TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

IB STANDARD LEVEL PHYSICS EXTENDED ESSAY

FACTORS AFFECTING THE SENSITIVITY OF THE WHEATSTONE BRIDGE IN ITS PURPOSE FOR RESISTANCE MEASUREMENT

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1. ABSTRACT

The reason for me to pick Wheatstone bridge as my subject is that it is a perfect example of electrical complexity that has many issues for many factors that have affected the flow of electricity (or have been affected from it). It is rich in topics, and I have thought that it would be a pleasure for me to do some research about it, and then present my extended essay. The part that bothered me about the measurements with the Wheatstone bridge was that, does it give precise results after it has just been balanced, or is it necessary to fulfill some conditions. For extremely precise results, the temperature must have been constant, to reduce the thermo-electric effect and keep the resistances constant. The temperature was not a problem, after it has been kept constant, but there is something more important about the resistance ratios. The current that is applied to the circuit must be suitable for the circuit, and to get the most precise results, electrical leakage that can result from the inductance or capacitance should be kept as minimum. The resistance to be measured and the one to be adjusted would be the only variable resistances, and the other ones should be kept in a constant ratio. In this experiment, they were kept to a constant ratio of 1 in order to have a wide range of measurement.
(Word Count: 230)

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2. INTRODUCTION

2.1. Aim of the Project

Aim of this project is to investigate the relation between the sensitivity of the Wheatstone bridge and bridge's resistances.

2.2. Background Research

Since the Wheatstone bridge was invented by Samuel Hunter Christie and later improved by Charles Wheatstone, the scientists used it to measure resistances (capacitance and inductance when functioning in alternating current too). It consists of the most basic electrical components, just four resistors and a galvanometer. Throughout the 19^{th} century, it helped some of the industrial improvements, for the precise measurement of the resistances to be used in electrical devices. At first, the galvanometers were not portable and too heavy to carry. However, D'Arsonval's new design of the galvanometer helped the improvements in the area of measurement. Portable ammeters, ohmmeters and voltmeter were produced; and then it was realized that they needed a shunt resistance to operate. This was causing an ignorable error in the measurement; however a Wheatstone bridge was still necessary for the precise measurements of the resistances. The error could be calculated and corrected, by knowing the value of the shunt resistance, but even that was not enough; so the Wheatstone bridge did not lose its popularity until the 20^{th} century.

Even if the precise measurement is possible with a Wheatstone bridge, there are conditions to be fulfilled when using it. The operation principle of the bridge is explained below:

2.3. Principles of the Wheatstone Bridge

In a bridge circuit, the current is splitted into two different paths as it enters the bridge, later combining at a single junction into the initial current. Bridge structures are used in electric circuits for a variety of purposes, with the help of little adjustments. In direct current, a bridge can be used to measure resistance, if four resistances are connected to the bridge in parallel. This bridge is known as the Wheatstone bridge and it consists of four resistors connected in parallel as pairs, with a galvanometer connected to the middle of the resistor on each path.

The Wheatstone bridge may be used to measure resistances to a high precision, but it also has another advantage as a measurement method. The Wheatstone bridge lacks the shunt resistance that a practical ohmmeter has, therefore being able to measure more precisely than an ohmmeter. A theoretical ohmmeter has a shunt resistance infinitely small; however a practical resistor would have a finite resistance therefore bypassing some of the current, leading to inconsistent results. Although a galvanometer is used to measure the current in the central arm of the Wheatstone Bridge, and its inner resistance may affect the outcome of the measurement, the deviation is often ignored. However the Wheatstone bridge can also be used to measure the inner resistance of the galvanometer, therefore letting the scientists correct the outcome of the measurement.

The principle for the Wheatstone bridge is quite simple. The system consists of four resistances paired parallel, with a galvanometer connected between the paired resistances to control if there is electrical current passing from it, but how can it be used to measure a resistance? According to Ohm's Law, deriving its name from Georg Ohm, the resistance is directly proportional with the voltage in a circuit, and inversely proportional with the current, found by dividing voltage by the electrical current.

$V = IR$

Therefore, the electrical current passing from a wire will decrease, if the resistance of that wire is increased. In this situation, the electrical current would be distributed inversely proportional to the total resistance in each branch of the circuit. The diagram for the Wheatstone bridge is shown below:

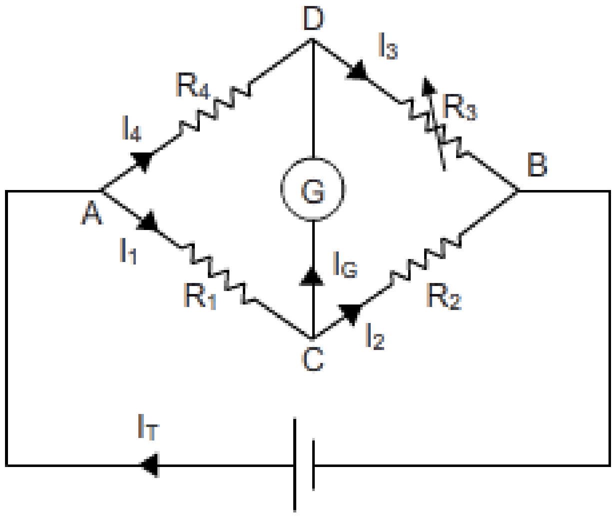


Figure 1: Wheatstone bridge circuit

It is not possible to calculate the potential difference between the terminals of the galvanometer via Ohm's Law. Therefore, we need to apply Kirchhoff's voltage and current rules in order to find an equation for the Wheatstone bridge. According to the Kirchhoff's current rule, the sum of the currents heading to a junction is equal to the sum of the currents leaving it. Therefore, according to Figure 1:

$I_4 + I_G = I_3$

$I_1 = I_G + I_2$

We know that the current flowing through the galvanometer is zero, so $I_4 = I_3\ and\ I_1 = I_2$.

If we apply the voltage rule on the junctions C and D, we would obtain:

$I_3R_3 - I_2R_2 + I_GR_G = 0; and$

$I_GR_G - I_4R_4 + I_1R_1 += 0$

Since the current passing through the galvanometer is zero, we would obtain the following equations:

$I_2R_2 = I_3R_3; and$

$I_1R_1 = I_4R_4$

If we divide each side, the equation would take the following form:

$$\frac{I_2R_2}{I_1R_1}=\frac{I_3R_3}{I_4R_4}; since\ I_4=I_3\ and\ I_1=I_2:$$

$$\frac{R_2}{R_1}=\frac{R_3}{R_4}; R_1\times R_3=R_2\times R_4$$

Therefore, the basic principle of the bridge is that if $R_1\times R_3=R_2\times R_4$, the potential difference between C and D would be zero, so there would be no current passing from the galvanometer, and the bridge is balanced. For instance (in Figure 1), if we are to find the resistance R_4, the equation can be rewritten as:

$$R_4=R_3\times\frac{R_1}{R_2}$$

in order to express the equations in terms of the adjustable resistances (which are adjustable through the rheostat). This shows that:

- If the ratio $\frac{R_1}{R_2}$ is excessively greater than (for example 10 or 100), resistances much higher than R_3 can be measured.
- If the ratio $\frac{R_1}{R_2}$ is excessively lower than (for example 0.1 or 0.01), resistances much lower than R_3 can be measured.
- The bridge can also be operated to measure by preserving the ratios of $\frac{R_3}{R_2}$ and adjusting only R_1 to stabilize the bridge.

2.4. The Galvanometer

D'Arsonval's galvanometer, invented by Jacques-Arsène d'Arsonval in 1882 consists of a pointer, attached to a coil of wire pivoting freely in the magnetic field of a permanent magnet. The electrical current flowing through the coil causes magnetic induction which exerts a torque on the pointer. As a result, the pointer moves in two directions on the scale, directly proportional to the current passing through the coil. The scale is calibrated to give a realistic result and to return the pointer to its initial position when no current is present, a spring is added to the system.

With D'Arsonval's and Weston's, galvanometers became portable to be used anywhere independent from the earth's magnetic field allowing sensitive and precise measurements. Ohm's law was formed consequently with the improvements in the galvanometer design.

D'Arsonval's galvanometer can be modified to measure both the potential difference and the electrical current, with the usage of a resistor.

2.5. Basic properties of the bridge

A Wheatstone bridge can measure resistances in the range between 10 ohms and 10000 naturally. In a standard experiment, the outcome would be accurate up to 99.9% even the internal resistances of the battery and the galvanometer are ignored.

"The components of the bridge, sometimes including the battery and the detector, may be assembled as a unit for convenience. The bridge resistance should be of "Manganin" for precise work on account of its low temperature coefficient of resistance and low thermoelectric e.m.f. to copper, and should be substantially free from inductance and capacitance."[1]

In a Wheatstone bridge, lower resistances are much more difficult to measure accurately. The reason is:

If the resistance to be measured is very low, the potential difference across the resistance is also low unless the current the current is large. Considering thermo-electric electromotive forces, the situation leads to a point where potential difference across the galvanometer is thoroughly manipulated by the thermo-electric effect instead of the potential difference resulting from the stabilization of the bridge. Since the resistance that is to be measured is very small, the potential difference created is also to be small. For example, a resistance of 0.001 ohm, a current of 0.1 A would only produce a potential difference of 0.1 mV across the resistance. To balance the bridge, only a small fraction of this is required. In order to have an accurate result, it is necessary for the adjustable resistance to endure very high currents and the unknown resistance be close enough to this resistance.

If the resistances to be measured are high, the potential difference applied to the bridge should be increased, while controlling the temperature of the resistance coils. If the system overheats, than the resistance would increase and the current flowing through it would decrease. Therefore the sensitivity is decreased. Insulation must be done thoroughly in order to prevent leakage currents. If it is not sufficient enough, the measurement would result in more than an ignorable error. Of course, this must be taken into consideration when measuring resistances more than 1000 ohms. Otherwise, it is not necessary to increase the voltage.

2.6. Medium Effect

There are medium-related factors affecting the sensitivity of the Wheatstone bridge. These are generally about extra resistances or temperature effect, which may cause a great deal in the outcome of a measurement (done with a Wheatstone bridge).

[1] Principles of Electrical Measurements.- H. Buckingham

- The resistance of the connecting leads may increase the resistance of a bridge in each arm. If the resistances of each arm are not close enough, this may cause mostly 1% deviation in the results.
- Another effect of the medium is the thermo-electric change. A 1°C change in temperature can affect the resistance of a conductor in the ratio of 0.01%, if a 1V voltage source is used.
- Temperature coefficient of a resistance can affect the outcome of the measurement. Even with a resistance of the coefficient 0.000004/°C, a 25°C increase would result in 0.01% decrease in resistance.

3. HYPOTHESIS

As mentioned previously, it has been stated that for an accurate measurement, it is necessary to choose close values of resistances for R_3 and R_4. If the ratio of $\frac{R_1}{R_2}$ is not much greater or lower than 1, i.e. $0.01 < Ratio < 100$ then it is possible to get accurate results. It is an important factor here that the resistance values of R_1 and R_2 should also be closer to that of R_3 and R_4; however the values of R_3 and R_4 should not exceed the values of R_1 and R_2 excessively. Instead, it is possible to choose R_1 and R_2 values much higher than R_3 and R_4 in order to manipulate the electrical current towards these resistors. This will create a higher potential difference across the resistors R_1 and R_2, and a higher electrical current flowing through R_3 and R_4. Therefore it will be possible to detect the smallest current that can cause a deflection in the multimeter, and to harvest more accurate results.

However, if resistance values of R_1 and R_2 lower which are than R_3 and R_4 are used, the deviation in the results should be higher than expected. The system would focus all the current to R_1 and R_2 instead of R_3 and R_4, in which R_4 the resistance to be measured and R_3 is the resistance to be adjusted according to R_4. Therefore, if R_3 and R_4 have values too extreme compared to R_1 and R_2, the experiment would not lead to accurate and clear results.

4. METHOD DEVELOPMENT AND PLANNING

The method will include the basic testing of the Wheatstone bridge, from the primary principle by testing the reliability of Wheatstone bridge. In the following experiment, a Wheatstone bridge is established with a constant ratio of $\frac{R_1}{R_2}$ (in which R_1 and R_2 equal to 10ohm). R_3 and R_4 resistance values are changing throughout the experiment, from lower than R_1 and R_2 to higher, in order to test this hypothesis. A rheostat is going to be used for the adjustable resistor R_3, and 17 different resistors of 17 different resistance values are going to be used for R_4 in which all of them are going to be used to measure throughout the experiment.

In this experiment, in order to test the hypothesis, every independent factor except the resistances of R_3 and R_4 should be controlled. High electrical current has a tendency to increase the temperature of a resistor, affecting its resistance and causing inaccuracy. The bridge resistances which are used in the experiment should be made of Manganin instead of copper in order to decrease this effect, on account of its low temperature coefficient of resistance and low thermo-electric electromotive force. However, it is difficult to find one of these resistors today, so the experiment is going to be done using copper resistors qualified enough for the experiment. The resistances should also be free of capacitance or inductance, which causes transient currents when any change to the system is made.

The voltage source should also be capable enough to apply a constant current to the bridge, to prevent any current changes that can result from the capacitance of the rheostat coil.

4.1. Research Question

How is the sensitivity of a Wheatstone bridge affected by the changes in the resistances R_3 and R_4?

4.2. Key Variables

Independent Variables:	The resistance of R_4
	Distance of the slider from the head of the rheostat
Dependent Variables:	The electrical current flowing through the galvanometer
	Potential difference between the terminals of the galvanometer
	The electrical current flowing through the resistors
	Temperature of the resistances
Controlled Variables:	Electromotive force

4.3. Materials

- A copper rheostat with the length of 100.00±0.05cm and the resistance of 150.00±0.05Ω
- 19 carbon composition resistors of the resistances 0.1, 1, 2, 4, 6, 8, 10, 10, 10, 20, 25, 30, 35, 40, 50, 60, 70, 90, 100 (±0.05Ω)
- A multimeter (Max input = 50A)
- An emf source (Max output = 110V)
- At least 15 wires of length 20±0.05cm with crocodile clips
- A ruler of the length 30cm (±0.05cm)

4.4. Method

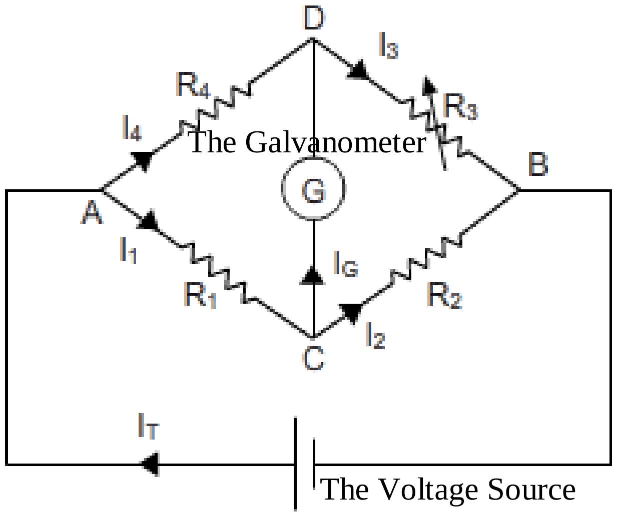


Figure 2: Wheatstone bridge circuit prepared for the experiment

1. Prepare the circuit as seen in Figure 2. Note that the rheostat will become R_3. Use the two 10Ω resistors for R_1 and R_2. Use the 0.1Ω resistor for R_4.
2. Connect one terminal of the galvanometer between the resistors, and the other one to the slider of the rheostat (R_3), as seen in Figure 2.
3. Connect the system to the voltage source. Give the system a potential difference of 30V.
4. Adjust the rheostat till no current passes from the multimeter (Check from the multimeter).
5. Measure and note the distance of the slider from where it touches the coil of the rheostat, to the initial point (head of the rheostat). Shut the voltage source down and disconnect it from the circuit.
6. Disconnect the 0.1Ω resistor from the circuit and connect the 1Ω resistor instead. Connect the system to the voltage source. Give the system a potential difference of 30V. Adjust the rheostat till no current passes from the multimeter (Check from the multimeter). Measure and note the distance of the slider from where it touches the coil of the rheostat, to the initial point (head of the rheostat). Shut the voltage source down and disconnect it from the circuit.
7. Disconnect the 1Ω resistor from the circuit and connect the 2Ω resistor instead. Connect the system to the voltage source. Give the system a potential difference of 30V. Adjust the rheostat till no current passes from the multimeter (Check from the multimeter). Measure and note the distance of the slider from where it touches the coil of the rheostat, to the initial point (head of the rheostat). Shut the voltage source down and disconnect it from the circuit.
8. Disconnect the 2Ω resistor from the circuit and connect the 4Ω resistor instead. Connect the system to the voltage source. Give the system a potential difference of 30V. Adjust the rheostat till no current passes from the multimeter (Check from the multimeter). Measure and note the distance of the slider from where it touches the coil

of the rheostat, to the initial point (head of the rheostat). Shut the voltage source down and disconnect it from the circuit.

9. Repeat the 8th step by disconnecting the 4Ω resistor from the circuit and connecting the 6Ω resistor instead. Note the results.
10. Repeat the 8th step by disconnecting the 6Ω resistor from the circuit and connecting the 8Ω resistor instead. Note the results.
11. Repeat the 8th step by disconnecting the 8Ω resistor from the circuit and connecting the 10Ω resistor instead. Note the results.
12. Repeat the 8th step by disconnecting the 10Ω resistor from the circuit and connecting the 20Ω resistor instead. Note the results.
13. Repeat the 8th step by disconnecting the 25Ω resistor from the circuit and connecting the 30Ω resistor instead. Note the results.
14. Repeat the 8th step by disconnecting the 30Ω resistor from the circuit and connecting the 35Ω resistor instead. Note the results.
15. Repeat the 8th step by disconnecting the 35Ω resistor from the circuit and connecting the 40Ω resistor instead. Note the results.
16. Repeat the 8th step by disconnecting the 40Ω resistor from the circuit and connecting the 50Ω resistor instead. Note the results.
17. Repeat the 8th step by disconnecting the 50Ω resistor from the circuit and connecting the 60Ω resistor instead. Note the results.
18. Repeat the 8th step by disconnecting the 60Ω resistor from the circuit and connecting the 70Ω resistor instead. Note the results.
19. Repeat the 8th step by disconnecting the 70Ω resistor from the circuit and connecting the 90Ω resistor instead. Note the results.
20. Repeat the 8th step by disconnecting the 90Ω resistor from the circuit and connecting the 100Ω resistor instead. Note the results.

4.5. Data Collection and Processing

In this section, all the values obtained from the experiment are interpreted for error analysis. In the experiment, the distance of the slider from the head of the rheostat was measured and noted in centimeters. Then 2 tables are formed (Data Collection is shown in Appendix 7.1.1) with these values to be able to do calculations. In Table 1, the resistances R_1, R_2, R_4, voltage of the battery and the current flowing through the galvanometer were listed. The current flowing through the galvanometer was listed in order to indicate that no current passed through it, and the bridge was balanced.

The resistance values of R_3 were calculated according to the following equation:

$$R_3 = Distance\ of\ the\ slider(\pm 0.05\text{cm}) \times \frac{Resistance\ of\ the\ rheostat(\pm 0.05\Omega)}{Horizontal\ length\ of\ the\ rheostat(\pm 0.05\text{cm})}$$

This equation would give the resistance of R_3 when the distance is compared to the total length of the rheostat. Finally, the errors were analyzed. The calculations are shown in Appendix 7.1.3.

5. CONCLUSION

In this extended essay, factors (related with the resistance to be measured and the adjustable one) affecting the sensitivity of a Wheatstone bridge for its purpose in measurement were investigated. The results indicated that, although precise measurement can be done with the help of a Wheatstone bridge, there are conditions for it that need to be fulfilled. Firstly, the values of R_1 and R_2 must be close enough to allow a sensitive measurement for both high and high values of resistances. It is important not to ignore the temperature change while balancing the bridge, since a shift in temperature can also affect the resistance of a resistor.

The actual and calculated values of R_4 should have been equal for all the trials; however the results clearly indicate the existence of a deviation with an increase in R_3 and R_4. As seen in Graph 2, the results differ increasingly with the number of trials, which tested R_3 and R_4 values in an increasing order. The absolute and percentage errors can be calculated as the following:

Mean of the Literature Values = 32.42

Mean of the Difference between the calculated and literature values = 32.42 – 30.77

= 1.65 = Absolute error

Percentage Error = Absolute Error/Literature Value = 1.65/32.42 = 0.0510 = 5.1%

The absolute error for the trials increased with the values of R_3 and R_4. However, since the absolute errors were small compared to the literature values, the percentage errors for the trials were not in increasing order, the first trial having the biggest percentage error. The reason for this is in the first trial, a 0.5Ω absolute error is compared to the literature value of 0.1Ω. In the last trial however, although the percentage error was 11%, a 10.75Ω deviation was compared to a 100Ω literature value. A graph was plotted to show the increase in the value of the absolute error with each trial.

Although the experiment resulted in a percentage error of 5.1% which is acceptable, it also showed clearly that with an increase in R_3 and R_4, the correlation of the results has clearly decreased.

6. EVALUATION

6.1. Sources of Error

- A source of error may be the increase in temperature. If the thermo-electrical friction coefficient of the resistors was too large, it may have caused the resistance to increase and current to decrease. It is an important fact that the experiment should be made in an isolated medium, in which the temperature is kept constant. The potential difference of the system should be limited to a minimum which could both allow a sensitive measurement and prevent overheating.
- Another source of error might have resulted from the multimeter itself. If the shunt resistance of the multimeter was too big, it may have caused inaccuracy; or the multimeter could not have get rid of its initial charge, causing inaccuracy at the beginning of the experiment. To correct this source of error, another multimeter with a smaller shunt resistance can be used.,
- Other than the stated reasons, the source of error may be what was tried to be proven in the hypothesis. The values of R_3 and R_4 should be smaller than that of R_1 and R_2 or close values for the measurement to be even more accurate.
- The resistance of the connecting leads could have caused the inaccuracy in the experiment. “A foot of 22 S.W.G. copper wire has a resistance of about 0.014 ohm.” This shows that the resistances of the bridge arms may have increased with the wires that connect them to each other.

Wheatstone bridge is an instrument that has brought a new meaning to electrical measurement. With it, the scientists have explored new and alternative ways of measurement (especially in alternating current), and with its help many factors that have once been ignored were brought to daylight. The Wheatstone bridge is a perfect and most basic example of circuit which describes the temperature’s effects on electricity, something which we cannot ignore especially when designing and constructing today’s technology. The bridge circuit is the only circuit when the current that is applied cannot be derived via Ohm’s law, and is a perfect example of the application of Kirchhoff’s rules. During the first time it was invented, it was a leap towards a new age for the electrical industry; and we are happy to see its mysteries solved today.

7. APPENDIX

7.1. Data Collection and Processing

7.1.1. Data Collection

# of trials	Resistance of R_4 (±0.05Ω)	Resistance of R_1 (±0.05Ω)	Resistance of R_2 (±0.05Ω)	Voltage of the battery (±0.05v)	Current flowing through the multimeter (±0.05A)
1	0.10	10.00	10.00	30.00	0.00
2	1.00	10.00	10.00	30.00	0.00
3	2.00	10.00	10.00	30.00	0.00
4	4.00	10.00	10.00	30.00	0.00
5	6.00	10.00	10.00	30.00	0.00
6	8.00	10.00	10.00	30.00	0.00
7	10.00	10.00	10.00	30.00	0.00
8	20.00	10.00	10.00	30.00	0.00
9	25.00	10.00	10.00	30.00	0.00
10	30.00	10.00	10.00	30.00	0.00
11	35.00	10.00	10.00	30.00	0.00
12	40.00	10.00	10.00	30.00	0.00
13	50.00	10.00	10.00	30.00	0.00
14	60.00	10.00	10.00	30.00	0.00
15	70.00	10.00	10.00	30.00	0.00
16	90.00	10.00	10.00	30.00	0.00
17	100.0	10.00	10.00	30.00	0.00

Table 1: Table showing the different resistances used during the experiment, the resistance of the rheostat, length of the rheostat (in order to calculate R_3), distance of the slider from the head of the slider, voltage of the battery, and the current that is read in the multimeter, to indicate that no current has passed through it.

# of trials	Resistance of the rheostat (±0.05Ω)	Length of the rheostat (±0.05cm)	Distance of the slider from the head of the rheostat (±0.05cm)
1	150.00	100.00	0.40
2	150.00	100.00	0.90
3	150.00	100.00	1.50
4	150.00	100.00	2.80
5	150.00	100.00	4.10
6	150.00	100.00	5.40
7	150.00	100.00	5.80
8	150.00	100.00	15.30
9	150.00	100.00	16.50
10	150.00	100.00	18.10
11	150.00	100.00	21.00
12	150.00	100.00	24.90
13	150.00	100.00	30.10
14	150.00	100.00	42.60
15	150.00	100.00	43.40
16	150.00	100.00	56.40
17	150.00	100.00	59.50

Table 2: Table showing the different resistances used during the experiment, the resistance of the rheostat, length of the rheostat (in order to calculate R_3), distance of the slider from the head of the slider, voltage of the battery, and the current that is read in the multimeter, to indicate that no current has passed through it.

7.1.2. Data Processing and Presentation

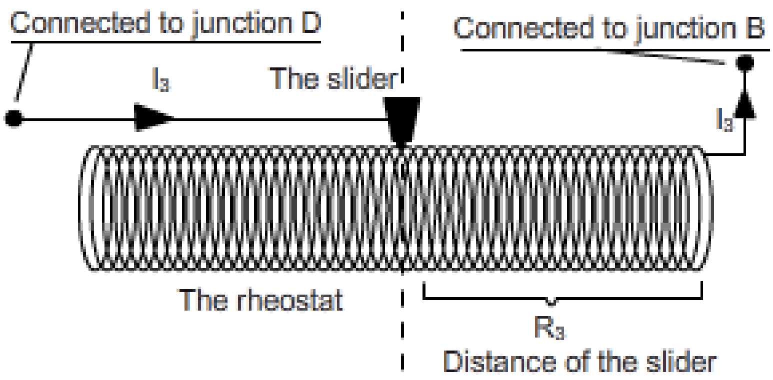


Figure 3: Figure representing the rheostat as the resistor R_3.

To see if the data collection was precise, we must calculate the resistance of R_3. Since $\frac{R_1}{R_2}$ is equal to 1 (because the resistances R_1 and R_2 are both equal to 10.00), R_3 that is calculated in the data processing (as in the equation below) should be equal to R_4. The resistance of R_3 is would be calculated as the following. Also, according to the equation about Figure 1 that has been mentioned before:

$$If\ R_1 \times R_3 = R_2 \times R_4\ and\ R_1 = R_2$$

$$then: R_3 = R_4$$

$$R_3 = Distance\ of\ the\ slider(\pm 0.05\text{cm}) \times \frac{Resistance\ of\ the\ rheostat(\pm 0.05\Omega)}{Horizontal\ length\ of\ the\ rheostat(\pm 0.05\text{cm})}$$

According to the formula above, all of the R_3 values can be calculated precisely. The calculations are showed in the following section.

7.1.2.1. Resistance Calculations

Trial 1: $R_3 = 0.40 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 0.60 \pm 0.08\Omega$

Trial 2: $R_3 = 0.90 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 1.35 \pm 0.08\Omega$

Trial 3: $R_3 = 1.50 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 2.25 \pm 0.08\Omega$

Trial 4: $R_3 = 2.80 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 4.20 \pm 0.08\Omega$

Trial 5: $R_3 = 4.10 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 6.15 \pm 0.08\Omega$

Trial 6: $R_3 = 5.40 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 8.10 \pm 0.08\Omega$

Trial 7: $R_3 = 5.80 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 8.70 \pm 0.08\Omega$

Trial 8: $R_3 = 15.30 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 22.95 \pm 0.09\Omega$

Trial 9: $R_3 = 16.50 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 24.75 \pm 0.10\Omega$

Trial 10: $R_3 = 18.10 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 27.15 \pm 0.10\Omega$

Trial 11: $R_3 = 21.00 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 31.50 \pm 0.10\Omega$

Trial 12: $R_3 = 24.90 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 37.35 \pm 0.11\Omega$

Trial 13: $R_3 = 30.10 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 45.15 \pm 0.11\Omega$

Trial 14: $R_3 = 42.60 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 63.90 \pm 0.13\Omega$

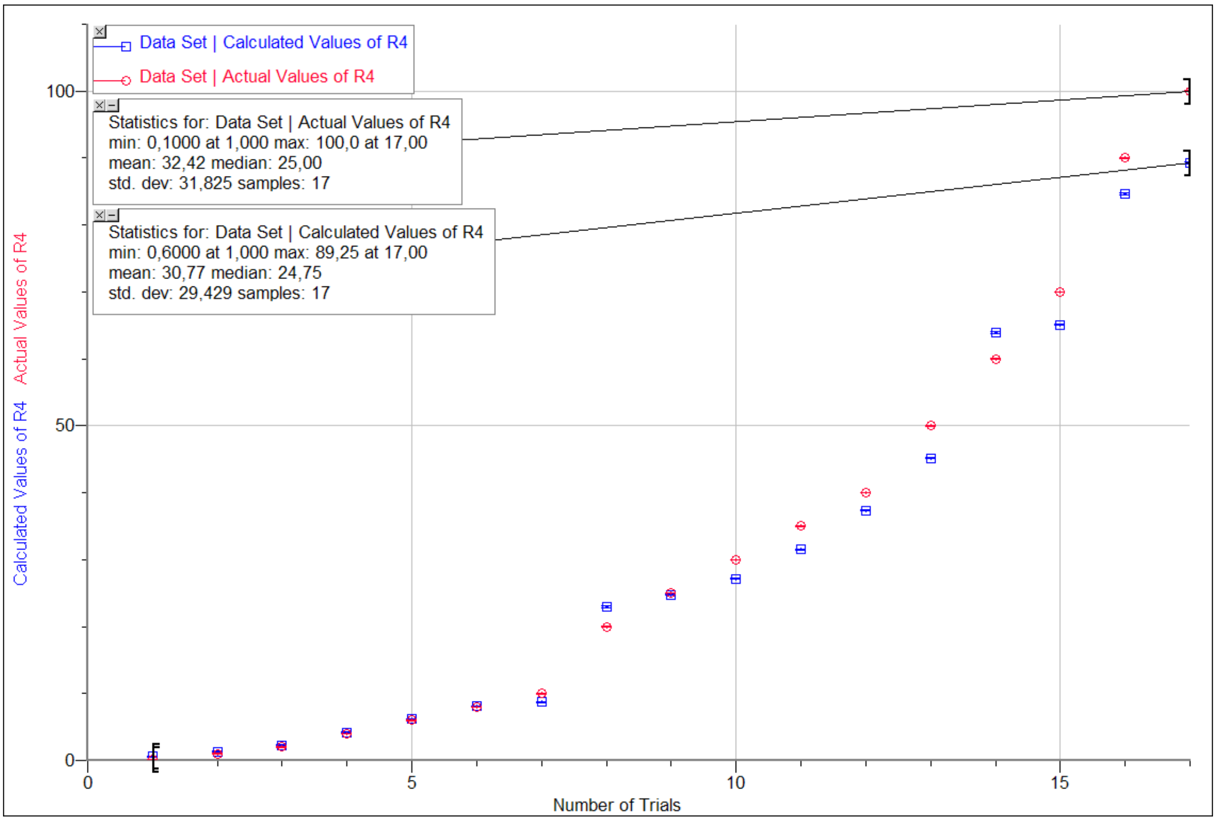
Trial 15: $R_3 = 43.40 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 65.10 \pm 0.13\Omega$

Trial 16: $R_3 = 56.40 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 84.60 \pm 0.15\Omega$

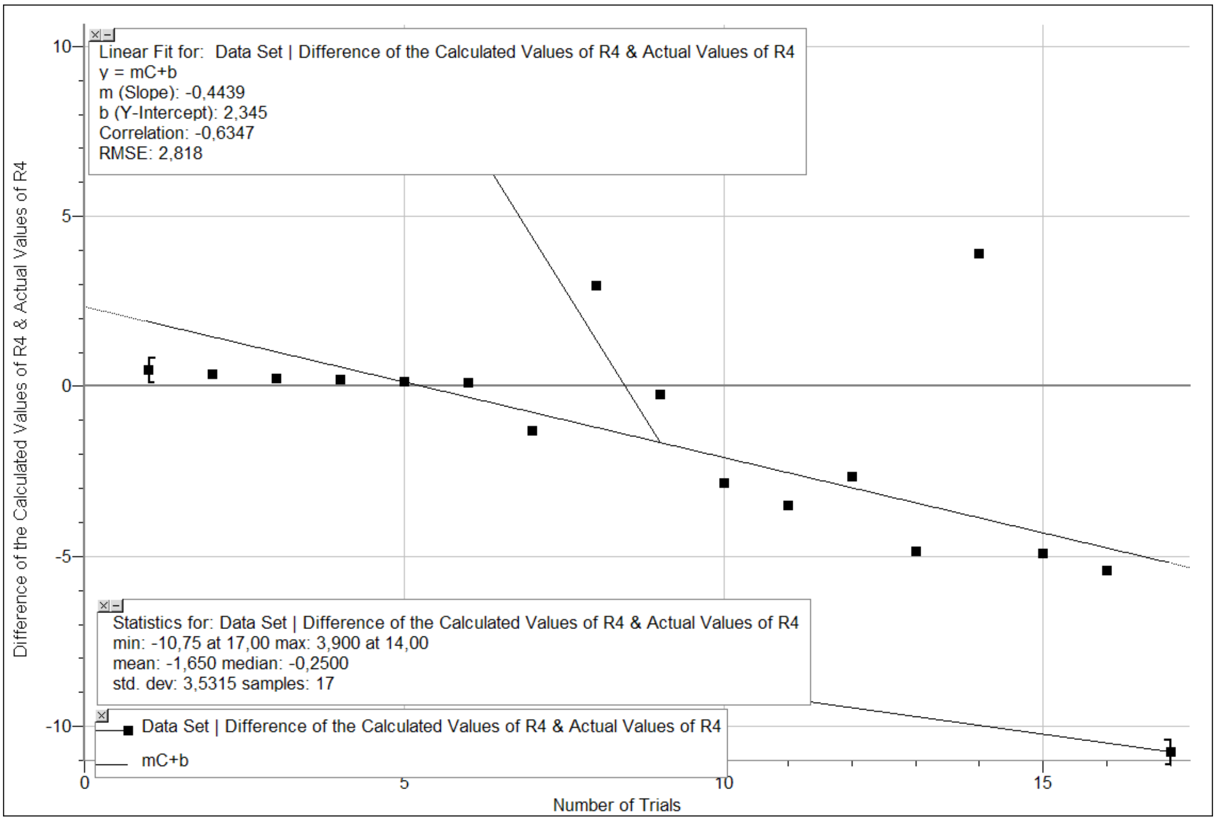
Trial 17: $R_3 = 59.50 \pm 0.05 \times \frac{150.00 \pm 0.05}{100.00 \pm 0.05} = 89.25 \pm 0.15\Omega$

# of trials	Resistance of the rheostat (±0.05Ω)	Length of the rheostat (±0.05cm)	Distance of the slider from the head of the rheostat (±0.05cm)	Calculated resistance of R_3 which should also be equal to R_4 (Ω)	Resistance of R_4 used in the experiment (±0.05Ω)
1	150.00	100.00	0.40	0.60 ± 0.08	0.10
2	150.00	100.00	0.90	1.35 ± 0.08	1.00
3	150.00	100.00	1.50	2.25 ± 0.08	2.00
4	150.00	100.00	2.80	4.20 ± 0.08	4.00
5	150.00	100.00	4.10	6.15 ± 0.08	6.00
6	150.00	100.00	5.40	8.10 ± 0.08	8.00
7	150.00	100.00	5.80	8.70 ± 0.08	10.00
8	150.00	100.00	15.30	22.95 ± 0.09	20.00
9	150.00	100.00	16.50	24.75 ± 0.10	25.00
10	150.00	100.00	18.10	27.15 ± 0.10	30.00
11	150.00	100.00	21.00	31.50 ± 0.10	35.00
12	150.00	100.00	24.90	37.35 ± 0.11	40.00
13	150.00	100.00	30.10	45.15 ± 0.11	50.00
14	150.00	100.00	42.60	63.90 ± 0.13	60.00
15	150.00	100.00	43.40	65.10 ± 0.13	70.00
16	150.00	100.00	56.40	84.60 ± 0.15	90.00
17	150.00	100.00	59.50	89.25 ± 0.15	100.00

Table 3: Table showing the resistance and the length of the rheostat, the distance of the slider from the head of the rheostat, the resistance of R_4 used in the experiment and the calculated resistance of R_3 which should be equal to R_4 as mentioned previously.



Graph 1: Graph showing the actual and calculated values of R_4 plotted with statistics in order to analyze errors.



Graph 2: Graph showing the difference between the actual and calculated values of R_4 (absolute error) this graph will aid in seeing how the results have deviated from the actual values with the increasing of the resistance values of R_3 and R_4.

7.1.3. Error Analysis

In the third table of Data Processing and Presentation, the column "Resistance of R_4 used in the experiment" is going to be used as the literature value for the error analysis, since the resistance values that belong to R_4 are measured and actual values. The absolute error is calculated as:

$$\Delta x = |x_0 - x|$$

Where Δx is the absolute error,

x_0 is the literature value,

x is the experiment value. Therefore, the absolute errors for all the trials are calculated as:

Trial 1:	$\Delta X = \lvert 0.10 \pm 0.05 - 0.60 \pm 0.08 \rvert$	$=0.50 \pm 0.03$
Trial 2:	$\Delta X = \lvert 1.00 \pm 0.05 - 1.35 \pm 0.08 \rvert$	$=0.35 \pm 0.03$
Trial 3:	$\Delta X = \lvert 2.00 \pm 0.05 - 2.25 \pm 0.08 \rvert$	$=0.25 \pm 0.03$
Trial 4:	$\Delta X = \lvert 4.00 \pm 0.05 - 4.20 \pm 0.08 \rvert$	$=0.20 \pm 0.03$
Trial 5:	$\Delta X = \lvert 6.00 \pm 0.05 - 6.15 \pm 0.08 \rvert$	$=0.15 \pm 0.03$
Trial 6:	$\Delta X = \lvert 8.00 \pm 0.05 - 8.10 \pm 0.08 \rvert$	$=0.10 \pm 0.03$
Trial 7:	$\Delta X = \lvert 10.00 \pm 0.05 - 8.70 \pm 0.08 \rvert$	$=1.30 \pm 0.03$
Trial 8:	$\Delta X = \lvert 20.00 \pm 0.05 - 22.95 \pm 0.09 \rvert$	$=2.95 \pm 0.04$
Trial 9:	$\Delta X = \lvert 25.00 \pm 0.05 - 24.75 \pm 0.10 \rvert$	$=0.25 \pm 0.05$
Trial 10:	$\Delta X = \lvert 30.00 \pm 0.05 - 27.15 \pm 0.10 \rvert$	$=2.85 \pm 0.05$
Trial 11:	$\Delta X = \lvert 35.00 \pm 0.05 - 31.50 \pm 0.10 \rvert$	$=3.50 \pm 0.05$
Trial 12:	$\Delta X = \lvert 40.00 \pm 0.05 - 37.35 \pm 0.11 \rvert$	$=2.65 \pm 0.06$
Trial 13:	$\Delta X = \lvert 50.00 \pm 0.05 - 45.15 \pm 0.11 \rvert$	$=4.85 \pm 0.06$
Trial 14:	$\Delta X = \lvert 60.00 \pm 0.05 - 63.90 \pm 0.13 \rvert$	$=3.90 \pm 0.08$
Trial 15:	$\Delta X = \lvert 70.00 \pm 0.05 - 65.10 \pm 0.13 \rvert$	$=4.90 \pm 0.08$
Trial 16:	$\Delta X = \lvert 90.00 \pm 0.05 - 84.60 \pm 0.15 \rvert$	$=5.40 \pm 0.10$
Trial 17:	$\Delta X = \lvert 100.00 \pm 0.05 - 89.25 \pm 0.15 \rvert$	$=10.75 \pm 0.10$

Relative error for each trial will be calculated as in the following equation:

$$\delta x = \frac{\Delta x}{x}$$

Where δx is the relative error,

Δx is the absolute error,

x is the literature value.

The percentage error is equal to the relative error multiplied by 100. The calculations are done accordingly below:

Trial 1:	$\delta x = \frac{0.50 \pm 0.03}{0.10 \pm 0.05}$	$=5{,}00 \pm 2{,}80$	$=500\% \pm 280\%$
Trial 2:	$\delta x = \frac{0.35 \pm 0.03}{1.00 \pm 0.05}$	$=0{,}35 \pm 0{,}05$	$=35\% \pm 5\%$
Trial 3:	$\delta x = \frac{0.25 \pm 0.03}{2.00 \pm 0.05}$	$=0{,}13 \pm 0{,}02$	$=13\% \pm 2\%$
Trial 4:	$\delta x = \frac{0.20 \pm 0.03}{4.00 \pm 0.05}$	$=0{,}05 \pm 0{,}01$	$=5\% \pm 1\%$
Trial 5:	$\delta x = \frac{0.15 \pm 0.03}{6.00 \pm 0.05}$	$=0{,}03 \pm 0{,}01$	$=3\% \pm 1\%$
Trial 6:	$\delta x = \frac{0.10 \pm 0.03}{8.00 \pm 0.05}$	$=0{,}01 \pm 0{,}04\times10^{-1}$	$=1\% \pm 4\times10^{-1}\%$
Trial 7:	$\delta x = \frac{1.30 \pm 0.03}{10.00 \pm 0.05}$	$=0{,}13 \pm 0{,}04\times10^{-1}$	$=13\% \pm 4\times10^{-1}\%$
Trial 8:	$\delta x = \frac{2.95 \pm 0.04}{20.00 \pm 0.05}$	$=0{,}15 \pm 0{,}02\times10^{-1}$	$=15\% \pm 2\times10^{-1}\%$
Trial 9:	$\delta x = \frac{0.25 \pm 0.05}{25.00 \pm 0.05}$	$=0{,}01 \pm 0{,}02\times10^{-1}$	$=1\% \pm 2\times10^{-1}\%$
Trial 10:	$\delta x = \frac{2.85 \pm 0.05}{30.00 \pm 0.05}$	$=0{,}10 \pm 0{,}02\times10^{-1}$	$=10\% \pm 2\times10^{-1}\%$
Trial 11:	$\delta x = \frac{3.50 \pm 0.05}{35.00 \pm 0.05}$	$=0{,}10 \pm 0{,}02\times10^{-1}$	$=10\% \pm 2\times10^{-1}\%$
Trial 12:	$\delta x = \frac{2.65 \pm 0.06}{40.00 \pm 0.05}$	$=0{,}07 \pm 0{,}02\times10^{-1}$	$=7\% \pm 2\times10^{-1}\%$
Trial 13:	$\delta x = \frac{4.85 \pm 0.06}{50.00 \pm 0.05}$	$=0{,}10 \pm 0{,}01\times10^{-1}$	$=10\% \pm 1\times10^{-1}\%$
Trial 14:	$\delta x = \frac{3.90 \pm 0.08}{60.00 \pm 0.05}$	$=0{,}07 \pm 0{,}01\times10^{-1}$	$=7\% \pm 1\times10^{-1}\%$
Trial 15:	$\delta x = \frac{4.90 \pm 0.08}{70.00 \pm 0.05}$	$=0{,}07 \pm 0{,}01\times10^{-1}$	$=7\% \pm 1\times10^{-1}\%$
Trial 16:	$\delta x = \frac{5.40 \pm 0.10}{90.00 \pm 0.05}$	$=0{,}06 \pm 0{,}01\times10^{-1}$	$=6\% \pm 1\times10^{-1}\%$
Trial 17:	$\delta x = \frac{10.75 \pm 0.10}{100.00 \pm 0.05}$	$=0{,}11 \pm 0{,}01\times10^{-1}$	$=11\% \pm 1\times10^{-1}\%$

8. BIBLIOGRAPHY

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