Experiment # 7

Circuit Analysis - 1
The Crunching Technique: (a) Resistors

Principles

Defining Circuit & Circuit Analysis

An electrical circuit, in general, consists of a number of electrical components that may be connected to one or more sources of electricity. Electrical components are of two types: *(i) passive*: resistors, capacitors and inductors, and *(ii) active*: diodes, transistors and integrated circuits. Similarly the sources of electricity are of two types: (i) DC, and (ii) AC. Both, the components and the sources may be combined in three different modes: (i) series, (ii) parallel, and (iii) series-parallel. A circuit may have any number of components of the three types and any number of sources of either type, connected together in any of the three possible modes.

> *The purpose of circuit analysis is to determine (i) the voltages across each component of a given circuit, (ii) the currents that pass through each one of them, (iii) potential differences between any two given points in the circuit, and (iv) the terminal voltages of all sources.*

For our experiment, we impose two constraints. First: we shall leave out active components and deal only with the passive ones. Second: we shall confine ourselves to DC sources of electricity only. Whatever rationale we develop here, however, will be equally applicable to all types of components and sources. Again, by imposing these constraints, we have not put any limit on the number of components or sources or on the mode of their combinations.

Although we have some basic rules that help us to reach the above mentioned objectives, their applicability is limited to the very basic circuits. These rules are:

(1) Components connected together in "series" share a common current (or charge) that passes through (or gets deposited on) them but each has its own characteristic voltage.

(2) Components connected together in "parallel" share a common voltage but each has its own characteristic current that passes through it.

(3) Equivalent resistances and equivalent capacitances, in series or parallel configurations, are given by following formulae:

$$R_{eq,\,series} = \sum_n R_n \qquad \frac{1}{R_{eq,\,parallel}} = \sum_n \frac{1}{R_n} \qquad \text{..........(1)}$$

$$\frac{1}{C_{eq,\,series}} = \sum_n \frac{1}{C_n} \qquad C_{eq,\,parallel} = \sum_n C_n \qquad \text{..........(2)}$$

(4) The battery equations for circuits with (i) resistors only, and (ii) capacitors only are:

$$V_S = R_{eq}\, I_S \qquad \text{and} \qquad Q_S = C_{eq}\, V_S$$

Junctions, Strings & Loops

A junction is a point in a circuit where a set of parallel-connected components are connected to other parts of the circuit. Thus, a junction is a point where at least 3 wires meet.

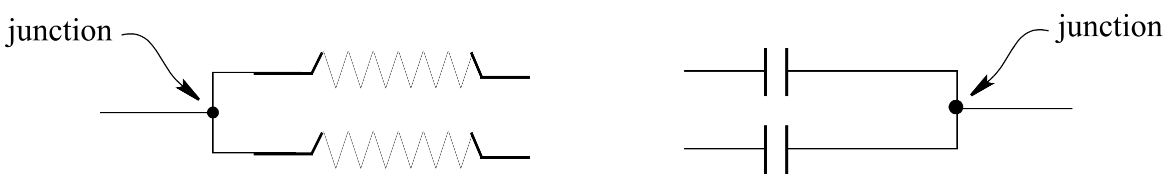


Fig (1) Junctions; A Minimum of Three Wires Meet

A string is an aggregate of components that are all connected in series to one another. We find strings in between a pair of junctions.

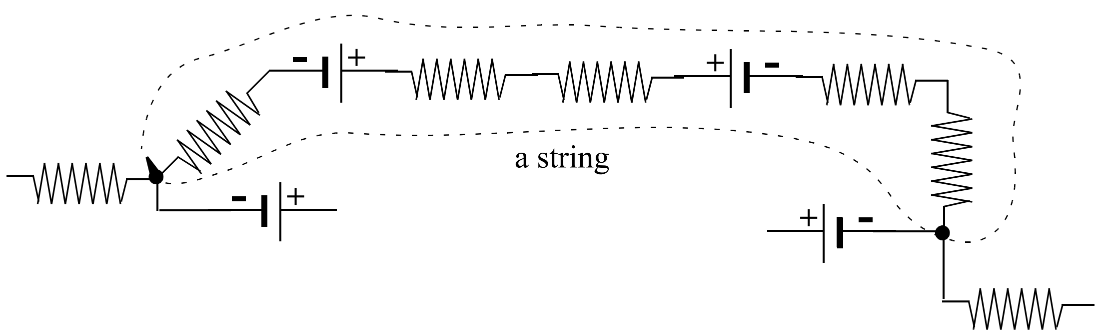


Fig (2) A string; A Series of Components in Between a Pair of Junctions

A loop is a closed configuration of components. It is made up of two strings in between a pair of junctions. It may also be a single string, folded around to make a closed configuration

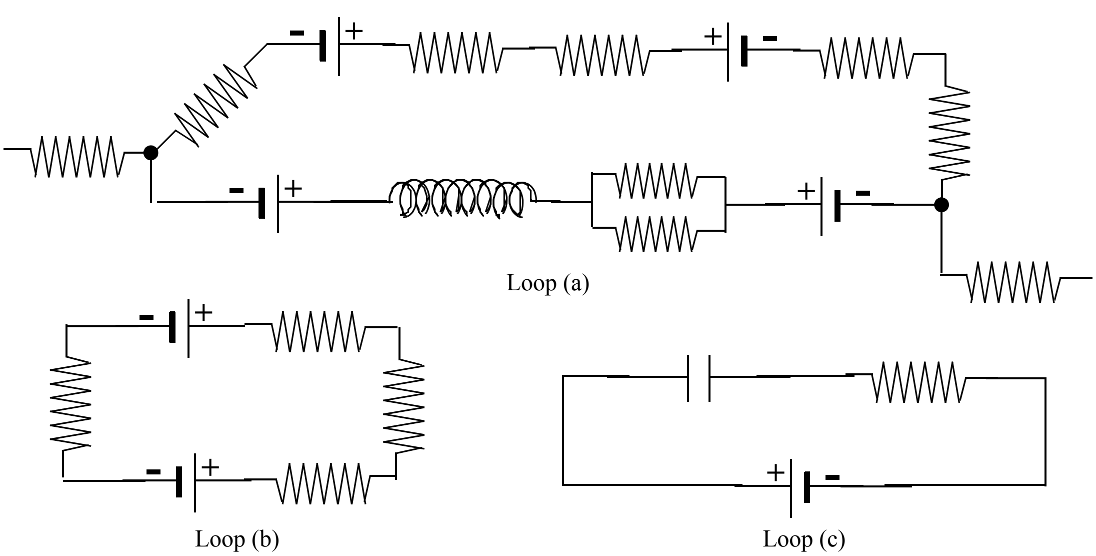


Fig (3) Examples of Loop

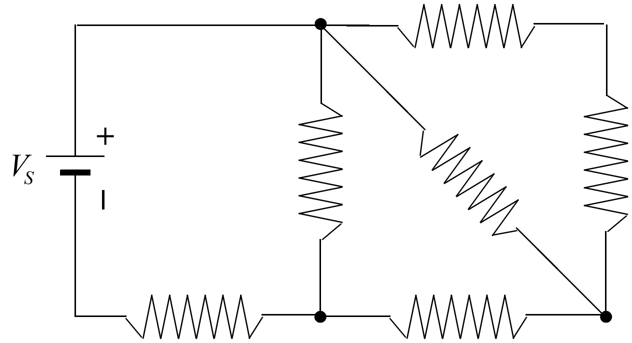
Basics of Crunching

Crunching technique can be applied to multi-loop circuits with two constraints (conditions): (i) all batteries should be in one string only, and (ii) there should be at least one pair of series- or parallel-connected components. In Fig (3), loop (a) is ineligible for crunching but loops (b) and (c) can be crunched. Loops (b) and (c) do not have junctions. There is only one string that has been made into a closed configuration.

To crunch, one seeks out a set of components that are either all in series or all in parallel. These are combined using either the series combination equation or the parallel combination equation. These are then replaced by one component. In what follows, we shall talk of resistors only but the same will equally apply to capacitors also. The set of components so chosen, must be as far away from the battery as possible. The ones in the vicinity of the battery must be crunched at the very end.

Objectives of the Experiment

To study the Crunching Technique as applied to the following circuit:



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

(ii) indirectly, by plotting a suitable graph.

Setting Up

We shall proceed with the crunching process. The circuit consists of one battery and a total of 6 resistors. The circuit is reproduced in Fig (4a). As can be seen, it has 3 junctions, (labeled *A*, *B* and *C*.), 5 strings and 5 loops. The states of the circuit during different stages of crunching are also shown in Fig (4).

In Fig (4a), the two resistors at the top left hand corner are found to be in series. This is our starting point. We promptly call them R_1 and R_2. We calculate their series combination as:

$$R_{1,2})_S = R_1 + R_2 = R_{12}$$

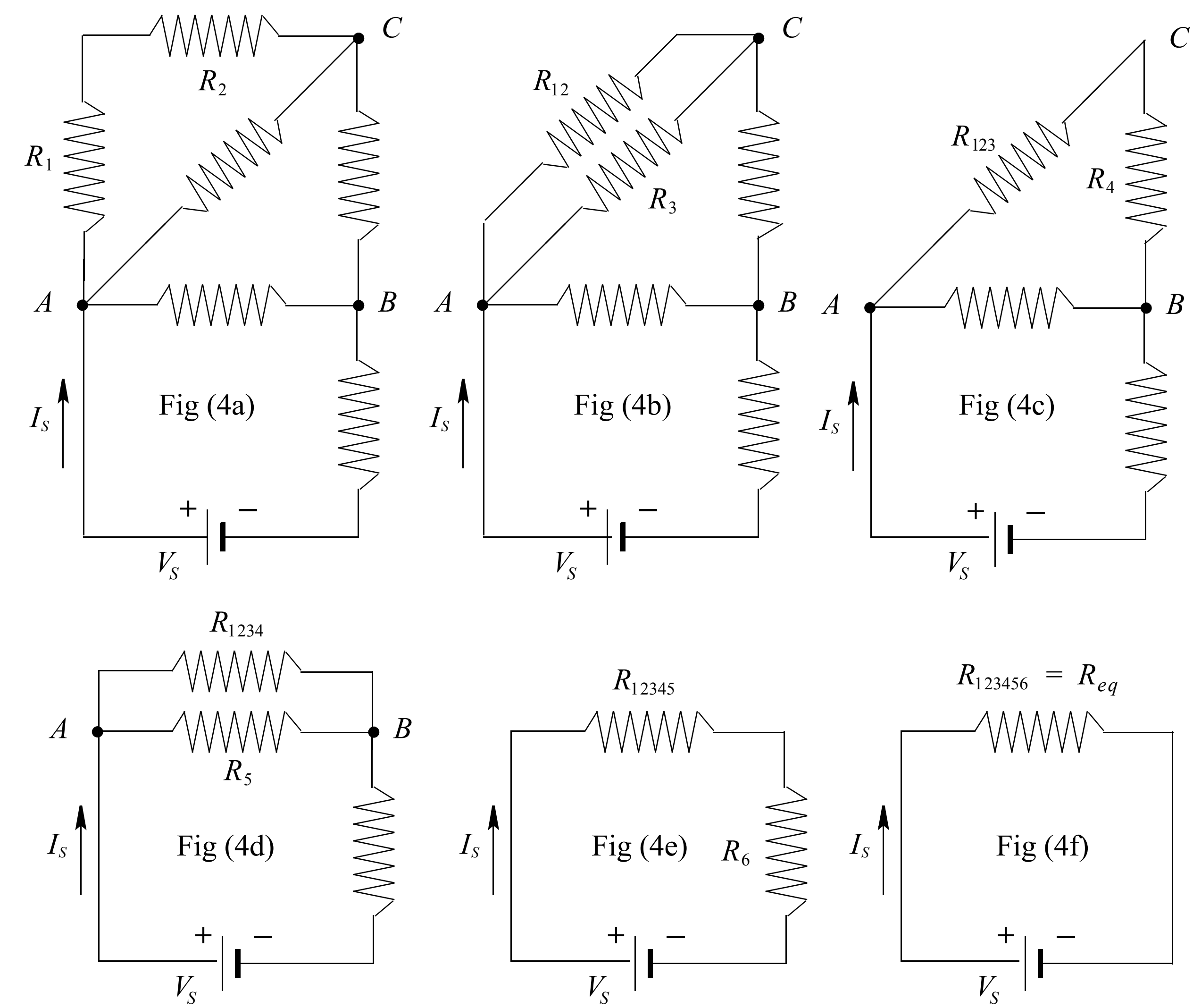


Fig (4) Steps of Crunching

In Fig (4b), the two resistors R_1 and R_2, are replaced by one resistor: R_{12}. Resistor R_{12} is found to be in parallel with another resistor which we name R_3. We calculate their parallel combination as:

$$R_{12,3})_P = [(R_{12}^{-1}) + (R_3^{-1})]^{-1} = R_{123}$$

In Fig (4c), the two resistors R_{12} and R_3 are replaced by one resistor; R_{123}. We find that junction C has disappeared and resistor R_{123} is now in series with another resistor which we name R_4. We calculate their series combination as:

$$R_{123,4})_S = R_{123} + R_4 = R_{1234}$$

In Fig (4d), the two resistors R_{123} and R_4 are replaced by one resistor:R_{1234}. Resistor R_{1234} is found to be in parallel with another resistor which we name R_5. We calculate their parallel combination as:

$$R_{1234,5})_P = [(R_{1234}^{-1}) + (R_5^{-1})]^{-1} = R_{12345}$$

In Fig (4e), the two resistors R_{1234} and R_5 are replaced by one resistor R_{12345}. We find that junctions B and C both have disappeared and resistor R_{12345} is now in series with the last resistor, to be named R_6. We calculate their series combination as:

$$R_{12345,\,6})_S = R_{12345} + R_6 = R_{123456} = R_{eq}$$

In Fig (4f) the two resistors R_{12345} and R_6 have been replaced by one resistor, R_{123456} or R_{eq}. This completes the crunching process. The whole circuit is replaced by one resistor and one battery. We now apply the battery equation and calculate the current I_S, supplied by the battery:

$$I_S = V_S / R_{eq}$$

We shall now proceed backward and calculate currents and voltages for each resistor. This can be done easily by following the scheme shown in Table # 1, below. We shall then follow it by calculating actual series and parallel combinations of resistors to get an expression for R_{eq} in terms of the six given resistors. This is given in Table # 2.

Table #1 Calculating Voltages and Currents for Every Resistor

	R	First: $V_S = R_{eq} I_S$ Subsequent $V = RI$	First $I_S = \frac{V_S}{R_{eq}}$ Subsequent $I = \frac{V}{R}$
	$R_{eq} =$ R_{123456}	$V_S =$ (given)	$I_S = \frac{V_S}{R_{123456}} =$
S	$R_6 =$	$V_6 = (R_6)(I_6) =$	$I_6 = I_S$
	$R_{12345} =$	$V_{12345} = (R_{12345})(I_{12345}) =$	$I_{12345} = I_S$
P	$R_5 =$	$V_5 = V_{12345}$	$I_5 = \frac{V_5}{R_5} =$
	$R_{1234} =$	$V_{1234} = V_{12345}$	$I_{1234} = \frac{V_{1234}}{R_{1234}} =$
S	$R_4 =$	$V_4 = (R_4)(I_4) =$	$I_4 = I_{1234}$
	$R_{123} =$	$V_{123} = (R_{123})(I_{123}) =$	$I_{123} = I_{1234}$
P	$R_3 =$	$V_3 = V_{123}$	$I_3 = \frac{V_3}{R_3} =$
	$R_{12} =$	$V_{12} = V_{123}$	$I_{12} = \frac{V_{12}}{R_{12}} =$

Table #1 Calculating Voltages and Currents for Every Resistor

	R	First: $V_S = R_{eq} I_S$ Subsequent $V = RI$	First $I_S = \frac{V_S}{R_{eq}}$ Subsequent $I = \frac{V}{R}$
S	$R_2 =$	$V_2 = (R_2)(I_2) =$	$I_2 = I_{12}$
	$R_1 =$	$V_1 = (R_1)(I_1) =$	$I_1 = I_{12}$

Table #2: Preparing to Develop an Equation for a Straight Line

to combine	process of combination	combined
$R_{1,2})_S$	$R_1 + R_2$	R_{12}
$R_{12,3})_P$	$[(R_1 + R_2)^{-1} + (R_3)^{-1}]^{-1} =$ $\left[\frac{(R_1 + R_2 + R_3)}{(R_3)(R_1 + R_2)}\right]^{-1} = \frac{(R_3)(R_1 + R_2)}{(R_1 + R_2 + R_3)}$	R_{123}
$R_{123,4})_S$	$\frac{(R_3)(R_1 + R_2)}{(R_1 + R_2 + R_3)} + R_4 =$ $\frac{(R_3)(R_1 + R_2) + (R_4)(R_1 + R_2 + R_3)}{(R_1 + R_2 + R_3)}$	R_{1234}
	Let $R_1 + R_2 = A$ $R_1 + R_2 + R_3 = B$	
	$\frac{(R_3)(A) + (R_4)(B)}{(B)}$	
$R_{1234,5})_P$	$\left[\left(\frac{(R_3)(A) + (R_4)(B)}{(B)}\right)^{-1} + (R_5)^{-1}\right]^{-1} =$ $\left[\frac{(B)}{(R_3)(A) + (R_4)(B)} + \frac{1}{(R_5)}\right]^{-1} =$	process continues
$R_{1234,5})_P$ (continued)	$\left[\frac{(R_5)(B) + (R_3)(A) + (R_4)(B)}{[(R_3 A) + (R_4 B)](R_5)}\right]^{-1} =$ $\left\{\frac{(B)(R_4 + R_5) + (R_3)(A)}{(R_5)[(R_3 A) + (R_4 B)]}\right\}^{-1} =$	R_{12345}

Table #2: Preparing to Develop an Equation for a Straight Line

to combine	process of combination	combined
	Let: $R_4 + R_5 = C$	
$R_{1234,5})_P$ (continued)	$\left\{ \dfrac{(B)(C) + (R_3)(A)}{(R_5)\left[(R_3 A) + (R_4 B)\right]} \right\}^{-1} =$ $\dfrac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{(B)(C) + (R_3)(A)}$	R_{12345} (continued)
$R_{12345,6})_S$	$\dfrac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{(B)(C) + (R_3)(A)} + \dfrac{R_6}{1}$	$R_{123456} = R_{eq}$

(A) Direct Verification

The circuit can be set up on a circuit board, such as the one shown in Fig (5). One can then measure all seven voltages and all seven currents using a DC voltmeter and a DC ammeter. These can then be compared with the calculated ones. These calculations are shown in Table #1 above, but necessary tables for these calculations for the experiment appear just after the Data Sheets

(B) Indirect Verification

Recall the battery equation:

$$V_S = R_{eq} I_S \qquad \text{..........(3)}$$

Using the value of R_{eq} from last row of Table (2), we get:

$$V_S = \left[\frac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{(B)(C) + (R_3)(A)} + \frac{R_6}{1} \right] (I_S)$$

Rearranging,

$$\frac{1}{I_S} = \frac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{(V_S)\left[(B)(C) + (R_3)(A)\right]} + \left(\frac{1}{V_S}\right)(R_6) \qquad \text{..........(4)}$$

One can measure source current I_S for a number of values of values of R_6. A graph of $(1/I_S)$ against R_6, will yield a straight line. The reciprocal of the slope of this straight line graph will produce V_S . The intercept represents the reciprocal of I_S for the case when R_6 is zero.

Procedure

(1) Direct Verification

(1) The circuit board, to be used in this experiment, is shown in Fig (5). The top and bottom lines of holes contain 20 holes each. These are arranged in 4 groups of 5 holes each. 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. The 5 holes in the upper part of the circuit board are not connected to the 5 holes in the lower part

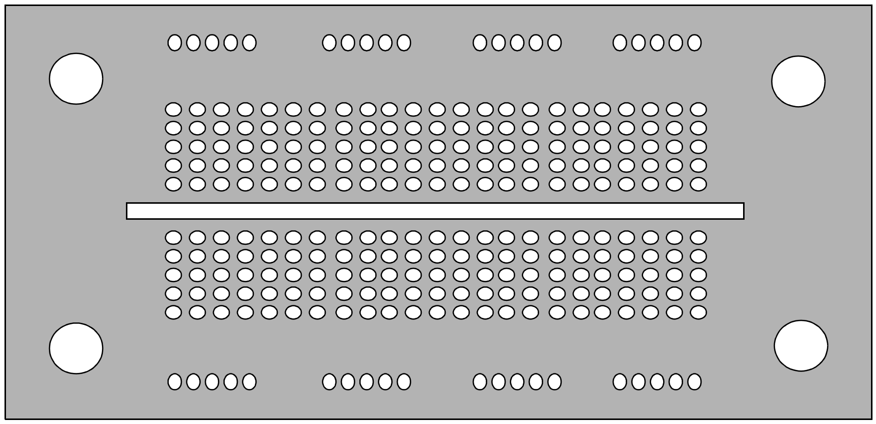


Fig (5) The Circuit Board

(2) The resistors to be used in this experiment have been chosen as: $R_1 = 47\ k\Omega$, $R_2 = 68\ k\Omega$, $R_3 = 56\ k\Omega$, $R_4 = 82\ k\Omega$, $R_5 = 150\ k\Omega$, and $R_6 = 100\ k\Omega$. Find the exact values of these resistors using the digital multimeter as ohmmeter (range $200\ k\Omega$) and record them in Table #1 of the data sheet.

The instructor may change these resistors and suggest a different set altogether.

(3) Start assembling the circuit by inserting the connecting wires on the board. These are represented by straight solid lines, with one filled circle at each end. All necessary connections are shown in Fig (6)

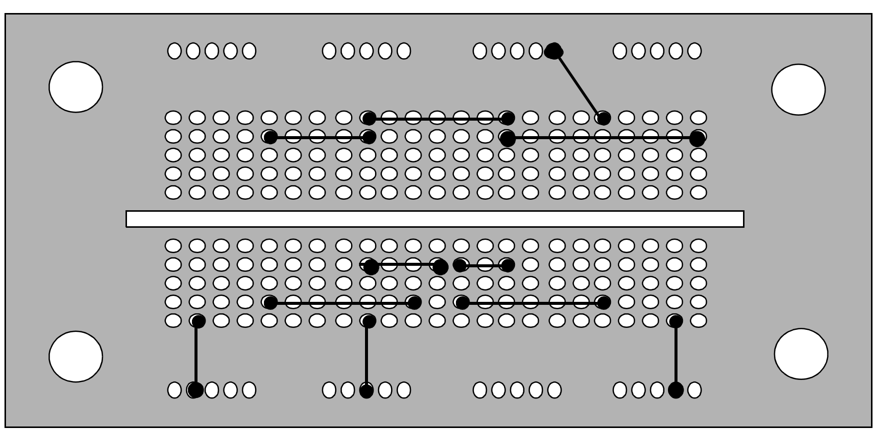


Fig (6) Inserting the Connecting Wires on the Circuit Board

(4) Next insert the resistors in their proper places. These positions are shown in Fig (7) as lines with double arrows. Connecting wires, already set up, are omitted here for clarity. Use a nose pliers (provided) to straighten out the terminals of resistors (if needed)

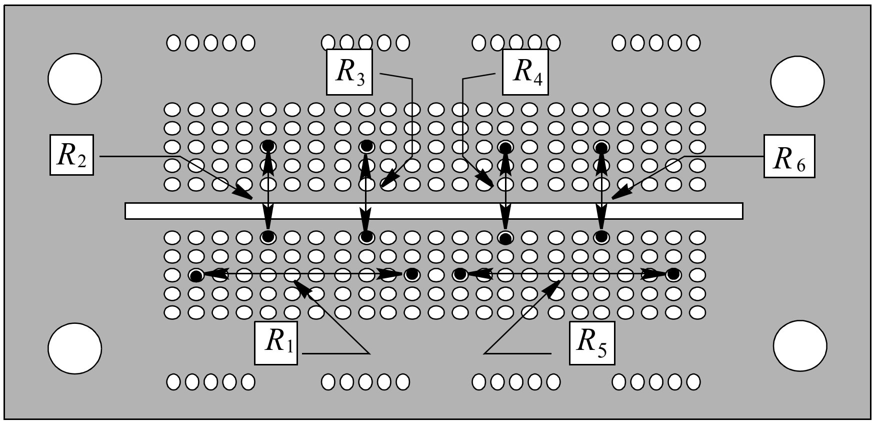


Fig (7) Mounting Resistors

The complete circuit is shown in Fig (8). We are ready to hook up the power supply.

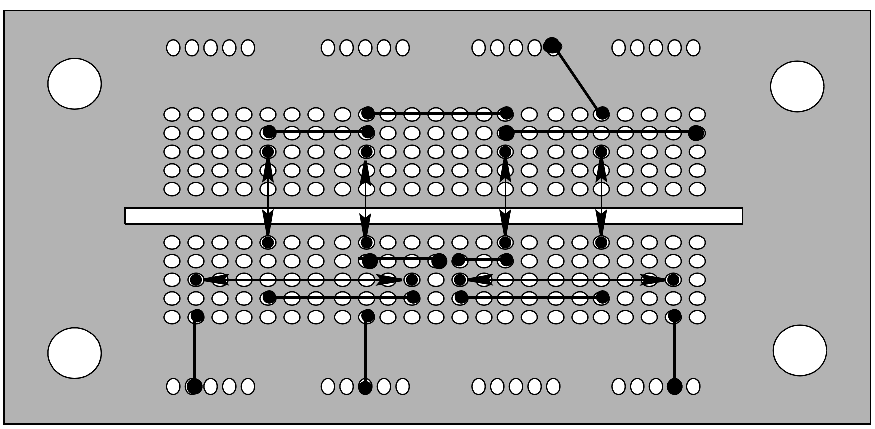


Fig (8) The Complete Circuit.

(5) Measure the equivalent resistance R_{eq} of the whole circuit (comprising of six resistors). This is accomplished by using an ohmmeter, in the manner shown in Fig (9). Set the ohmmeter to the 200 $k\Omega$ range. Please note that power supply has not yet been connected to the circuit. Record the value of R_{eq} in the data sheet.

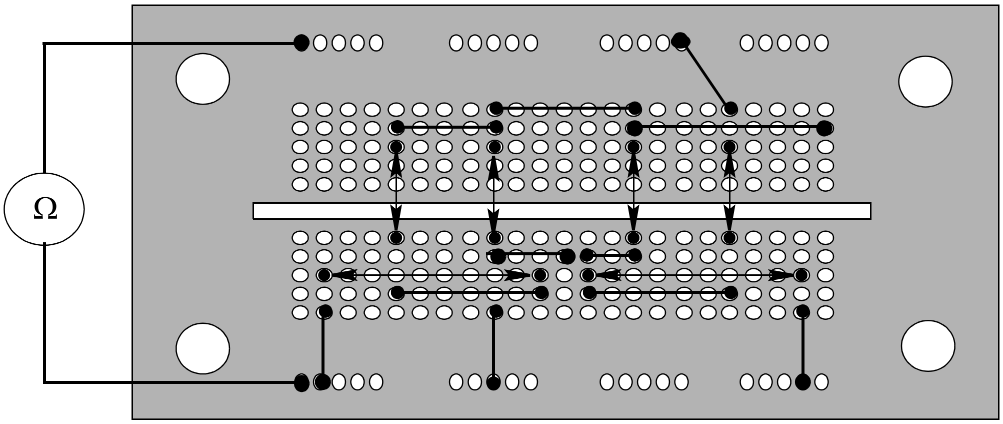


Fig (9) Measuring the Effective Resistance of the circuit.

(6) Connect the circuit board to the 5 volt (fixed) output terminals of the stabilized DC power supply. Measure all seven voltages using the given multimeter as voltmeter (set to $20V$ DC). Details of measurement are given in Fig (10), (11) and (12). Each diagram shows voltmeter connections to the circuit with proper polarities which must be set correctly. Each diagram shows several voltmeters, connected simultaneously. There is, however, only one voltmeter. Voltages are measured one after the other and not all at the same time

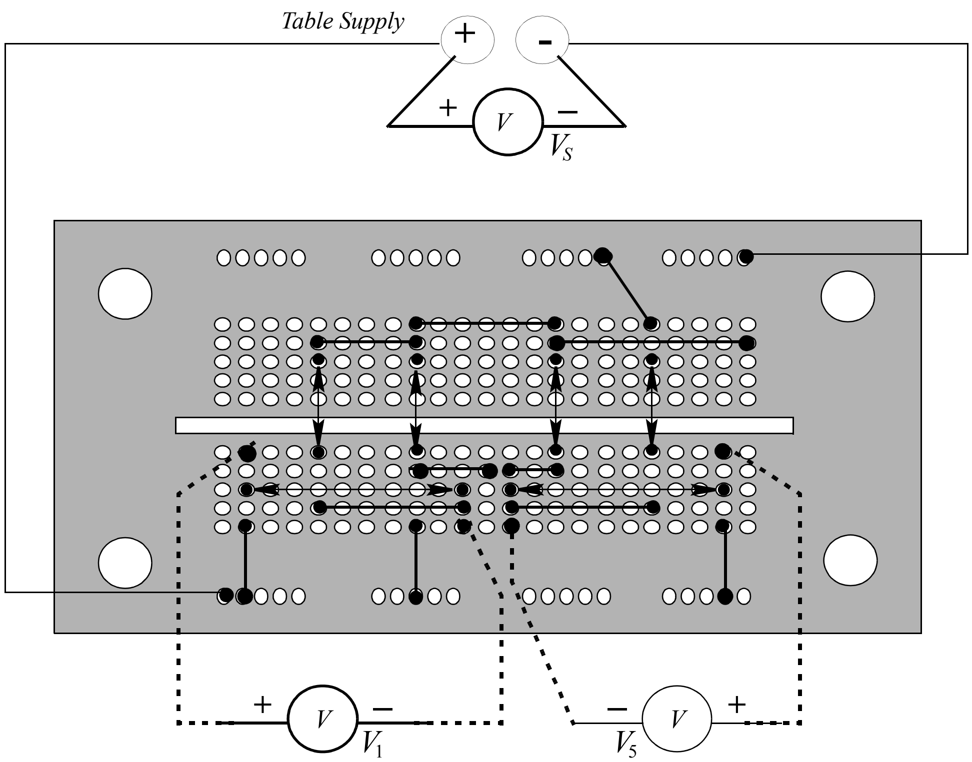


Fig (10) Measuring Voltages Across the Power Supply and Across Resistors R_1 and R_5

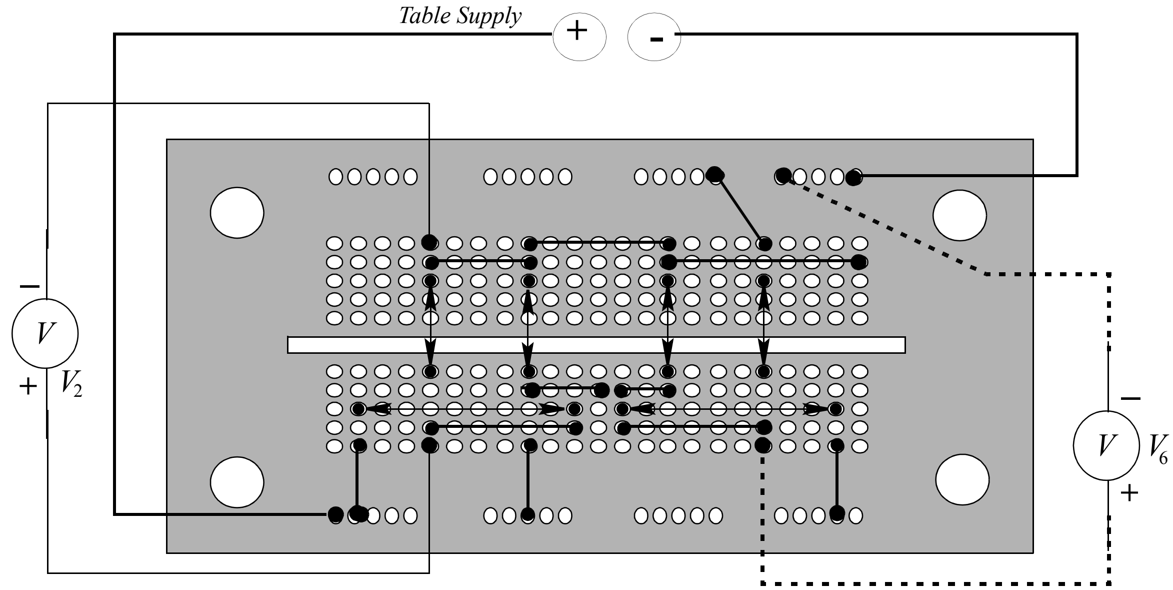


Fig (11 Measuring Voltages Across Resistors R_2 *and* R_6

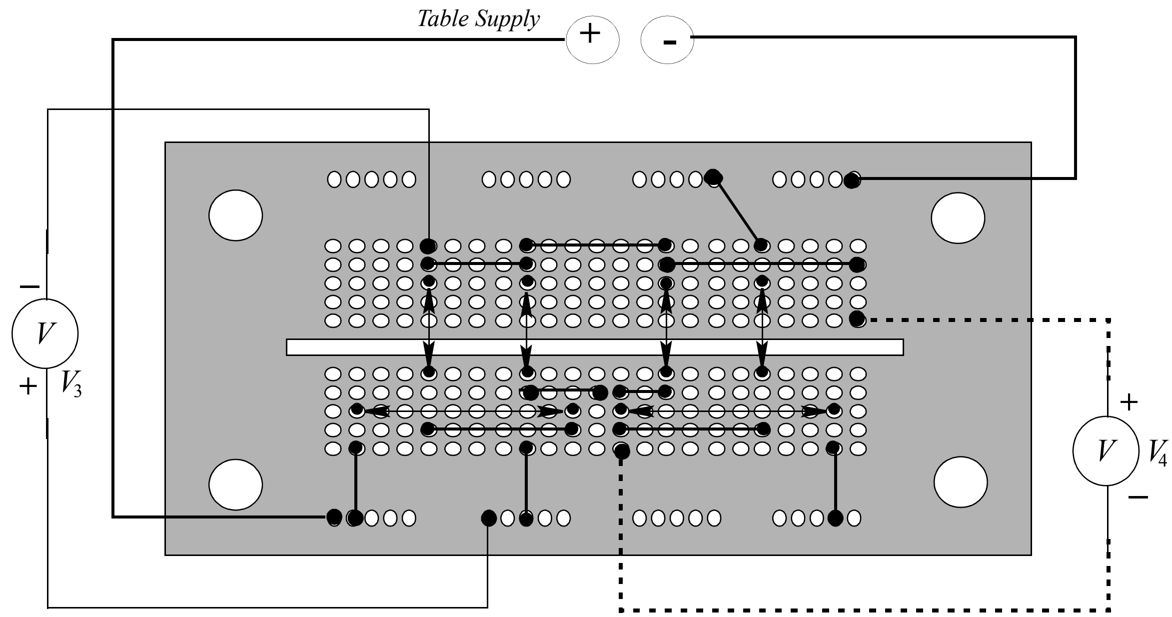


Fig (12 Measuring Voltages Across Resistors R_3 *and* R_4

(7) Measure all seven currents using the given multimeter as ammeter (set to $2\ mA$, DC). Details of current measurement are given in Fig (13), (14) and (15).

For measuring a current, one has to break the circuit and connect ammeter in series. To facilitate this, a *jump* wire (marked *J*) is provided with each resistor. Thus for each current measurement, there is onejump wire. One needs to pull this wire out after connecting the ammeter at points shown in the diagram. Removing jump wire puts ammeter in series with the resistance whose current is being measured. In Fig (13), the ammeter is measuring the supply current I_S. When this value has been recorded, remove the ammeter, reconnect the wire from the positive terminal of table supply to the circuit board, as before. Note that no jump wire is needed for measuring I_S.

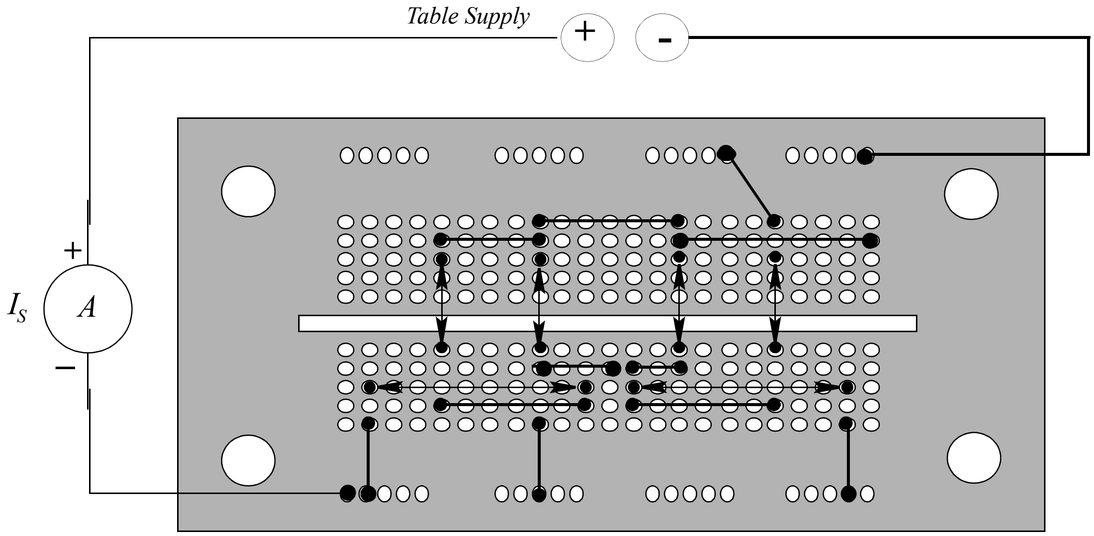


Fig (13) Measuring Source Current I_S

Next proceed to measure the other six currents, one at a time. For each measurement, connect the ammeter as shown and then remove the jump (*J*) wire. When the ammeter reading has been recorded, remove the ammeter and replace the jump wire. Follow diagrams (14) and (15) carefully.

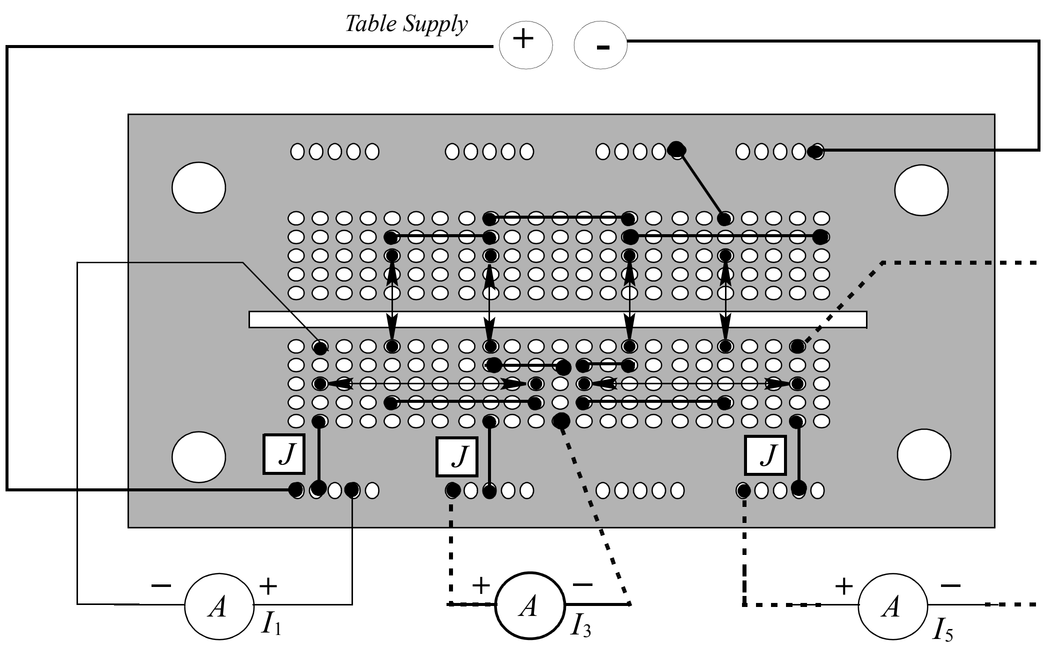


Fig (14) Measuring Currents I_1 *,* I_3*, and* I_5

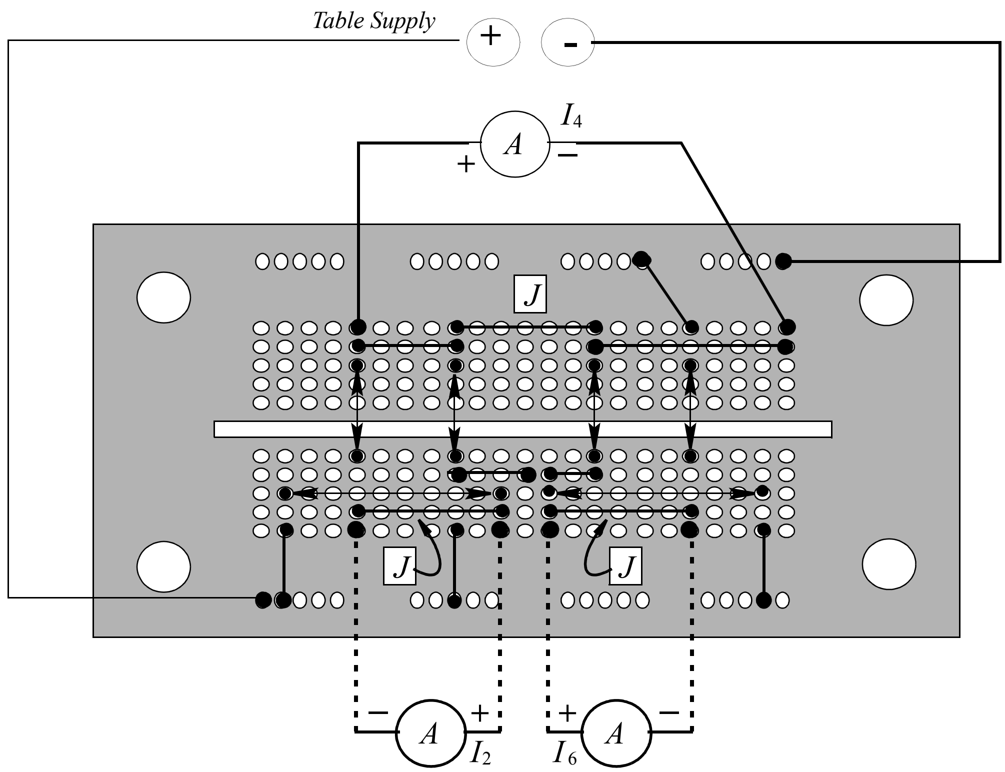


Fig (15) Measuring Currents I_2, I_6, and I_4

(8) When all currents have been measured then this part of the experiment ends. Remove meter and switch off. Do not disconnect the circuit.

(b) Indirect Verification

(1) Set up the circuit as shown in Fig (16)

(2) Set the given multimeters as ammeter; to measure current in the range of 2 mA, DC.

(3) Replace R_6 by a resistance box. Set it to zero resistance. Record it as the first trial value of R_6.

(4) Switch on the circuit and the ammeter. Read and record the value of I_S

(5) For the next 24 trials increase R_1 in steps of 5 $k\Omega$; (last setting: 120 $k\Omega$). For each value of R_6, read and record values of I_S

(6) This completes the experiment. Switch off and disconnect. Arrange everything neatly on the table.

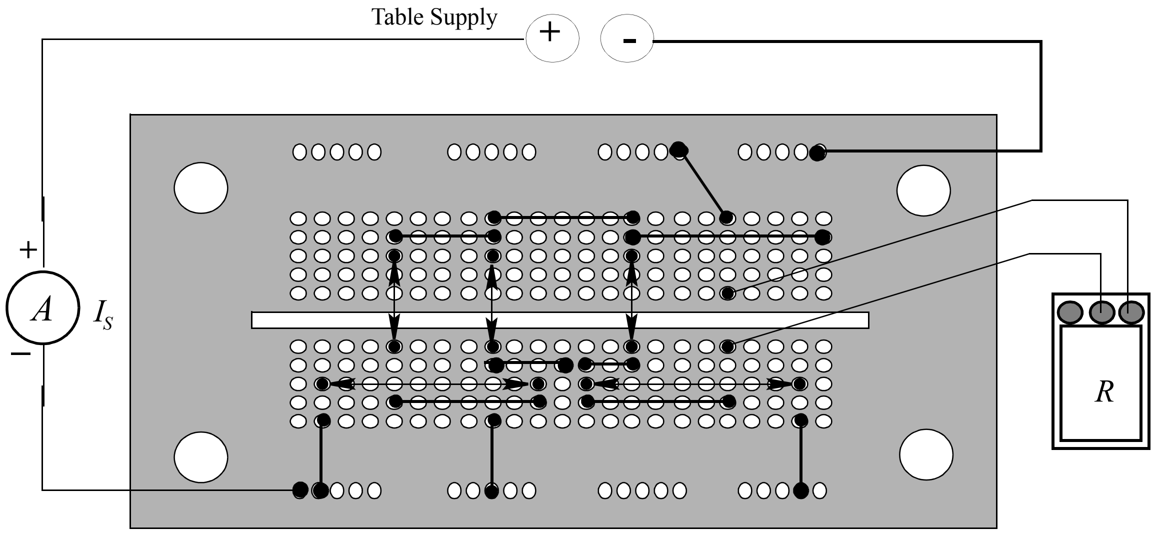


Fig (16) Circuit for Plotting a Suitable Graph

Calculations & Graphs

(A) Pregraph Calculations

(1) Calculate currents and voltages for all six resistors, by completing Table #1.

(2) Calculate R_{eq} by using the formula in the middle column of the last row of Table #2, (reproduced below for ready reference). When carrying out these calculations, convert $k\Omega$ to Ω.

$$R_{eq} = \frac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{(B)(C) + (R_3)(A)} + R_6 \qquad \text{..........(5)}$$

where

$$A = R_1 + R_2 \qquad B = R_1 + R_2 + R_3 \qquad C = R_4 + R_5$$

(3) Calculate the y-axis intercept b of the graph as;

$$b = \left(\frac{1}{V_S}\right)\left(\frac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{\left[(B)(C) + (R_3)(A)\right]}\right) \qquad \text{..........(6)}$$

Calculate the reciprocal of b. This will represent the ***expected*** *value* of the source current I_S, when R_6 is zero.

(4) Find reciprocals of all 25 values of I_S. This should be done on the computer. Ask the computer to display the data in scientific notation and show 4 decimal places. When punching the currents in the computer data sheet, convert them to *amperes* from *milliamperes*. Example: 0.0222 *mA* = 0.0222 x 10^{-3} *A*. You should also punch the data in scientific notation.

(B) Graph

There is only one graph. Plot $(1/I_S)$ on the y-axis and R_6 on the x-axis. Ask the computer to fit a straight line (or a second order polynomial) and print the equation of the line with 5 decimal places. The value of r^2 should also be printed out.

(C) Postgraph Calculations

(5) Take the reciprocal of the slope (printed out by the computer). This is the ***experimental*** value of V_S . Compare with the actual value that was measured in step (6) of *Procedure*. Find percent error.

(6) Find the reciprocal of the y-axis intercept, printed out by the computer. This is the ***experimental*** value of the source current I_S, when R_6 is zero. Also take the reciprocal of the value of *b*, as found from Eqn (6) above. This is the ***expected*** value of the source current I_S, when R_6 is zero. Compare the two and find percent error.

(7) Complete the report with *Results* (special *Results* sheet is 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

Supply Voltage V_S : Nominal value: 5 *Volts* Actual value: *Volts*
Equivalent Resistance R_{eq} as found in step (5) of Procedure: k¾

Table 1: Resistor Values

Resistor	Nominal Values ($k\Omega$)	Actual Values (Ω)	Resistor	Nominal Values ($k\Omega$)	Actual Values (Ω)
R_1			R_4		
R_2			R_5		
R_3			R_6		

Table 2: Experimentally Measured Values of Voltages and Currents

Resistor Voltages	Voltages (V)	Resistor Currents	Currents (mA)	Currents (μA)
V_s		I_S		
V_1		I_1		
V_2		I_2		
V_3		I_3		
V_4		I_4		
V_5		I_5		
V_6		I_6		

(ii) Indirect Verification:

Table 3: Varying R_6 and Measuring I_S

Trial #	R_6 $(k\Omega)$	I_S (mA)	Trial #	R_6 $(k\Omega)$	I_S (mA)	Trial #	R_6 $(k\Omega)$	I_S (mA)
1	0		11	50		21	100	
2	5		12	55		22	105	
3	10		13	60		23	110	
4	15		14	65		24	115	
5	20		15	70		25	120	
6	25		16	75		26		
7	30		17	80		27		
8	35		18	85		28		
9	40		19	90		29		
10	45		20	95		30		

Additional Data or Information (if any):

Pre-Graph Calculations

(a) Calculating R_{eq}

Table 3. Finding R_{eq}

	combining	Your combination	result
1	$R_{1,2})_S$		R_{12}
2	$R_{12,3})_P$		R_{123}
3	$R_{123,4})_S$		R_{1234}
4	$R_{1234,5})_P$		R_{12345}
5	$R_{12345,6})_S$		$R_{123456} = R_{eq}$

(b) Calculating Voltages and Currents for all Resistors

Table 4. Calculating Voltages and Currents for all Resistors

	R	your values Ω	$V = RI$ V	$I = V/R$ A	I mA
	$R_{123456} = R_{eq}$		(given)		
S	R_6				
	R_{12345}				
P	R_5				
	R_{1234}				
S	R_4				
	R_{123}				
P	R_3				
	R_{12}				
S	R_2				
	R_1				

Calculating the Intercept

$$b = \left(\frac{1}{V_S}\right)\left(\frac{(R_5)\left[(R_3 A) + (R_4 B)\right]}{\left[(B)(C) + (R_3)(A)\right]}\right)$$

where

$$A = R_1 + R_2 \qquad B = A + R_3 \qquad C = R_4 + R_5$$

Calculating the Intercept b

	steps of calculations	using nominal values	using your values
	$R_1 = 47000\,\Omega$ $R_2 = 68000\,\Omega$ $R_3 = 56000\,\Omega$ $R_4 = 82000\,\Omega$ $R_5 = 150000\,\Omega$ $R_6 = 100000\,\Omega$ $V_S = 5.00\,V$		
1	$A =$ $R_1 + R_2$	$47000 + 68000 =$ $115,000\,\Omega$	
2	$B =$ $A + R_3$	$115000 + 56000 =$ $171,000\,\Omega$	
3	$C =$ $R_4 + R_5$	$82000 + 150000 =$ $232,000\,\Omega$	
4	$(R_3)(A)$	$56000 \times 115000 =$ 6.440×10^9	
5	$(R_4)(B)$	$82000 \times 171000 =$ 1.40220×10^{10}	
6	$(R_3)(A) + (R_4)(B)$ or (#4) + (#5)	$6.440\times10^9 + 1.40220\times10^{10} =$ 2.04620×10^{10}	
7	$(R_5)[(R_3)(A) + (R_4)(B)]$ or $R_5 \times$ (#6)	$150000 \times 2.04620\times10^{10} =$ 3.06930×10^{15}	

Calculating the Intercept b

	steps of calculations	using nominal values	using your values
	$R_1 = 47000\,\Omega$ $R_2 = 68000\,\Omega$ $R_3 = 56000\,\Omega$ $R_4 = 82000\,\Omega$ $R_5 = 150000\,\Omega$ $R_6 = 100000\,\Omega$ $V_S = 5.00\,V$		
8	$(B)(C)$ or $(\#2)\times(\#3)$	$171000 \times 2322000 = 3.96720\times10^{10}$	
9	$(B)(C)+((R_3)(A))$ or $(\#8)+(\#4)$	$3.96720\times10^{10} + 6.440\times10^{9} = 4.61120\times10^{10}$	
10	$\left[\frac{(R_5)[(R_3)(A)+(R_4)(B)]}{(B)(C)+((R_3)(A))}\right]$ or $\frac{(\#7)}{(\#9)}$	$\frac{3.06930\times10^{15}}{4.61120\times10^{10}} = 66.5185\times10^{3}\,\Omega$	
11	$b = \left(\frac{1}{V_S}\right)\times\left[\frac{(R_5)[(R_3)(A)+(R_4)(B)]}{(B)(C)+((R_3)(A))}\right]$ or $b = \left(\frac{1}{V_S}\right)\times(\#10)$	$\frac{66.5185\times10^{3}}{5.00} = 13312.36988\ \frac{\Omega}{V}$	
12	$\frac{1}{b}$	$75.1181\times10^{-6}\,A$	

The equation printed out by the computer contains slope and intercept.

(1) Take reciprocal of slope. This is V_S . Compare with the actual value and find percent error.

(2) Take reciprocal of intercept. It should match the last number in row #12 of this table.

Table of Results

Name: **Date:** **Partner's Name**

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Crunching A Six-Pack (of Resistors)

(i) Direct Verification

Verification By Direct Measurements Using a Multimeter

Table 4: Experimental & Expected Values of Voltages and Currents

Source and Resistor Voltages V				Source and Resistor Currents μA			
	Experimental	Expected	Percent Error		Experimental	Expected	Percent Error
V_s				I_S			
V_1				I_1			
V_2				I_2			
V_3				I_3			
V_4				I_4			
V_5				I_5			
V_6				I_6			

(ii) Equivalent Resistance of the Circuit

Table 6. Equivalent Resistance of the Given Circuit

	Expected Value (from Table 3) $k\Omega$	Experimental Value (step 5 of Procedure) $k\Omega$	% error
R_{eq}			

(iii) Indirect Verification:

Verification By Studying the Inverse Dependence of Source Current I_S on R_6

(a) Source Voltage V_S.

Description	Expected Value	Experimental Value	Error
source voltage	(V)	(V)	%

(b) Source Current I_S when R_6 is zero.
(i) as found by using indirect method.

Description	Expected Value	Experimental Value	Error
source current as calculated using component values	(step #12 of table #6)	(step #2 of postgraph calculations)	%

(b) Source Current I_S when R_6 is zero.
(ii) as found by setting R_6 equal to zero in the experiment.

Description	Expected Value	Experimental Value	Error
source current as found by setting $R_6 = 0$ in the experiment	(step #12 of table #6)	(step #3 of indirect verification)	%