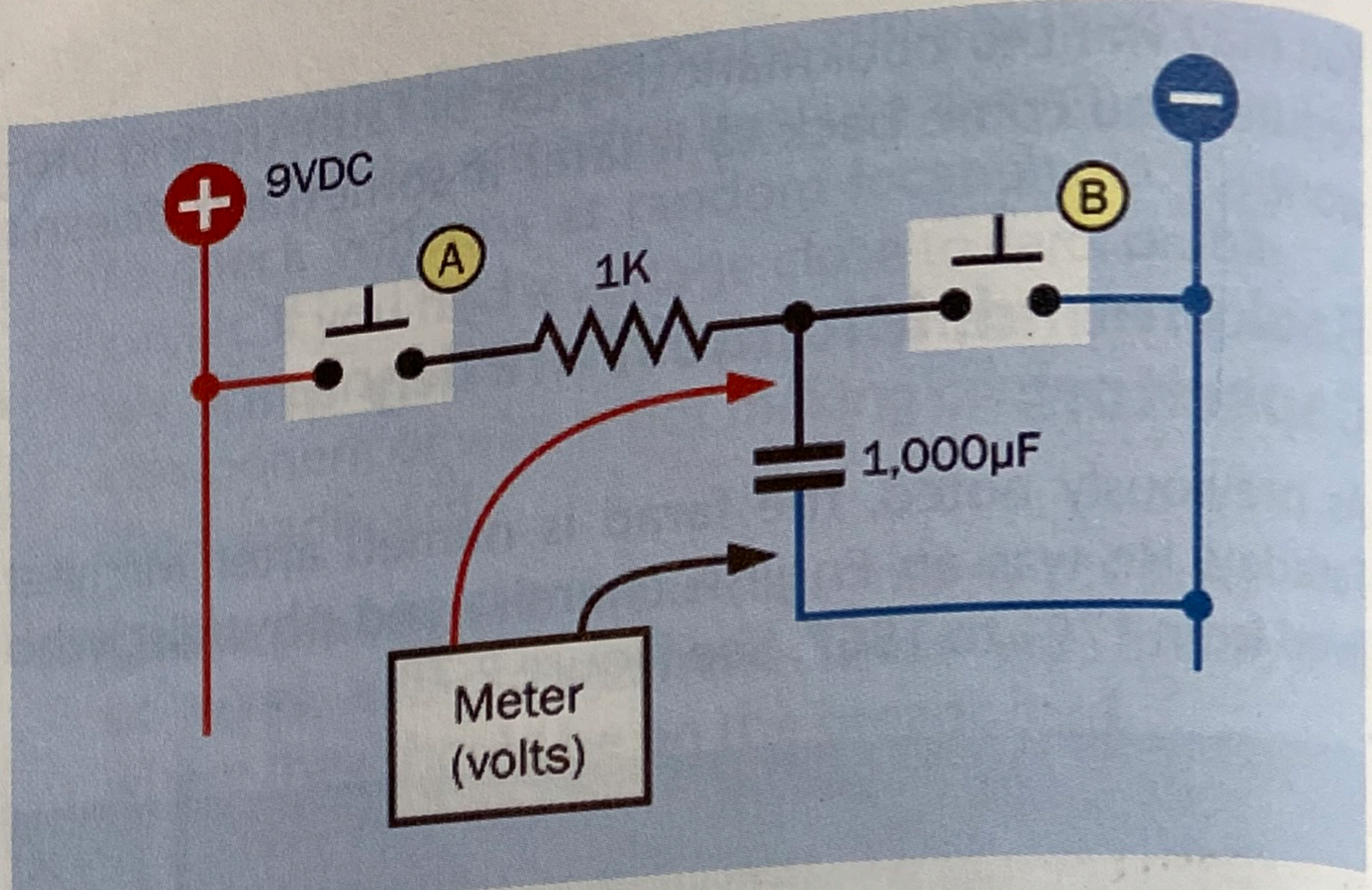

Figure 2-80 *This schematic shows the same circuit as the preceding figure, which shows the breadboarded version.*

The positive side of the capacitor has become "more positive" and the negative side has become "more negative" as electron-holes and electrons have been attracted to each other on the plates. The potential difference between the leads of the capacitor has increased, while current has not passed through it. One of the first statements you will find, when you read any introductory electronics text, is:

- A capacitor blocks DC (direct current).

So long as you apply a steady electrical potential to the capacitor, this is true.

An RC Network

Remove the 1K resistor and substitute a 10K resistor. If the meter shows that there is still some voltage across the capacitor, discharge it by pressing button B.

Now repeat the test. How long does the capacitor take to reach 9.0V, charging through a 10K resistor?

This simple combination of a capacitor and a resistor is known as an *RC network* (R for resistor, C for capacitor). It's a very important concept in electronics. Before I explain what it does, here are some questions to consider:

- Did the capacitor take exactly 10 times as long to reach 9 volts when you used the 10K resistor instead of the 1K resistor?
- Did the voltage across the capacitor rise at a steady rate, or did it increase faster at the beginning of the experiment—or toward the end?

- If you wait long enough, will the capacitor ever reach the initial value that you measured as the voltage of your battery?

Voltage, Resistance, and Capacitance

Think of the resistor as a faucet restricting the flow of water, and the capacitor as a balloon that you are trying to fill (see Figure 2-81). If you screw down the faucet until only a trickle comes through, the balloon will take longer to fill. But a slow flow of water should still fill the balloon if you wait long enough. Assuming that the balloon doesn't burst, the process will end when the pressure inside the balloon is equal to the water pressure in the pipe supplying the faucet.

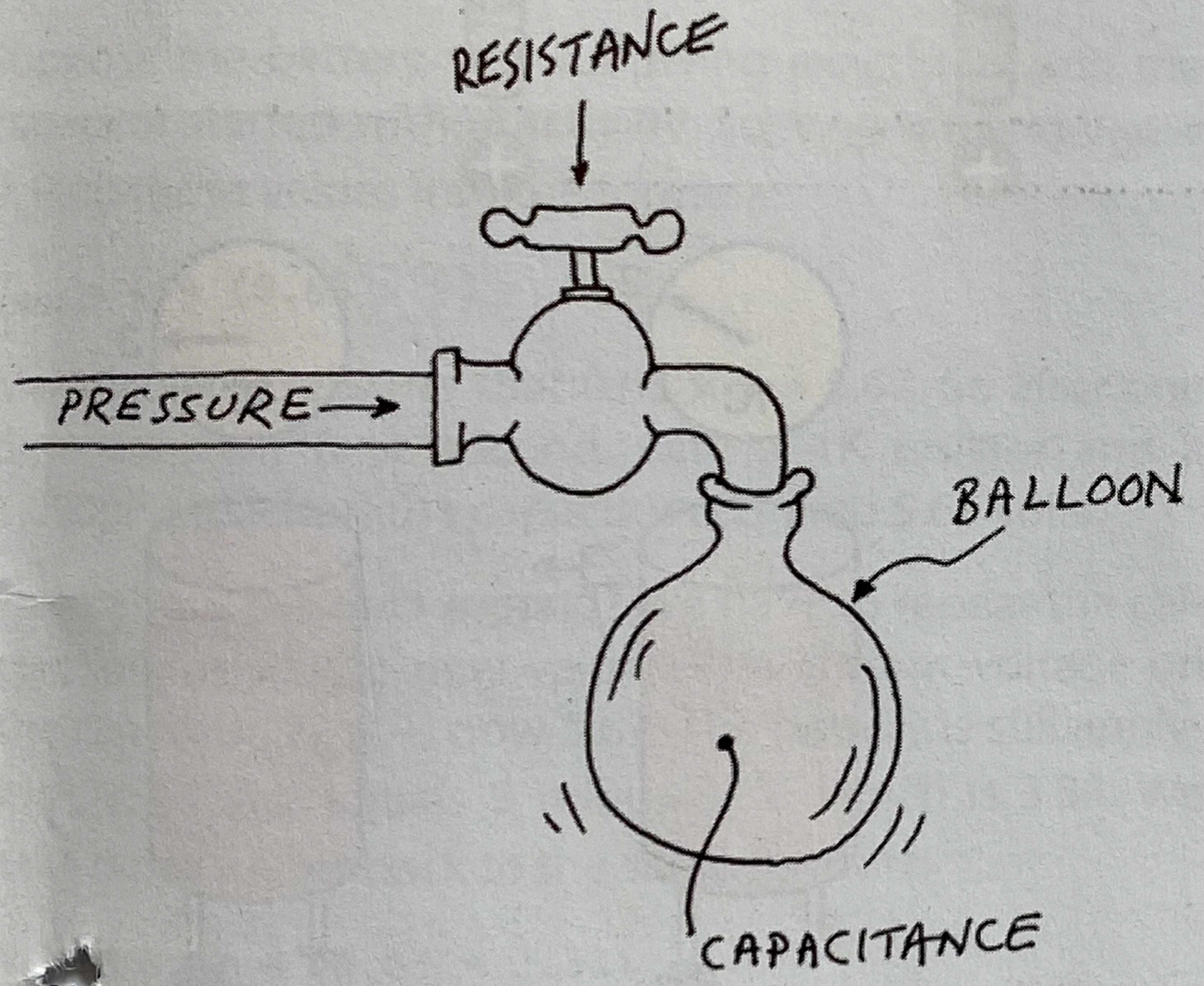

Figure 2-81 *Water flowing into a balloon can be compared with electrons flowing into a capacitor.*

But this description leaves out an important factor. As the balloon starts to fill, it stretches, exerting more pressure on its contents. As the pressure inside the balloon increases, it pushes back against the incoming flow of water. Consequently we may expect the water to flow in more slowly as the process continues.

How does this compare with electrons flowing into a capacitor? The concept is similar. Initially, the electrons go rushing in, but as they occupy more of the electron-holes, the newcomers take longer to find a resting place. The charging process gets slower, and slower. In fact, theoretically, the charge on the capacitor never quite reaches the voltage being applied to it.

Background: The Time Constant

The speed with which a capacitor charges is measured with a function known as the "time constant." The definition is very simple:

$$T = R \times C$$

where T is the time constant, in seconds, if a capacitor of value C (measured in farads) is being charged through a resistor of R ohms.

Going back to the circuit you first tested, using a 1K resistor, we can put the values of the components that you used into the time-constant formula—but only if we convert the units to ohms and farads. Well, 1K is 1,000 ohms, and 1,000μF is 0.001 farads. So the calculation becomes very easy:

$$TC = 1{,}000 \times 0.001$$

Therefore, for those values of a resistor and a capacitor, TC = 1.

But what exactly does this mean? Does it mean that the capacitor will be fully charged in one second? Sorry, it's not that simple.

- T, the time constant, is the number of seconds required for a capacitor to acquire 63% of the voltage being supplied to it, if it starts with zero volts.

What if the capacitor doesn't start from zero? If we start measuring after the capacitor has already acquired some voltage, the definition becomes a bit more complicated. If V_{DIF} is the difference between the voltage on the capacitor and the supply voltage, T is the number of seconds required for a capacitor to add 63% of V_{DIF} to its current charge.

(Why 63%? Why not 62%, or 64%, or 50%? The answer to that question is too complicated for this book, and you'll have to read about time constants elsewhere if you want to know more. Be prepared for differential equations.)

A comparison may be helpful. Figure 2-82 shows a greedy guy who is ready to eat some cake. At first he's ravenously hungry, so he takes 63% of the cake and eats it in one second, which is his time constant for eating cake. In his second bite, he takes another 63% of the cake that is left—and because he's not feeling so hungry anymore, he requires one more second (remember, this is his time constant). In his third bite, he takes 63% of what still remains, and still ingests it in one second. And so on. He is gradually filling up with cake, like a capacitor filling up with electrons. But he never quite eats all the cake, because he only takes 63% of whatever is left.

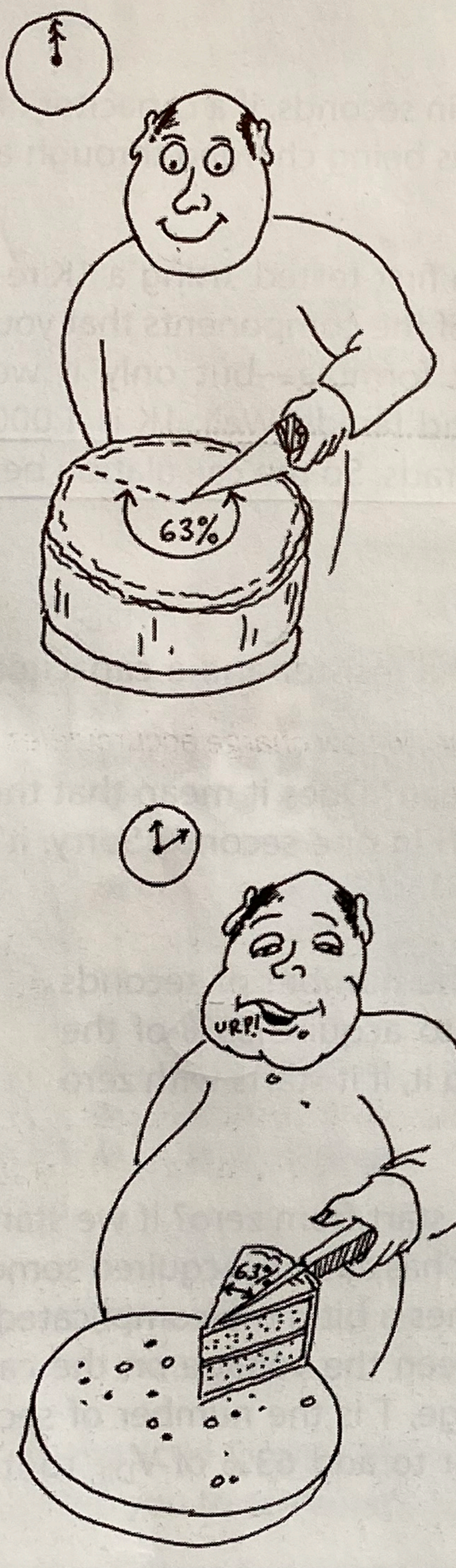

Figure 2-82 *If our gourmet always eats just 63% of the cake still on the plate, he "charges up" his stomach in the same way that a capacitor charges itself. No matter how long he keeps at it, the cake is never quite gone and his stomach is never completely filled.*

Figure 2-83 shows the process another way. After each time constant (which is one second, if we have a 1,000µF capacitor and a 1K resistor), the capacitor acquires another 63% of the difference between the charge it had and the voltage being applied.

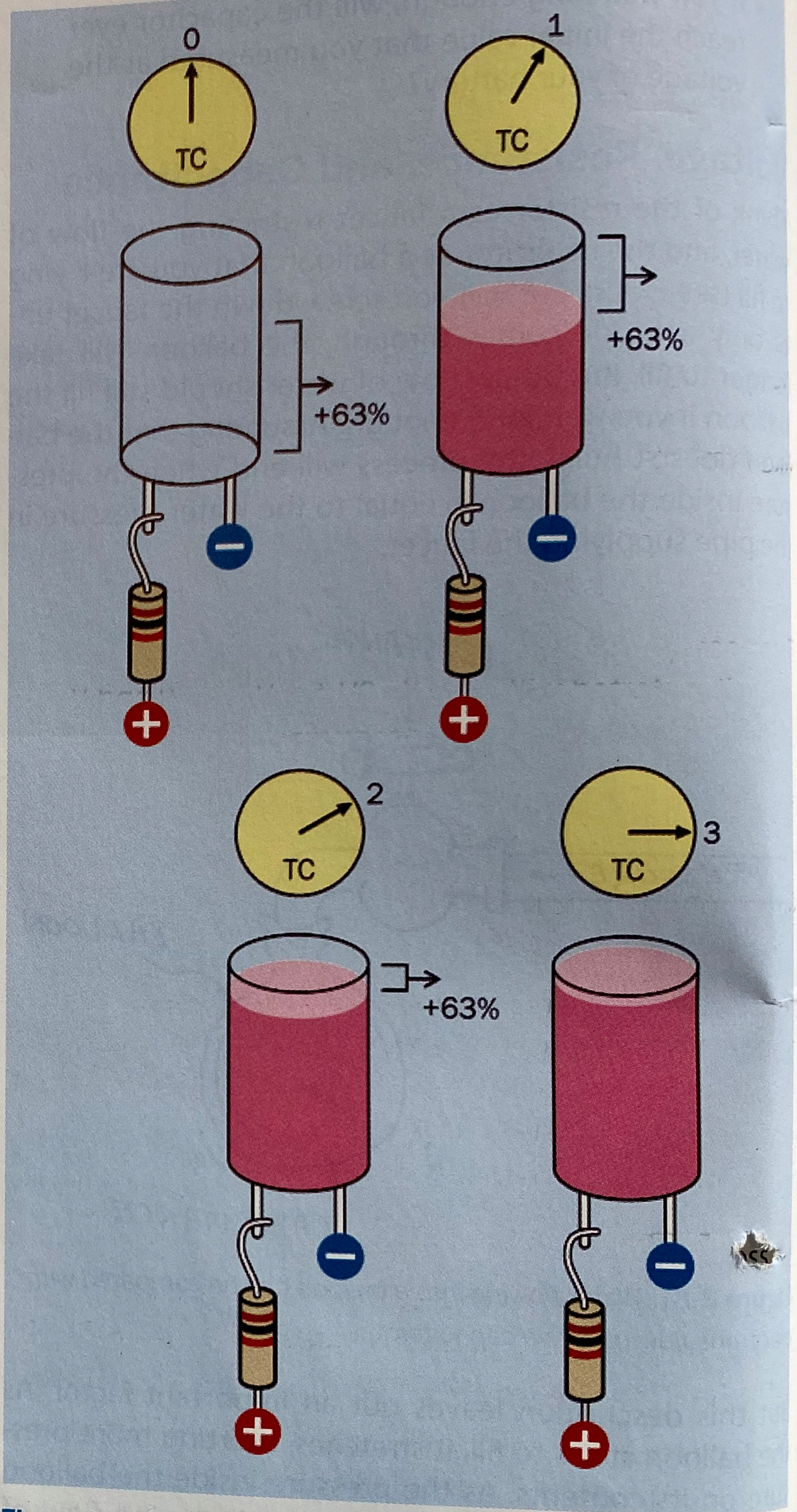

Figure 2-83 *Another way of looking at a charging capacitor.*

In a perfect world of perfect components, the charging process for a capacitor would continue for an infinite time. In the real world, we say rather arbitrarily:

- After five time constants, the charge on the capacitor will be so close to 100 percent, we can think of the process as being complete.

Background: Graphing It

I want to draw a graph showing the voltage in a capacitor as it charges. To do this, I'm going to calculate the data by using the time-constant formula.

Suppose V_{CAP} is the voltage on a capacitor right now, while V_{DIF} is the difference between that amount of charge and the battery voltage being applied (as before). The formula shown below will tell me what the new voltage on the capacitor will be after one time constant. I'll call the new voltage V_{NEW}. The formula looks like this:

$$V_{NEW} = V_{CAP} + (0.63 \times V_{DIF})$$

The 0.63 value is the same as 63 percent.

Suppose the battery was supplying exactly 9V and the capacitor started with exactly 0V. So, $V_{CAP} = 0$ and $V_{DIF} = 9$. Plug those values into the formula:

$$V_{NEW} = 0 + (0.63 \times 9)$$

My calculator tells me that 0.63 × 9 = 5.67. So after one time constant (one second, with a 1K resistor and a 1,000μF capacitor) the capacitor acquired 5.67 volts.

What about the next second? We have to repeat the calculation, using the new values. The current voltage on the capacitor, V_{CAP}, is now 5.67. The battery is still applying 9V, so V_{DIF} equals 9 minus 5.67, which is 3.33. We take those values back to the same formula:

V_{N}[illegible] $5.67 + (0.63 \times 3.33)$

My calculator tells me that 0.63 times 3.33 equals 2.1, approximately. And 2.1 plus 5.67 equals 7.77. So, after two seconds, the capacitor has acquired 7.77 volts.

We can repeat this calculation any number of times, creating a sequence of numbers like this (rounded to two decimal places), showing the voltage on the capacitor at the end of each second, assuming a power supply of 9V:

After 1 second: 5.67 volts

After 2 seconds: 7.77 volts

After 3 seconds: 8.54 volts

After 4 seconds: 8.83 volts

After 5 seconds: 8.94 volts

After 6 seconds: 8.98 volts

The graph in Figure 2-84 was created by drawing a smooth curve through those values. I didn't bother to go beyond six seconds, because the values climb so close to 9V.

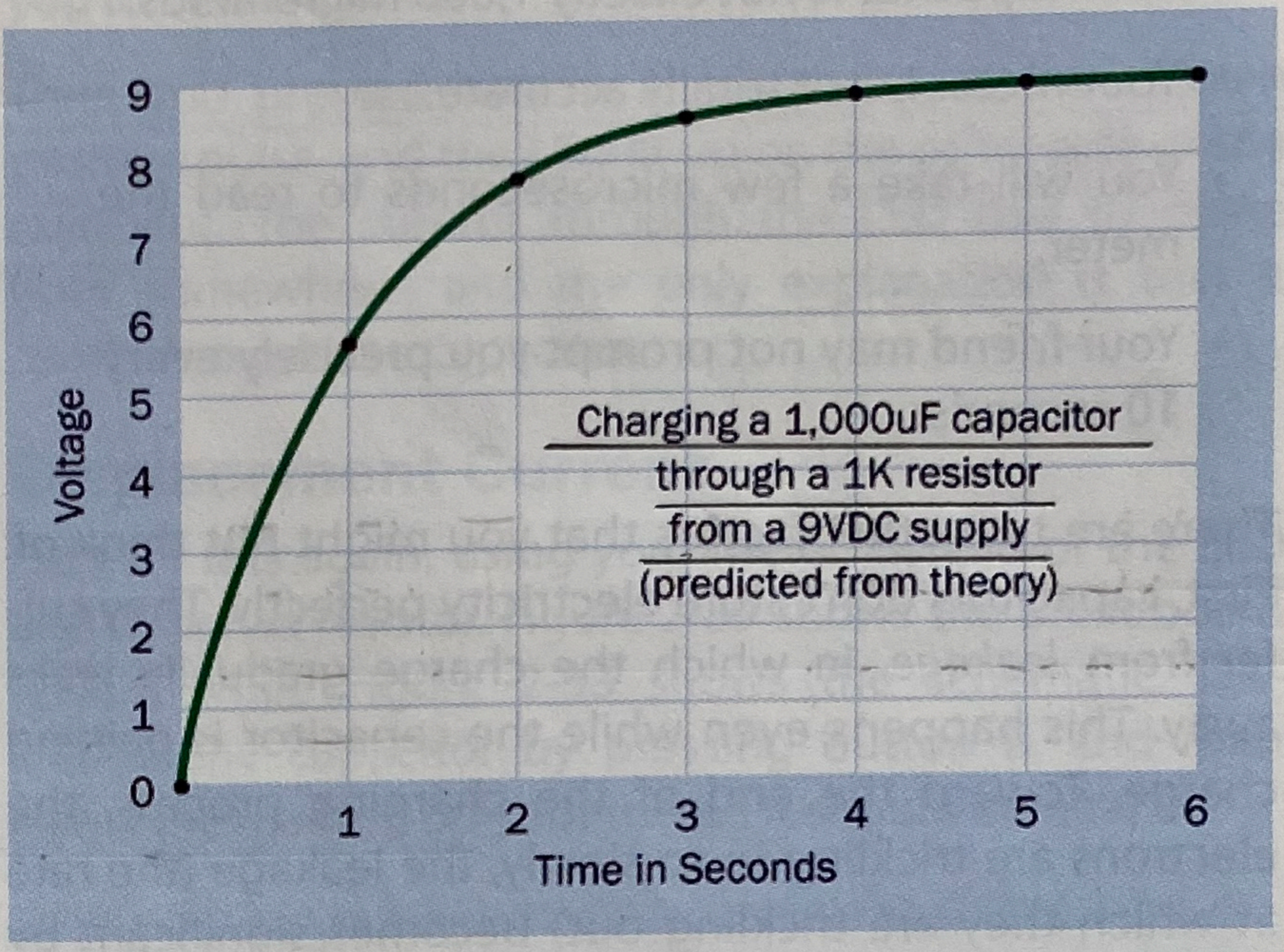

Figure 2-84 *A graph can help to show how charge accumulates on a capacitor over a period of time.*

Experimental Verification

I've told you how to calculate the charge on a capacitor in an RC network. But—how do you know I'm right? Should you just take my word for it?

Maybe you should test it yourself. In other words, you could do some *experimental verification*, which is a big part of Learning by Discovery.

Go back to the circuit that you used before, and make sure you have the 10K resistor in it, not the 1K resistor. Ask a friend to sit beside you, keeping track of the time, while you watch the display of volts on your multimeter. Every 10 seconds, your friend says "Now!" and you write down the voltage on the meter at that moment. You follow this procedure for one minute.

Because you're using a 10K resistor, not a 1K resistor, the time constant is now 10 seconds instead of 1 second. So, your readings should look like the series of voltages that I tabulated above at 1-second intervals, except that yours will be at 10-second intervals.

The voltages that you measure should be close to mine, but they won't match precisely. Why? I can think of many reasons.

- Your battery doesn't provide exactly the same voltage as mine.
- Your resistor isn't precisely 10,000 ohms.
- Your capacitor is not exactly 1,000 microfarads.
- Your meter is not totally accurate.
- You will take a few microseconds to read the meter.
- Your friend may not prompt you precisely every 10 seconds.

There are two other factors that you might not think of. First, capacitors don't store electricity perfectly. They suffer from *leakage*, in which the charge gradually leaks away. This happens even while the capacitor is gaining charge. Toward the end of the charging process, the electrons are trickling in so slowly, the leakage (the rate at which they are trickling out) becomes significant by comparison.

Additionally, your meter has an internal resistance. It's very high, but still, it passes a small amount of current. This means that the meter is stealing a little bit of the charge from your capacitor while you are measuring the voltage. Yes, the process of making a measurement changes the value that you are trying to measure! This is actually a common problem in physics and engineering.

I can think of ways to minimize all of these factors, but I can't imagine a way to eliminate them completely. There will always be some experimental error. This is the challenge when you use an experiment to verify a theory. Verification can be a very lengthy process, requiring a lot of patience—which is why theorists tend to have different personalities from experimentalists.

Capacitive Coupling

Now that I've told you how capacitors become charged and discharged, I have to go back to the statement I made before:

- A capacitor blocks DC (direct current).

You may remember, I also said, "So long as you apply a steady electrical potential to the capacitor, this is true."

But what if there isn't a steady electrical potential? What happens at the moment when a capacitor goes from having no charge on it to connecting suddenly to a source of voltage?

Ahhh, that's a different matter. Under those circumstances, the capacitor *allows a signal to pass through*.

How can this be? The plates inside a capacitor don't touch each other, so, how can a pulse of electricity jump from one to the other?

I'll deal with the "how" and "why" in a moment. First you need to make sure that what I'm talking about actually happens.

Take a look at the components on the breadboard in Figure 2-85. The layout is similar to the circuit in Figure 2-79, but the 10K resistor has moved from the left side to the right side, and an LED and a 470-ohm resistor have been added.

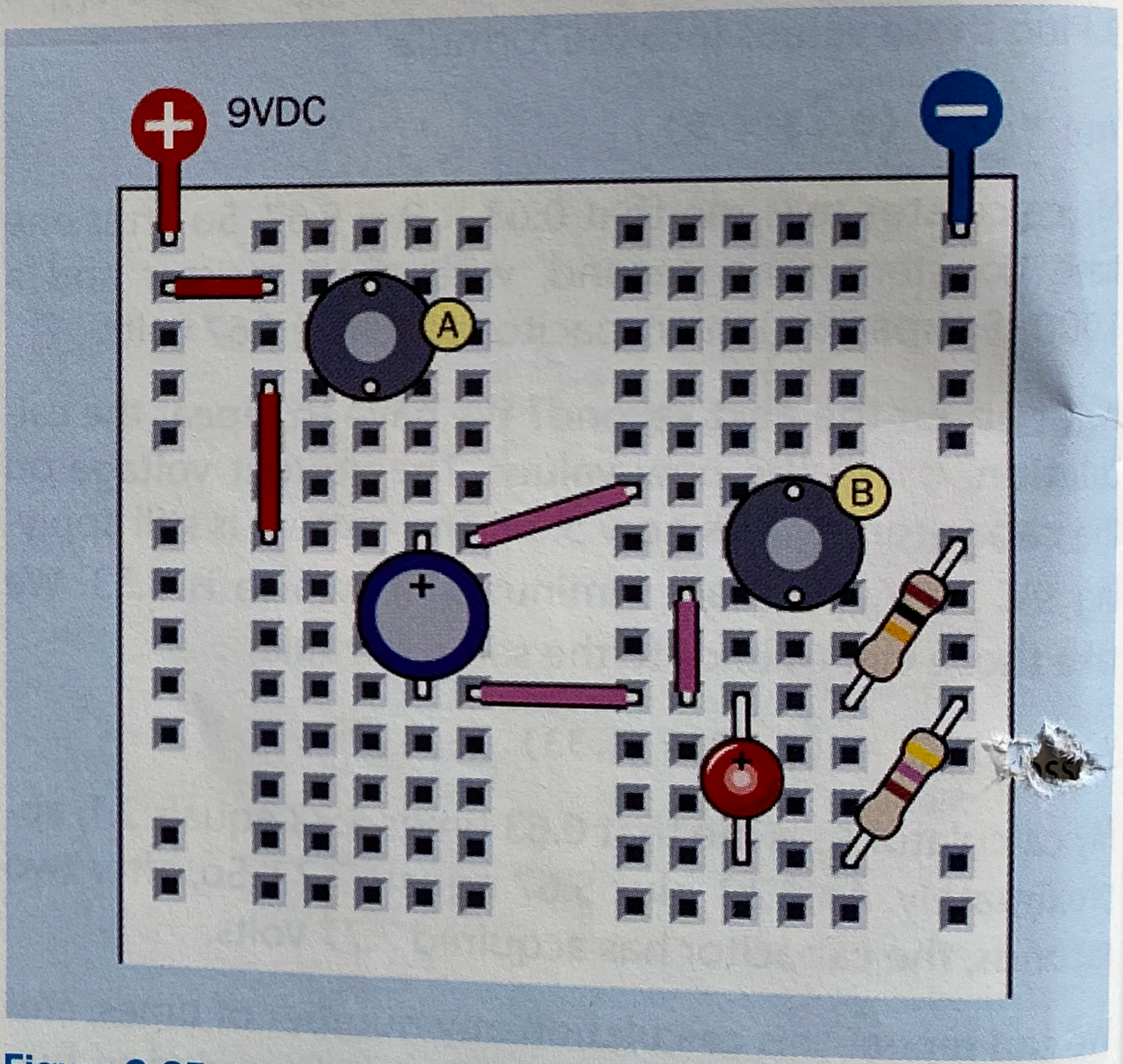

Figure 2-85 *The flashing of a red LED shows how the behavior of a capacitor changes when there is a quick change in voltage.*

The breadboarded circuit is redrawn as a schematic in Figure 2-86, which may help to clarify it.

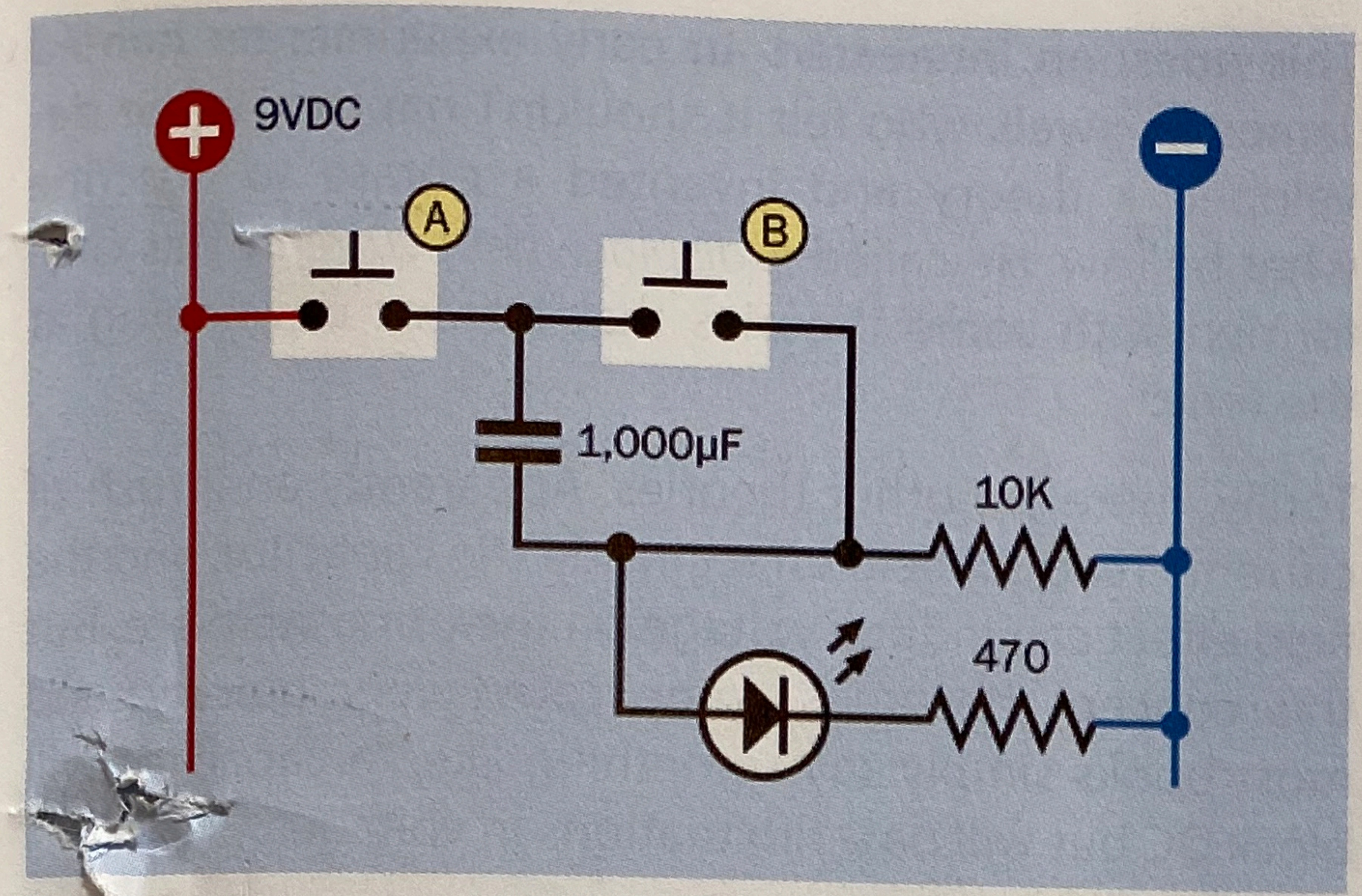

Figure 2-86 *This schematic shows the same circuit as in the preceding figure depicting a breadboarded version.*

And just to make sure there is no confusion, I'm showing the component values in Figure 2-87.

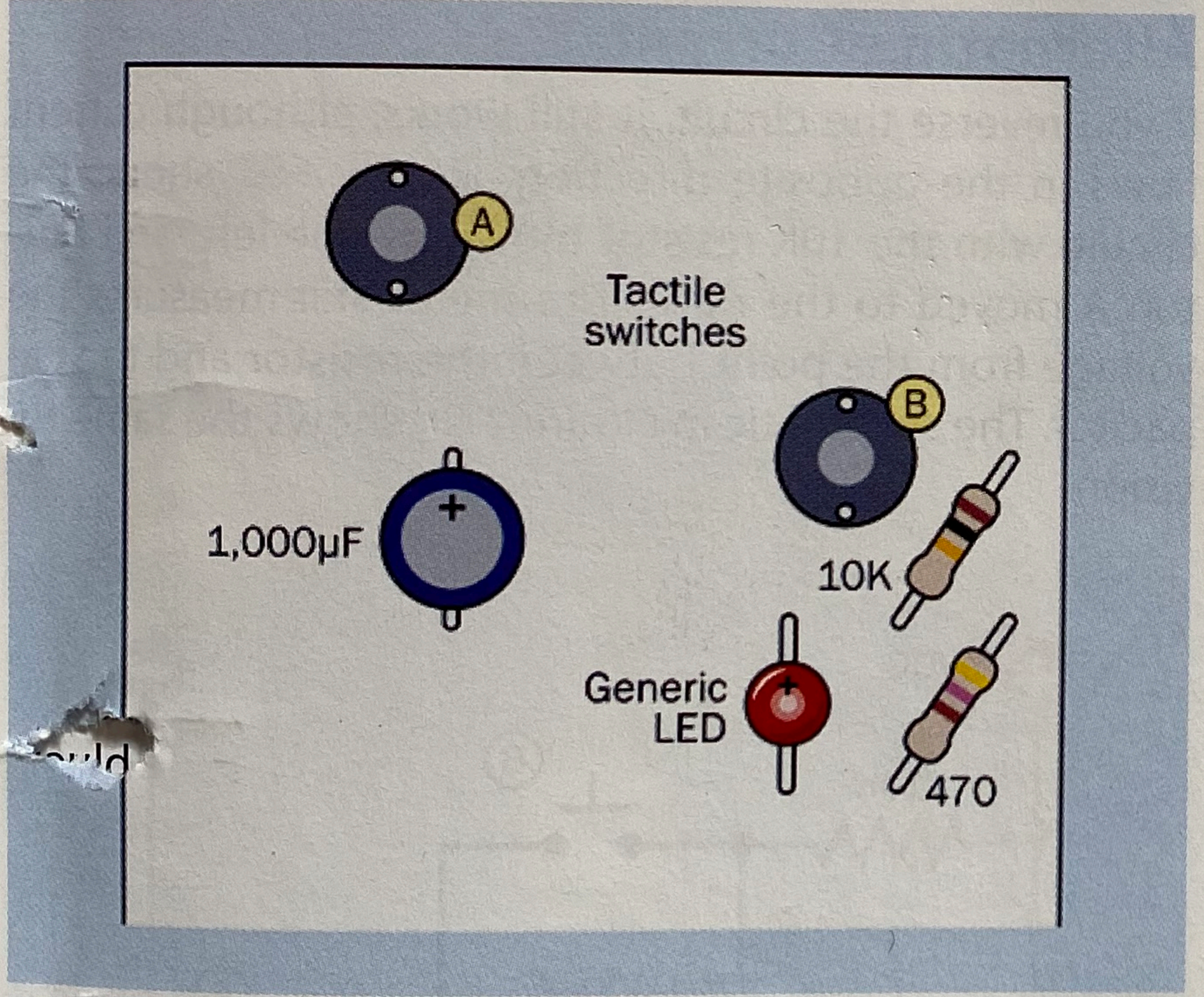

Figure 2-87 *Component values for the breadboarded circuit.*

After you assemble the circuit, first remember to press button B to discharge the capacitor. Now hold down button A, and—why did the LED just flash and slowly fade away?

Press button A again. This time, not much happens. Evidently, the capacitor has to begin in a discharged state for this to work. So, press button B to discharge it. Now press button A again, and the LED flashes again.

We know that the capacitor started with almost no positive voltage on its lower pin, because it was connected to negative ground through the 10K resistor. We also know that the capacitor started with almost no positive voltage on its upper pin, because button B shorted both sides of the capacitor together. (That was why I asked you to discharge it.)

Then you pressed button A, which applied a sudden positive pulse, and the LED lit up on the other side of the capacitor. The current through the LED had to come from somewhere, and the only explanation is that it came through the capacitor.

Displacement Current

Let's try this again, using your meter instead of the LED and its series resistor. Figure 2-89 shows the breadboard layout, while Figure 2-88 shows the schematic. Discharge the capacitor by pressing button B, and then check the reading on your meter. It should be near 0V.

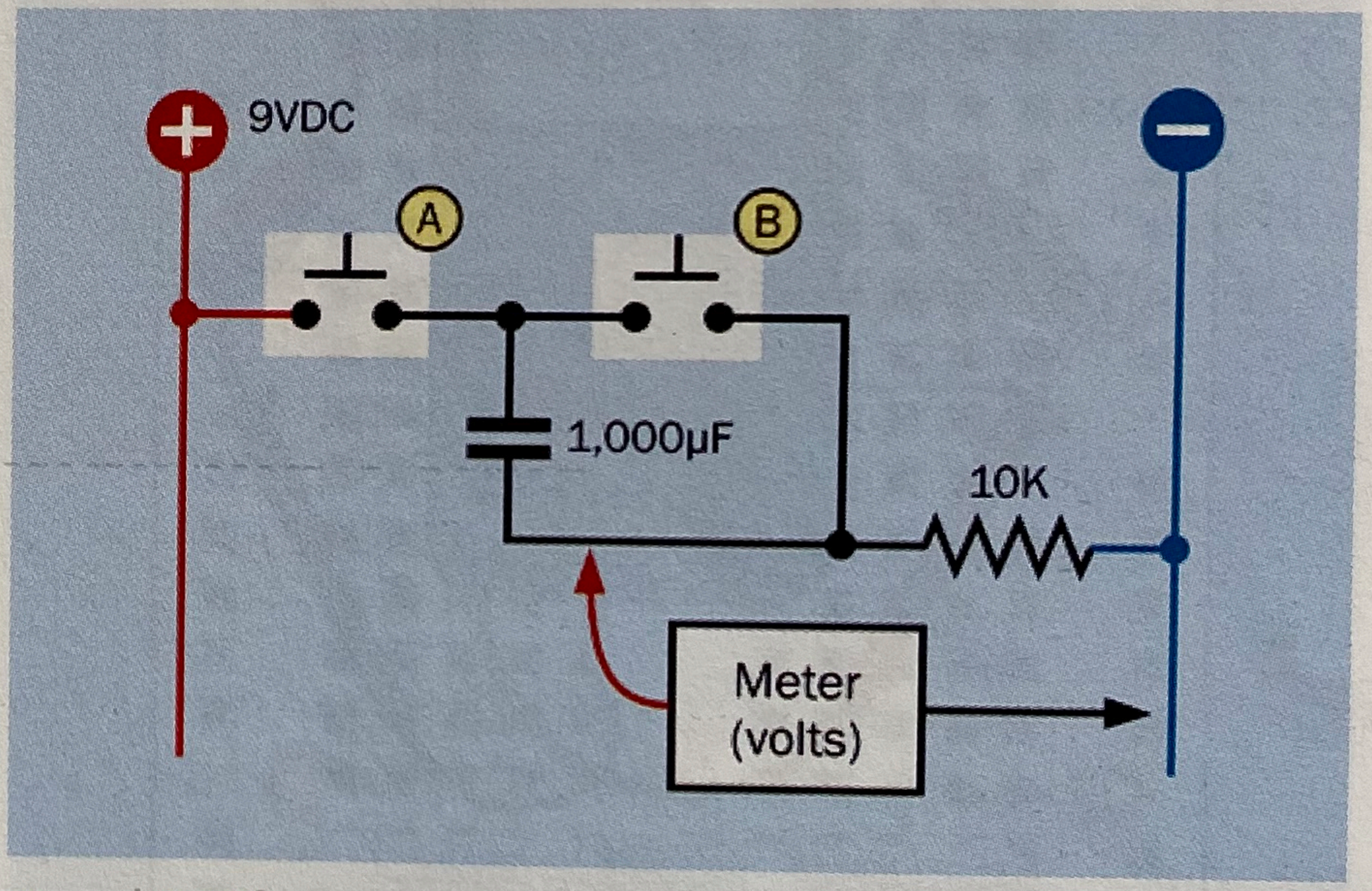

Figure 2-88 *The schematic version of the preceding breadboarded circuit.*

Watch your meter very carefully while you press button A. A digital meter does not respond very quickly, but still you will see a sudden rise in the voltage, after which the voltage gradually diminishes.

When I connected this circuit with an oscilloscope, which can measure and display very rapid changes in voltage, the trace looked look like the curve that I added at the bottom of Figure 2-89. The rise in voltage was so fast, it appeared to be instant.

The way that a capacitor allows a sudden fluctuation in voltage to pass through is well known, and is often used in electronics. But how can it happen?

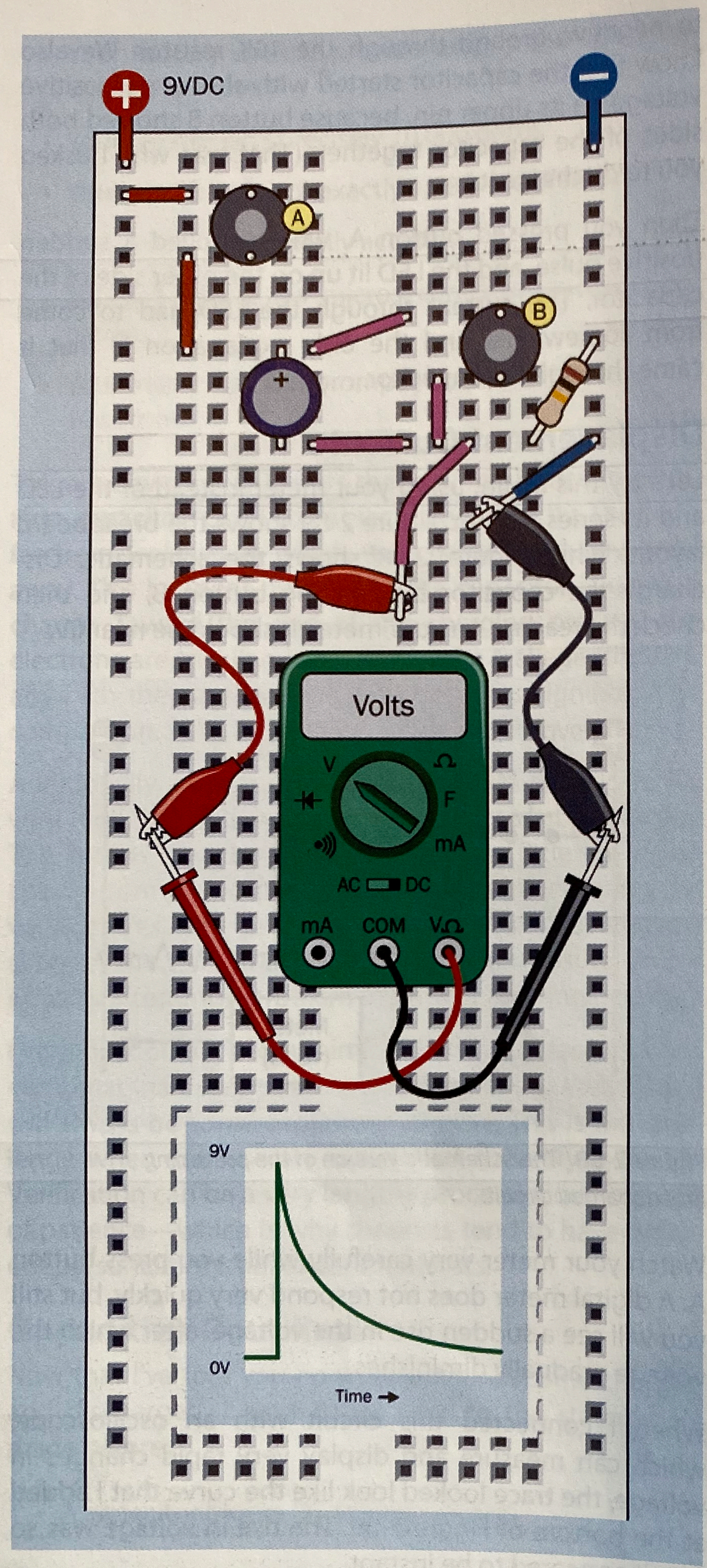

Figure 2-89 *A meter has been substituted for the LED and 470-ohm series resistor that were used in the previous version of this circuit.*

This question interested an early experimenter named James Maxwell, who felt it shouldn't happen; so he developed a theory and invented a phrase to describe what he saw. He called it *displacement current*. This conformed with some theories that he was developing at the time.

Today, there are other theories. Apparently an inrush of current creates a field effect inside the capacitor, and the field effect can induce voltage on the opposite plate. But this concept becomes complicated very quickly, and most books simply say something like, "a capacitor will block DC but will pass fluctuations in voltage."

If you substitute a smaller capacitor, you'll find that it passes a briefer pulse. Remove the meter, put the LED and its 470-ohm resistor back into the circuit, and try 100µF, 10µF, 1µF, and 0.1µF capacitors. By the end of the series, the LED barely flickers.

Alternating Current

If you reverse the circuit, it still works, although current flows in the opposite direction. Figure 2-91 shows the circuit, with the 10K resistor moved to the left, and button A moved to the right. The meter still measures the voltage from the point between the resistor and the capacitor. The schematic in Figure 2-90 shows the same revision.

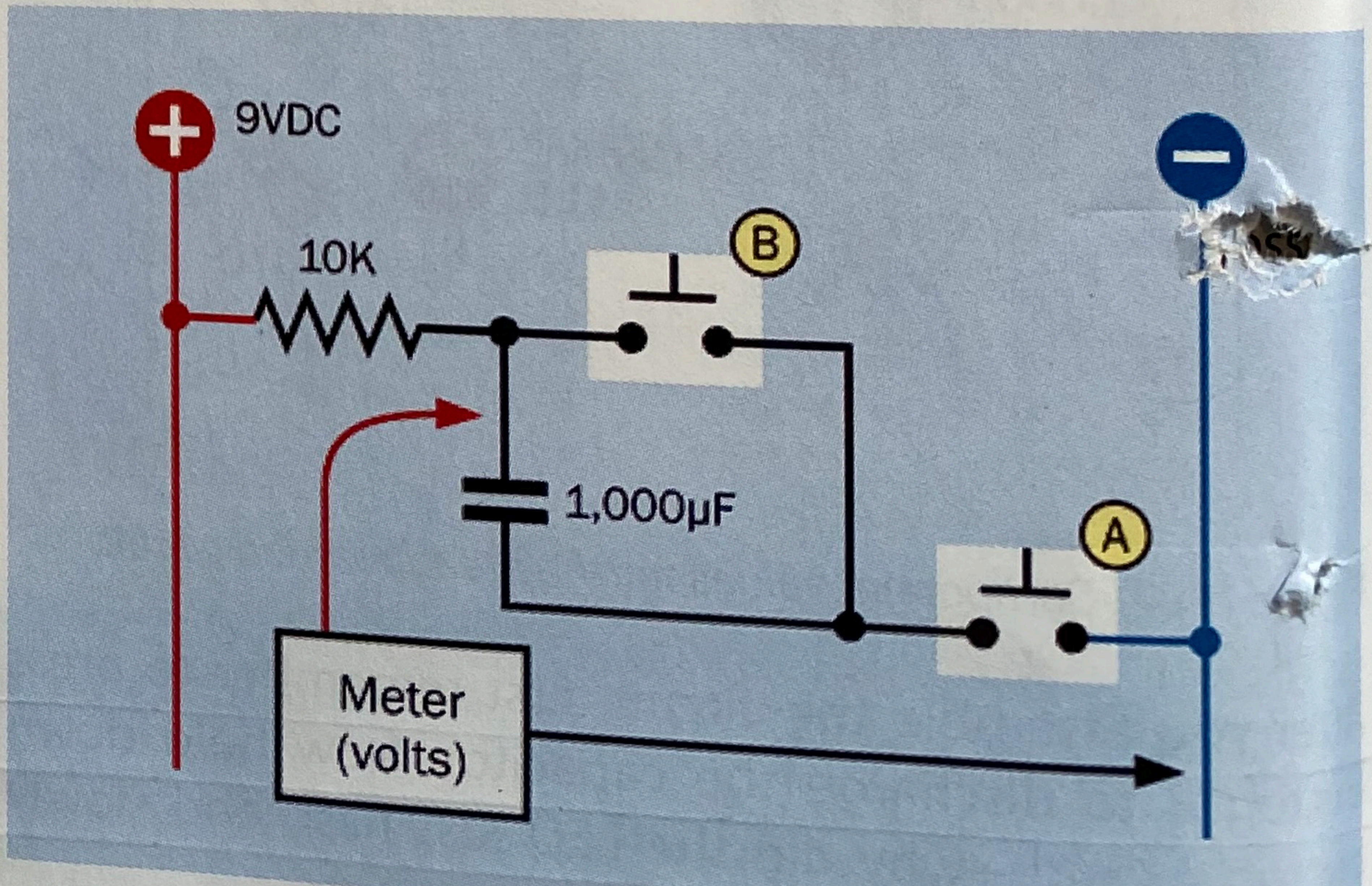

Figure 2-90 *A schematic of the next and final breadboarded circuit in this experiment.*

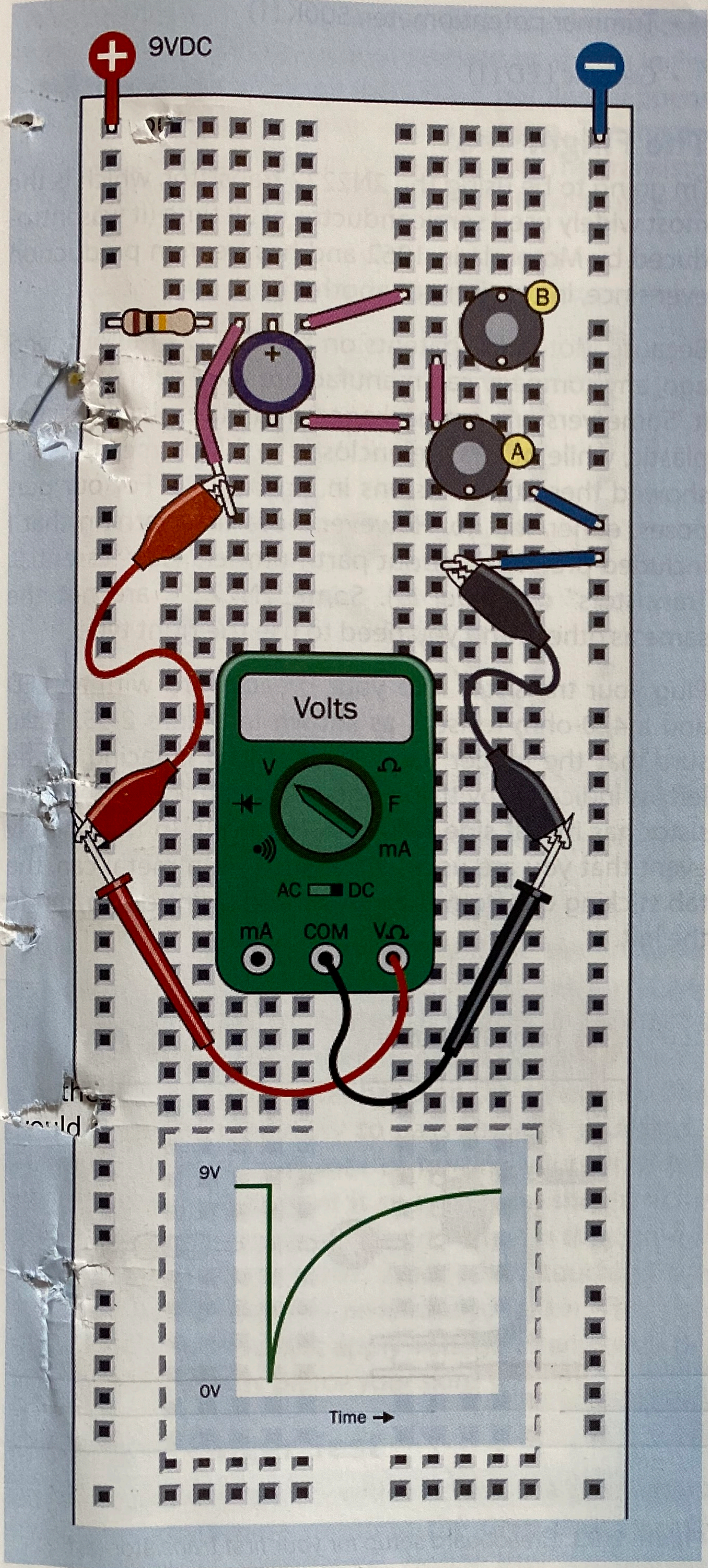

Figure 2-91 *The previous circuit has been modified, with the voltages reversed.*

After you press and release button B to discharge the capacitor, the meter measures approximately 9VDC, because the upper pin of the capacitor is connected with the positive bus through the 10K resistor. The capacitor is blocking DC, so it appears to have infinite resistance, and the positive charge has "nowhere to go." This is illustrated in Figure 2-92, which shows how the voltage between a pair of resistors increases when the resistance increases between that point and ground.

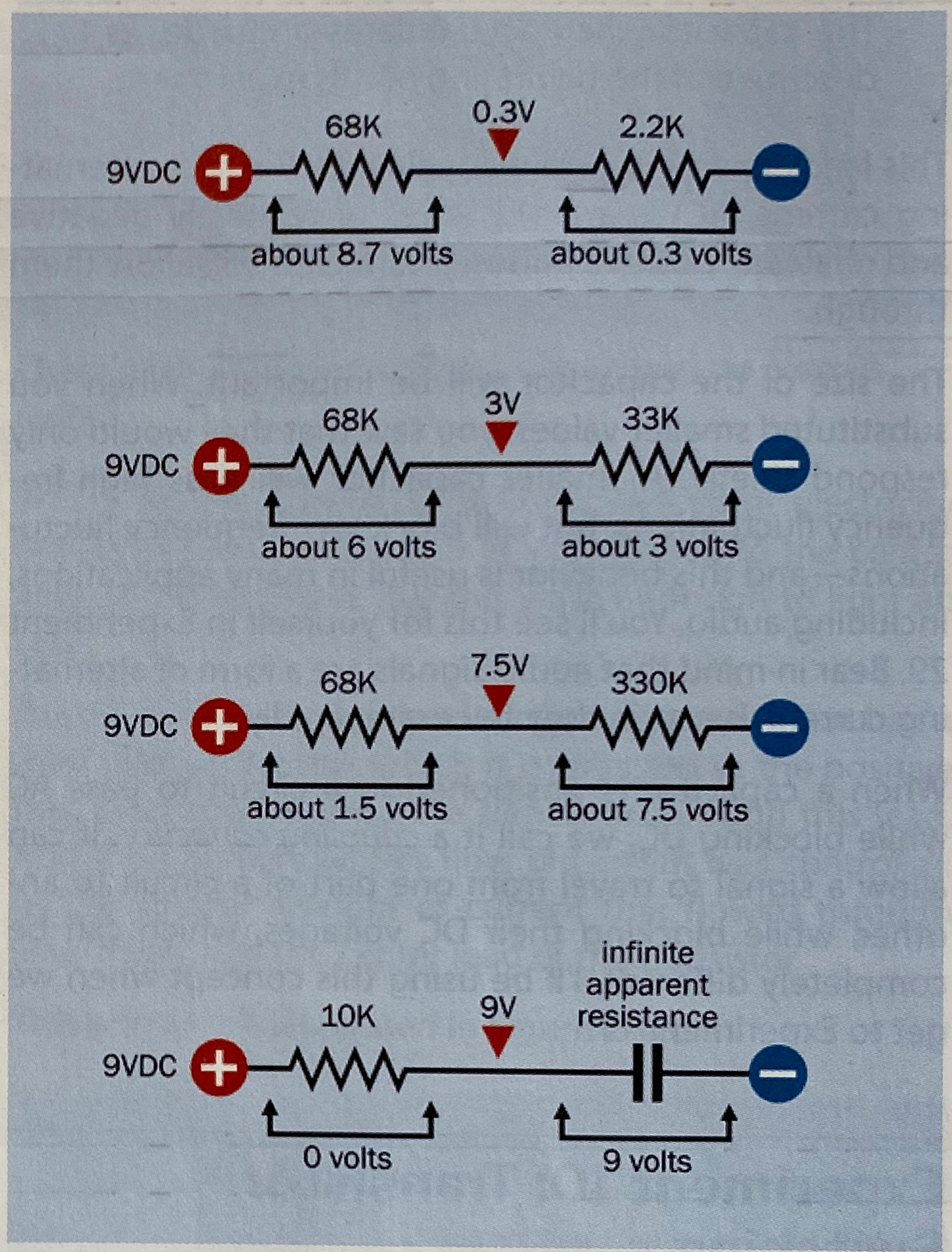

Figure 2-92 *When you have a pair of resistors in series, and the left one is connected with the power supply while the right one is connected with negative ground, the voltage between the resistors increases as the value of the righthand resistor increases. A capacitor has an almost infinite effective resistance to DC current.*

However, when you press button A in your breadboarded circuit, this creates a negative pulse. The effective resistance of the capacitor disappears momentarily as the pulse passes through, causing your meter reading to fall. Then the capacitor slowly recharges, just as it did in your very first test in this experiment.

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.

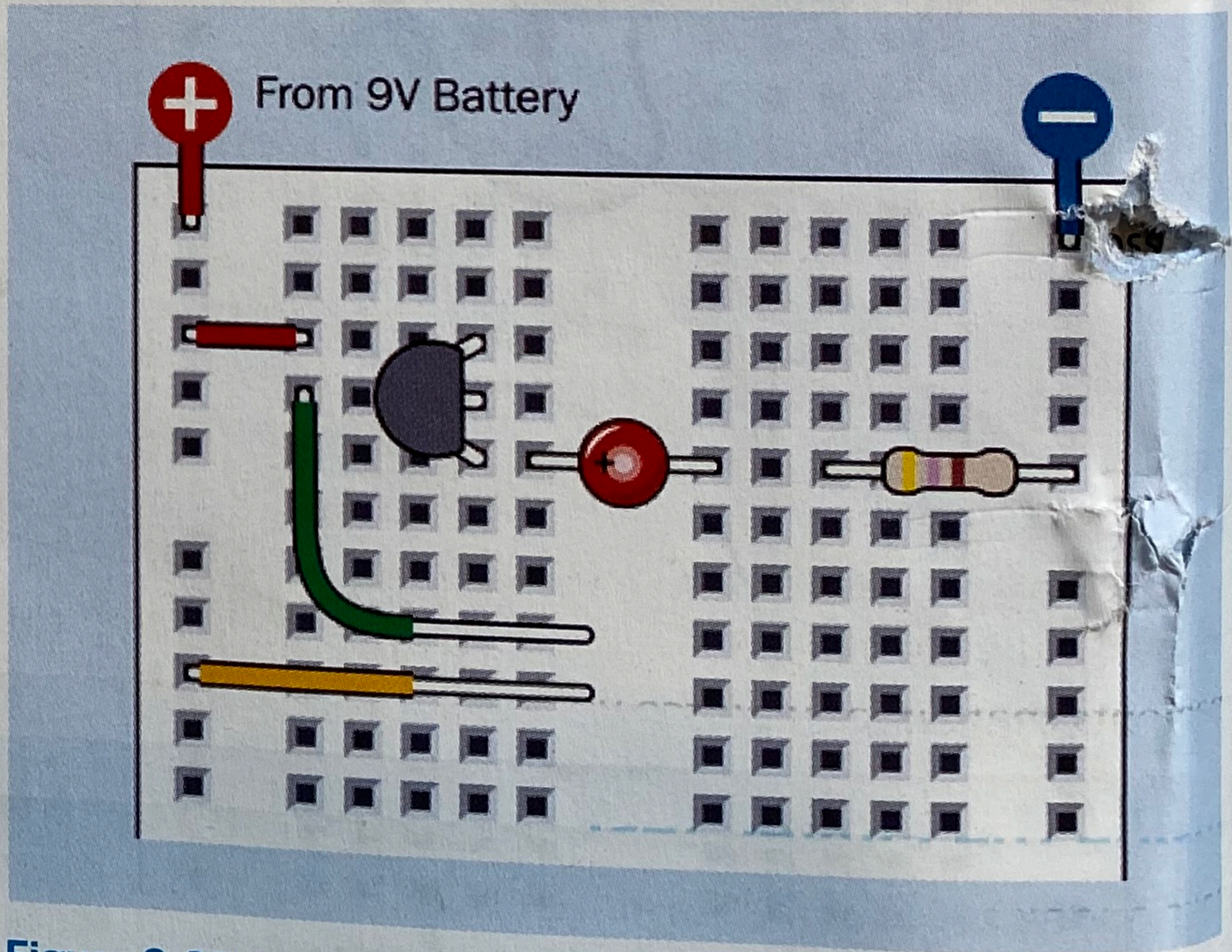

Figure 2-93 *Breadboard setup for your first transistor test.*

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 leg of each, so that they rest flat on the breadboard.