Extended experimental investigation: Electrical conductivity of graphite

This sample is intended to inform the design of assessment instruments in the senior phase of learning. It highlights the qualities of student work and the match to the syllabus standards.

Criteria assessed

- Knowledge and conceptual understanding
- Investigative processes
- Evaluating and concluding

Assessment instrument

The response presented in this sample is in response to an assessment task.

Extended experimental investigation in the context of electricity

Task: Develop or modify an electrical circuit to explore an aspect of electric circuit behaviour.

Concepts that could be explored include:

- capacitance or inductance
- resistivity
- alternating current rectification and smoothing
- non-ohmic resistors
- performance of diodes and/or transistors.

Time: 4 weeks

Report: Present your findings in a scientific report.

Word limit: The discussion and conclusion of the report are to be no more than 1500 words.

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Instrument-specific criteria and standards

Student responses have been matched to instrument-specific criteria and standards; those which best describe the student work in this sample are shown below. For more information about the syllabus dimensions and standards descriptors, see www.qsa.qld.edu.au/1964.html#assessment.

	Standard A
Knowledge and conceptual understanding	The student work has the following characteristics: • reproduction and interpretation of complex and challenging electric circuit concepts • comparison and explanation of complex electric circuit concepts, processes and phenomena • linking and application of algorithms, concepts and theories to find solutions in complex and challenging electric circuit situations
Investigative processes	The student work has the following characteristics: • formulation of justified significant hypotheses which inform effective and efficient design, refinement and management of investigations • safe selection and adaptation of equipment, and appropriate application of technology to gather, record and process valid data • systematic analysis of primary and secondary data to identify relationships between patterns, trends, errors and anomalies
Evaluating and concluding	The student work has the following characteristics: • analysis and evaluation of complex scientific interrelationships • exploration of scenarios and possible outcomes with justification of conclusions • discriminating selection, use and presentation of scientific data and ideas to make meaning accessible to intended audiences through innovative use of range of language, diagrams, tables and graphs

Note: Colour highlights have been used in the table to emphasise the qualities that discriminate between the standards.

Student response — Standard A

The annotations show the match to the instrument-specific standards.

The electrical conductivity of graphite pencils

Introduction:

The electrical conductivity of a substance is a measure of the ease with which the valence electrons move throughout its structure, and thus is dictated by its bonding. Metallic bonding produces the greatest conductivity, as it involves a lattice of positively charged nuclei, with electrons free to move throughout the lattice (Science Daily, 2010). Thus, when an electrical charge is applied to the metal, the electrons are able to easily move through it and therefore it can be said to be a good conductor. Substances bound by covalent bonding, on the other hand, are usually poor conductors (insulators) as the electrons are tightly held within the covalent bonds.

reproduction and interpretation of complex and challenging concepts →

There are some exceptions. For example, the covalent molecular substance graphite. Graphite is a pure carbon substance, where three of its valence electrons are covalently bonded to three other carbon atoms, forming a layered structure. However, the fourth valence electron is left unbonded, and thus is able to move freely. These valence electrons allow the flow of electricity through the substance in certain directions when an electrical current is applied to graphite.

The "lead" in pencil is, contrary to its name, predominately made up of a combination of graphite and clay, with wax and other additives in small quantities. Clay, unlike graphite, is an insulator: that is it does not conduct electricity well, due to the covalent bonds holding valence electrons tightly in place. The shade of pencil is dependent on percentage of each component. Pencils range from 9H, with 41% graphite and 53% clay, to 9B, with 93% graphite and 1% clay (Everything2 Media, 2012).

Figure 1: Shades of lead pencils and percentages of carbon

discriminating selection, use and presentation of scientific data and ideas to make meaning accessible to intended audiences through innovative use of range of tables →

Hardness	9H	8H	7H	6H	5H	4H	3H	2H	H	F	HB	B	2B	3B	4B	5B	6B	7B	8B	9B
Carbon (%)	41	44	47	50	52	55	58	60	63	66	68	71	74	76	79	82	84	87	90	93
Clay (%)	53	50	47	45	42	39	36	34	31	28	26	23	20	18	15	12	10	7	5	2

Given that graphite is more conductive than clay, as the concentration of graphite increases, the conductivity should increase. The resistance of an object, a measure of the conductivity of a circuit component, can be calculated using Ohm's law, which considers electrical resistance as the ratio of the voltage applied to the current which flows through it, or the degree to which the voltage is resisted (Equation 1):

$$R = \frac{V}{I}$$

where R = resistance (Ω), V= voltage (V) and I = current (A) (Nave, 2001).

comparison and explanation of complex concepts, processes and phenomena

However, this relationship only holds true for ohmic conductors, where graphing voltage over current produces a linear trend, with the gradient related to the resistance (Refer to Figure 2). That is, the resistance of the circuit component remains constant for all voltages. This relationship does not hold, however, for non-ohmic conductor such as diodes. Diodes allow current to flow only one direction and allow no current to flow until a given voltage is reached, at which point almost infinite current is allowed (Refer to Figure 3).

Figure 2: Current v. Voltage for Ohmic Conductor

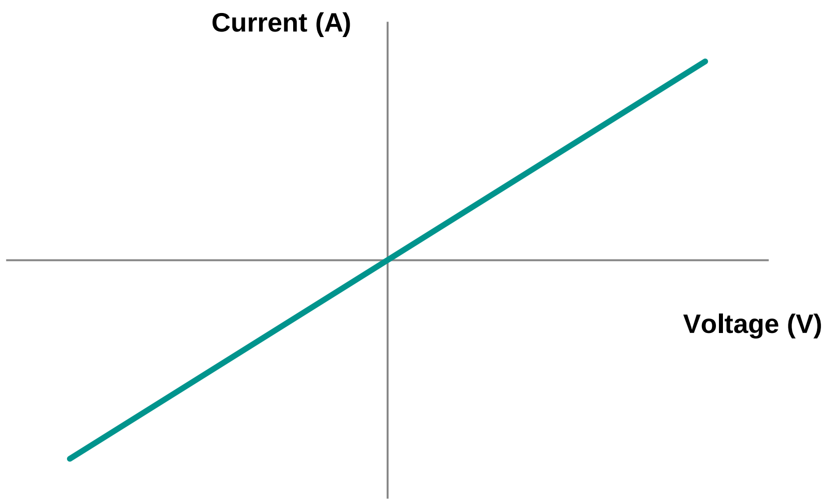
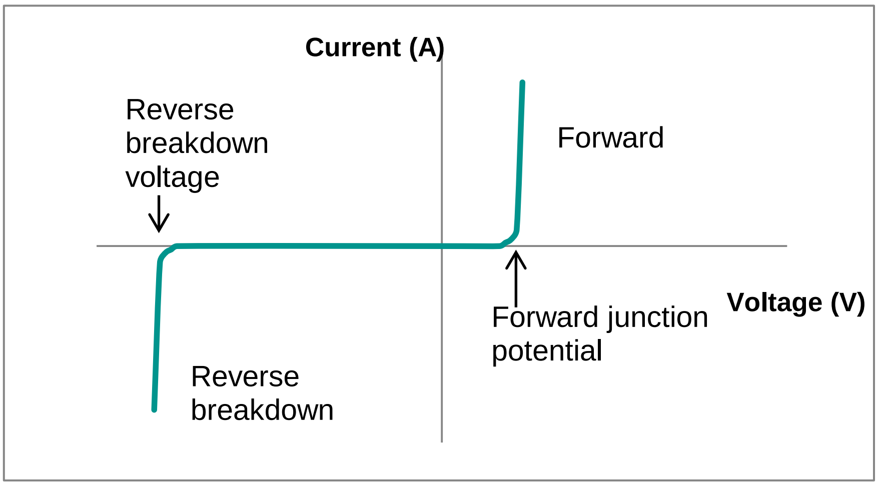
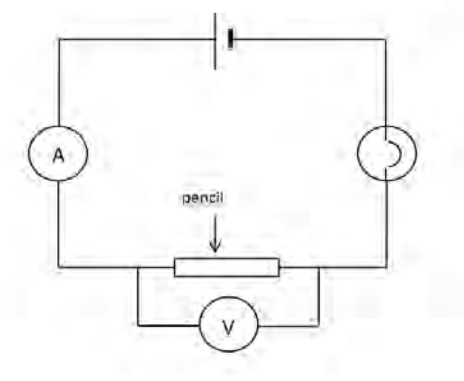


Figure 3: Current vs. Voltage for Diode



reproduction and interpretation of complex and challenging electric circuit concepts	Resistance is dependent on three factors; the cross-sectional area, length and composition of the circuit component (as discussed), summarised in equation 2 below: $$R = \frac{\rho L}{A}$$ Where ρ =resistivity of material, L = length and A = cross sectional area (Nave, 2001). A longer circuit component means that the electrical current must be exposed to the resistive material for a greater distance, and thus the overall resistance is increased. On the other hand, an increased cross-sectional area increases the space through which the current can follow, and thus it can flow more easily leading to a decline in the resistance (Henderson, 2012). The resistivity of the material is determined by the bonding and structure of the resistor material as discussed earlier.
formulation of justified significant hypothesis	In this experiment, length and cross-sectional area of the pencils tested will be kept constant. Thus, the resistance recorded should be proportional to the resistivity due to the chemical composition of the circuit component. This will allow the influence of graphite concentration on resistance to be investigated. ***Aim:*** To investigate how the percentage of graphite in pencil “lead” influences its electrical resistance. ***Hypothesis:*** It is predicted that higher concentrations of graphite will lead to lowered resistance due to graphite’s superior conductivity over clay.
selection and adaptation of equipment, and appropriate application of technology to gather, record and process valid data	***Materials:*** 2 x multimeters alligator clip wires 6 x pencils (Ranging from 2H – 8B) Light bulb Powerpack
effective and efficient design, refinement and management of investigations	Figure 4: Circuit diagram  ***Method:*** 1. A circuit was set up, as shown in Figure 4. 2. The ends of the 2H pencil were attached to alligator clips and leads in the circuit. The length of the graphite was measured using a ruler. 3. The Powerpack was set to 2V, generating the current through the circuit. 4. Multimeters were used to measure both the current and voltage, which were recorded in Table 1. 5. Steps 2-4 were repeated for voltages of 4V, 6V, 8V, 10V and 12V. 6. Steps 1-4 were repeated for HB, 2B, 4B, 6B and 8B pencils.

Results:

Table 1: Ohmic resistance of pencils

Pencil	Power Pack Voltage (V)	Current (A) $\pm$ 0.01	Recorded Voltage (V) ± 0.05
2H	2	0.07	1.6
	4	0.11	2.5
	6	0.14	3.3
	8	0.18	4.2
	10	0.21	4.9
	12	0.24	5.6
HB	2	0.09	1.0
	4	0.14	1.4
	6	0.18	1.8
	8	0.22	2.2
	10	0.26	2.5
	12	0.29	2.9
2B	2	0.11	0.6
	4	0.16	0.9
	6	0.20	1.2
	8	0.24	1.4
	10	0.28	1.6
	12	0.31	1.8
4B	2	0.12	0.4
	4	0.17	0.6
	6	0.21	0.8
	8	0.25	0.9
	10	0.28	1.0
	12	0.32	1.2
6B	2	0.12	0.4
	4	0.17	0.5
	6	0.21	0.7
	8	0.25	0.8
	10	0.29	0.9
	12	0.32	1.0
8B	2	0.12	0.2
	4	0.17	0.3
	6	0.21	0.4
	8	0.26	0.5
	10	0.29	0.5
	12	0.32	0.7

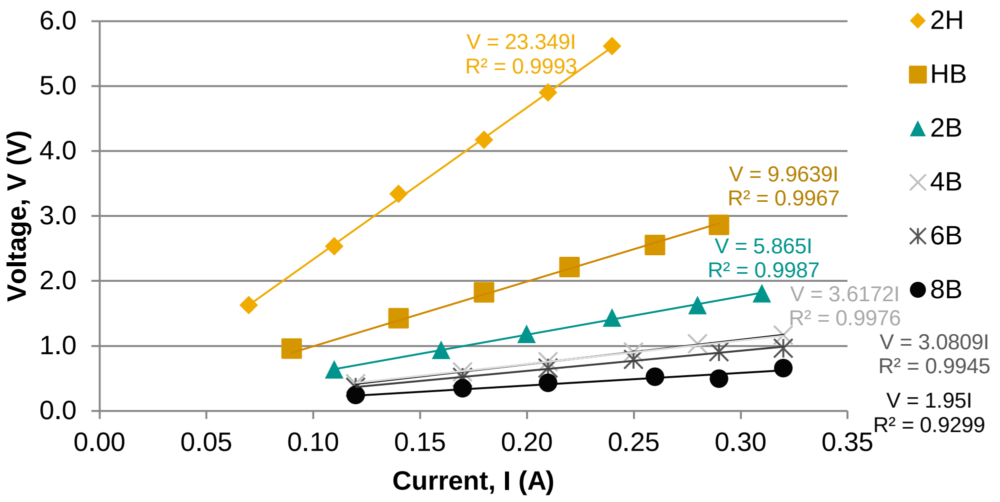
systematic analysis of primary data to identify relationships between patterns and errors

selection and adaptation of equipment, and appropriate application of technology to record and process valid data

Discussion:

In order to compare the resistance of various pencils, the nature of this resistance, ohmic or otherwise, was first tested by graphing the voltage over current (Refer to Figure 5). The R^2 values of the trend lines, which were close to 1, confirm that the pencils' resistance is linear. As the graphs are linear, they can be said to be ohmic resistors. It was also noted that the trends became less accurate, indicated by lowered R^2 values, as the resistance declined. This is because as the voltages and currents recorded became smaller, the uncertainty involved in the experiment became more influential, resulting in less accurate trends.

Figure 5: Ohmic resistance of pencils

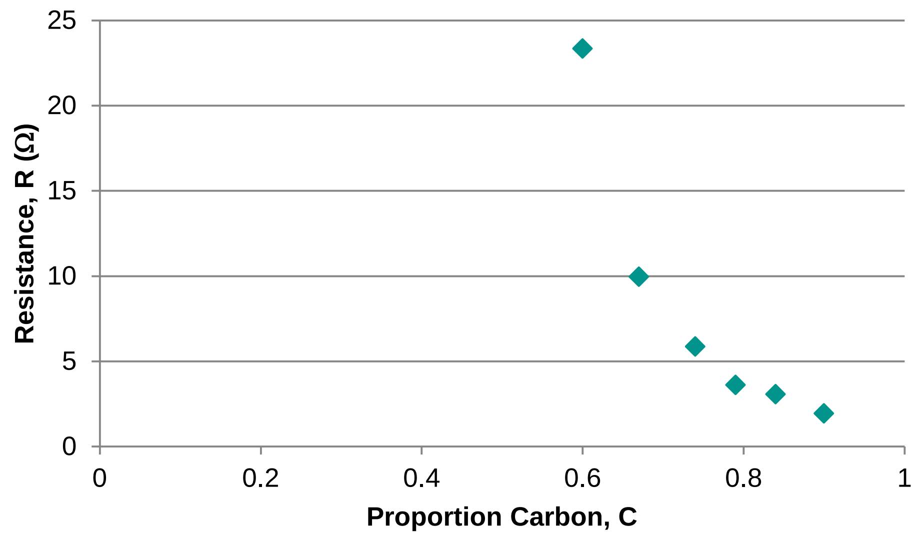


The equations for the linear trend lines were ascertained, with the gradient denoting the resistance of the pencil. These trend lines were plotted with a set intercept at the origin given that theoretically when there is no current, there cannot be voltage. As all pencils were ohmic resistors, it was then possible to analyse the influence of carbon percentage by plotting this against the gradient resistances (Refer to Table 2 and Figure 6).

Table 2: Resistance compared to carbon concentration

Pencil	***Carbon (%)***	***Resistance (Ω)***
2H	60	23.3
HB	68	10.0
2B	74	5.9
4B	79	3.6
6B	84	3.1
8B	90	2.0

Figure 6: Effect of carbon concentration on resistance

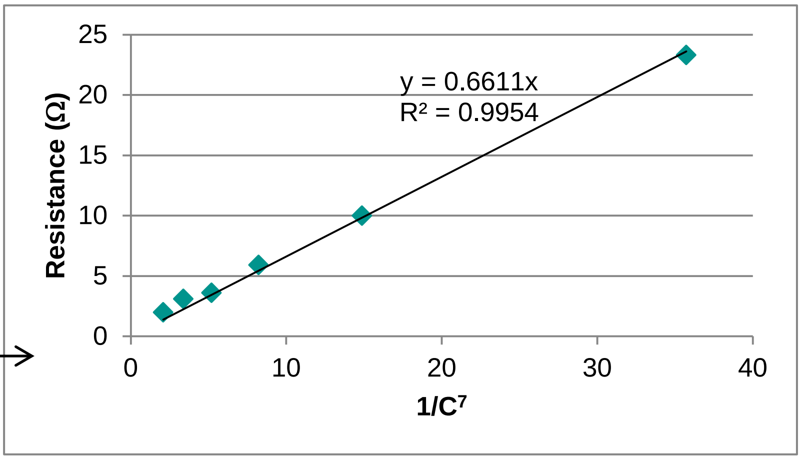


The relationship between the resistance and carbon proportion was expected to be a decreasing function, as carbon is a more effective conductor than clay, given the assumption that clay acts as an insulator. Thus an increase in carbon would lead to a decrease in resistance. Given this relationship, it would be expected that as the concentration of carbon approached zero, the resistance would approach infinity. Similarly, it was expected that as the percentage of carbon increased, the resistance would approach zero, levelling out at the resistance of pure graphite. Thus, it was expected that the model would most closely model an inverse function, $R = \frac{k}{C^n}$ where C is the carbon proportion. This trend was observed, with the graph representing what appeared to be an inverse function, and thus graphs were plotted for $R = \frac{1}{C^n}$, with n starting at one and then increasing in order to find which graph produced the most linear trend.

systematic analysis of primary data to identify relationships between patterns

From this, it was found that $R = \frac{1}{C^7}$ produced the most linear trend, with an R^2 of 0.9954 showing the closest correlation between the data and a linear trend (refer to Graph 5). From this, the coefficient of proportionality, k could be found, represented by the gradient of the linear trend. Thus, the trend that best fits the data is given by $R = \frac{0.661}{C^7}$ (refer to Figure 7).

Figure 7: Testing inverse trend



discriminating selection, use and presentation of scientific data and ideas to make meaning accessible to intended audiences through innovative use of graphs

analysis and evaluation of complex scientific interrelationships discriminating selection, use and presentation of scientific data and ideas to make meaning accessible to intended audiences through innovative use of language exploration of scenarios and possible outcomes with justification of recommendations	The value of the power, 7, indicates the rate at which the function approaches the asymptote. This model is only valid for proportions of carbon greater than zero and less than or equal to one. This is because when carbon proportion is zero (i.e. pure clay); the resistance predicted by the model cannot be calculated (division by zero). This is in keeping with the theoretical trend in which resistance should approach infinity as the proportion of carbon approaches zero. Similarly, the model is not valid for proportions of carbon greater than one, as by definition this is impossible. It is expected that at this point, the resistance of pure graphite in this experiment is $0.42 \pm 0.25\Omega$ (Refer to Appendix: Figure 9). In comparison, the resistance of pure graphite predicted by the trend line is given by the constant of proportionality, 0.66Ω, a difference of 57% (Refer to Appendix, Figure 10 and 11). This error falls within the range of uncertainty of the expected resistance calculation. However, the difference in these predictions can also be attributed to a number of other factors. Firstly, published values for the resistivity of graphite varied greatly depending on the source accessed. Thus, the accuracy of the resistivity used is poor, and thereby the resistance calculated is equally inaccurate. As a result, the prediction made is inconclusive, and the difference in the two values could equally be due to an inaccurate resistivity being used as it would be due to inaccuracies in the trend plotted. That said, it is also possible that resistance may have existed in other components of the circuits, such as the light bulb, increasing the overall resistance recorded and contributing to the difference. Thirdly, the composition and distribution of graphite and clay within the pencil could not be ascertained or controlled. Ideally, the distribution would be consistent, with the carbon spread evenly throughout the pencil. However, it is possible that this was not the case and that in some areas, there was a concentration of clay while in others there was a concentration of graphite. This means that in some instances, the resistance of almost pure clay would have increased the resistance recorded, and would have therefore contributed to increased resistance overall. In the experiment, one of the major limitations was the use of a power pack, where the direct current produced resembled an absolute value sine waveform. This meant that the voltage being produced was variable, around the given (or mean) value rather than a constant voltage produced. This led to variation in the voltage recorded, and thus, despite using apparatus with the capacity to measure voltage within millivolts, voltage could only be accurately recorded to 0.1V. This could be improved by utilising batteries, which provide a steady voltage, to provide the voltage output and thus to give more accurate recordings for voltage. A second error was in the control of the length of the pencil. As discussed in the introduction, the length of the resistor influences its resistance, and this was a variable that was intended to be controlled. However, this was not done particularly accurately, with pencils varying by as much as 0.5cm, or approximately 3%, in length when being tested, due to the inaccuracy due to the sharpening of pencils. This undermines the accuracy of the findings. Fortunately, since the same brand of pencil was used throughout, the cross-sectional area was consistent. It is possible to use the cross-sectional area and length of each pencil and using this to calculate the resistivity (see Appendix: Figure 8) in order to more accurately analyse the trend under investigation. One extension of the experiment would be to test pencils with great concentrations of clay (i.e. 8H – 2H) in order to provide a more comprehensive investigation of the conductive properties of lead. This would also allow greater experimentation into the approach to infinite resistance, as theoretically predicted. It would also be interesting to test whether this relationship holds for other molecular lattice structures, such as silicon, in order to generalise this relationship to the bonding structure present.

justification of conclusions →	***Conclusion:*** When an electric current was applied to pencils of varying hardness, it was found that as proportion of graphite increases, resistance declines in keeping with the equation: $R = \frac{0.661}{C^7}$. This supports the hypothesis that, due to carbon being more effective conductor than clay, resistance will decrease with the percentage of graphite.

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linking and application of algorithms to find solutions in complex and challenging electrical situations

Appendix:

Figure 8: Resistivity calculation (HB pencil)

$$R = \frac{\rho L}{A}$$

$$\rho = \frac{RA}{L}$$

When $R = 10.0\Omega$, $L = 17\ cm = 0.17\text{m}$, $A = \pi r^2 = \pi \times 0.001^2 = 3.14 \times 10^{-6}\text{m}^2$

$$\rho = \frac{10.0 \times 3.14 \times 10^{-6}}{0.17}$$

$$\rho = \frac{10.0 \times 3.14 \times 10^{-6}}{0.17}$$

$$\rho = 1.85 \times 10^{-4}\ \Omega\text{m}$$

Figure 9: Resistance of 100% Graphite

$$R = \frac{\rho L}{A}$$

When $\rho = 7.84 \times 10^{-6}\ \Omega\text{m}$ (Belgrave, 2004)

$$L = 16.7\ cm = 0.167 \mp 0.0005m = 0.167m \mp 0.3\%\ ,$$

$$R = 0.001 \mp 0.0003m = 0.001 \mp 30\%$$

$$A = \pi r^2 = \pi \times 0.001^2 = 3.14 \times 10^{-6} \mp 60\%\text{m}^2,$$

$$R = \frac{7.84 \times 10^{-6} \times 0.167}{3.14 \times 10^{-6}} \mp (0.3\% + 60\%)$$

$$R = 0.42 \mp 0.25\ \Omega$$

Figure 10: Resistance of 100% Graphite (Trend line)

$$R = \frac{0.661}{C^7}$$

When $C = 1$,

$$R = \frac{0.661}{1^7}$$

$$R = 0.661\ \Omega$$

Figure 11: Resistance of 100% Graphite (Trend line)

$$\%\ error = \frac{|theoretical - trendline|}{theorectical} \times 100\%$$

$$\%\ error = \frac{|0.42 - 0.661|}{0.42} \times 100\%$$

$$\%\ error = \frac{0.241}{0.42} \times 100\%$$

$$\%\ error = 57\%$$

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