# Engineering 1040

# Laboratory Exercises (Electric Circuits/Digital Logic Modules)

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Acknowledgements: Dr. J.E. Quaicoe for significant parts of the first two labs.

Dr. N. Krouglicof for the greater part of the last three labs.

### Preface

The five laboratory exercises in this manual have been designed to reinforce the concepts encountered in the Electric Circuits and Digital Logic course modules. They form a mandatory portion of the course, and while they are valued at 5% of the overall mark (10% including the Mechanisms Module(s)), unexcused missed labs will result in an incomplete grade for the course. Official documentation, such as a doctor's note in the case of illness, is required in order to be excused from graded work. Documented valid reasons for missing graded work, including labs, will permit the transfer of the relevant marks to either the midterm or the final examination as agreed to by the instructor and the student.

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# Submission Format for Labs Associated with the Circuits/Digital Logic Portions of Engineering 1040

#### General:

(1) Use a **cover page** as shown following these **general** instructions:

(2) Start the **Prelab** immediately after the cover page. *EACH PERSON* in the group must submit a Prelab. To obtain full marks for a lab report, the Prelabs for all but the first experiment must be shown to the lab Teaching Assistant before the lab starts.

(3) The name of the person must be attached to the top of each Prelab.

(4) Label the Prelab sections as they are in the online manual.

(5) Use only one side of the paper in answering the Prelab questions as well as in the experimental write-up.

(6) Start the actual lab write-up (one per **group**) **after** the last page of the Prelab. See the write-up requirements following the sample cover page in this document. Put the words "**Lab Report**" at the top margin of the first page of the actual write-up of the experiment.

(7) Label the lab report sections as they appear in the online manual.

(8) Staple the Cover Page, Prelabs, and Lab Write-up together in a single package.

(9) Graphs may be done manually or electronically (for example, using Microsoft Excel or any other convenient software).

(10) Submission of each lab package is required at the start of the subsequent lab.

The following four pages elaborate on some of the above points.

# **Sample Cover Page**

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**Engineering 1040** 

Lab #n

Title: Title of Lab as it Appears in the Online Manual

Names: Name 1 and Student Number

Name 2 and Student Number

Date: Date that experiment was done

### <u>Prelab:</u> Name of first person and Student Number

At the end of person #1's Prelab, on a new page start the second person's Prelab with

### <u>Prelab:</u> Name of second person and Student Number

#### Lab Report

**<u>Purpose</u>**: Restate the purpose of the lab as found in the online manual – feel free to use your own words.

<u>Apparatus and Materials</u>: List in a column. Be sure to give the make and model of the apparatus if applicable. For example for the first lab:

- (1) 2 Fluke 8010A Digital Multimeters (DMM)
- (2) 1 Sun Equipment Powered Breadboard; Model: PBB-4060B
- (3) Standard Resistors: 4.7  $\Omega$ , 18  $\Omega$ , 39  $\Omega$ , 47  $\Omega$ , 68  $\Omega$ , 82  $\Omega$ , 2×100  $\Omega$ , 150  $\Omega$ , 330  $\Omega$
- (4) Two sets of leads with banana plugs and alligator clips
- (5) Various connecting wires

**Theory:** Give the equations used (along with the meanings of their symbols). For example, in Lab #1, part of the theory would be:

<u>Ohm's Law:</u> The voltage (v), current (i) and resistance (R) either for a circuit element or the whole circuit are related as

$$v = iR \dots (1)$$

.... and so on (for example, in Lab 1, you would also give the power formula).

**Procedure:** You may simply say "As per lab manual."

Label each part of the Experiment report according to the titles given in the manual. **Part #n: Title of this part.** For example in Lab #1 you would have first

#### Part 4.1 OHM'S LAW

The first sub-heading should be:

#### Data:

Put the labeled circuit diagram (if relevant) at the beginning of this section.

Under this sub-heading, also put (for example):

#### TABLE 1 - Voltage and Current Measurements for a <u>99.4</u> $\Omega$ Resistor

Carefully draw the table and fill it in with the measured or calculated values as required.

Also, in the case where table entries require calculations, **provide sample calculations**. That is, if there are several calculations which have exactly the same form, provide a

single sample. The other calculations will, of course, be completed and entered into the table, but there is **no need to show many calculations** which are identical in form.

The next heading should be (as required)

#### **Questions, Discussion and Conclusion(s):**

Label these according to their labels in the manual.

**Repeat the above format for subsequent parts** of the experiment. For example in Lab #1, the next heading would be

#### Part 4.2 VOLTAGE AND CURRENT MEASUREMENTS FOR A SIMPLE SERIES CIRCUIT

The first sub-heading should be:

#### <u>Data:</u>

Put the labeled circuit diagram (if relevant) at the beginning of this subheading.

Under this sub-heading, also put (for example):

#### TABLE 2 - Resistance, Current and Voltage Measurements

Carefully draw the table and fill it in with the measured or calculated values as required.

Also, in the case where table entries require calculations, provide sample calculations.

The next heading should be (as required)

#### **Questions, Discussion and Conclusion(s):**

Label these according to their labels in the manual.

... and so on.

# This general approach should be taken in all lab write-ups. It may vary slightly depending on the requirements.

#### EXP 1040-EL1 BASIC RESISTIVE CIRCUIT PARAMETERS

#### PURPOSE

To (i) investigate the relationship between voltage and current in a simple resistive circuit and to (ii) examine the condition for maximum power transfer to a load in such a circuit.

#### **1.0 INTRODUCTION**

(Note: A significant portion of this introduction to the Digital Multimeter is either taken directly or adapted from a Laboratory Manual for the former Engineering 1333 Basic Electrical Concepts and Circuits course prepared by Dr. J. Quaicoe.)

The **digital multimeter** (DMM) is one of the most versatile, general-purpose laboratory instruments capable of measuring dc and ac voltages and currents as well as resistance. The quantity being measured is indicated by a numerical display as opposed to a needled deflection on a scale as in analog meters. The numerical readout offers the advantages of higher accuracies, elimination of parallax reading error or misreading of the scale and increase in the speed of measurements.

A *typical* DMM has three terminals of which one is a COMMON ungrounded terminal (usually black). One of the two terminals (usually red), is the positive reference terminal for current measurements (mA) and the other is the positive reference terminal for voltage and resistance (V/k $\Omega$ /s). Several switches are provided to select the measurement mode (i.e., DC mA, DCV, ACV, etc.) and the meter range. For this course the DMM which will be *commonly used* is the **Fluke 8010A**. For this reason, the Fluke DMM is discussed in more detail here. Figure EL1.1 shows the front panel features of the Fluke 8010A.



Figure EL1.1 The display for the Fluke 8010A (taken from [1]). Label 9 does not apply here.

The main elements of the meter are as follows: (1) An LCD Digital splay.

- (2) **AC/DC Function Switch** (should be OUT for dc and IN for ac measurements).
- (3) V/mA/k $\Omega$ /S Function Switches for measuring voltage, current, resistance and conductance. These are used in combination with (2) depending on whether the circuit is ac or dc. The conductance measurements required pushing the k $\Omega$  switch along with a **pair** of conductance range switches.
- (4) **Range Switches** for selecting the measurement ranges switch IN means that the range is selected.
- (5) **mA Input Connector** this is protected with a 2A fuse. Use the **red** lead in this input.
- (6) **COMMON Input Connector**. This is the test lead connector used as the 'low' or 'common' input for all measurements. To keep from being confused, use the **black lead** in this input.
- (7) V/mA/kΩ/S Input Connector. This is the test lead connector used for all voltage, resistance, continuity and conductance measurements. Use the red lead in this connector.
- (8) **10A Input Connector**. This is used for the 10A Range current function. (It won't be used in this course.)
- (9) Not available on the 8010A meter.
- (10) **Power Switch**. IN is ON.

#### Before connecting the meter, the appropriate measurement mode must be selected and the meter range set to its highest value.

In this experiment, the measurement of current, voltage and resistance using the DMM is examined.

#### 1.1 Voltage Measurements - The DMM as a Voltmeter

Voltage is measured **ACROSS** a given element by placing the meter in **PARALLEL** with the element. The positive (red) lead is connected to the assumed positive reference and the negative (black) lead to the assumed negative reference. With this connection the meter will read positive if the assumed polarities (i.e. the +- directions) are correct. See Figure EL1.2.

All measurements of voltage or potential difference in a circuit require that a reference point, assigned a voltage of zero, be established. Such a point is known as the REFERENCE NODE and is indicated on a circuit by the "ground" symbol. In our simple circuits it will be assumed to be the same as the node to which the negative terminal of the voltage supply is connected.

#### 1.2 Current Measurements - The DMM as an Ammeter

Current **THROUGH** an element is measured by placing the meter in **SERIES** with the element. This may require the circuit connection to be broken (open-circuited) and the meter placed in the circuit. **Power should be OFF when disconnecting any element**. The meter will read positive when conventional current is flowing into the positive (red) lead. See Figure EL1.3.



Figure EL1.2 Voltage measurement with the Fluke 8010A (taken from [1]).



Figure EL1.3 Current measurement with the Fluke 8010A (taken from [1]).

#### 1.3 Resistance Measurements - The DMM as an Ohmmeter

The resistance of a resistor can be measured using the DMM. The resistor is connected between the positive voltage lead and the common lead. When the  $k\Omega$  mode is selected the resulting display is a measure of the resistance. See Figure EL1.4.

Although resistive elements come in many shapes and sizes, a large class of resistors fall into the category which is used for circuit components. The most common type of resistor is the carbon composition or carbon film resistor. Multicolored bands are painted on the resistor body to indicate the standard value of the resistance. Figure A.1 in the appendix gives the colour codes for carbon composition resistors.



Figure EL1.4 Resistance measurement with the Fluke 8010A (taken from [1]).

#### **1.4** The Accuracy of the Measurements

The accuracy with which the DMM measures each quantity and the frequency range of the input quantity being measured are specified by the manufacturer (usually underneath the meter). These specifications should be examined to determine the accuracy of the reading.

#### REFERENCES

- [1] 8010A/8012A Digital Multimeters Instruction Manual, John Fluke MFG. CO., INC., 1993.
- [2] E.W. Gill, Engineering1040, Mechanisms and Electric Circuits, Electric Circuits, Module, 2008.

#### 2.0 PRELAB

- 2.1 Read Section 1 of EXP 1040-E1L and pages 8-20 of Reference [2].
- 2.2 Determine the colour coding for each of the following resistors: i) 4.7  $\Omega$  ii) 18  $\Omega$  iii) 47  $\Omega$  iv) 100  $\Omega$  v) 330  $\Omega$
- 2.3 If the resistor in 2.2 (v) has a 'gold' band tolerance, determine the range of values which the resistance may take.
- 2.4 For  $R < 200 \text{ k}\Omega$ , the 8010A DMM has a maximum error given by  $\pm (0.2\%)$  of the reading + 1 digit). Consider the following example: A resistor with colour bands indicating a resistance of 100  $\Omega$  and a tolerance of  $\pm 5\%$  is measured with the DMM and found to have a value of 98.1  $\Omega$ . The maximum error is found as follows:

98.1  $\Omega \pm (0.2\% \text{ of } 98.1 \Omega + 1 \text{ digit})$  where one digit now corresponds to 0.1  $\Omega$ . Therefore, the measurement becomes 98.1  $\Omega \pm (0.002 \times 98.1 \Omega + 0.1\Omega) = 98.1 \Omega \pm (0.2 \Omega + 0.1\Omega) = 98.1 \Omega \pm 0.3 \Omega$ 

Note that  $(0.002 \times 98.1 \Omega)$  was rounded to  $0.2 \Omega$  since it is not meaningful to say that the precision of the error is greater than that indicated by the last digit measurable by the device. From the point of view of the error, the resistance value lies in the range extending from 97.8  $\Omega$  to 98.4  $\Omega$ . Notice that this value is well within the tolerance specified (the manufacturer's tolerance of ±5% guarantees that the resistance is somewhere between 95  $\Omega$  and 105  $\Omega$ ). Thus, using the multimeter and the specified accuracy we have determined a much smaller error on the value of the actual resistance.

Using the above example, determine the error and range of values for a standard value 150  $\Omega$  resistor which is measured with the DMM as having a resistance of 148  $\Omega$ . Does this fall within the gold-band tolerance?

- 2.3 The components of the circuit of Figure EL1.5 has the following values:  $v_s = 10 \text{ V}$ ,  $R_1 = 100 \Omega$ ,  $R_2 = 150 \Omega$ . Use Kirchhoff's voltage and current laws to find
  - i) the currents through the resistors having the directions shown in the figure,
  - ii) the voltages across the resistors having the polarities shown in the figure,
  - iii) the power dissipated by each resistor, and
  - iv) the power supplied by the source

Show that the total power developed in the circuit is equal to the total power dissipated.



Figure EL1.5 A series circuit containing two resistors.

2.4 In Figure EL1.5, determine the equivalent resistance "seen" by the voltage source, i.e the input resistance of the circuit, given by  $R_{in} = v_s/i_1$ .

#### 3.0 APPARATUS AND MATERIALS

2 Fluke 8010A Digital Multimeters (DMM) 1 Sun Equipment Powered Breadboard; Model: PBB-4060B Standard Resistors: 4.7  $\Omega$ , 18  $\Omega$ , 39  $\Omega$ , 47  $\Omega$ , 68  $\Omega$ , 82  $\Omega$ , 2×100  $\Omega$ , 150  $\Omega$ , 330  $\Omega$ Two sets of leads with banana plugs and alligator clips Various connecting wires

#### 4.0 EXPERIMENT

#### 4.1 OHM'S LAW

Consider the simple circuit shown in Figure EL1.6:



Figure EL1.6 A simple single-resistor dc circuit.

- 4.1.1 Construct the circuit of Figure EL1.6 on the breadboard using a 100  $\Omega$  resistor. The A represents a DMM used as an ammeter and the V represents a DMM used as a voltmeter. The latter DMM will be used to measure the resistance before being actually used as a voltmeter. DO NOT CONNECT OR TURN ON the voltage source at this stage. *Measure* the value of *R* using the DMM specified by setting that device on the 200  $\Omega$  range (also see the Introduction to the lab). Record the value in the title of Table 1.
- 4.1.2 Connect the voltmeter DMM ACROSS R in accordance with the directions given for voltage measurements specified in the Introduction to the lab. That is, connect the red lead from the voltmeter to the + side of R shown in the diagram and the black lead to the side of R. Set the voltmeter range to 20 V dc. Connect the ammeter (DMM) with the red lead on the same node as the black lead for the voltmeter and the black lead on the same node as COM terminal of the powered breadboard. Set the ammeter range to 200 mA. Connect the red lead from the 0 to 16 V terminal of the breadboard power to the same node as the + side of R. NOW turn on the voltage source (powered breadboard) and adjust the supply until the voltmeter (DMM) reads approximately 2 volts.

- 4.1.3 Record the voltmeter reading and the ammeter reading for the situation in 4.1.2 in Table 1. Adjust the power supply to give voltmeter readings of approximately 5, 8, 11 and 14 volts making sure to read the corresponding ammeter readings. Record all voltmeter and corresponding ammeter readings in Table 1.
- 4.1.4 From the data of Table 1, plot a graph of voltage versus current and from it determine the value of R. Compare this value with the value of R measured using the DMM in 4.1.1 and suggest possible reasons for any discrepancy.

Voltage (V) ±(0.1%+1digit) <sup>*</sup>	Current (A) ±(0.3%+1digit)*

TABLE 1 - Voltage and Current Measurements for aΩ Resistor

\* These accuracies for the voltage and currents are found on the bottom of the 8010A.

#### 4.2 VOLTAGE AND CURRENT MEASUREMENTS FOR A SIMPLE SERIES CIRCUIT

- 4.2.1 On the breadboard, set up the circuit of Figure EL1.7, but **do not yet connect the voltage source**. Resistor  $R_1$  is the standard 100  $\Omega$  used in part 4.1. Record its measured value in Table 2. Again using the DMM as an ohmmeter, measure the standard 150  $\Omega$  resistor and also record its value in Table 2.
- 4.2.2 Now connect the voltage source (using the red lead from the 0-16 V to node A and the



Figure EL1.7 A series circuit with two resistors. Note the *chosen* polarities for the voltages and the directions for the currents.

black lead from the COM terminal to node B). Using one of the DMMs as a voltmeter set to read **dc volts**, switch on the source and adjust it to give a reading of +10 V dc on the DMM.

- 4.2.3 Measure the voltages across  $R_1$  and  $R_2$  with the polarities shown. Record the readings in Table 2.
- 4.2.4 Using the second DMM measure, and record in Table 2, the currents through each resistor taking into account the correct sign as indicated by the directions in Figure EL1.7.
- 4.2.5 Using the measured quantities, calculate the power dissipated by each resistor. Record the results in Table 2.
- 4.2.6 Compare the measured and standard values of the resistances and the measured and calculated values of the currents, voltages and power. Comment on the results.
- 4.2.7 Verify that the power delivered by the voltage source is equal to the total power dissipated by the resistors.

Parameter/Variable	Calculated or Standard (Prelab)	Measured
$R_1(\Omega)$		
$R_2\left(\Omega ight)$		
<i>i</i> <sub>1</sub> (mA)		
<i>i</i> <sub>2</sub> (mA)		
$v_{AB}(V)$		
$v_1(V)$		
$v_2(V)$		
$P_1(\mathbf{W})$		
$P_2(W)$		
$\sum P_{\text{dev}}(W)$		
$\sum P_{\text{diss}}(\mathbf{W})$		

TABLE 2 – Resistance, Current and Voltage Measurements

#### 4.3 POWER TRANSFER TO A LOAD RESISTOR

Here we use the same circuit set-up as in Figure EL1.7, but now we will consider that  $R_2$  is a **load resistor** ( $R_L$ ) and we wish to determine the power absorbed by the load for various resistive values, while keeping  $R_1$  fixed at its measured value found in step 4.2.1. Also, notice that the polarities have been changed (this is an arbitrary decision) – see Figure EL1.8.



Figure EL1.8 A series circuit containing a single resistor  $R_1$  connected to a resistive load  $R_L$ .

- 4.3.1 Using the DMM as an ohmmeter, measure the following standard resistors and record the values in Table 3: 4.7  $\Omega$ , 18  $\Omega$ , 39  $\Omega$ , 47  $\Omega$ , 68  $\Omega$ , 82  $\Omega$ , 100  $\Omega$ , 150  $\Omega$ , 330  $\Omega$ . The 100  $\Omega$  resistor is in addition to the one used in part 4.2.1. Also, you have already measured the 150  $\Omega$  resistor and may use its value as found in 4.2.1.
- 4.3.2 With  $R_L$  (i.e.  $R_2$ ) taking the successive measured values of the 4.7  $\Omega$ , 18  $\Omega$ , 39  $\Omega$ , 47  $\Omega$ , 68  $\Omega$ , 82  $\Omega$ , 100  $\Omega$ , 150  $\Omega$ , and 330  $\Omega$  resistors, use the DMM as a voltmeter to determine the load voltage  $v_L$  across  $R_L$ . When the 4.7  $\Omega$  and 18  $\Omega$  resistors are used for  $R_L$  it might be useful to set the DMM on the 2 V range. For the other resistors use the 20 V range. Record all voltage readings in Table 3.
- 4.3.3 Using the measured values for  $v_L$  and  $R_L$  calculate, and record in Table 3, the power absorbed by each load resistor.
- 4.1.5 From the data of Table 3, plot a graph of Load Power versus Load Resistance, sketch a smooth curve through the points, and from this graph, observe and record the value of  $R_L$  for which the maximum power is absorbed. How does this resistance compare with  $R_1$ ? How does the power absorbed by  $R_1$  compare with that absorbed by the load resistor when the latter absorbs maximum power?

#### 5.0 CONCLUSIONS

State a conclusion for each of the three parts of the experiment.

Standard Value of $R_L$ ( $\Omega$ )	Measured Value of $R_{\rm L} (\Omega)$	Load Voltage, v <sub>L</sub> (V)	Load Power, P <sub>L</sub> (W)
4.7			
18			
38			
47			
68			
82			
100			
150			
330			

**TABLE 3 – Load Power Measurements** 

#### APPENDIX A

#### (Taken from a Laboratory Manual for the former Engineering 1333 Basic Electrical Concepts and Circuits course prepared by Dr. J. Quaicoe.)

Figure A.1 shows the color code for carbon composition resistors, along with the procedure for determining the resistance and tolerance from the color codes.

Table A.1 gives a list of readily available standard values of resistors. (The Boldface figures are available in the laboratory). If a designer requires other than a standard value, such as 3.8 k $\Omega$ , then a 3.9 k $\Omega$  resistor will probably be employed since a 3.8 k $\Omega$  resistor falls within the limits of a 3.9 k $\Omega$  resistor with a 10% tolerance.



Figure A.1 Color code for carbon composition [2]

Example: Find the resistance value and the tolerance of a resistor having the following color bands.

	A - Gray		B - Red
	C - Black		D - Silver
Solution:	Gray = 8	Red = 2	Black = $0$
	Silver = $\pm 10$	)%	
	From $R = A$	B. H 10 <sup>C</sup> , tolera	ance = D
	R = 82 H 10	$^{0}, \pm 10\%$	
	= 82.0 Ω, ±	= 8.2 Ω	

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		Ohms (Ω)			Kilo (k	ohms Ω)	Meg (N	gohms IΩ)
0.10	1.0	10	100	1000	10	100	1.0	10.0
0.10	1.0	10	110	1100	11	110	1.0	11.0
0.11	1.1	12	120	1200	12	120	1.1	12.0
0.12	13	13	120	1200	13	120	1.2	12.0
0.15	1.5	15	150	1500	15	150	1.5	15.0 15.0
0.15	1.5	16	160	1600	16	160	1.5	16.0
0.10	1.0	18	180	1800	18	180	1.0 1.8	18.0
0.10	2.0	20	200	2000	20	200	2.0	20.0
0.20	2.0	20	200	2000	20	200	2.0	20.0
0.22	2.2	22	220	2200	24	240	2.2 2.4	22.0
0.24	2.4	27	240 270	2700	27	240 270	2.4	
0.30	3.0	30	300	3000	30	300	3.0	
0.33	33	33	330	3300	33	330	33	
0.36	3.6	36	360	3600	36	360	3.5	
0.39	39	39	390	3900	39	390	39	
0.43	43	43	430	4300	43	430	43	
0.15	47	47	470	4700	47	470	47	
0.51	51	51	510	5100	51	510	51	
0.51	56	56	560	5600	56	560	56	
0.62	6.2	62	620	6200	62	620	6.2	
0.62	6.8	68	680	6800	68	680	6.8	
0.75	75	75	750	7500	75	750	75	
0.75	82	82	820	8200	82	820	82	
0.91	9.1	91	910	9100	91	910	9.1	

#### **Sample Graph**

Note the labeling in the following graph, which is meant only as an example of how data should be presented graphically. Specifically note: (1) title; (2) name, symbol and unit for both the abscissa and ordinate (3) both axes labeled with appropriate scales; (4) data points indicated (here small crosses are used) and a best-fit curve drawn through the data points, which may or may not lie on the curve itself. There are ways of calculating a curve of best-fit, but here we simply "guess" how the curve may most accurately be drawn to represent the overall nature of the data. In this example, our guess is that the curve of best-fit is a straight line.



#### EXP 1040-EL2

#### **PURPOSE**

To (i) further verify the validity of the basic circuit laws i.e. Ohm's law and Kirchhoff's Laws when applied to a resistive circuit and (ii) briefly examine some simple ideas associated with troubleshooting a circuit.

#### **1.0 INTRODUCTION**

Circuit analysis is the process by which all voltages and currents associated with each element in a given circuit are evaluated. Conversely, circuit synthesis (or circuit design) involves determining the necessary circuit element values and their interconnection in order to achieve desired voltages and currents. Two simple but sufficient laws form the basis for electric circuit analysis and synthesis. The first of these describes the characteristics or properties of a particular element irrespective of how it is connected to other elements in a circuit. It is often expressed in terms of the current THROUGH and voltage ACROSS the element i.e. the *i*-*v* characteristics of the element and is named **Ohm's law**. The second is a network law that applies to the interconnection of elements rather than to individual elements. The law describes the inherent constraints on voltage and current variables by virtue of interconnections and is expressed in **Kirchhoff's laws**, which really follow from **the conservation of energy and continuity of current (or conservation of charge) principle**.

In this experiment, the basic laws are examined by investigating the behaviour of a simple circuit.

#### 1.1 Ohm's Law

Ohm's Law is based on a linear relationship between voltage and current. Ohm's Law states that the voltage across many types of conducting materials is directly proportional to the current flowing through the material. It is expressed mathematically as

$$v = Ri$$
 1.1

where the constant of proportionality, R is called the RESISTANCE. A resistance for which the voltage versus current relationship is a straight line is a LINEAR RESISTANCE. A linear resistance obeys Ohm's Law because the resistance is always constant. However, a resistance whose ohmic value does not remain constant is defined as a NONLINEAR RESISTANCE. Many resistors lose their linearity as the operating conditions (eg. temperature) changes.

#### **1.2** The Electric Circuit

An electric circuit consists of circuit elements, such as energy sources and resistors, connected by electrical conductors or leads to form a closed path or combination of paths through which current can flow. A point at which two or more elements have a common connection is called a NODE. A two-terminal circuit element connected between two nodes is called a BRANCH. A branch may contain more than one element between the same nodes.

When two or more circuit elements are connected together an ELECTRIC NETWORK is formed. If the network contains at least one closed path, the network is called an ELECTRIC CIRCUIT.

#### 1.3 Kirchhoff's Laws

#### 1.3.1 Kirchhoff's Current Law (KCL)

Kirchhoff's current law describes current relations at any node in a lumped network. It states that the algebraic sum of the currents entering (or leaving) any node or cutset (supernode) is zero. (The idea of a supernode is not part of this course.) Kirchhoff's current law relates to the conservation of charge since a node cannot store, destroy or generate charge. It follows that the charge flowing out of a node exactly equals the charge flowing into the node. An equivalent way of saying this is to say that the current at a node is continuous.

1.3.2 Kirchhoff's Voltage Law (KVL)

Kirchhoff's voltage law describes voltage relations in any closed path in a lumped network. It states that the algebraic sum of the voltages around any closed path is zero. Kirchhoff's voltage law expresses the principle of conservation of energy in terms of the voltages around a closed path. Thus, the energy lost by a charge travelling around a closed path is equal to the energy gain.

#### 1.4 Voltage Notations

It is usual to express all potentials in a circuit with respect to a reference point (assumed to have zero potential). For example, the potential of point A or the voltage of point A with respect to some reference point is indicated as  $v_A$ . The potential of a point with respect to a second point other than the reference point is indicated by a double subscript. For example, in Figure EL2.1, the potential of A with respect to B is indicated as  $v_{AB}$ . The second subscript indicates the reference point. Thus the potential of B with respect to A is represented by  $v_{BA}$ .



- [1] The Introduction and Appendix A of laboratory exercise EXP 1040-EL1.
- [2] E.W. Gill, Engineering1040, Mechanisms and Electric Circuits, Electric Circuits, Module, 2008.
- [3] S. Wolf and R. Smith, *Electronic Instrumentation Laboratories*, Prentice-Hall, NJ. 1990.

#### 2.0 PRELAB

- 2.1 Read Section 1 of EXP 1040-EL1 and pages 13–26 of Reference [2].
- 2.2 Determine the colour coding for each of the following resistors: i) 820 k $\Omega$  ii) 1 k $\Omega$  iii) 6.8 M $\Omega$  iv) 18 M $\Omega$
- 2.3 Consider the circuit of Figure EL2.2.
  - i) Write the Kirchhoff's voltage law equations for loops *adba* and *adcba*.
  - ii) Write the Kirchhoff's current law equations for nodes *d* and *c*.
  - iii) Use the four equations in (i) and (ii) to find the currents  $i_1$ ,  $i_2$ ,  $i_3$ , and  $i_4$ .
  - iv) Find the voltages across the resistors having the polarities shown in the figure,
  - v) Determine the power dissipated by each resistor.
  - vi) Find the power supplied by the source and compare with the total power developed in the circuit.
- 2.4 In Figure EL2.2, determine the equivalent resistance "seen" by the voltage source, i.e. the input resistance of the circuit, given by  $R_{in} = v_{AB}/i_1$ .
- 2.5 Troubleshooting is the process of identifying and locating a failure (fault) or problem in a circuit. Generally, the problems are due to **open** circuits or **short** circuits. Consider the circuit of Figure EL2.2. A DMM set to measure the voltage across  $R_4$  reads  $v_{CB} = 2.28$  V. Determine if there is a fault in the circuit. If there is a fault, identify it as either a *short* or *open* circuit.

#### **3.0 APPARATUS AND MATERIALS**

1 Fluke 8010A Digital Multimeter (DMM) 1 Sun Equipment Powered Breadboard; Model: PBB-4060B Standard Resistors:  $2 \times 100 \Omega$ , 150  $\Omega$ , 220  $\Omega$ One set of leads with banana plugs and alligator clips Various connecting wires

#### 4.0 EXPERIMENT

#### 4.1 **RESISTANCE MEASUREMENT USING THE DMM**

- 4.1.1 With the DMM set to measure RESISTANCE, measure and record in Table 1, the resistance of each resistor in the circuit of Figure EL2.2. Note that the resistance of each resistor must be measured separately. Also, record the standard values.
- 4.1.2 Construct the circuit of Figure EL2.2 on the breadboard provided. **Do not** connect the voltage source to the circuit. With the DMM set to read RESISTANCE connect the DMM to nodes *a* and *b* and record the equivalent resistance of the resistive circuit as  $R_{in}$  in Table 1. Also, record in Table 1  $R_{in}$  calculated using the values measured in 4.1.1.



Figure EL2.2 Series-parallel circuit for analysis and experimentation.

#### 4.2 VOLTAGE AND CURRENT MEASUREMENTS USING THE DMM

- 4.2.1 Connect the voltage source to the resistive circuit at points *a* (red lead) and *b* (black lead). Set the DMM to read **dc volts**, and adjust the 0 to 16 V voltage source from the breadboard to give a +8 V dc reading on the DMM. Record this as  $v_{ab}$  in Table 1. Note: It may not be possible to adjust the source to read *exactly* +8 V simply record the closest value that you are able to obtain.
- 4.2.2 Recall the voltage measurement technique from the information given in Lab 1. Measure and record, in Table 1, the dc voltages **across** the resistors in the circuit of Figure EL2.2 with the polarities as specified. Set the DMM on the most appropriate **range** for these measurements.
- 4.2.3 Recall the current measurement technique from the information given in Lab 1. With the DMM set on **dc amps**, measure the current flowing in each resistor with the directions specified in Figure EL2.2. Record the results in the Table 1.
- 4.2.4 Using the measured quantities, calculate the power dissipated by each resistor. Record the results in Table 1.
- 4.2.5 Compare the measured (or 'standard' in case of the resistors) and calculated results of the resistances, currents, voltages and power. Comment on the results.
- 4.2.6 From the results for the measured voltages in Table 1 verify that (within expected errors) KVL has been satisfied for (i) mesh *adba*, (ii) loop *adcba* and (iii) mesh *dcbd*. Briefly discuss any discrepancy. Note: a **mesh** is a **loop** that does not contain any other loop(s). For example, in this circuit, loop *adcba* contains mesh *adba* and mesh *dcbd*.

- 4.2.7 From the results for the measured currents in Table 1, verify that (within expected errors) KCL has been satisfied for (i) node *d* and (ii) node *c*. Briefly discuss any discrepancy.
- 4.2.8 Verify that the power delivered by the voltage source is equal to the total power dissipated by the resistors.

#### 4.3 TROUBLESHOOTING

- 4.3.1 Verify the troubleshooting problem in Section 2.5.
- 4.3.2 Provide an analysis of the problem and discuss the conceptual basis for identifying the type of fault.

#### 5.0 CONCLUSIONS

Parameter/Variable	Standard or Calculated	Measured
$R_1(\Omega)$		
$R_{2}\left( \Omega ight)$		
$R_{3}\left( \Omega ight)$		
$R_{4}\left( \Omega ight)$		
$R_{ m in}\left(\Omega ight)$		
$v_{ab}$ (V)		
$v_1(V)$		
$v_2$ (V)		
$v_3(V)$		
$v_4(V)$		
<i>i</i> <sub>1</sub> (mA)		
<i>i</i> <sub>2</sub> (mA)		
<i>i</i> <sub>3</sub> (mA)		
$i_4$ (mA)		
$P_1(W)$		
$P_2(W)$		
$P_3$ (W)		
$P_4(W)$		
$P_{\rm dev}$ (W)		
$P_{\rm diss}$ (W)		

## TABLE 1 – Resistance, Current and Voltage Measurements

#### APPENDIX A (Modified from the former Engineering 1333 Lab manual by Dr. John Quaicoe)

This appendix contains several important ideas that will be useful in any of your encounters with real electric circuits. In reality, measurements in a circuit will depend on all elements of the circuit and all connectors as well as on the operating conditions.

#### A.1. Resistors

The flow of charge through any material encounters an opposing force. This opposition, due to the collisions between electrons and between electrons and other atoms in the material, which converts electrical energy into heat, is called the **resistance** of the material. A device specifically designed to have resistance is called a **resistor**.

#### A.1.1 Factors Which Affect Resistance

The resistance of any material with a uniform cross sectional area depends on the material used, the length, the cross-sectional area and temperature under which operation occurs.

#### **Conductor Length and Cross Sectional Area**

If the effects of temperature are neglected, resistance depends directly on the length of the material and inversely on the cross-sectional area. In equation form, the resistance of a conductor at room temperature of  $20^{\circ}$ C is expressed as:

$$R = \rho l/A \tag{A.1}$$

where R is the resistance in ohms l is the length in metres or feet A is the cross-sectional area in m<sup>2</sup> or circular mils (CM)  $\rho$  is the resistivity or specific resistance in  $\Omega$ ·m or  $\Omega$ ·CM/ft.

Electrical conductors are generally circular in cross-section with wire diameters measured in mils.

$$1 \text{ mil} = 1/1000 \text{ in} = 10^{-3} \text{ in}$$
 (A.2)

The cross-sectional area of a conductor is for convenience defined in **circular mils**. The circular mil is the area of a circular cross-section having a diameter of 1 mil.

Area (circle) = 
$$\pi d^2/4$$
 (A.3)

Since the area depends on the square of the diameter for any arbitrary diameter, d in mils, the area in circular mils is given by,

$$A = d^2 \operatorname{cir\,mils}\,(\mathrm{CM}) \tag{A.4}$$

It is still quite common to define the resistivity in the Imperial (English) system as the resistance of a 1 ft. length of conductor with an area of 1 CM. Of course, the SI unit for

resistivity, as is easily deduced from equation (A.1), will be the  $\Omega \cdot m$ . Table A.1 lists resistivity values of common conducting materials in both SI and Imperial units.

Conducting Material	Resistivity (Ω·m)	Resistivity (Ω·cir mil/ft)
Aluminum	2.83 x 10 <sup>-8</sup>	17.0
Brass	7 x 10 <sup>-8</sup>	42.0
Copper annealed	1.72 x 10 <sup>-8</sup>	10.37
Copper hard-drawn	1.78 x 10 <sup>-8</sup>	10.7
Gold	2.45 x 10 <sup>-8</sup>	14.7
Lead	22.1 x 10 <sup>-8</sup>	132
Nichrome	100 x 10 <sup>-8</sup>	600
Platinum	10 x 10 <sup>-8</sup>	60.2
Silver	1.64 x 10 <sup>-8</sup>	9.9
Tin	11.5 x 10 <sup>-8</sup>	69.2
Tungsten	5.52 x 10 <sup>-8</sup>	33.2
Zinc	6.23 x 10 <sup>-8</sup>	37.4

Table A.1 The resistivities of common conducting materials at 20°C

#### **Examples:**

1. An annealed copper bar measures  $1 \ge 3$  cm and is 1/2 m long. What is the resistance between the ends of the bar.

#### Solution:

$$R = \rho l/A$$
  
= (1.72 x 10<sup>-8</sup>) x (5 x 10<sup>-1</sup>)/(1 x 10<sup>-2</sup> x 3 x 10<sup>-2</sup>)

$$= 2.85 \times 10^{-5} \Omega$$

2. Find the resistance of an annealed copper wire 200 ft. long with a 100 mil diameter.

#### Solution:

$$A(\text{cir mil}) = d^2 = (100)^2 = 10^4 \text{ CM}$$
$$R = \rho l/A = (10.37) \text{ x } (200)/10^4 = 20.7 \text{ x } 10^{-2} \Omega$$

#### **Temperature Effects**

For most conductors, as the temperature increases either from current flowing through it or by heat absorption from the surrounding medium, the resistance increases. This is due to the increased molecular movement within the conductor which hinders the flow of charge. The resistance increases almost linearly with increase in temperature.

The relationship between temperature and resistance is expressed as:

$$(|T| + t_1)/R_1 = (|T| + t_2)/R_2$$
(A.5)

where |T| is the inferred absolute zero of the material involved in °C

 $R_1$  is the resistance of the material at the temperature  $t_1^{\circ}$ C

 $R_2$  is the resistance of the material at the temperature  $t_2^{\circ}$ C

The relationship between temperature and resistance may be expressed by

$$R_2 = R_1 \left[ 1 + \alpha_1 (t_2 - t_1) \right] \tag{A.6}$$

where  $\alpha_1$  is the temperature coefficient of resistance,

 $R_1$  is the resistance at the temperature  $t_1$ , and

 $R_2$  is the resistance at the temperature  $t_2$ .

Table A.2 lists the inferred absolute zero and temperature coefficients of common conducting materials.

Most materials exhibit an increase in resistance with an increase of temperature and are said to have a positive temperature coefficient of resistance. However, some materials, such as carbon and semiconductor materials, exhibit a decrease in resistance with an increase of temperature and are said to have a negative temperature coefficient of resistance.

#### **Examples:**

1. What is the resistance of an annealed copper wire at  $10^{\circ}$ C if the resistance is 50  $\Omega$  at  $60^{\circ}$ C.

Solution: $t_2 = 60^\circ$	$( T  + t_1)/R_1 = ( T  + t_2)/R_2$ $R_2 = 50 \ \Omega$	$ T  = 234.5^{\circ}$
$t_1 = 10^{\circ} \mathrm{C}$	$R_1 = ?$	
	$R_{I} = ( T  + t_{1}) R_{2} / ( T  + t_{2})$	
	= 50  x (244.5)/(294.5) = 4	41.5 Ω

2. What is the resistance of a copper wire at 10°C if the resistance at 20°C is 4.33  $\Omega$  and if  $\alpha_1 = 0.00393?$ 

Solution:

 $R_2 = R_1(1 + \alpha_1 \Delta T)$ = 4.33 [1 + 0.00393 (10-20)] = 4.16 \Omega

Table A.2 Inferred absolute zero and temperature coefficients for common conducting materials

Conducting Material	Inferred Absolute zero (C)	Temperature coefficient ( $\Omega$ . C/ $\Omega$ at 0°C)
Aluminum	-236	0.00424
Brass	-480	0.00208
Copper, annealed	-234.5	0.00427
Copper, hard drawn	-242	0.00413
Gold	-274	0.00365
Lead	-224	0.00466
Nichrome	-2270	0.00044
Platinum	-310	0.00323
Silver	-243	0.00412
Tin	-218	0.00458
Tungsten	-202	0.00495
Zinc	-250	0.00400

#### A.1. 2 Wire Tables [3]

Circular cross-section wire is designed by a gauge size of number representing a certain diameter wire. The wire table is designed primarily to standardize the size of wire produced by manufacturers. The American Wire Gauge (AWG) sizes are given in Table A.3. Note that the larger the gauge number, the smaller the diameter of the conductor.

APPLICATIONS	AWG #	AREA (CM)	$\Omega/1000 \text{ ft}$ (20 <sup>0</sup> C)	Max Current (90 <sup>°</sup> C)
Power distribution	00	133,100	0.078	186
	1	83,690	0.124	137
	4	41,470	0.240	89
House main power carriers	6	26,240	0.395	65
	8	16,510	0.620	48
Lighting, outlets, general home use	12	6,530	1.588	20
	14	4,110	2.52	15
Television, radio	20	1,021.5	10.1	-
	22	642.4	16.1	-
Telephone instruments	28	159.8	64.9	-
	35	31.5	329.0	-
	40	9.9	1049.0	-

An examination of the table shows that if the gauge number changes by 10, the crosssectional area changes by approximately a factor of 10. Thus the resistance also changes by approximately 10 times. For example, AWG 4 has a cross-sectional area of 41,470 CM and resistance of 0.240  $\Omega$ /1000 ft. whereas AWG 14 has a cross-sectional area of 4,110 CM and a resistance of 2.52  $\Omega$ /1000 ft. i.e. an increase of 10 in the gauge number represents a decrease in the area by a factor of approximately 10 and an increase in the resistance by a factor of approximately 10.

#### A.1.3 Types of Resistors

Resistors are used for many purposes and are therefore made in many forms. The most common of the resistor types are the carbon composition resistor, the wirewound resistor, the

metal film resistor and the carbon film resistor. They all belong in either of two groups: fixed or variable.

The most common of the low-wattage, fixed-type resistors is the carbon composition resistor. It is made of hot-pressed carbon granules mixed with varying amounts of binding material to achieve a large range of resistance values. They are used extensively in electronic applications. They are relatively inexpensive, reliable and free of stray capacitance and inductance. They are available in power ratings up to 2W with resistance values in the range of 1 to 22 M $\Omega$  and 5 to 20% tolerance. The resistance value of carbon composition resistors and tolerances are specified by a set of colour-coded bands painted on the resistor body. Each colour represents a digit in accordance with Figure A.1 in the appendix of Exp. 1040-EL1. The resistance value as indicated by the colour bands of carbon composition resistors is called the nominal value of resistance.

Wire wound resistors are commercially available for high precision, low resistance and high power dissipation applications. They usually consist of Nichrome or copper-nickel wire wound on a ceramic tube and protected from mechanical and environmental hazards by a protective coating of vitreous enamel or silicone. Their resistance values range from 1 $\Omega$  to 100 k $\Omega$  with a tolerance range of 0.0005% and above and a maximum power rating of 200 W.

A third group of resistors consist of a thin film of material deposited on insulating materials to provide very high resistance paths. Depending on the material used, the resistors are classified as carbon film, metal film or metal-oxide film resistors. Their values range up to  $10,000 \text{ M}\Omega$ .

Variable resistors come in many forms, but basically they can be separated into the linear or non-linear types. Variable resistors usually have three leads: two fixed and one moveable. If contacts are made to *only two leads* of the resistor, the variable resistor is being employed as a *rheostat*. If *all three contacts* are used in a circuit it is termed as *potentiometer* or 'pot'. The value of the overall resistance and the power ratings of variable resistors are usually stamped on their cases.

Because the resistance of a conducting film varies with length, cross-section and temperature, it is possible to use resistance measurement to sense changes in any of those parameters. A device that responds to one physical effect is called a **transducer**. Electrical transducers are often used in instrumentation for non-electrical quantities such as temperature, light, and strain. The resistance of the device can be measured and the magnitude of the physical or chemical parameter inferred from the resistance value.

Typical examples of resistive transducers are:

- 1. The **thermistor**: a two-terminal semiconductor device designed specifically to exhibit a change in electrical resistance with a change in its body temperature.
- 2. The **strain gauge**: a device which converts linear dimension changes into resistive changes.
- 3. The **photoconductive cell**: a two-terminal device whose resistance depends upon the intensity of light impinging on the cell.

#### EXP 1040-EL3 **Applications of Resistive Networks**

#### **PURPOSE**

To (1) investigate the idea of voltage division using a single source and (2) to examine the utility of a Wheatstone bridge circuit for resistance measurements.

#### 1.0 **INTRODUCTION**

Using the laws discussed in the course material - namely Ohm's law, Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) – we are now in a position to study many different circuits having a variety of real-world applications. In this lab we consider two such applications, and while the analysis associated with them is relatively straight forward, they are of significant modern-day importance.

#### 1.1 **Voltage Divider Circuits**

A voltage source is sometimes required to supply a particular voltage to a load and, in fact, it may be required to supply several loads with certain specified voltages simultaneously. *Ideally*, the voltage supplied should not depend on the size of the load.

As a first example, consider the circuit shown in Figure EL3.1 in which a simple voltage divider circuit is connected in series with the load. Notice the situation has been depicted in two equivalent ways. In the second schematic, the negative terminal of the source is assumed to be *electrical ground*. An *electrical ground* is a *reference level* from which other voltages are measured. An ideal electrical ground can absorb an unlimited amount of current without changing its potential. Here, then, conventional current flows from the positive terminal of the source, through the resistors, and back to the source, via the ground path (the closed path connection is not explicit in the schematic diagram, but it is understood).



 $v_{s}$  is the source voltage.  $i_{L}$  is the load current.

 $R_{\rm s}$  is a series dropping resistor  $R_{\rm L}$  is the load resistor.

 $v_{\rm D}$  is the voltage drop across  $R_{\rm s}$ .

 $v_{\rm L}$  is the voltage drop across  $R_{\rm L}$ .

Figure EL3.1 Two equivalent schematics (a) and (b) for a simple voltage divider. From Section E2.5.1 of the class notes Electric Circuits Module we know that

$$v_{\rm L} = v_{\rm s} \left[ \frac{R_{\rm L}}{R_{\rm s} + R_{\rm L}} \right] \quad (1)$$

However, this type of voltage divider has a serious disadvantage since the value of  $v_L$  depends on the value of  $i_L$ , and the latter will change depending on the value of the load resistance.

To help overcome the problem referred to above it is possible to construct a voltage divider with a *bleeder resistor*  $R_{\rm B}$  as shown below in Figure EL3.2 and as discussed in Section 2.5.1 (page 29) of the class notes Electric Circuits Module.



Figure EL3.2 Two representations (a) and (b) of a voltage divider with a bleeder resistor

Strictly, the voltage across the parallel section of the circuit is (by the voltage divide 'rule'),

$$v_{\rm L} = v_{\rm s} \left[ \frac{R_{\rm B} \| R_{\rm L}}{R_{\rm S} + (R_{\rm B} \| R_{\rm L})} \right]$$
 (2)

where

$$R_{\rm B} \parallel R_{\rm L} = \left[\frac{R_{\rm B}R_{\rm L}}{R_{\rm B} + R_{\rm L}}\right] \qquad (3)$$

As shown in the class notes, the advantage of this kind of voltage division is that when  $R_{\rm B} \ll R_{\rm L}$ , the load voltage is essentially independent of the load resistance and

$$v_{\rm L} = v_{\rm s} \left[ \frac{R_{\rm B}}{R_{\rm S} + R_{\rm B}} \right] \tag{4}$$

Because the load voltage is less affected by the load resistance in this situation, we say there is better *voltage regulation* in this circuit than that in Figure EL3.1

#### **1.2** The Wheatstone Bridge

The Wheatstone bridge circuit is mainly used to measure an unknown resistance. However, the principle of the Wheatstone bridge is used in many *transducers* – devices that convert one kind of energy into another – and instrumentation systems to measure a physical variable such as

strain, temperature, and pressure. A Wheatstone bridge circuit is shown in Figure EL3.3. In this figure  $R_3$  is a variable resistance, which models the transducer. If a change in physical variable results in a change in resistance of the transducer, the Wheatstone bridge can be used to convert the change in resistance to a change in voltage, which can be measured.



Figure EL3.3 A Wheatstone bridge.

When the voltage  $v_{ab}$  is zero, the bridge is said to be *balanced*. If two resistances (say  $R_1$  and  $R_2$ ) are known and another (say  $R_x$ ) is unknown, then a fourth, adjustable known resistance  $R_3$  (potentiometer), can be used to determine the unknown resistance  $R_x$  under balanced conditions.

When  $R_3$  is actually a transducer, whose resistance changes with some change in a physical parameter such as temperature, then if  $R_1$ ,  $R_2$ , and  $R_x$  are known the voltage  $v_{ab}$  is an indicator of the size of the measured parameter.

#### **Balanced Conditions:**

As noted, for balanced conditions the voltage  $v_{ab}$  is zero. Also, under these conditions, using the voltage divide rule twice gives

$$v_{ad} = v \left[ \frac{R_{\rm x}}{R_{\rm 1} + R_{\rm x}} \right] \quad (5)$$

$$v_{bd} = v \left[ \frac{R_3}{R_2 + R_3} \right] \quad (6)$$

We have also seen from Section 2.5.4 of the Electric Circuits Module lecture notes that

$$R_{\rm x} = \left(\frac{R_1}{R_2}\right) R_3 \quad (7)$$

#### **Unbalanced Conditions:**

When the bridge is not balanced – i.e.  $v_{ab} \neq 0$  – then using Kirchhoff's laws it is straight forward to show that

$$v_{ab} = v \left[ \frac{R_{\rm x}}{R_1 + R_{\rm x}} - \frac{R_3}{R_2 + R_3} \right]$$
 (8)

From this equation we see immediately that if any three of the resistances are fixed in value, then a change in the other resistance results in a change in  $v_{ab}$ . Thus, a variation in  $v_{ab}$  is effectively a measure of a change in the variable resistance.

#### REFERENCES

- [1] The Introduction and Appendix A of laboratory exercise EXP 1040-EL1.
- [2] E.W. Gill, Engineering1040, Mechanisms and Electric Circuits, Electric Circuits, Module, 2008.

#### 2.0 PRELAB

- 2.1 Carefully read Section 1 (Introduction) of this experiment and the sections referred to in reference [2].
- 2.2 Refer to Figure EL3.1. The series dropping resistor has a value of 1.0 k $\Omega$ . (a) Determine the value of the load resistor  $R_{\rm L}$  so that  $v_{\rm L} = 7.5$  V if the source voltage is 10 V. (b) If the load resistance is increased by 25%, calculate the new  $v_{\rm L}$ .
- 2.3 Refer to Figure EL3.2. (a) Design a voltage divider (i.e, find  $R_s$  and  $R_B$ ) for the load resistance  $R_L$  obtained in part (a) of Question 2.2 so that it can operate at  $v_L = 7.5$  V from a 10 V source. Assume that the bleeder current  $i_B$  is 75 mA. (b) If the load resistance is increased by 25% calculate the new load voltage. Compare this result with that obtained in Question 2.2 (b). Comment on the comparison.

#### **3.0 APPARATUS AND MATERIALS**

1 Fluke 8010A Digital Multimeter (DMM) 1 Sun Equipment Powered Breadboard; Model: PBB-4060B Standard Resistors: 1 k $\Omega$ , 3 × 120  $\Omega$ , others as calculated in design Potentiometers: 200  $\Omega$ , 5 k  $\Omega$ One set of leads with banana plugs and alligator clips and various connecting wires

#### 4.0 EXPERIMENT

#### 4.1 Voltage Divider

4.1.1 Familiarize yourself with potentiometers – the lab attendants will help. On the breadboard, construct the voltage divider circuit as shown in Figure EL3.1, using a 1 k $\Omega$  resistor for  $R_s$  and a 5 k  $\Omega$  potentiometer (variable resistor) as the load resistor  $R_L$ . Ensure that the source voltage is 10 V after connecting to the circuit. Adjust the variable resistor to get an output (load) voltage of  $v_L = 7.5$  V. Measure the value of  $R_L$  for this condition. Comment on any discrepancies between the measured and calculated value in Question (2.2) of the Prelab.

- 4.1.2 Vary the potentiometer resistance from 680  $\Omega$  to 5 k  $\Omega$  and obtain the load voltage  $v_L$  in each case. Tabulate your results and plot  $v_L$  as a function of  $R_L$ .
- 4.1.3 Construct the voltage divider found in Figure EL3.2 and measure the load voltages to verify your design of Question 2.3 of the Prelab. Use the nearest available resistance values to those you calculated in the design. Comment on your findings.

#### 4.2 Wheatstone Bridge

- 4.2.1 On the breadboard, construct the Wheatstone bridge circuit of Figure EL3.3 using three 120  $\Omega$  (nominal) resistors for  $R_1$ ,  $R_2$ , and  $R_x$  and a 200  $\Omega$  potentiometer (pot) for  $R_3$ . Also, measure and record the actual values of the 120  $\Omega$  resistors. Ensure that the source voltage v is 10 V after it is connected to the circuit. Use the DMM as a voltmeter in the branch between nodes *a* and *b*.
- 4.2.2 Adjust the pot until the bridge is balanced. Measure and record the value of  $R_3$  for this condition. Confirm your observation by calculating  $R_3$  from equation (7) and comment on any discrepancies.

#### **5.0 DISCUSSION**

- 5.1 Comment on probable applications of a voltage divider circuit.
- 5.2 Discuss any technical difficulties encountered during the lab.

#### EXP 1040-DL1 Introduction to Logic Gates and Ladder Diagrams

#### PURPOSE

To (i) familiarize the student with the basic logic gates, AND, OR, NOT, and NAND; (ii) implement basic logic gates using relay logic; and (iii) learn how to represent logic circuits by means of ladder diagrams.

#### **1.0 INTRODUCTION**

Logic circuits may be implemented (constructed) in a variety of ways, perhaps most commonly today via electronic components. In this lab and the next, however, we consider the implementation of basic logic expressions using a simple circuit board in conjunction with a few pneumatic cylinders. This allows us to explore basic logic circuits without having to resort to sophisticated solid state circuitry (transistors, etc.).

#### 2.0 PRELAB

There is no prelab for this session. However, students need to read Section D1.3, pages 10-18 of the Digital Logic Module before the lab session.

#### **3.0 APPARATUS AND MATERIALS**

1 Logic Board Various banana plug connectors AC power (from main lab supply)

#### 4.0 EXPERIMENT

#### 4.1 Board Familiarization

4.1.1 Normally-open Switch

To gain familiarity with the laboratory test panel, implement the simple circuit shown in Figure DL1.1. PB1 refers to one of the two push buttons available on the panel. This specific circuit utilizes a "normally open" contact. When PB1 is pressed, the green indicator light should illuminate.



Figure: DL1.1 Simple circuit employing push button and a green indicator light.

4.1.2 Normally-closed Switch

Repeat exercise 4.1.1 using the "normally closed" contact of PB1. See Figure DL1.2.



Figure DL1.2 Simple circuit employing a normally closed contact.

#### 4.2 AND Gate

Using the two push buttons, PB1 and PB2, implement an **AND** operation. In other words, the green indicator light should only illuminate if and only if both buttons are pressed simultaneously. In your lab report provide:

- the ladder diagram implementation (similar to Figure DL1.1 or DL1.2),
- the standard symbol for a two input AND gate,
- The truth table. Note that the truth table should include all four combinations of the two inputs. Assume that a high or logic "1" occurs when the button is pressed.
- Provide a practical application of this circuit (hint: think safety).

#### 4.3 OR Gate

Repeat part 4.2 above in its entirety; however, this time implement an **OR** operation using the two push buttons, PB1 and PB2. In this case, the green indicator should illuminate if at least one of the two buttons is pressed. For the practical application consider convenience instead of safety.

#### 4.4 OR Gate

Repeat part 4.2 above for a "NAND" gate. Note that this will require normally closed contacts. It is not necessary to provide a practical application for this circuit.

#### 4.5 NOR Gate

Repeat part 4.2 above for a **NOR** gate. Note that this will require normally closed contacts. It is not necessary to provide a practical application for this circuit.

#### 4.6 Inequality Comparator

Figure DL1.3 represents a circuit that is sometimes referred to as an **inequality comparator**. Implement the circuit and experimentally determine the truth table. Note that this circuit employs both the "normally opened" and "normally closed" contacts of both push buttons. In the lab report, provide both the common name for this circuit as well as the standard logic symbol. Why is this circuit referred to as an "inequality comparator"?



Figure DL1.3 Circuit that implements an "inequality comparator".

#### 4.7 Inverter

An **inverter** or **NOT** gate can be implemented with a relay as shown in Figure DL1.4. When the push button is pressed, the coil of relay 1 is energized. This opens the normally closed contact of relay 1 which turns the Green indicator light off. Implement the circuit and experimentally determine the operation. In the lab report, provide the standard logic symbol for a **NOT** gate.



Figure DL1.4 Circuit that implements a NOT gate.

#### 4.8 Latch (Priority on Set)

A relay can also be used to "latch" the state of the output such that the indicator light is illuminated when the push button is pressed and stays illuminated even if the button is released. A second push button must be used to reset the circuit back to its initial ("OFF") state. In Figure DL1.5, PB1 energizes relay 1 when it is pressed. One of the sets of contacts on relay 1 is used to maintain the relay energized even if PB1 is released. The normally closed contact of button PB2 de-energizes the relay when the button is pressed (i.e., resets the latch).

Implement the circuit and experimentally determine the operation. Be sure and verify what happens when both buttons are pressed simultaneously. Note that you must use a different set of relay contacts to energize the green indicator light. This particular latching configuration is referred to **as priority on SET**.



Figure DL1.5 Implementation of a "latch" circuit using a relay.

#### 4.9 Latch (Priority on Re-Set)

An alternative latch configuration is implemented in Figure DL1.6. This configuration is referred to as **priority on RESET**. Implement the circuit and experimentally determine the operation. Be sure and verify what happens when both buttons are pressed simultaneously. In terms of operation, what is the main difference between "priority on SET" and "priority on RESET"? Provide a practical application of both latch configurations (once again think safety).



Figure DL1.6 Implementation of "priority on RESET".

#### EXP 1040-DL1 Introduction to Sequential Circuits, Ladder Diagrams and Relay Logic

#### PURPOSE

To (i) introduce ladder diagrams and relay logic and (ii) demonstrate a simple pneumatic system.

#### **1.0 INTRODUCTION**

Ladder Diagrams (Figure DL2.1) are a graphical representation of sequential control circuits that are widely used in industry. Although originally intended as a way of representing relay logic, ladder diagrams are now the standard means of programming microprocessor based PLCs (Programmable Logic Controllers). They are prevalent in a many engineering fields including automation, process control and manufacturing.

In this lab a sequential logic circuit will be implemented using the pneumatic test board. The pneumatic test board has three pneumatic cylinders that are activated by solenoid valves. The position of each cylinder is monitored by two limit switches. One limit switch is activated when the cylinder is fully extended and the other is activated when the cylinder is fully retracted. By energizing a solenoid you are able to extend a cylinder and by de-energizing the solenoid the cylinder will retract.

#### 2.0 PRELAB

There is no prelab for this session. However, students need to read Unit D2 of the Digital Logic Module before the lab session.

#### **3.0 APPARATUS AND MATERIALS**

1 Logic Board Various banana plug connectors AC power (from main lab supply) Compressed air source

#### 4.0 EXPERIMENT

#### 4.1 Limit Switch Familiarization

Limit switches A0 and A1 in Figure DL2.1 are used to sense when cylinder A is retracted and extended respectively. Each switch incorporates both a normally opened and normally closed set of contacts. Cylinders B and C employ switched B0 /B1 and C0/C1 respectively. These six switches are identified on the wiring panel as S1 through S6. An indicator light can be used to verify the operation of the switches. Sketch a circuit that illuminates the green light when cylinder A extends and the red light when cylinder A retracts. Implement the circuit on the pneumatic test board and verify the operation by manually depressing the limit switches. Use the circuit to determine the correspondence between the six limit switches and the wiring terminals S1 through S6.





#### 4.2 Solenoid Valve Familiarization

Solenoid valves S1, S2 and S3 control the three cylinders A, B and C. As shown in Figure DL2.1, when the solenoid valves are not energized, the cylinders are retracted; i.e., pressure is applied to the rod side of the cylinder. Energizing the solenoid changes the position of the valve such that the cap side of the cylinder is pressurized and the

cylinder extends. Sketch a circuit that extends cylinder A when push button PB1 is depressed and retracts A when the button is released. Implement the circuit on the pneumatic test board and verify the operation. There are a many "pinch" points on the test board so be sure and keep your fingers away from the cylinders.

#### 4.3 Implementation of a Simple Latch

Using relay 1 design a circuit that latches the state of push button PB1 such that cylinder A extends when PB1 is depressed and stays extended even if PB1 is released. The cylinder retracts only when push button PB2 is depressed. Implement the circuit on the pneumatic test board and verify the operation.

#### 4.4 Sequential Logic Circuit 1

4.4.1 Familiarization with the Logic Sequence

The ladder diagram shown in Figure DL2.1 is a sequential logic circuit that will make two cylinders follow the sequence:

Cylinder A – extend -> Cylinder B – extend -> Cylinder A – retract -> Cylinder B – retract

The operation of the logic circuit can be described as follows.

• Push button PB1 initiates the start of the sequence; i.e., extend cylinder A by activating solenoid A. Relay 2 is latched when PB1 is depressed if and only if the last step in the sequence (limit switch B0, retract B) has been completed. This also maintains solenoid A energized.

• Once cylinder A has finished extending (i.e., switch A1 is active), the circuit advances to the second "rung" of the ladder which activates solenoid B (cylinder B extends).

• When switch B1 is activated (i.e., B extended), the circuit advances to the third rung in the ladder. Relay 4 is latched which in turn resets relay 2 de-energizing Solenoid A and retracting A.

• In a similar fashion, the fourth rung in the ladder resets relay 3 which retracts B.

• Notice that each rung in the ladder is latched by the completion of the action associated with the previous rung.

#### 4.4.2 Implementation of the Logic Sequence

Implement the circuit described in 4.4.1 and verify the operation.

#### 4.5 Sequential Logic Circuit 2

Modify the circuit in section 4.4 to implement the following sequence:

Cylinder A – extend -> Cylinder B – extend -> Cylinder B – retract -> Cylinder A – retract

#### 5. Lab Report

5.1 Provide a short written lab report that includes ladder diagrams of all the circuits design during the lab.

5.2 Explain the operation of the circuit developed in part 4.5 above.