INVESTIGATION

Pencil leads: 20 project ideas

From a physicist's point of view, a pencil is a cantilever with an electrically conducting central core. The lead (and the complete pencil) is an example of a composite material.

Pencils leads are electrical conductors despite the fact that they do not contain any metallic lead at all. Rather they are made from a mixture of graphite and clay.

Some modern pencils are manufactured to close tolerances and thus make ideal samples to experiment with. The discussion that follows is based on the Cumberland Pencil Company's *Derwent Graphic* range of pencils that are readily available in art shops and stationers etc (figure 1). The company have a website at www.pencils.co.uk

Figure 1. *The Derwent Graphic range of pencils.*

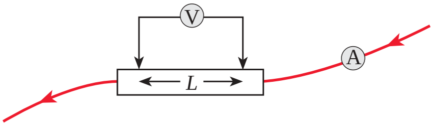

Figure 2. *Avoiding possible contact resistance at the current connections to the sample. L is the effective length of the sample.*

Some basic graphite data

Pure graphite is classed as a semi-metal and has a typical electrical resistivity of $3 \times 10^{-5}\ \Omega$ m. For comparison, copper has a resistivity of $2.2 \times 10^{-8}\ \Omega$ m and nichrome 'resistance wire' has a value of $1.1 \times 10^{-6}\ \Omega$ m. The carrier density in graphite is 3.5×10^{24} m^{-3} (compared to most metals with a value typically a factor of 10^4 larger). The temperature coefficient of resistance for graphite is –0.0005 K^{-1}, which (although of opposite sign) makes it about ten times less sensitive to temperature changes than copper.

Data on the pencils

I am indebted to Barbara Murray, the Quality Systems Manager of the Cumberland Pencil Company, for the product-specific information that follows. The pencil leads come in a range of 20 grades labelled 9H (the 'hardest' with most clay and least graphite) to 9B (the 'blackest'—or softest—with least clay and most graphite). Not all the grades have the same lead diameter: from 9H through to 2B they are 2.2 mm in diameter: the 3B, 4B and 5B are 2.8 mm; from 6B to 9B are 3.5 mm.

The 9B is approximately 25% clay to 75% graphite. This percentage of clay is increased in more or less equal steps to the 9H, which is approximately 75% clay. It is not company policy to reveal the exact percentages.

Practical considerations

Using $R = \rho l/A$ suggests that a 15 cm long pencil lead will have a resistance of the order of 1 Ω. Measuring this value to a reasonable precision will in itself provide a student with reasonable technical challenge; not only is it quite small, but there may well be a contact resistance of a similar magnitude with the rest of the measuring circuit. Four-terminal methods (so that the connections supplying the current are not also part of the potential difference measurement, see figure 2) can get round the problem of contact resistance. Alternatively, the contact resistances can be minimized by copper plating the ends of the leads. A suitable recipe for a plating solution is: 300 ml water, 60 g of copper sulphate and 15 ml of concentrated sulphuric acid. Carry out a safety assessment before using the acid —goggles, lab coats, gloves etc will be needed.

Small resistances can be measured by several

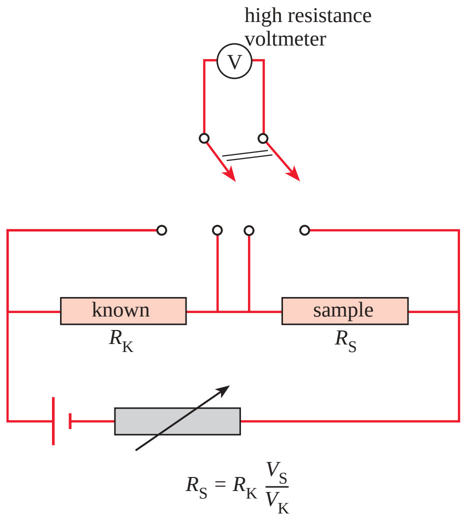

Figure 3. *Comparison of a sample with a known resistance.*

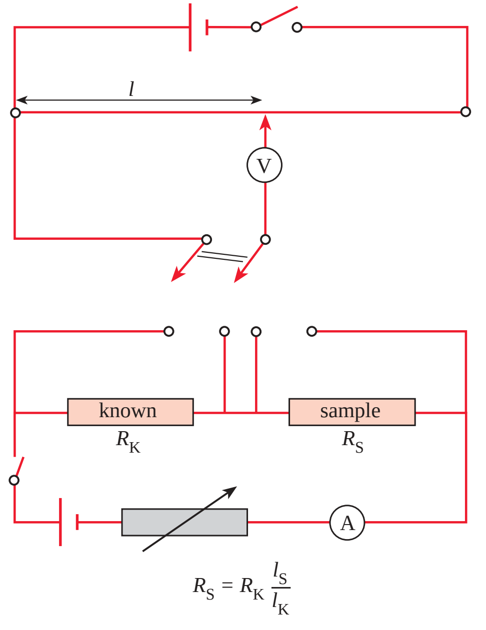

Figure 4. *Potentiometer method for comparing two resistances.*

methods, e.g. comparison (see figure 3) and null (e.g. a potentiometer, see figure 4) methods, or the more adventurous can research Kelvin's clever modification of the Wheatstone bridge [1].

The contact resistance itself could be the focus of the investigation (different contact areas, applied pressure, nature of the 'other electrode' (type of metal?), and maybe 'wetness' all being relevant), in which case the bulk resistance of pencil lead itself will need to be allowed for.

Interpolating the proportions of clay (and taking into account the changes in lead diameters) suggests that the resistance of a 15 cm long pencil lead will vary by an order of magnitude from the softest to the hardest. This in itself is a nice theoretical modelling exercise for the student.

Using two different currents and comparing the derived values of resistance provides a simple check to determine whether the current is causing enough self-heating to change the resistivity.

Besides finding effective resistivity values for the different hardnesses, the data could also be analysed in terms of $I = nAvq$ to find the drift speed v of the charge carriers.

An alternative model system?

A model system can be made by mixing iron filings with clay. Dissolve the clay to get slurry thin enough to pour easily (so called 'slip'), then the iron filings can be easily and uniformly dispersed. Conductors of various shapes can be moulded and dried. Electrodes can be put in place before 'setting'. Too much clay and you will have an insulator; thus the so-called metal–insulator transition can be investigated as the proportion of iron filings to clay is varied.

For the more ambitious?

The hardest leads or the dilutest iron filing clay composites may well exhibit some sort of magnetoresistance (the variation of resistance with an applied magnetic field). The Hall effect is another possibility worth looking for.

'Two-dimensional' conductors?

An infinite variety of differently shaped 'two-dimensional' conductors can be drawn or shaded in on graph paper. As obvious problem here is measuring the actual thickness of the graphite that has been deposited and ensuring that it is constant (width and length are obviously relatively easy to confine). Incorporating the shaded paper into a capacitor will allow an average thickness to be found.

Other questions arise. Does a drawn pencil line have the same 'electrical structure' as the solid lead from which it was drawn? Does the paper substrate provide any parallel conducting path? Another alternative is to sprinkle powdered pencil lead onto sticky paper (the sticky strip on the back of a 'stick it' label, or paper that has been sprayed with 'spray mount') or press the sticky surface into the powder and shake off any excess.

A research program or group?

There are so many ways that pencil leads can be investigated that they lend themselves to either an ongoing project as students build on the work of others from previous years, or in the same year to form a team to investigate some of the different aspects suggested, thus giving school students a flavour of how research is carried forward.

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Reference

[1] Worsnop B L and Flint H T 1957 *Advanced Practical Physics for Students* 9th edn (London: Methuen) p 540