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Teaching the Factors Affecting Resistance Using Pencil Leads

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The aim of this paper is to provide a way of teaching the factors that affect resistance using mechanical pencil leads and the brightness of the light given out by a light bulb connected to an electrical circuit. The resistance of a conductor is directly proportional to its length (L) and inversely proportional to its cross-sectional area (A). Additionally, the resistance depends on the type of conductor. Resistance R can be thus be expressed as $R = \rho L/A$, where ρ is the resistivity of the conductor.

In Turkey, the concept of resistance is taught in the sixth grade of the primary school curriculum. The related objectives of the program are "to be able to realize that the brightness of a light bulb in an electrical circuit can change depending on the length of the conductor in the circuit, its cross-sectional area and its type through experimentation" and "to be able to conclude that the resistance of a conductor changes depending on its length, its cross-sectional area and its type." As a consequence of these two objectives, students are expected to understand what factors the resistance of a conductor depends on by observing how the brightness of the light bulb is affected by the change in the characteristics of the conductor. In this context, textbooks suggest working with copper wires having different lengths and thicknesses. While in principle this should result in slightly more or less current through the bulb, in practice the resistance of the copper or iron wires is much less than either the bulb or the contact resistance between the wires and the connectors, so the resulting changes in the bulb are imperceptible. Thus, many science teachers that we interviewed said that the brightness of the light bulb did not change when they attempted the experiments shown in the textbooks. Teachers reported that most of the students reached wrong conclusions, believing that the resistance of a conductor was not dependent on its length, cross-sectional area, or type, and they indicated that the activity was avoided in the classroom for this reason.

Copper, aluminum, or iron wires have low resistance because their resistivity is low. When the lengths of the conductors are doubled, their resistances also double. In this case, while the brightness of the light bulb is expected to diminish, it appears as if there is no change in brightness. In fact, the brightness does diminish, but our eyes cannot discern the change in brightness. The same situation occurs when the cross-sectional area or the type of the conductor is changed.

This problem can be overcome using conductors with higher resistance. For example, carbon can be used because its resistivity is approximately 1000 times that of copper or iron. Additionally, almost all students own pencils. Pencil "leads" that are a mixture of graphite and clay are very suitable for this purpose.

Activity

The materials needed for this experiment are a power

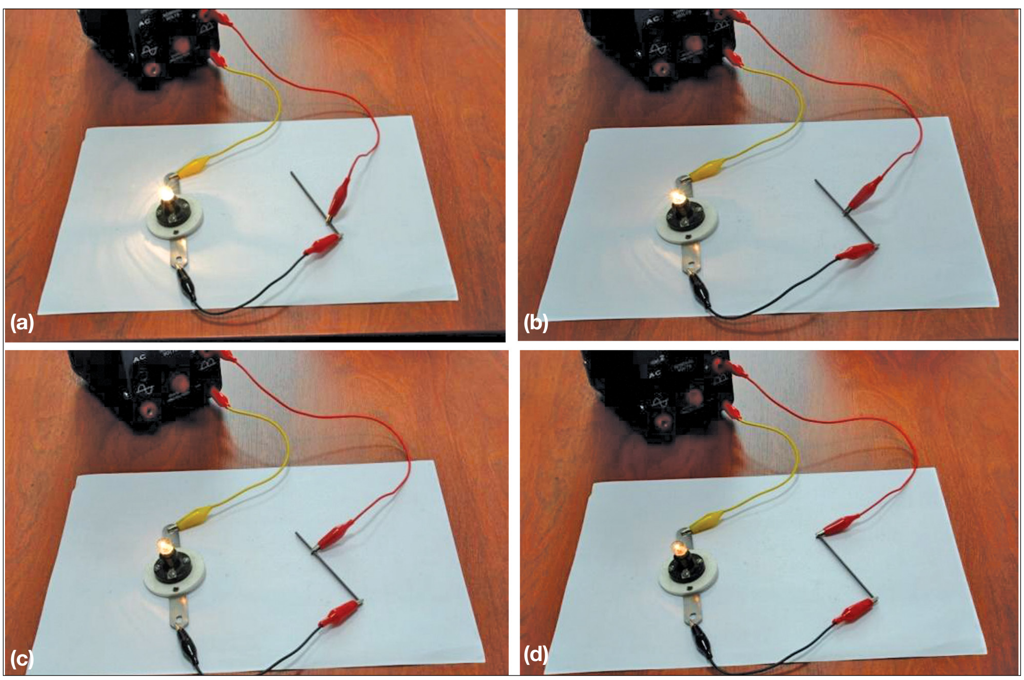

Fig. 1. Experiments demonstrating that the resistance of a conductor increases with the length of the conductor (the power supply has voltage of 4 V).

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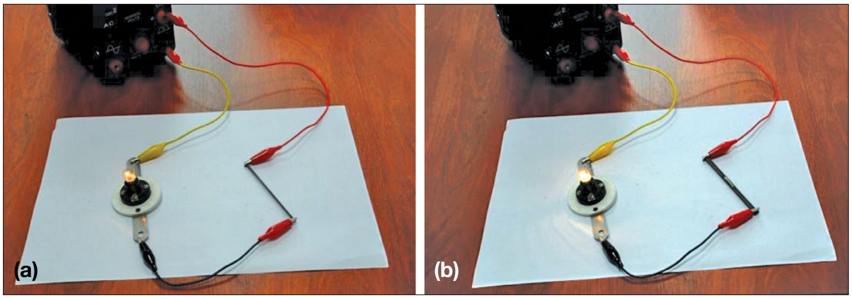

Fig. 2. Experiments demonstrating that the resistance of a conductor decreases as cross-sectional area of the conductor increases (the power supply has voltage of 4 V). (a) Single pencil lead. (b) Two pencil leads (taped together at the center).

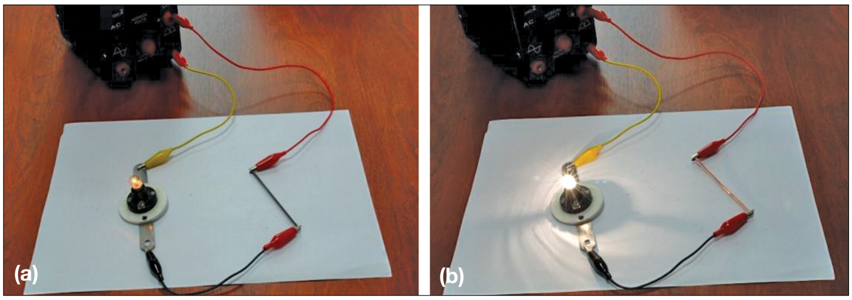

Fig. 3. Experiments demonstrating that the resistance of a conductor depends on the material of the conductor (the power supply has voltage of 4 V). (a) Pencil lead. (b) Copper wire of the same thickness and length as the pencil lead.

supply (or battery), a 2.5-V (or 1.5-V) light bulb, connection cables, three 2B mechanical pencil leads (having diameter of 2×10^{-3} m, length of 8.5×10^{-2} m, and cross-sectional area of 3.14×10^{-6} m^2), and a copper wire of the same diameter and length as the pencil lead. The experiment described in the steps below was carried out at different times with sixth-grade students (aged 12–13 years) at different schools.

To have the students discover what factors the resistance depends on, an experiment was devised to show how a change in the length of a pencil lead, and then in its diameter and type, can affect resistance and how this can change the brightness of a light bulb. Before starting the experiment, the students were taught the concept of resistance as "a material's opposition to the flow of electric current." It was explained that as resistance increased, electrical energy would decrease and, as a result, the brightness of a light bulb connected to the electrical circuit would decrease, and that the opposite would happen in reverse.

(a) Change in resistance depending on length: To demonstrate the relationship between the resistance and a conductor's length, as shown in Figs. 1(a)-(d), one end of the pencil lead was fixed with an alligator clip while another clip was used to touch the lead at different points to vary its length. At the end of this procedure, the students could see that as the length increased, the brightness of the light bulb diminished. It was explained to the students that as the length of the pencil lead increased, its resistance increased as well, and because of this the electrical energy available to the light bulb decreased, diminishing the brightness of the light bulb.

(b) Changes in resistance depending on the cross-sectional area of the conductor: To show that resistance decreases as cross-sectional area increases, a pencil and two pencil leads (of the same length) were used, as shown in Figs. 2(a) and (b). The students observed the effect of using the single pencil lead and then two pencil leads (attaching the two leads with tape in the middle) on the brightness of the bulb. The figure shows that when there were two pencil leads (i.e., when the cross-sectional area was greater), the light bulb was brighter. It was explained to the students that the brightness of the light bulb had increased because the electrical energy available to it had increased owing to the decrease in resistance.

(c) Changes in resistance depending on the type of conductor: To show how resistance depends on the type of conductor, pencil leads and copper wires having approximately the same thickness and length as the leads were used, as shown in Figs. 3(a) and (b). (Iron, aluminum, and other types of wire can also be used.) It was observed that the brightness of the light bulb was affected by the type of material providing the resistance. By the end of the experiment, the students had learned that resistance was dependent on the length, cross-sectional area, and type of the conductor by observing the brightness of the light bulb.

Discussion and recommendations

Wolf and Streckert[1] calculated the resistivity of graphite using a pencil lead. They drew a series of dark lines of different thicknesses and lengths on a piece of paper with a pencil, and then measured the resistances of the lines with an ohmmeter and measured l with a ruler (A, the thickness of the line, is estimated to be 10 μm and the width of it is measured as 0.3 cm). Similarly, Kamata and Abe[2] measured the electrical conductivity and resistance of a thick line drawn on paper with a 6B pencil using a tester made of a simple light-emitting diode.

Derman and Goykadosh[3] reported that while constructing measurable thin film resistors using paper and pencil, it was almost impossible to produce identical and repeatable results. Due to this fact, they suggested that straight lines could be drawn on Scotch® Magic Tape that can allow for uniform shading. In this way, they were able to define factors such as length and diameter that resistance depends on using an ohmmeter, and they observed an increase and decrease in the resistance by setting up series and parallel circuits. The pencil leads used in this activity can also be used in setting up series and parallel circuits. The hands-on activity described in this paper was tested with sixth-grade students and found to be useful in helping students develop a conceptual understanding of resistance. The activity might also be conducted without using a light bulb and power supply depending on the grade level and teaching objectives. The variables on which resistance depends can be observed using mechanical pencil leads and a digital multimeter by conducting measurements and making graphical drawings. Such activity can be carried out as follows.

i) One probe of a multimeter is fixed to one end of the mechanical pencil lead. The other probe is touched against the lead at various distances (e.g., 1, 2, 3, and 4 cm, and so on) from the first probe to show that resistance of the lead depends on the length of the lead. For each length, the resistance is measured with the ohmmeter. The students can see a linear relationship by drawing a graph of length versus resistance. (Better results can be obtained when mini grabber probes are used since they are more convenient and have lower resistance than normal probes.)

ii) The number of pencil leads used in parallel (one, two, three, four, and so on) can be increased to show that the resistance depends on the cross-sectional area of the leads. Measurements are conducted for each combination of leads with the ohmmeter. The students can observe the inverse proportionality by drawing a graph of cross-sectional area versus resistance.

iii) Nichrome wire that has the same cross-sectional area as the mechanical pencil leads can be used to show that the resistance depends on the type of conductor. The students read different values when they measure resistances with the ohmmeter. Nichrome wire needs to be used for this measurement. The resistance values of copper or aluminum wires are very low and nearly the same as the resistance of the ohmmeter's probes. The resistivity of nichrome wire is about 100 times those of copper and aluminum.[4] Nichrome is widely used in electric heating elements. The reason for using copper in part c of the experiment above is that copper can easily be obtained and provides better results in the observation of the brightness of the light bulb.

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Editor's Note: See also last month's "Little Gems" column, "Exploring electric circuits and resistance using pencil lead," by Chris Chiaverina, *Phys. Teach.* **52**, 570–573 (Dec. 2014) for other related classroom ideas.