Experiment # 11

Kirchhoff's Rules & Wheatstone's Bridge

Principles

No new principles are involved in this experiment. We shall, however, recall the Wheatstone's Bridge circuit and the Kirchhoff's rules, for ready reference.

Wheatstone's Bridge Circuit

Wheatstone's bridge network consists of one voltage source and five components. A general bridge circuit is shown in Fig (1).

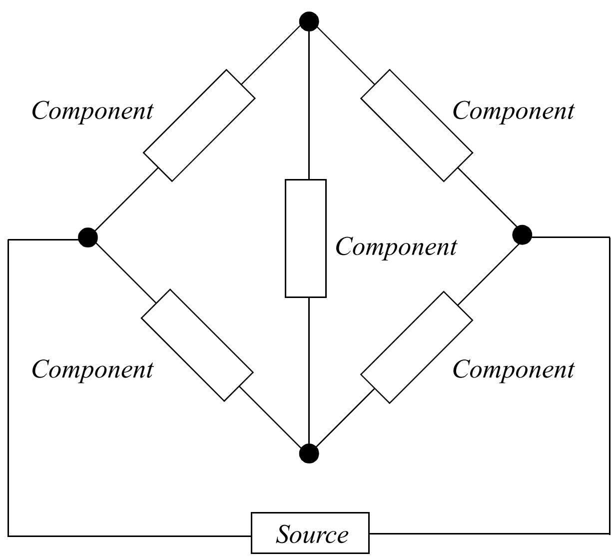

Fig (1) A Wheatstone's Bridge Circuit

Kirchhoff's Rules

Next we recall Kirchhoff's rules in the form of junction and loop equations. The general form of a loop equation is:

$$\sum_n V_n = 0 \qquad ....(1)$$

In terms of *source* and *sink* voltages, we write:

$$\sum_n V_{n,\,sources} = \sum_n V_{n,\,\text{sinks}} \qquad ....(2)$$

For a circuit that consists of resistors and batteries only, we may rewrite Eqn (1) as:

$$\sum_n V_{n,\,batteries} = \sum_n R_n\, I_n \qquad ....(3)$$

where we applied Ohm's law to the resistor voltages.

The general form of the junction equation is:

$$\sum_n I_n = 0 \qquad \text{..........(4)}$$

Or, in terms of currents *going into* the junction and *coming out* of it:

$$\sum_n I_{in} = \sum_n I_{out} \qquad \text{..........(5)}$$

As for the source, it will be assumed that it has negligible internal resistance and that its emf can be expressed as V_S . Source current will be I_S and the Ohm's law for it will be:

$$V_S = R_{eq} I_S \qquad \text{..........(6)}$$

Objectives of the Experiment

To study Kirchhoff's Rules as applied to a Wheatstone's Bridge circuit;

(i) directly, by comparing the calculated and the measured values of currents and voltages for all five components in the circuit and the source,

(ii) indirectly, by plotting a suitable graph.

Setting Up

As stated above, a Wheatstone's bridge circuit consists of one voltage source (a battery, may be) and five components (resistors, for example). Thus it is a single source circuit and one would expect to analyze it using the rules for the series and parallel combinations of components. A look at the circuit diagram shows that no two components are in series and no two are in parallel. There is no starting point for combining the components and hence it is impossible to reduce the five components to just one component. This circuit (and other similar circuits) must, therefore, be analyzed using Kirchhoff's rules.

For the sake of simplicity, we pick up the Wheatstone's bridge circuit that was used in a previous experiment. It is shown in Fig (2), next page. It has 5 resistors and one battery. Even though an analysis of this circuit was given for that experiment, we had postponed the proper solution till such time that Kirchhoff's rules were introduced. Having studied these rules in the last experiment, we shall now carry out the rigorous analysis.

To describe the currents, one would normally assign a different current number to each of the 5 currents (passing through the 5 resistors) and ending up with five unknowns. One would then find 5 equations that will have to be solved simultaneously. As there are four branch points and seven loops, finding five equations will not be a problem; solving them, however, will be a test of nerves. By cleverly naming them, however, it is possible to reduce the number of unknown currents to a manageable number! Please also keep in mind that (i) it is not necessary to use both junction and loop equations, and (ii) a loop need not necessarily contain a source.

(A) Direct Verification

The circuit below is the same Wheatstone's Bridge circuit that was used in the earlier experiment of the same name. By judiciously selecting the names, the five unknown currents have been expressed in terms of three currents: I_S, I_1 and I_2. Thus we have only three unknowns and we need solve only three equations simultaneously. Again, as it was not necessary to include one (or more) junction equation, no junction equation is used. All five currents will be determined by using three loop equations.

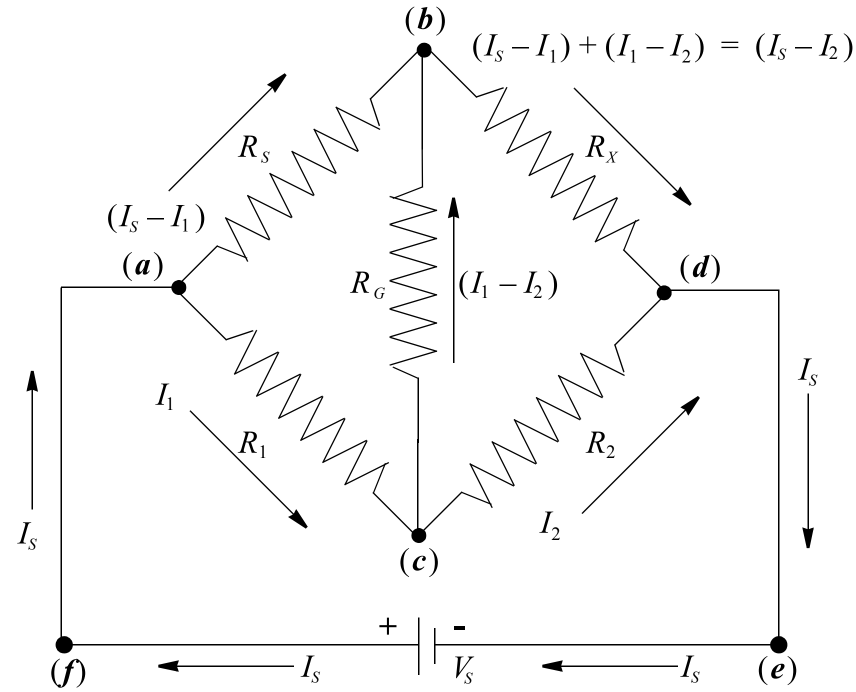

Fig (2) A Wheatstone's Bridge Circuit

Consider loop (*facdef*), traversed clockwise:

$$V_S = R_1 I_1 + R_2 I_2 \quad \text{..........(7)}$$

Next consider the loop (*abca*), traversed counter-clockwise:

$$0 = R_1 I_1 + R_G (I_1 - I_2) - R_S (I_S - I_1)$$

Expanding the above we get:

$$0 = R_1 I_1 + R_G I_1 - R_G I_2 - R_S I_S + R_S I_1 \quad \text{..........(8)}$$

The third loop is (*cbdc*), traversed clockwise:

$$0 = R_G (I_1 - I_2) + R_X (I_S - I_2) - R_2 I_2$$

Expanding the above we get:

$$0 = R_G I_1 - R_G I_2 + R_X I_S - R_X I_2 - R_2 I_2 \quad \text{..........(9)}$$

To eliminate the source current I_S, we first rearrange Eqns (8) and (9):

$$R_1 I_1 + R_G I_1 + R_S I_1 = R_S I_S + R_G I_2 \qquad \text{..........(10)}$$

$$R_2 I_2 + R_G I_2 + R_X I_2 = R_X I_S + R_G I_1 \qquad \text{..........(11)}$$

Then we multiply equation (10) by R_X and equation (11) by R_S:

$$R_X R_1 I_1 + R_X R_G I_1 + R_X R_S I_1 = R_X R_S I_S + R_X R_G I_2 \qquad \text{..........(12)}$$

$$R_S R_2 I_2 + R_S R_G I_2 + R_S R_X I_2 = R_S R_X I_S + R_S R_G I_1 \qquad \text{..........(13)}$$

Subtracting Eqn (13) from Eqn (12) we get:

$$R_X R_1 I_1 + R_X R_G I_1 + R_X R_S I_1 - R_S R_2 I_2 - R_S R_G I_2 - R_S R_X I_2 = R_X R_G I_2 - R_S R_G I_1$$

Rearranging, we find:

$$(R_X R_1 + R_X R_G + R_X R_S + R_S R_G) I_1 = (R_S R_2 + R_S R_G + R_S R_X + R_X R_G) I_2$$

The sum of the three terms $R_X R_G$, $R_X R_S$, and $R_S R_G$ that appear on both sides of the equation, is, in fact, a combination of products of R_G, R_S and R_G in *cyclic order,* and may be written as $R_X R_G + R_G R_S + R_S R_X$. Let:

$$R_X R_G + R_G R_S + R_S R_X = a \qquad \text{..........(14)}$$

We now rewrite the last equation as:

$$(R_X R_1 + a) I_1 = (R_S R_2 + a) I_2$$

This equation can be solved for I_2 in terms of I_1:

$$I_2 = \left(\frac{R_X R_1 + a}{R_S R_2 + a} \right) I_1 \qquad \text{..........(15)}$$

We shall now plug in this value of I_2 in Eqn (7):

$$V_S = R_1 I_1 + \left(\frac{R_X R_1 + a}{R_S R_2 + a} \right) R_2 I_1 = \left\{ R_1 + \left(\frac{R_X R_1 + a}{R_S R_2 + a} \right) R_2 \right\} I_1$$

$$V_S = \left\{ \frac{R_1(R_S R_2 + a) + R_2(R_X R_1 + a)}{R_S R_2 + a} \right\} I_1$$

Expanding the parentheses in the numerator, simplifying and rearranging, we get:

$$V_S = \left\{ \frac{(R_1 R_2)(R_S + R_X) + (R_1 + R_2)(a)}{(R_S R_2 + a)} \right\} I_1 \qquad \text{..........(16)}$$

We use this result to find I_1:

$$I_1 = \left\{ \frac{R_S R_2 + a}{(R_1 R_2)(R_S + R_X) + (R_1 + R_2)(a)} \right\} V_S \qquad \text{..........(17)}$$

That's one unknown current determined!

The current I_2 can now be determined using Eqn (15). The third current I_S can be determined by rearranging Eqn (10) *or* Eqn (11). Rearranging Eqn (10) we get:

$$I_S = \left(1 + \frac{R_1 + R_G}{R_S}\right) I_1 - \left(\frac{R_G}{R_S}\right) I_2 \qquad \text{..........(18)}$$

Mission accomplished. We determined the three currents: I_1, I_2 and I_S by solving the three loop equations (#s 7, 8 & 9) simultaneously.

Knowing I_1, I_2 and I_S, we can, not only calculate the remaining three currents but we can also determine voltages across all five resistors. Currents through all 5 resistors and voltages across all 5 of them are listed here:

$$I_{R1} = I_1, \; V_{R1} = R_1 I_{R1} \qquad \text{..........(19)}$$

$$I_{R2} = I_2, \; V_{R2} = R_2 I_{R2} \qquad \text{..........(20)}$$

$$I_{RS} = (I_S - I_1), \; V_{RS} = R_S (I_S - I_1) \qquad \text{..........(21)}$$

$$I_{RX} = (I_S - I_2), \; V_{RX} = R_X (I_S - I_2) \qquad \text{..........(22)}$$

$$I_G = (I_1 - I_2), \; V_G = R_G (I_1 - I_2) \qquad \text{..........(23)}$$

(B) Indirect Verification

Let us find the ratio of the two currents: I_1 and I_2. This can be done using Eqn (15):

$$\frac{I_2}{I_1} = \left(\frac{R_X R_1 + a}{R_S R_2 + a}\right) \qquad \text{..........(24)}$$

Let

$$b = R_S R_2 + a \qquad \text{..........(25)}$$

Then we can rewrite Eqn (24) as:

$$\frac{I_2}{I_1} = \frac{R_X R_1 + a}{b}$$

Expanding:

$$\frac{I_2}{I_1} = \frac{a}{b} + \left(\frac{R_X}{b}\right) R_1 \qquad \text{..........(26)}$$

This corresponds to the equation of a straight line, $y = b + mx$, with R_1 being the independent or the x variable and (I_2 / I_1) being the dependent or the y variable. The slope and the intercept are given by:

$$\text{slope} = \frac{R_X}{b} \qquad \text{..........(27)}$$

$$\text{y-axis intercept} = \frac{a}{b} \qquad \text{..........(28)}$$

Thus, if we select several values of R_1 and for each determine the ratio (I_2 / I_1), then plotting (I_2 / I_1) on y-axis and R_1 on x-axis, we should get a straight line of slope and intercept as given by Eqns (27) and (28).

The intercept gives us the ratio of I_2 to I_1 when R_1 is zero. As $b > a$, we find that $I_2 < I_1$. As such, the intercept (as printed out by the computer) must be a fraction. The slope, on the other hand, has units of conductance and is the equivalent conductance of the other four resistances in the circuit. Please note that R_1 does not appear as a member-resistance either in a or in b.

(C) The Balanced Bridge or the Galvanometer Null

Having found the general solution of the Wheatstone's Bridge circuit, we are now in a position to extract the condition for a balanced bridge (the one used for determining the value of an unknown resistance in an earlier experiment). We replace R_G by the galvanometer G. It is easily seen that a galvanometer null will be obtained if $I_1 = I_2$ or $I_2/I_1 = 1$. Letting $I_2/I_1 = 1$ in Eqn (24) we get:

$$R_X R_1 + a = R_S R_2 + a$$

Cancelling out the term a from the two sides we get:

$$R_X R_1 = R_S R_2$$

Or

$$\frac{R_S}{R_X} = \frac{R_1}{R_2} \qquad \text{..........(29)}$$

This is the rigorous proof of the balanced bridge equation, developed in the Wheatstone's Bridge experiment, using philosophical arguments!

A very interesting aspect of the present study is that we would expect the straight line to pass through the point $I_2/I_1 = 1$ either directly or by extrapolation. The value of R_1 (found from the computer-printed equation, by setting $y = 1$), will necessarily produce galvanometer null! Let's call this value of R_1 as R_{null}. If we replace R_1 by R_{null} then a galvanometer, placed in series with R_G, will read *zero*. Alternatively, if we place two ammeters in the circuit, one to read I_1 and the other to read I_2, and replace R_1 by R_{null}, the two ammeters will display identical currents (to three places of decimal). We shall certainly verify this statement, in this experiment.

(D) The Equivalent Resistance R_{eq} of the Wheatstone's Bridge Circuit

The equivalent resistance R_{eq} of the Wheatstone's Bridge circuit can be found by placing an ohmmeter across terminals a and d of the circuit, (see Fig 2). The circuit will not be connected to the battery, at this time. The magnitude of the resistance indicated by the meter, will be the equivalent resistance of the Wheatstone Bridge. Such a value will simply be an *experimental* value. To maintain our pride in ***always being able to predict***, we shall now find a value of R_{eq} *mathematically:*

R_{eq} will have to be calculated in a round about way. We shall insert the values of I_1 and I_2 from Eqns (17) and (15) in Eqn (18), in order to calculate I_S. We shall solve this equation for (I_S / V_S), which will be G_{eq}. We shall then take a simple reciprocal to get R_{eq}.

Recall Eqn (17)

$$I_1 = \left\{ \frac{R_S R_2 + a}{(R_1 R_2)(R_S + R_X) + (R_1 + R_2)(a)} \right\} V_S \, 0 \qquad \text{......Eqn (17)}$$

Recall Eqn (15)

$$I_2 = \left(\frac{R_X R_1 + a}{R_S R_2 + a} \right) I_1 \qquad \text{......Eqn (15)}$$

Inserting the value of I_1 from Eqn (17) into Eqn (15), we get:

$$I_2 = \left(\frac{R_X R_1 + a}{R_S R_2 + a} \right) \left\{ \frac{R_S R_2 + a}{(R_1 R_2)(R_S + R_X) + (R_1 + R_2)(a)} \right\} V_S$$

Cancelling out $R_S R_2 + a$ from numerator and denominator, we get:

$$I_2 = \left(\frac{R_X R_1 + a}{(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)} \right) V_S \qquad \text{....Eqn (15a)}$$

Now recall Eqn (18)

$$I_S = \left(1 + \frac{R_1 + R_G}{R_S}\right) I_1 - \left(\frac{R_G}{R_S}\right) I_2 \qquad \text{......Eqn (18)}$$

and insert values of f I_1 and I_2 from Eqns (17) and (15a) into Eqn (18), to get:

$$I_S = \left(1 + \frac{R_1 + R_G}{R_S}\right)\left(\frac{R_S R_2 + a}{(R_1 R_2)(R_s + R_X) + (R_1 + R_2)(a)} \right) V_S$$

$$- \left(\frac{R_G}{R_S}\right)\left(\frac{R_X R_1 + a}{(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)} \right) V_S$$

$$\frac{I_S}{V_S} = \left(1 + \frac{R_1 + R_G}{R_S}\right)\left(\frac{R_S R_2 + a}{(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)} \right)$$

$$- \left(\frac{R_G}{R_S}\right)\left(\frac{R_X R_1 + a}{(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)} \right)$$

Now $(I_S / V_S) = G_{eq}$. It can be written as:

$$G_{eq} = \left(\frac{R_1 + R_G + R_S}{R_S}\right)\left(\frac{(R_S R_2 + a)}{(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)} \right)$$

$$- \left(\frac{R_G}{R_S}\right)\left(\frac{(R_X R_1 + a)}{(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)} \right)$$

$$G_{eq} = \frac{(R_1 + R_G + R_S)(R_S R_2 + a) - (R_G)(R_X R_1 + a)}{(R_S)\left[(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)\right]}$$

Taking reciprocal (since $R_{eq} = 1/G_{eq}$), we get

$$R_{eq} = \frac{(R_S)\left[(R_1 R_2)(R_s + R_x) + (R_1 + R_2)(a)\right]}{(R_1 + R_G + R_S)(R_S R_2 + a) - (R_G)(R_X R_1 + a)} \qquad \text{..........(30)}$$

Equation (30) adequately takes care of our pride!

Procedure

(i) Direct Verification

(1) The circuit board, to be used in this experiment, is shown in Fig (3)

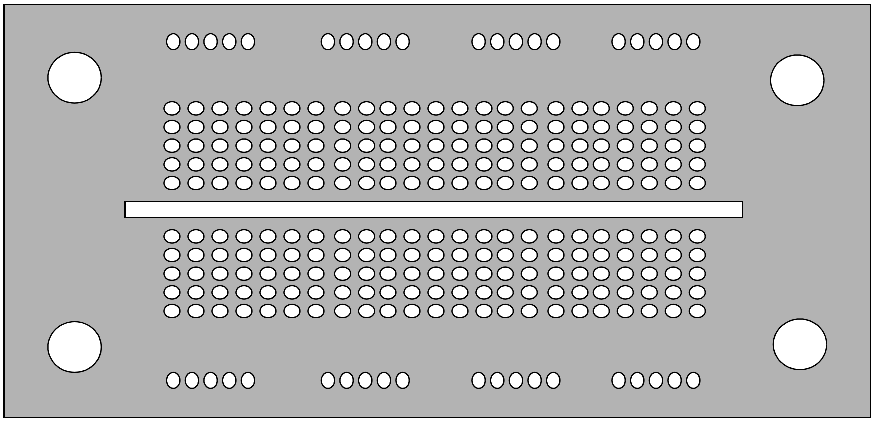

Fig (3). The Circuit Board

The top and bottom lines of holes contain 20 holes each, in 4 groups of 5 holes. All 20 holes in the top line are internally electrically connected together. The 20 holes in the bottom line are also similarly connected. But the holes in the top line are not connected to the holes in the bottom line. In between the top and bottom lines, we have two sets of 23×5 holes. All 5 holes in a column are connected together but holes in one column are not connected to the holes of any other column.

(2) The resistors to be used in this experiment have been chosen to be: 33 $k\Omega$, 56 $k\Omega$, 15 $k\Omega$, 100 $k\Omega$ and 10 $k\Omega$. Label the given resistors respectively as R_1, R_2, R_S R_X and R_G . Find the exact values of these resistors using the digital multimeter as ohmmeter (range 200 $k\Omega$) and record them in the data sheet, in ohms (and not in $k\Omega$).

(3) Set up the circuit on the circuit board using the given connecting wires, as shown in Fig (4). Connecting wires are shown as solid lines with filled circles at the two ends.

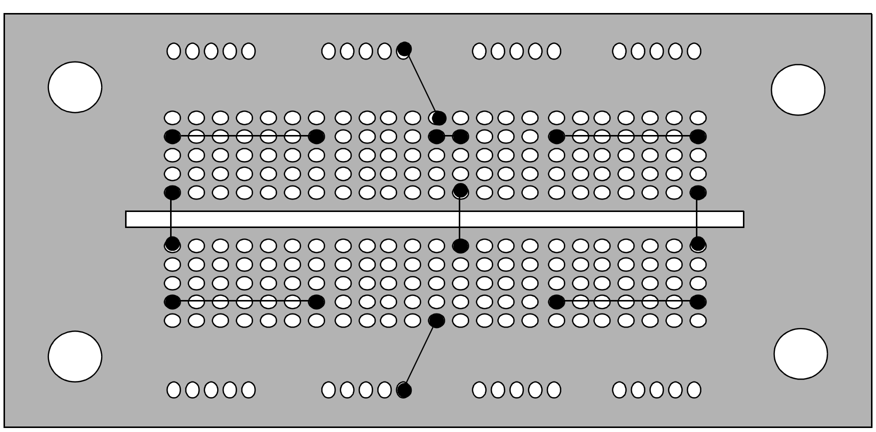

Fig (4) Inserting Connecting Wires for the Wheatstone's Bridge Circuit on the Circuit Board

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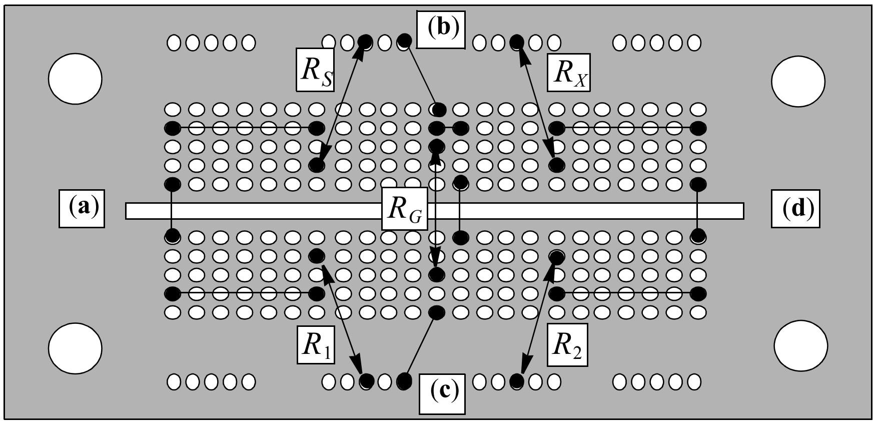

Fig (5) Inserting the 5 Resistors and Completing the Circuit

(4) Now insert the resistors. Resistors are shown by double arrows with filled circles at the ends. Please note that the entire top line of 20 holes is branch point b, the entire bottom line is branch point c, the entire right-most column (10 holes) is branch point d and the left-most column is branch point a

(5) Measure the equivalent resistance R_{eq} of the whole circuit (comprising of five resistors). This is accomplished by using an ohmmeter, in the manner shown in Fig (6). Please note that power supply has not yet been connected to the circuit. Record the value of R_{eq} in the data sheet

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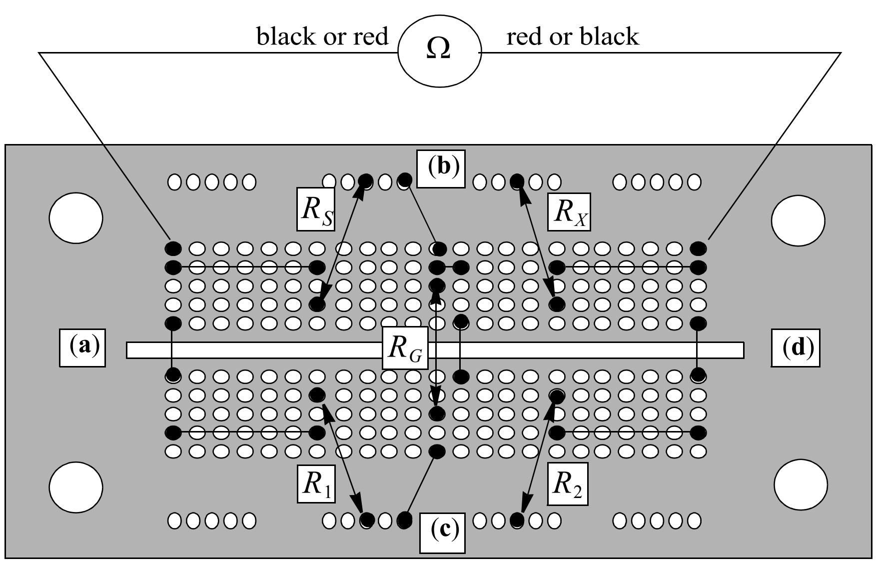

Fig (6 Measuring the Effective Resistance of the circuit.

(6) Connect the circuit board to the power supply and measure all six voltages, using one multimeter as voltmeter (set to 20 volts DC). The meter will read voltages to three decimal places of one volt. Details of measurement are shown in Fig (7).

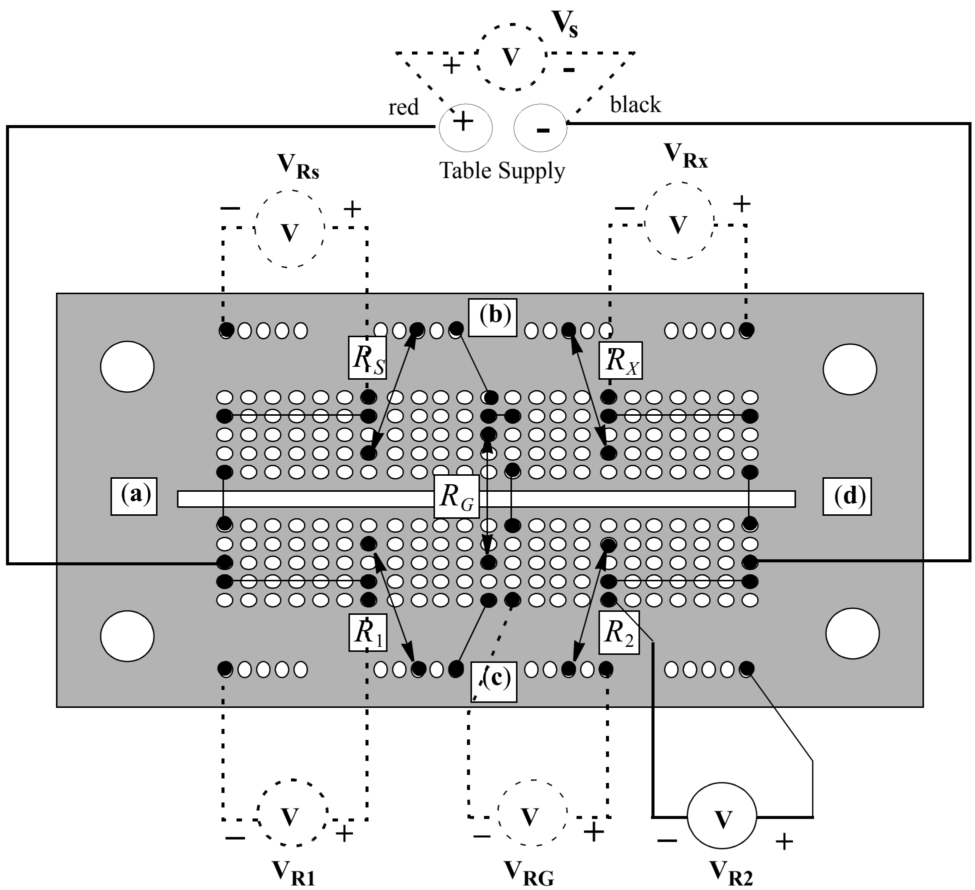

Fig (7Measuring Voltages on the Wheatstone's Bridge Circuit

(7) Measure all six currents using one multimeter as ammeter (set to $2\ mA$ range). Details of current measurement are shown in Fig (8). Five positions of the ammeter are shown with dotted lines. This means that the ammeter is not connected at these positions. We shall, however, be connecting the ammeter to these positions, one at a time; and when connected, the solid-line "jumper" wire (marked **"J"**) will be removed for the duration of measurement.

Even though all currents are in μA, one is sincerely advised to use the smallest mA range in the ammeter. Even the more sensitive (4.5-digit) digital multimeters display smaller-than-the-actual currents. On the milliampere range, values are, more or less, exact.

In Fig (8), the ammeter is shown measuring $I_{RG} = (I_1 - I_2)$. Ammeter is shown connected by solid lines (ending in solid circles). However, one should measure the supply current I_S, first. The arrangement is shown with dotted lines. When this value has been recorded, remove the ammeter, reconnect the wire from the positive terminal of power supply to the circuit board, as shown in Fig (7). Next proceed to measure the other 5 currents, one by one. For each measurement, connect the ammeter as shown by dotted lines (except the one for $I_{RG} = I_1 - I_2$) and remove the jumper wire (**J**). When the ammeter reading has been recorded, remove the ammeter and replace the jumper wire. There is no jumper wire for measuring I_S.

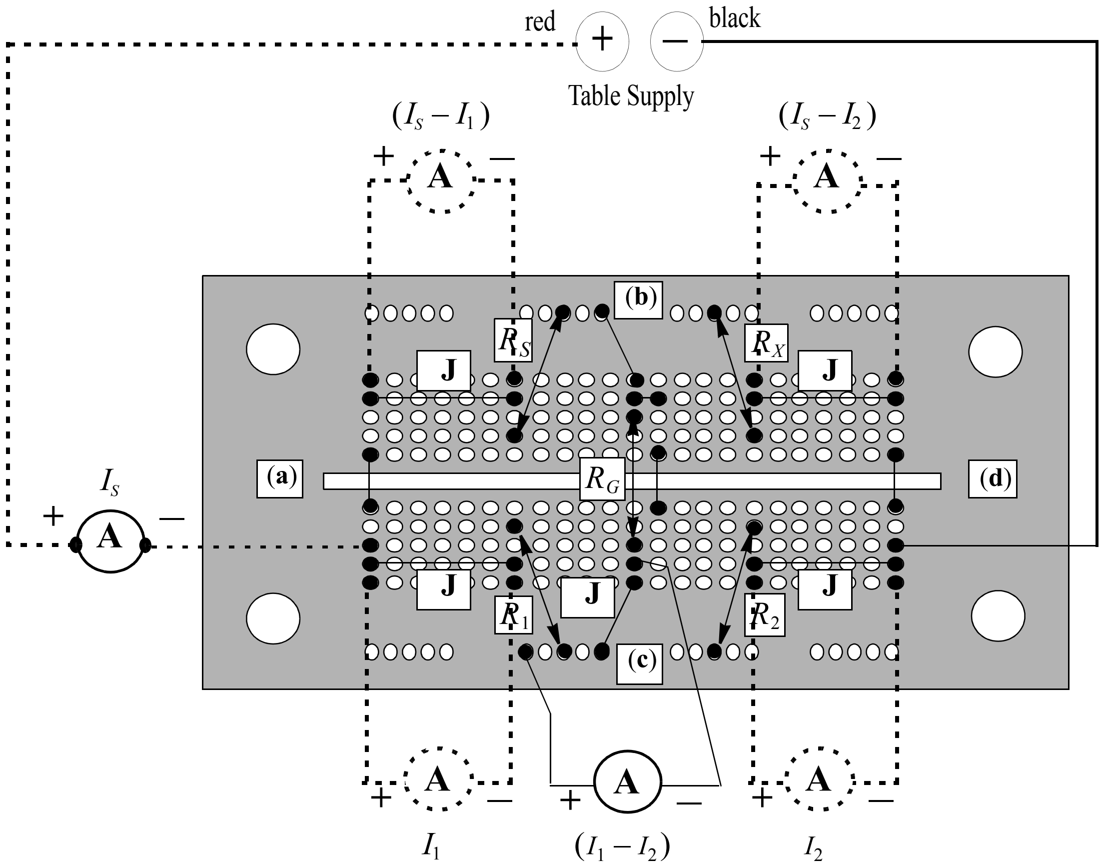

Fig (8) Wheatstone Bridge Circuit and Current Measurements

(8) This part of the experiment ends. Remove the ammeter and switch off. Do not disconnect circuit.

(b) Indirect Verification

(1) Set up the circuit shown in Fig (9)

(2) Use both multimeters as ammeters. Select DC amperes, range: $2\ mA$. (One multimeter is already set to the desired range.) We shall be using both ammeters simultaneously.

(3) Replace R_1 by a resistance box. Set it to $0\ k\Omega$. Record it as the first trial value of R_1.

(4) Set one ammeters to measure I_1 and the other to measure I_2. Remove jumper wires for both, R_1 and R_2

(5) Switch on the circuit and the two ammeters. Read and record values of I_1 and I_2 as the first trial values of I_1 and I_2.

(6) For the next 21 trials increase R_1 in steps of $1\ k\Omega$; (last setting: $21\ k\Omega$). For each, read and record values of I_1 and I_2.

(7) This completes the experiment. Switch off but leave everything as it is now. We are going to come back and do some more work.

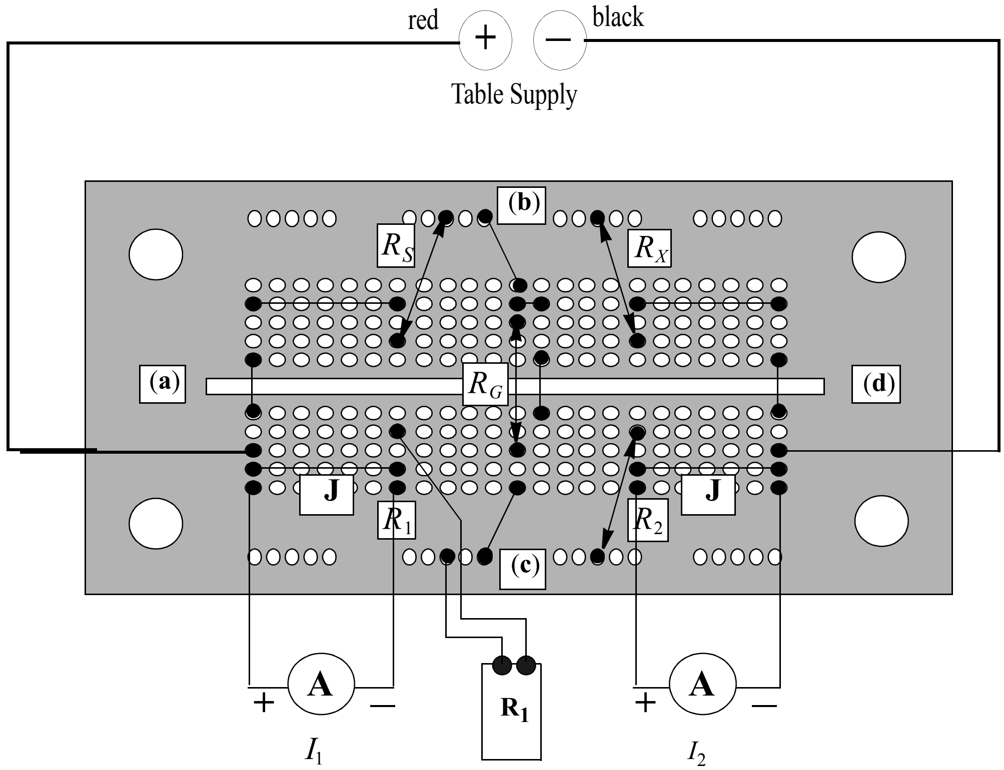

Fig (9) Circuit for Plotting a Suitable Graph

Calculations & Graphs

(i) Direct Verification

(1) To facilitate calculations, that may appear to be rather complicated, a table of calculations (called *Calculations Table*) is provided. It appears after the data sheet. The table also shows *Sampl*e calculations carried out using the nominal values of the resistors. Your calculations, using actual values of resistors, will be somewhat different but should generally match with the *Sample*. If you make any error in your calculations, it will be immediately detected. Include the *Calculations Table* sheets in your report as *Pre-Graph Calculations*.

(2) To compare the calculated (predicted) values of all parameters with their corresponding experimentally measured values, enter them side by side in the *Results Table*. Calculation of *percent errors* is not required.

(ii) Indirect verification

(3) Calculate (I_2 / I_1) for all 22 trials.

(4) Plot (I_2 / I_1) on y-axis and R_1 on x-axis, using a computer and get a straight line fit. Record values of the slope and intercept, as printed by the computer. Enter with correct interpretations in the *Results Table*, together with their calculated counterparts (from *Calculations Table)*. Find percent errors.

(iii) The Equivalent Resistance R_{eq}

(5) The value of R_{eq} has also been calculated in the *Calculations Table*.

(6) Find R_{eq} using V_S and I_S from the Data Table. This calculation uses Ohm's law. We shall call it the *Ohm's Law Value*. R_{eq} was also measured directly using an ohmmeter (step 5 of procedure) and was entered in the Data Table. We shall call it the *Ohmmeter Value*. Compare both these values of R_{eq} with the calculated value (*step (5) above*). Enter all 3 values in *Results* table. Calculate percent errors.

(iv) The Balanced Bridge.

(7) Write the equation of the straight line as printed out by the computer. Set (I_2 / I_1) equal to unity and solve for R_1. This is your R_{null}, the resistance needed for balancing the bridge or for the galvanometer null.

(8) The value of R_{null} has also been calculated in the *Calculations Table*. Enter both in the Results Table and find percent error.

(9) Now go back to your circuit on the table. Set this value of R_{null} in the resistance box and read the currents I_1 and I_2 . These will be found to be equal! Record in the Data Table. Values of R_{null} will be entered in the *Results Table* and percent errors will be found

(10) Disconnect the circuit and place everything neatly on the table.

(11) Complete the report by carefully completing the *Results*. Use the *Results* sheets provided.

Conclusions and Discussions

Write your conclusions from the experiment and discuss them.

What Did You Learn in this Experiment?

A hearty and thoughtful account of what you learned in this experiment by way of the principle and the techniques of experimentation, should be given.

Data & Data Tables

Name.................................... **Date**..............................

Instructor.............................. **Lab Section**...................

Partner.......................... **Table #**..........................

(i) Direct Verification

Table 1: Resistor Values

Resistor	Nominal Values (as determined from the color code) ($k\Omega$)	Actual Values (as determined using an Ohmmeter) (Ω)
R_{eff} (from step 5)	-------	
R_1		
R_2		
R_S		
R_X		
R_G		

Table 2: Measuring Voltages and Currents

Voltage names	Voltages (V)	Current names	Currents (mA)	Currents (μA)
V_S (from step 6)		I_S		
V_{R1}		$I_{R1} = I_1$		
V_{R2}		$I_{R2} = I_2$		
V_{RS}		$I_{RS} = (I_S - I_1)$		
V_{RX}		$I_{RX} = (I_S - I_2)$		
V_{RG}		$I_{RG} = (I_1 - I_2)$		

(ii) Indirect Verification:

Table 3: Varying R_1 and Measuring I_1 & I_2

Trial #	R_1 $(k\Omega)$	I_1 (mA)	I_2 (mA)	Trial #	R_1 $(k\Omega)$	I_1 (mA)	I_2 (mA)
1	0			12	11		
2	1			13	12		
3	2			14	13		
4	3			15	14		
5	4			16	15		
6	5			17	16		
7	6			18	17		
8	7			19	18		
9	8			20	19		
10	9			21	20		
11	10			22	21		

Balancing the Bridge

Setting R_1 to the value found from graph;

I_{R1} = mA

I_{R2} = mA

Pre-graph Calculations

$R_1 = 33000\Omega$ $R_2 = 56000\Omega$ $R_S = 15000\Omega$ $R_X = 100000\Omega$ $R_G = 10000\Omega$ $V_S = 5.000V$

$R_1 =$ $R_2 =$ $R_S =$ $R_X =$ $R_G =$ $V_S =$			
	expression	sample Calculates	your values
a	$R_X R_G + R_G R_S + R_S R_X$	2.65×10^{9}	
b	$R_S R_2 + a$	3.49×10^{9}	
c	$(R_1 + R_2)(a)$	2.3585×10^{14}	
d	$(R_1 R_2)(R_S + R_x) + c$	4.4837×10^{14}	
e	$R_x R_1 + a$	5.95×10^{9}	
f	$R_1 + R_G + R_S$	58000	
p	$R_S d$	6.72555×10^{18}	
q	fb	2.0242×10^{14}	
r	$R_G e$	5.95×10^{13}	
s	$q - r$	1.4292×10^{14}	
R_{eq}	p/s	47.05814442×10^{3} ¾	
I_1	$\frac{b V_S}{d}$	38.91875014×10^{-6} A	
I_2	$\frac{e I_1}{b}$	66.35145081×10^{-6} A	
t	$f I_1$	2.2572875	

$R_1 = 33000\Omega$ $R_2 = 56000\Omega$ $R_S = 15000\Omega$ $R_X = 100000\Omega$ $R_G = 10000\Omega$ $V_S = 5.000V$

$R_1 =$	$R_2 =$	$R_S =$	$R_X =$	$R_G =$	$V_S =$

	expression	sample Calculates	your values
u	$R_G I_2$	0.6635145	
v	$t - u$	1.59377299	
I_S	v / R_S	106.2515333×10^{-6} A	
I_{RS}	$I_S - I_1$	67.33278316×10^{-6} A	
I_{RX}	$I_S - I_2$	39.90008249×10^{-6} A	
I_{RG}	$I_1 - I_2$	$-27.43270071\times10^{-6}$ A	
V_{R1}	$R_1 I_{R1}$	1.2843187 V	
V_{R2}	$R_2 I_{R2}$	3.715681245 V	
V_{RS}	$R_S I_{RS}$	1, 009991747 V	
V_{RX}	$R_X I_{RX}$	3.990008249 V	
V_{RG}	$R_G I_{RG}$	–0.274327007 V	
V_S	$R_{eq} I_S$	4.9999999 V	
Slope	$\frac{R_X}{b}$	28.6533×10^{-6} ¾$^{-1}$	
Intercept	$\frac{a}{b}$	0.75931232	
w	$b - a$	8.40×10^{8}	
$R_{1,null}$	$\frac{w}{R_X}$	8400 ¾	

Table of Results **Name:** **Date:**

Studying Kirchhoff's Rules as Applied to a Wheatstone's Bridge Network.

(i) Direct Verification

Table 1. Calculated & Measured Values of Currents & Voltages

Serial #	Currents	Calculated Values μA	Measured Values μA	Voltages	Calculated Values (V)	Measured Values (V)
1	I_S			V_S		
2	$I_{R1} = I_1$			V_{R1}		
3	$I_{R2} = I_2$			V_{R2}		
4	$I_{RS} = (I_S - I_1)$			V_{RS}		
5	$I_{RX} = (I_S - I_2)$			V_{RX}		
6	$I_{RG} = (I_1 - I_2)$			V_{RG}		

(ii) The Equivalent Resistance of the Circuit R_{eff}:

Predicted Value:
(Calculations Table) $k\Omega$

Ohm's Law Value: $k\Omega$ percent error %

Ohmmeter Value $k\Omega$ percent error %

(ii) Indirect Verification:

(a) Ratio of Currents I_1 & I_2 when R_1 is shorted out.

Predicted value
(Calculations Table)

Experimental Value (i) percent error %
(Indirect Verification)

Experimental Value (ii) percent error %
(Data Table at R_1 = 0)

(b) Effective Conductance of Resistances R_2 , R_S , R_X & R_G

Predicted value
(Calculations Table) $\mu\Omega^{-1}$

Experimental Value (i)
(Indirect Verification) $\mu\Omega^{-1}$

percent error %

(iii) Value of Resistor R_{Null} *for balanced bridge:*

Calculated Value
(Calculations Table) $k\Omega$

Experimental Value: $k\Omega$
(Indirect Verification)

percent error %

Measured value of I_1 = mA

Measured value of I_2 = mA