Here’s a very simple multi-part electrical experiment that our beginning students enjoy doing. Despite its outward simplicity, with this experiment students can verify for themselves a number of basic ideas about electrical circuits and resistors. It also offers some interesting side trips into related areas of technology, as well as an opportunity for students to try innovations of their own.

All that’s needed for the activity is some stiff cardboard, some Magic™ tape,1 drafting vellum,2 a few #1 pencils, a ruler, drawing compass, and an ohmmeter. The ohmmeter can typically be a multimeter found in most physics and technology labs.

To start, two elementary but all-important rules of electric circuits will be verified, namely that resistors in series add, and that for resistors in parallel their conductances (inverse of resistance) add.

The usual way of performing such verifications is for students to measure, one by one, the resistance of a number of fixed resistors. The resistors are then connected, first in series and then in parallel, and the students measure the overall resistance of each configuration. The observed results confirm the above two rules. Our experiment does essentially the same thing, but with one major difference. Here, students construct their own resistors by drawing rectangles on a smooth flat surface and filling them in with a dark graphite pencil.3 Graphite has a resistivity of about 800 microhm-cm at room temperature.4 What the students are really doing is making an elementary version of thin-film resistors, a type of resistor long employed in microwave technology, and more recently in wireless systems and small portable equipment.5

When we first started doing this experiment, our students used only pencil and paper, and they were able to construct perfectly good, easily measurable thin-film resistors. But it was nearly impossible to get uniformity of results. Paper, even stiff cardboard, is just too fibrous to produce closely repeatable results. Eventually, we discovered that Magic™ tape affixed to cardboard provides a smooth surface that easily can be written on with a pencil; the tape’s smoothness permits uniform shading. Drafting vellum also has a sufficiently smooth surface to allow reasonably repeatable resistance and is useful where larger surface areas are needed.

The gap between the ends of the rectangles is deliberately made small (~1 mm) so that later on, when the rectangles (resistors) are connected in series (by filling in these gaps) the additional graphite will have little effect on the overall series resistance. Students measure the resistance of each of these shaded rectangles using an ohmmeter.

It is desirable for the three rectangles to have nearly equal resistance; this is accomplished by what might be called a repetitive shade-and-measurability.

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**Experiment in Three Parts**

**A. Layout for resistors in series**—Attach approximately 26 cm of the 1-inch-wide tape to the cardboard. Draw three identical rectangles on the tape, positioned end-to-end as shown in Fig. 1a, each rectangle measuring 7 by 0.7 cm. These rectangles should be drawn carefully, and uniformly shaded in with a #1 pencil.

![Fig. 1](https://via.placeholder.com/150)

**Fig. 1.** Sketch of experimental layouts using six identical rectangles, each 7 by 0.7 cm. Those in (a) will be connected in series by filling in the gaps. Those in (b) will be joined in parallel by shading in the two end rectangles shown by dashed lines.
sure technique. Leave the rectangle with the lowest resistance value alone, gradually reduce the resistance of the other two rectangles by progressively darkening the shading (i.e., laying down a thicker film of graphite). By slowly and carefully shading, the authors were able to obtain resistance values typically of 175, 181, 184 kΩ, a spread of less than 6%. To ensure uniformity (and repeatability) of resistance measurements, note that ohmmeter probes usually terminate in a point. It’s best not to make contact with the graphite film directly with the point, since the graphite thickness may not be uniform throughout. Instead, make contact via an intermediate conductor such as a tiny square of aluminum cooking foil. Alternatively, simply lay the probe down broadside, perpendicular to the strip.

B. Layout for resistors in parallel—
In a manner similar to part A, and using the same dimensions, follow the layout of Fig. 1b, drawing three rectangles side-by-side on a new strip of tape. The three rectangles must fit within the 1-in width of the tape. To achieve this, the gap spacing should be about 1 mm. [The spacing here is kept narrow so that later (in part C) when the connecting end strips are drawn, the resistance of the connections will have little effect on the overall results.] The two end rectangles shown as dashed lines in the figure should not be drawn just yet, but their dimensions should be approximately 0.5 by 2.5 cm. Once again, shade in the three rectangles so that they have nearly equal resistance, as measured with the ohmmeter. The resistance values of these side-by-side rectangles do not have to be the same as those of the end-to-end rectangles of part A.

C. Final connections —
Now connect the three rectangular resistors of part A in series by filling in the two gaps between them; measure the result. The overall resistance, of course, should be three times the value of any one individual resistor. In a similar fashion, connect the three resistors of part B in parallel by drawing and shading in the two end rectangles (shown as dashed in Fig. 1b). For \( n \) equal resistances in parallel, theory predicts that the overall resistance is \( 1/n \) times that of any one resistor. Students should satisfy themselves that this fact is also verified by direct measurement.

The experiment will certainly work just as well if the resistances are not all equal, and students should not spend too much time trying to make them exactly the same. For the series connection, the total resistance will obviously still be the sum of the three individual resistances; for the parallel arrangement, the following well-known formula gives the desired result: 

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1/R_{\text{total}} = 1/R_1 + 1/R_2 + 1/R_3,
\]

where \( R_1, R_2, \) and \( R_3 \) are the three different resistances. The main reason for desiring equal resistances is that it may make the results a bit more intuitive and easier to see for students entirely unfamiliar with circuits.

Interesting Extensions

The instructor can stop with the basic experiment, but it’s possible to expand on the thin-film idea and go further. Students should be encouraged to create their own, more complex series-parallel circuits (using different resistance values) to predict, and then measure the resistive results. Having done experiments with different circuit configurations, a logical next step might be to investigate variable resistances, still based on the thin-film concept.

One way to start would be to draw a long rectangle (say 30 cm by 1/2 cm) on Magic\textsuperscript{TM} tape and fill it in uniformly. Then students can effectively vary the resistance by keeping one probe of the ohmmeter fixed at one end of the rectangle and moving the other probe slowly down the length of the strip; that is, progressively increasing the distance between the two probes.

If the rectangle has been constructed with reasonable uniformity, the resistance between probes should be directly proportional to the distance separating them. Data could be taken on measured resistance versus length, in cm, and then plotted. The result, not surprisingly, should be a straight line whose slope is the resistance per cm of length. Teachers will realize that what has actually been constructed is a form of thin-film potentiometer. Commercial potentiometers usually have the resistance element circular in shape; this configuration can also be duplicated with homemade resistors.

The most logical procedure for creating a circular resistive element is simply to draw two concentric circles of different diameters, and then shade in the area between them. Such a construction can be done easily on a piece of drafting vellum. A 5- by 5-in section serves very well, with the circular resistor drawn and shaded as in Fig. 2, leaving a small gap in the circle so that the circumferential resistance can be measured end-to-end.

Now a number of new measurements are possible. For example, students could measure total resistance (from one end) versus angle. For this, divide the circle into, say, eight segments (a segment every 45°, except for the last one, which because of the gap must be slightly smaller). Mark the segments off very lightly with a graphite pencil or a nonconducting colored pencil. Students then make measurements of resistance (from one fixed end) to each segment and use the data to plot measured resistance versus total angle. The result once again should be a plot that is reasonably linear.

An interesting variation on this, and something our students enjoy doing, is determining the value of \( \pi \) electrically. That is, instead of determining \( \pi \) in the usual sense as the ratio of two lengths (circumference to diameter), now students make the measurement based on the ratio of two thin-film resistances, one circumferential, the other radial. To do this, use the circular layout of Fig. 2,
but this time draw a radius from the circle’s center to the circumference, as shown in Fig. 3. The width of this radius bar should be the same as the width of the circumference.

Measure the resistance of the radius, and then the resistance of the circumference. The ratio of the two resistances should of course be $2\pi$, and with reasonable care and luck, a figure somewhere in the neighborhood of the true value can be obtained. Students should be encouraged not to “influence” the data so as to get the expected result. It might prove helpful however, to take the average of results from many students, in order to arrive at a more reliable value. The fun part is seeing how close students can get to $\pi$ by doing the work honestly. In general, students should be cautioned not to expect “Bureau-of-Standards” accuracy. This experiment is for education and entertainment; results within ±50% of anticipated values are perfectly fine.

Industrial Aspects

It might be worthwhile to discuss with your class some relevant ideas on thin-film resistors in general. One interesting item, for example, is the seemingly strange choice of units used in the industry, namely ohms per square. Suppose you have a thin-film resistor that measures 1 cm square. Further, suppose the resistance from one edge of the square to the opposite edge is 1 k$\Omega$. If two of these squares are placed side-by-side as in Fig. 4a, the total resistance is halved to 500 $\Omega$. However, if the resistors are repositioned to be in series, as in Fig. 4b, then the original resistance is doubled to 2000 $\Omega$.

Now suppose that a new square-shaped resistor is made (of the same material) equal in size to four of the original squares. Its overall dimensions will be 2 cm by 2 cm, but as can be seen, the resistance from one side to the other still will be 1 k$\Omega$. Think of the new (larger) square as being made up of two 500-$\Omega$ resistors in series, or two 2000-$\Omega$ resistors in parallel. What should be evident is that the resistance of a square of this material of any size will have the same value. For this reason the resistances of thin-film resistors are characterized by the descriptive term of so many “ohms per square.”

References

1. Manufactured by Minnesota Mining and Manufacturing (3M) Co. We use type 810, 1 in wide. For a list of local suppliers of 1-in wide tape, call (3M) Co. customer service at 800-364-3577. Give your zip code.

2. Drafting vellum (sometimes called tracing vellum) is available in art supply stores. One manufacturer of such vellum is Clearprint Paper Co., 1482 67th St., Emeryville, CA 94608; 800-766-7337 (in particular, their part No. 7020 PV. Stock No. 70201510).

3. The observation that graphite rubbed on paper can conduct electricity is certainly not new. An experiment similar to ours is discussed in Ref. 5. That 1996 paper, in addition to describing circuit concepts, explains how to determine graphite film resistivity. Our work, aimed especially for the beginning student, puts greater emphasis on circuit and industrial applications. The two articles complement each other.

