ECE 203 — DC CIRCUITS

LABORATORY MANUAL

Rose-Hulman Institute of Technology

Spring 2016-2017

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ECE 203 DC Circuits
Laboratory Manual

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Lab 0 Laboratory Introduction

1.0 Purpose of Laboratories

Labs are a very important part of any ECE course. It is vital that all electrical and computer engineers become proficient in using measuring equipment; failure to achieve this is like *being a tailor who can't use a tape-measure* - you won't get much repeat business. So there are three main purposes of these labs.

1.1 Familiarity with equipment

You will be introduced to the basic equipment in an electrical laboratory, i.e. power supplies, voltmeters, ammeters, ohmmeters, function generators, and oscilloscopes.

1.2 Tie-in to theory

This is two-fold. First, you will see that classroom theory is borne-out in practice. Second, you will see that the first point is not achieved perfectly!!! There will always be some experimental error in your readings and you must account for this.

1.3 Develop problem-solving skills

Engineers are people who solve problems. Some of these are *design* problems, while others are *equipment operation* problems. You will encounter many of the latter in the lab. This will probably be irritating at first, but de-bugging circuits is an essential skill of any working electrical or computer engineer.

2.0 Materials

The following items need to be brought to each lab. Your lab grade may be reduced if you do not bring these items.

- This laboratory manual.
- A laboratory log book.
- The pre-lab work
- The parts kit for the course. You will purchase this from the Instrument Room (C114).

3.0 Equipment

Each bench in the lab has six pieces of equipment on it. When you enter the lab you should check that these are present and working.

- 54622D Oscilloscope: 4 channels.
- E3631A Programmable DC power supplies: 0 to 6 V @ 5A, and ±25 V @ 1A, all floating w.r.t. ground.
- Two 34401A Digital Multimeters (DMM). These can be set to measure voltage, current, or resistance.
- Two 33220A Function generators. These can output sine, square, triangle, or ramp waveforms.

All the user manuals can be downloaded from the Agilent website

(http://www.home.agilent.com)

4.0 What is Expected of You

The first thing that is expected of you is *Professional Work*, i.e. the kind of work that you would expect to be paid for when you are working (the fact that it is you who are paying us is irrelevant!!)

This means that you are expected to know the procedures and requirements of each lab. Saying "I didn't know we were supposed to do that" is not acceptable, *your lab grade will be lowered* for not knowing you were supposed to do that.

It is essential that you read the complete lab ahead of time and if there are parts you do not understand; see the instructor to get them resolved.

Most labs will be made-up of three distinct parts:

- Pre-lab assignments. These

help you prepare for the actual lab and are usually predictions of what you will measure.
- Actual lab work. This usually consists of constructing circuits, troubleshooting problems, making measurements, recording data, etc. Instructions will be given in a lot of detail in the early labs, but this level of detail will reduce as you are expected to become more independent as the labs progress.
- Post-lab assessment consists of analysis of lab results. Be sure to read the lab procedure ahead and leave enough time for this.

5.0 Lab Journal

All engineers have to develop a habit of recording what they are doing (or have done). Sometimes this is done interactively, e.g. when supervising a power system, or chemical plant; but most times it consists of paper and pencil, which is transferred to a computer record later. The purpose of your lab logbook is to get you started on this habit.

Typically the record kept by a working engineer shows the steps taken when developing a new circuit or system. It sometimes becomes a legal document in such things as patent applications, or liability issues; obviously, the accuracy of such a record is vital.

Each lab partner needs to have a lab book (two books per group) as the book will be turned in at the end of each lab and may not be returned in time for you to complete the pre-lab assignment for the next lab. The owner of the lab book will record all the data, while the other partner builds the circuits etc. Obviously, these duties rotate for each lab session.

The lab log must record *all actions that were taken* in the lab, even mistakes and "dead-ends" have to be recorded. You are also expected to supplement this with your own initiative, e.g. if it says "compare your experimental results with the theoretical predictions" you are expected to calculate and present experimental errors.

The following points will help you to keep a satisfactory lab book.

- Number all pages (in ink) as soon as you get the book.
- Create a "Contents" page and enter the title of each lab (with its page number) when you start it. The instructor may want to put the lab grade here.
- Do not tear-out any pages. Write on the front page and leave the back page for such things as handouts, diagrams, graphs, etc.
- Make all entries (except graphs) in ink. If you make a mistake, cross it out with a single line.
- Treat the lab book as a "diary" and write down everything that was done, so that your steps could be repeated exactly by someone else.
- Each lab must start with a title page on a separate sheet of your lab book. On this page write the title in large letters and follow this by the bench number and any equipment that was additional to the items in part 3.0 above. Include your name (the recorder), your partner's name, the bench number, room number, and date. Write a description of any specific additional equipment or components required to complete the lab beyond standard RLC and IC components specified in your schematics.

- Place the pre-lab after the title page. Submit the pre-lab on engineering paper at the beginning of lab. Make a photocopy in the library before submission.
- Overall lab format and headings should match the formatting of the lab manual.
- Record your procedure in enough detail that someone else could repeat and verify your measurements and analysis. Do not refer to the lab manual. Your lab log should be a complete record of your work independent of the lab manual.
- Use tables wherever possible. If you read the lab ahead of time, you should be able to build a table for most all required data and then just in the blanks when you get to lab.
- All calculations, including percent error, should be first shown in their symbolic form before plugging in numbers to reach a result.
- Wherever possible, you should perform a percent error calculation to show how close your pre-lab prediction (the nominal result) is to the measured or calculated value.
- If your percentage error is low (usually within 5%), there is no need for any additional comment or explanation. If the percentage error is high, you must fix your experiment, retake the data, recalculate your answer or provide a reasonable explanation for the discrepancy.
- When answering lab manual questions or explaining your results - be brief and concise but use full sentences.
- Each member of the team must sign and date the last page of the record.

As a final point, *neatness does count*. While you will not be penalized for crossing out errors, hurried lettering, or spelling errors, remember someone else has to read and interpret what you've written. In the near-term this will be the grader, but you will be required to refer back to your record on later labs *including labs in later courses*. Also, you need to develop the habit of producing readable records quickly for work in industry.

6.0 Circuit Diagrams

These are the "lifeblood" of circuit analysis. No circuit is so simple that you can wire it "in your head"; you always need to have the diagram in front of you. Also, a circuit diagram without labels is next to useless, this means that all sources, all element values, and all pin numbers need to be labeled; the polarity of all voltages and currents need to be indicated.

Your instructor will not help you de-bug your circuit unless you have an up-to-date circuit diagram.

Schematic Diagrams do not display the exact physical layout of a circuit but, as the name implies, they show a *scheme* of the wiring — there are several ways to actually wire the circuit that will obey the connections of the schematic.

A schematic of every circuit built and tested in the lab must be included in the lab book. Clearly label all components in the schematic. Label all quantities in the schematic for which you are collecting data. The label in the schematic must match the label used to identify the data which must also match any references to the data in tables or graphs. All labeled voltages and currents must have polarity clearly marked.

Figure 1 shows a correctly laid-out schematic diagram of an op-amp inverter. Note the following:

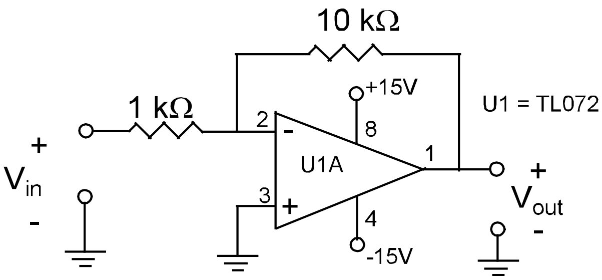

Figure 1 — Proper Schematic Diagram

- It is laid-out from left to right because this is the direction that the signal is flowing.
- Standard symbols for the devices (resistors and the op-amp chip) are used, not outlines of their physical shapes.
- The chip pin numbers for the semiconductor are included.
- The ±15 V power supply voltages are labeled, while the power supplies themselves are omitted.
- Integrated circuits are labeled with their standard numbers (TL072), or they are given a "U" number that is referenced elsewhere.
- The "A" on "U1A" means that this is one of the op-amps on the U1 chip; the other op-amp is labeled "U1B".

If you modify the circuit during the lab, be sure to update the diagram. Small changes (e.g. changing a resistor value) can be made on the original diagram, but for larger ones you'll need to re-draw it.

7.0 Tables & Graphs

These are important ways to convey significant amounts of information in very compact forms. Here are a few tips.

- Use tables to present data, not sentences. Every table *must* have a title and clear column headings.
- Think ahead and organize your table so that you can easily notice trends in your data.
- Put units at the top of the column to save space.
- Make tables large; there should be enough room in the table to cross-out an entry and insert a correction.
- Every graph *must* have a title and each axis *must* be labeled.
- Axis divisions *must* be "reasonable", i.e. 1, 2, 5, 10, etc.
- Always show the zero point on each axis, unless you are making a logarithmic plot.
- Draw a smooth curve through the points. You will need to exclude "obviously bad" data points to do this — ideally, you should re-take these points if time permits.

When attaching pages to the lab book make sure they are permanently fastened (do not leave loose pages in the book). Also, all work should be read with the book in the upright position if possible. If you need to turn it sideways, make the *right side* of the page become the *bottom*. As shown in Figure 2.

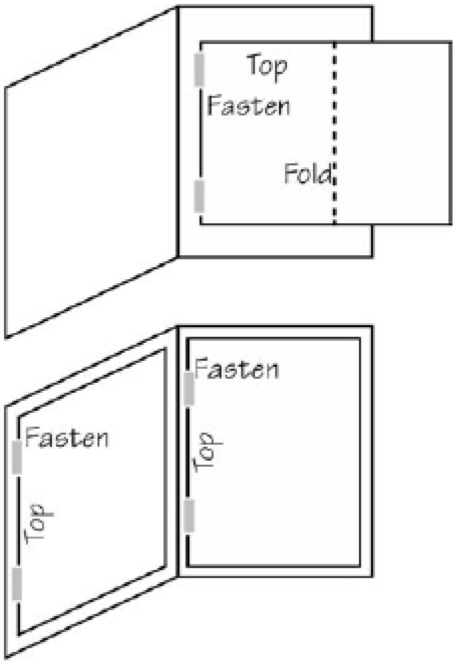

Figure 2 — Fastening Pages

8.0 Wiring Breadboards

Breadboards are a quick and easy way to construct circuits. They enable changes to be made and errors to be corrected rapidly.

There are many ways to construct a circuit on a breadboard and if you do not follow *orderly procedures* your wiring will be chaotic and error-prone. Here are some simple tips to avoid "spaghetti-wiring". If your board looks like a bowl of spaghetti, your instructor will refuse to help you de-bug the circuit.

- Connect the power supplies to the long strips along the top of the breadboard, then run short wires into the circuit. Use the long strip at the bottom for grounds.
- Build your circuit from left to right in the same direction as the "signal flow" of your circuit diagram.
- Don't crowd components — you can always use wires to connect them when they are well spaced.
- Use the shortest wire that will do the job and flatten-out "humps" of wire so that they don't get caught.

Figure 3 shows these tips applied to an op-amp circuit.

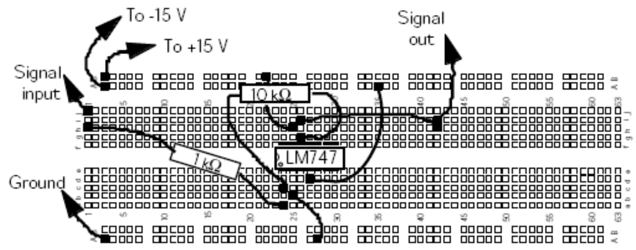

Figure 3 — Proper Breadboard Layout

9.0 Using the Oscilloscope

The oscilloscope is probably the most useful piece of measuring equipment that an engineer can use. It shows you the shape of the waveform that you are working with.

Often when something is going wrong with a circuit and the cause of the trouble is not obvious, looking at the waveform gives the answer — you may be thinking you were working with a pure sine wave until the 'scope shows that the top is cut off by saturation.

You may be thinking that since this is a "DC circuits" course, the waveforms will only be flat lines and not very interesting. This will be true for much of the time, but we will also be looking at signals (sine waves) that have been produced by a DC power supply; so this will be a good time to learn some basic oscilloscope conventions.

- Channel 1 should display the input signal, with the trace toward the upper half of the screen.
- Channel 2 should display the output signal, with the trace toward the lower half of the screen.
- Make the waveform as large as possible, i.e. don't display six

cycles if you only need to see one.
- Simple images can be sketched into your lab book, but complex images need to be captured, printed-out and attached to the book.

10.0 Safety

Clearly, there is no need to say this is a very important topic; it is something we are all responsible for. The old cliché which says that "safety is no accident" rings true — safety doesn't just happen any more than accidents just happen.

We all have to pay attention to what we are doing at all times. There are two things we need to be aware of. First there is the electricity — it's not to be feared, but it *must* be respected and secondly there is physical equipment that can hurt you.

Let's consider the second item first. When you are in a lab there is equipment that can fall on you or snag loose items, so following these rules is essential.

- Proper footwear is *required*, you are not permitted to wear sandals or go barefoot.
- When working with machinery, e.g. motors, do not have loose clothing, remove all jewelry (especially rings), and if you have long hair tie it back.
- Keep the workspace tidy; don't place equipment near the edge of the bench.

The first item is concerned with electric shock. You may be thinking that in this lab we will only be working with a few volts so this is not an issue. Hopefully, that will be the case but remember things like the ±15 V DC power supply are powered by 120 V ac and any piece of equipment can malfunction — safety is about staying safe when things go wrong!!

Electric shock does several things to the body, in extreme cases it stops the heart and/or lungs and the victim needs emergency measures to survive, lesser effects are burns, but the most common injury from electric shock results from people jumping, tripping and falling.

Electric shock happens when you become part of the circuit and current flows through your body; the best way to avoid this is to follow these rules.

- Turn off the circuit before working on it, this will also protect the electronic chips that can be damaged by open circuits.
- Treat a circuit as if it were energized (even when you know it isn't) so never put both hands on parts that could be live. Never have your feet touching ground, correct footwear should ensure this.
- Never work alone, that way if the unthinkable happens you have someone to help you.
- If you are the "someone" called upon to help in the above situation, always disconnect the power at the main supply (this means you need to know where the main supply switch is) *before* going to assist the victim. You don't know what caused the accident and you don't want to become the next victim.
- Being certified to administer CPR is highly recommended. You should also encourage your friends and potential lab partners to do the same — after all the only person you cannot administer CPR is to yourself!!

11.0 Reading Components

The parts you will be using are very small and don't have room for labeling their values, so they are coded. Being able to interpret the codes is essential to any electrical or computer engineer.

11.1 Resistors

These have either three or four colored bands with the following meanings:

Black……..0	Blue………6
Brown…….1	Violet……..7
Red……….2	Grey………8
Orange…...3	White……..9
Yellow……4	Gold….0.01 or 5%
Green…….5	Silver…0.1 or 10%

If you have difficulty remembering the code, just think of: **B**lack **B**ears **R**un **O**ver **Y**ellow **G**rass **B**ut **V**iolet **G**ently **W**alks – **G**o **S**ee **N**ow. Then arrange the resistor so that the band closest to one end is on the left (see Figure 4) and start reading the bands, as follows:

1st band — The tens digit of an integer.

2nd band — The units digit of an integer.

3rd band — The multiplier a power of 10.

4th band — % tolerance (20% if no band).

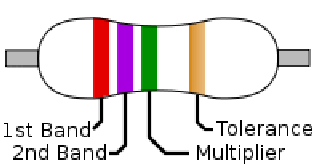

Figure 4 — Resistor Alignment

For example, if the bands are:

red-violet-orange-gold,

then the resistor's value is given from red = 2, violet = 7, orange = 3, and gold = 5%, which is: 27 x 103 = 27 kΩ. The tolerance of 5% means that the actual value could be anything between 25.65 and 28.35 kΩ.

Here are some other examples.

green-blue-brown = 56 x 10 = 560 Ω

brown-green-red = 15 x 10^2 = 1.5 kΩ

grey-red-silver = 82 x 10^{-1} = 8.2 Ω

11.2 Capacitors

Capacitors have strange markings that are not as simple to decode as resistors. They come in many shapes, sizes, colors, and values, and the rules for decoding the value are not followed by all manufacturers. If you are in doubt, locate the original manufacturer and seek information from that source.

In general, if the value on the capacitor has no decimal point, has more than two digits, and has as its last digit a number other than zero, then:

- the value is in picofarads.
- the first two numbers are the first two digits of the capacitance
- the last digit is the multiplier as a power of 10.

For example, in Figure 5 below, the capacitor's numeric code is listed as <u>104</u>. This means that the capacitance is <u>10</u>x$10^{\underline{4}}$ pF, or 0.1μF.

Figure 5 – A 0.1 μF ceramic capacitor.

It's easy to think you have a 20-pF capacitor when you actually have a 0.2 μF capacitor. It's a good practice to always measure the value of the capacitance with an LCR meter.

11.3 Operational Amplifiers

The operational amplifier (op-amp for short) is a highly versatile device that can provide a wide range of gains, can change the resistance seen by other devices, and block unwanted signals. The standard symbol for an op-amp is shown in Figure 6.

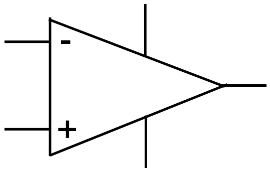

Figure 6 —Symbol for an Op-Amp

The op-amp that will be used in this course is the TL072, which is an integrated circuit (IC) that comes in an 8-pin *dual in-line package* (DIP). The *pin-out* is interpreted by looking down on the chip with the notch or dot (sometimes both) at the top as shown in Figure 7.

The pins are spaced to fit directly into the breadboard with the op-amp *straddling* the gutter in the middle of the breadboard.

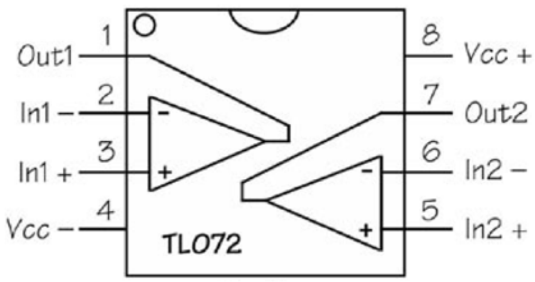

Figure 7 — Pin-Out for the TL072 Op-Amp

As can be seen, there are actually two op-amps on the chip and each has two inputs. The *inverting* and *non-inverting* inputs to unit 1 are pins 2 & 3 respectively, while those for unit 2 are pins 6 & 7. The *output* of unit 1 is pin1, while that of unit 2 is pin 7. Each unit needs positive and negative external power supplies and these are provided by pins 8 & 4. Note that the voltages $V_{cc}+$ and $V_{cc}-$ are with respect to ground, which is not needed by the chip itself but is needed by all other signals. The correct power supply connections are shown in Figure 8.

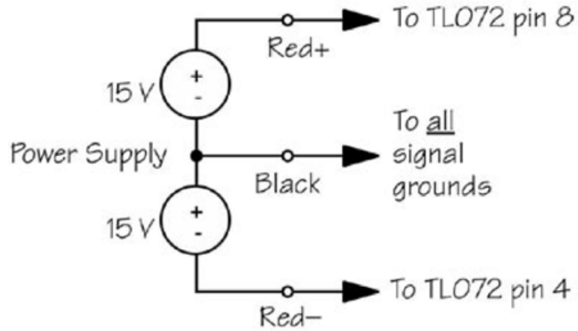

Figure 8 — Power Supplies for the TL072

11.4 ESD protection

Integrated circuits (IC) can be destroyed by electrostatic discharge (ESD). Humans can create ESD, what you may recognize as a static electric shock, up to several thousand volts. This voltage may be discharged into the IC if you touch it without grounding your body first. Semiconductor companies report that 30-40% of all customer returns are due to damage as a result of ESD. There are ways to prevent ESD from destroying your IC chips.

- Always carry your IC chips in an ESD guarded container. This will usually have ESD protection foam in an enclosed plastic case (Styrofoam will work in a pinch).
- Before removing your IC chip from the ESD container, you should touch the ground terminal of a power supply that is powered “on” with one hand, while handling the chip with the other hand. This will ensure that any electrical charge on your body has been discharged before you touch the chip.
- In industry you will use a grounding strap that will continuously connect your body to ground and eliminates the chance that you will build up static charge.

11.5 ECE203 Lab Kit Parts List

- 120 Ω
- 200 Ω
- 1.2 kΩ
- 1.5 kΩ
- 2.4 kΩ
- 3.6 kΩ
- 15 kΩ
- 20 kΩ
- 47 kΩ
- 51 kΩ
- 100 kΩ
- 120 kΩ
- 750 kΩ
- TL072 Op Amp

12.0 Lab tutorial videos

To prepare for lab you should read the lab manual and you can also learn a lot by watching the available video tutorials. There are three types of video tutorials. The "How to" videos are good for learning how to use an unfamiliar piece of equipment or performing a new task. There are also available for each lab "Introduction" videos. The "Introduction" videos present an overview of the tasks you will complete in each lab. It discusses common mistakes encountered when making measurements and in most cases it discusses the pre-lab calculations that you will make. All of the videos are available to watch before lab and even during lab. They can be accessed at the following link:

http://bit.ly/1Z0BJHa

Lab 1 Laboratory Measurement Techniques

The objective of this lab is to become acquainted with the equipment in the Circuits Lab and apply some basic techniques to measure voltage, current, resistance and power.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of your lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 In order to prepare for lab watch the video, ***Laboratory Measurement Techniques*** it is in the *ECE203 Lab Tutorials* Video Menu. This video should give you an idea of what you will do in the lab. The lab is at the following link: http://bit.ly/1UzsLA1. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will need to learn how to operate the DC power supply and the Digital Multimeter (DMM) to make basic measurements of resistance, voltage, and current. You will use a breadboard to build your circuits. You are also encouraged to watch the following instructional videos both before lab and during lab, these are in the *How_to_Videos* menu:

- How_To Full Playlist (https://youtu.be/UMJrYOe450Y)
- How_to_Breadboard (http://bit.ly/1UfXi7b)
- How_to_Setup_DMM (http://bit.ly/1Uzt1yZ)
- How_to_measure_R_with_DMM (http://bit.ly/1Xv8pap)
- How_to_measure_V_with_DMM (http://bit.ly/1QXJqw7)
- How_to_measure_I_with_DMM (http://bit.ly/254n7uG)
- How_to_use_DCPowerSupply (http://bit.ly/1UztyAZ)
- How_to_read_ResistorCode (http://bit.ly/22mjjmf)
- How_to_build_a_simple_circuit (http://bit.ly/1TOjvJz)
- How_to_ohm_the_ammeter (http://bit.ly/1UzuOnO)

These videos will show you the correct way to interpret your breadboard, how to apply the resistor color code, and how to operate the digital multimeter. Alternately you can read through the instruments' user manual which are available on-line and a printed copy is available in the lab.

1.3 Your written pre-lab work should include the following:

- Determine the coding bands for **all** of the unique resistors in your parts kit. The inventory of parts is in part 11.5 of the prior section. Summarize these results in a table similar to the one shown in Table 1-1.
- Apply the techniques presented in the lectures to make predictions for the measurements of voltage, current, and power that will be taken in parts 2.4 through 2.5 for **all** of the unique resistors in your kit. Carry-out all your calculations with 4 significant digits and report at least 3 significant digits.

- Summarize these results in a table similar to the one shown in Table 1-1.
- Submit a copy of the pre-lab on engineering paper at the beginning of lab. Make a copy in the library before submission.

Table 1-1: Example of Ideal Predictions

(Note: these are not the same resistor values that you will use)

Table 1 predicted values for circuit of Figure 1

R(kΩ)	Color code	V (Volts)	I (mA)	P (mW)
1.5	Br-G-R	5.000	3.333	16.67
2.0	R-Bk-Or	5.000	2.500	1.250
51	G-Br-Or	5.000	0.9804	0.4902
120	Br-R-Y	5.000	0.4167	0.2083

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

Each week you will have to complete a pre-lab that typically involves finding values on a circuit that you will build during the lab session. You should always use the measured values of your resistors in those calculations and these will be the predicted values that you will compare to your measured values. Therefore the first step in this week's lab will be to get those measured resistor values.

2.1 Measuring Resistance using the Ohmmeter: Use an ohmmeter to measure the resistance of each resistor in your kit by using the digital multimeter (DMM) in its ohmmeter function. Figure 1-1 shows a photograph of this setup; be sure to use the 2W terminals not the 4W terminals. Record the values of all resistors in your kit on a table similar to Table 1-2 in your lab manual.

Table 1-2: Example of Measured Resistors Table

Resistor	Measured, kΩ	Nominal, kΩ	% error
150 Ω		0.15	
200 Ω		0.2	
1.2 kΩ		1.2	

Note that the percent error formula is given by the following equation,

$$\%\,error = \frac{measured - nominal}{nominal}\ x\ 100$$

Notice that the above formula assumes the nominal value is accurate and gives a positive error when the measurement is high and a negative error when the measurement is low.

You are going to also determine the values of **five** of the resistors in your kit in three ways: color code, direct measurement by an ohmmeter, and measurement of voltage and current.

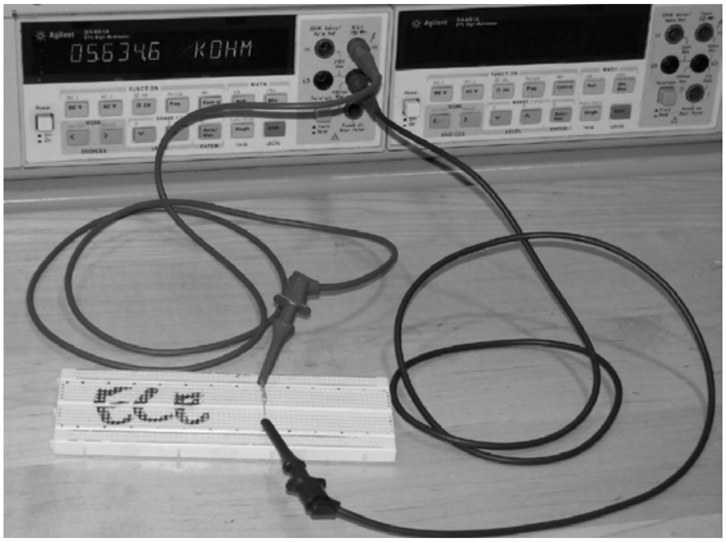

Figure 1-1: Ohmmeter Setup

2.2 Ohmmeter the Ammeter: Each week that you will use the ammeter to measure current, you should confirm that there is not a blown fuse. If the fuse is blown, all of the current measurements will be 0A. To confirm that the fuse is good, you will use the ohmmeter to test the ammeter. You should record the resistance reading of the left and right ammeter in your lab notebook to indicate that you have done this. You ohmmeter the ammeter by using the following instructions:

- Turn on both DMMs, setting the left one to measure current and the right one to measure resistance. The leads should be between the com port and bottom right port on the ammeter. The leads should be between the com port and top right port on the ohmmeter. Note that to measure current the red lead of the left DMM goes in the bottom terminal NOT the top terminal.
- Connect the red leads and black leads together on the DMMs.
- Measure the resistance of the ammeter (the left DMM) by noting the reading on the ohmmeter (the right DMM). If it is approximately 5Ω - 10Ω then the left ammeter's fuse is okay. If the fuse is blown you will typically measure an open circuit, which will be indicated on the ohmmeter as an overload ("OVLD")
- To test the ammeter function of the right DMM, repeat the measurement by reverse the connections and settings of the left and right meters.

2.3 Five Resistor Measurements: Select the following five resistors from your kit: 120 Ω, 1.2 kΩ, 15 kΩ, 47 kΩ, and 100 kΩ. Record their color code and measured resistance in a table similar to Table 1-3. You can use this same table for the next part.

Table 1-3: Nominal & Actual Resistances measured with the ohmmeter (Sample)

$R_{nominal}$ Ohmmeter (kΩ)	Color Code	$V_{Measured}$ (V)	$I_{Measured}$ (mA)	$R_{Measured}$ (kΩ)	% error
0.12	br-red-br				

2.4 Measuring the resistance using voltage and current measurements: You will also measure the resistance of the five resistors from part 2.2 by applying a voltage and measuring the current using the circuit shown in Figure 1-2. Note that the voltmeter is in parallel with the resistor, while the ammeter is in series. Record this data in a table similar to Table 1-4.

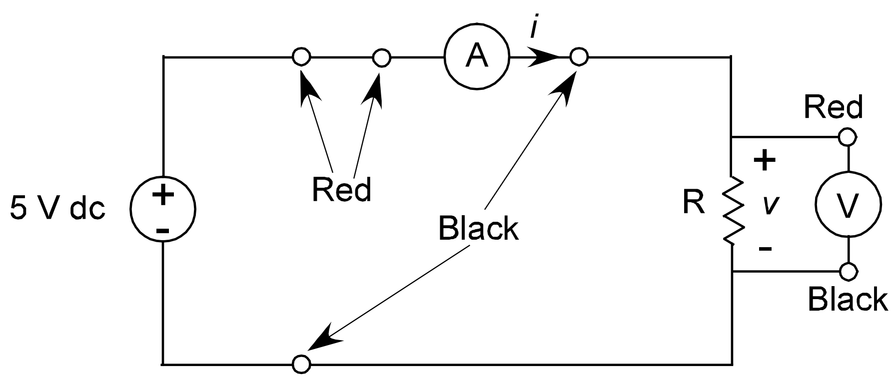

Figure 1-2: Circuit Diagram for *v* - *i* Measurement

A photograph of the entire setup is shown in Figure 1-3. Getting the correct polarity on the red and black terminals will give you positive readings.

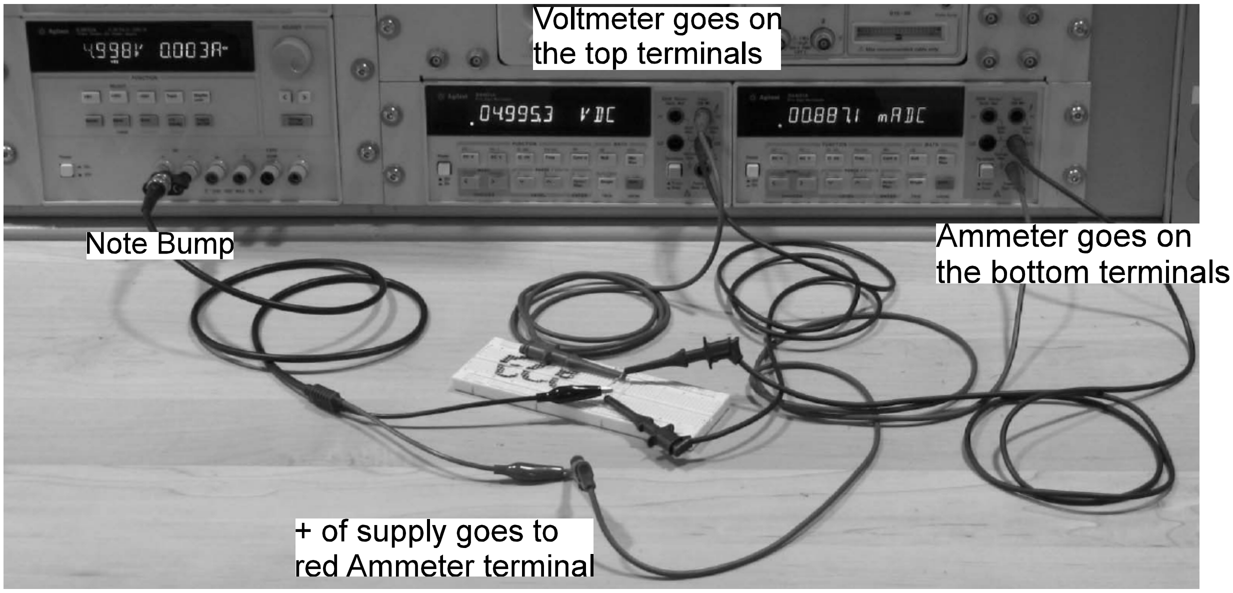

Figure 1-3: Resistor *v* — *i* Measurement Setup

Follow the instructions below to set-up and make the measurements of voltage and current:

- Put one of the resistors into your breadboard and connect one DMM as a voltmeter by placing the red lead at the top of the resistor and the black lead at the bottom. Set this DMM to “DC V”.
- Connect the second DMM as an ammeter by placing the black lead at the top of the resistor and leave the red lead disconnected for the time being. Set this DMM to “DC I”.
- Get a two-wire lead with red and black probes on one end and a BNC (Bayonet Neill-Concelmann, a shiny round connector) on the other. Attach this to a BNC-to-Banana adapter; note that the adapter has a bump on one edge with “GND” that means it connects to ground terminal.
- Press the “POWER” button to turn on the Agilent E3631 triple power supply, which is shown in Figure 1-4 (do not press the OUTPUT ON/OFF button yet).
- On the power supply, press +6V, press DISPLAY LIMIT (the cursor should be blinking under the voltage), click the left arrow to move the cursor before the decimal point, set the output voltage to 5 V by turning the ADJUST knob.

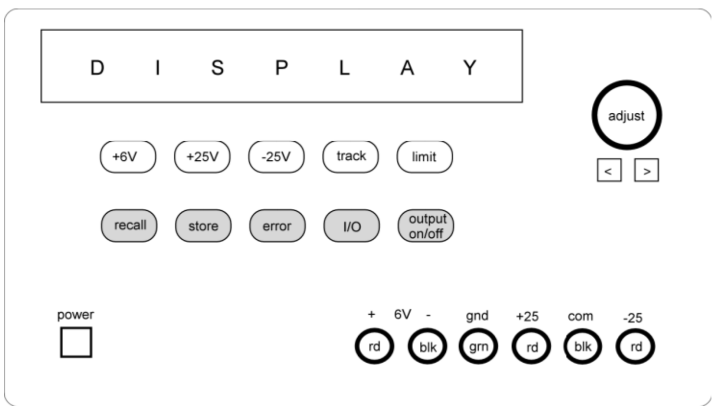

Figure 1-4: Agilent E3631 triple power supply

- Plug the adapter into the +6 V red and black terminals with the bump of the adapter on the black terminal.
- Connect the black probe to the bottom end of the resistor and connect the red probe to the red ammeter lead that was left disconnected.
- Turn the DMMs on and then press OUTPUT ON/OFF to energize your circuit. You may have to adjust the power supply voltage so that you read 5 V on the DMM. Record the voltage and current in Table 1-4. Then use your measurements of voltage and current to compute the resistance (R= V/I). Note that on this table the nominal values are now the ohmmeter measurements from part 2.2.
- Compute the percent error between the resistance you derived from the voltage and current measurements and the nominal resistance value. Include your results on the data table. Do this for all five resistors.

Table 1-4: Error Analysis for Voltage & Current (Sample)

$R_{nominal}$ Ohmmeter (kΩ)	$V_{Measured}$ (V)	$I_{Measured}$ (mA)	$R_{Measured}$ (kΩ)	% error

- When you have finished, press OUTPUT ON/OFF once again to de-energize your circuit. Do not turn off the power supply itself, just its output.
- *Compare the two methods of measuring resistance: 1) ohmmeter and 2) voltage and current measurements. Comment on which method of resistance measurement do you think is more accurate? Which method would be easier to apply in the field?*

2.5 Power dissipated by a resistor: Use the results of part 2.4 to calculate "actual" power dissipated for each resistor by applying the following formula:

$$P_{Actual} = \frac{V_{Measured}^2}{R_{Measured}}$$

Compare these values to the nominal power values found vy using the nominal resistor value. Record the voltage and power and % error in a data table similar to Table 1-5. Note that on this table $P_{nominal}$ is the power calculated using the ohmmeter resistor value from part 2.2.

Table 1-5: Error Analysis for Power (Sample)

$R_{nominal}$ Ohmmeter (kΩ)	$P_{nominal}$ (mW)	P_{Actual} (mW)	% error

2.6 Graph of Power vs. Resistance: Plot a graph of Power vs. Resistance with $R_{Nominal}$ as the x-axis and P_{Actual} as the y-axis. Make the graph cover at least half a page. You will notice that the graph is somewhat "cramped" because both the x and y axes cover a large range of values. When this happens, it is usually better to plot the graph on logarithmic axes. So, re-do the graph with $\log(R_{Nominal})$ as the x-axis and $\log(P_{Actual})$ as the y-axis. Be sure to calculate the log of each value using log-based 10 on your calculator not log-based *e*. For example, $\log_{10}(10) = 1.0$. You can create the graphs by hand, in Excel or Logger Pro.

Comment on what you can conclude about the shape of the linear graph versus the logarithmic graph.

2.7 Using the double output power supply: In this part you will determine the output voltages of the ±25 V DC power supply. Set the outputs to +15 V DC and -15 V DC by following the steps below:

- Push the button labeled +25V to select the 0 to +25V adjustable supply and press

OUTPUT ON/OFF to energize the +25V supply.

- Press TRACK to allows for simultaneous adjustment of the 0 to -25V supply as the 0 to +25V supply is adjusted—that is the -25V supply "tracks" the +25V supply.
- Turn the ADJUST knob to 15V to set the dual supply to +15V and -15V simultaneously.
- Press +25V to confirm presence of +15V and press -25V to confirm presence of -15V.
- Now that the dual power supply has the correct settings, make three measurements.
  1. Using the DMM that is set to measure voltage, measure the voltage difference +15 V to COM, NOTE: COM is the "common" black terminal in between the ±25 V red terminals.
  2. Measure the voltage difference -15 V to COM.
  3. Measure the voltage difference +15 V to -15 V. To measure +15 V to -15 V, you will need to get a single banana-banana connector for the -25 V terminal and put an alligator clip on the end. On the power supply, connect the +15 V to the positive (red) on the DMM and the -15 V to the com (black) on the DMM.

- Add the magnitudes of the first two DMM readings and compute the percent error by which their sum differs from the third reading. Ideally this should be zero, but all meters have inaccuracy and a small discrepancy will be likely.
- Draw a schematic in your lab book that explains the connections made and the measurements taken. You will refer to this diagram in later labs where you will use the dual power supply.

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab
- ☐ Title, name, partner, date, room , station
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Connect pre-lab at beginning of lab

2.1 Measuring Resistance using the Ohmmeter
- ☐ Procedure
- ☐ Table of nominal and measured resistance, % error

2.2 Five Resistor Measurements
- ☐ Procedure
- ☐ Table of color code, nominal and measured resistance, % error for 5 resistors

2.3 Ohmmeter the Ammeter
- ☐ Procedure
- ☐ Resistance values measured for both DMMS

2.4 Measure resistance using voltage and current measurements
- ☐ Procedure
- ☐ Circuit describing set-up
- ☐ Table of resistance, voltage, current measurements, % error
- ☐ Formulas used
- ☐ Comment on results, comparing the two measurements

2.5 Power dissipated by a resistor
- ☐ Procedure
- ☐ Table of resistance (from ohmmeter & measured), voltage, power, % error
- ☐ Formulas used

2.6 Graph of power vs. resistance
- ☐ Procedure
- ☐ Each graph should be at least ½ page large, have a descriptive title, clearly labeled axes, including units
- ☐ Data points should be clear and connected by a smooth line, ignoring any obviously bad data
- ☐ Comment on the shape of the curves

2.7 Using the double output power supply
- ☐ Procedure
- ☐ Confirmation the sum of the magnitudes for the positive and negative power supplies is the same as measured across the two
- ☐ Schematic describing the connections and measurements taken

Ensure that all team members sign and date the last page.

Lab 2 KVL and KCL

The objectives of this lab are to measure circuit voltages and currents and relate them to Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL). You will use the conservation of energy to verify your measurements by computing the total power absorbed and the total power generated.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of your lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 Read section 1.5 (passive sign convention) and 2.4 (Kirchhoff's Laws) in your textbook. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will use the Digital Multimeter (DMM) to measure voltage and current. Review your work in lab 1 and you may want to review the **How_to** videos.

1.3 Apply the techniques presented in the lectures to make predictions for the measurements that will be taken in parts 2.1 and 2.2. Your written pre-lab work should include the following:

- Copy Figure 2-1 in your lab book. You are going to build this circuit during lab using the resistors in your kit.
- Use the measured values of the resistors in your kit to calculate the values of the voltages and currents labeled in Figure 2-1. Use the voltages and currents to calculate the power delivered or absorbed for each element and organize your results in a table. Confirm that the circuit obeys the law of conservation of energy.
- Copy Figure 2-3 in your lab book. You are going to build this circuit during lab using the resistors in your kit.
- Use the measured values of the resistors, KVL and KCL to calculate the value of the voltages and currents for all of the elements in the circuit. To solve this problem you need to label all 5 currents and get 5 equations. There will be 2 KCL and 3 KVL equations. Use Maple or your calculator to solve for the currents and use the currents to calculate the voltages.
- Compute the power associated with each element and state whether the element is absorbing or delivering power. Organize your results in a table and verify that the total power absorbed is equal to the total power delivered in the circuit.
- Next you will use NI Multisim to check your hand calculations. Install Multisim by navigating to the following folder: \\rose-hulman.edu\dfs\Software\Course Software\NI LabView Spring 2016 Follow the instructions in the ***Readme.txt*** file then install the software by clicking ***setup.exe***. Accept all defaults. Copy and paste the serial number from the Readme file. Select Install NI Circuit Design Suite. Accept all defaults.
- Study the following videos to learn how to use NI Multisim:
  - Commonly used circuit components: http://goo.gl/LYNSY
    Measure DC voltage with a voltmeter: http://goo.gl/iDPZM
- Simulate the circuit in Figure 2-1 in NI Multisim. You will use the same multimeter

shown in the video to measure all of the voltages and currents in the circuit. Use one Multimeter instrument set to voltage (V) to measure across each of the elements in the circuit. Then use one Multimeter instrument set to current (A) to measure the current through each of the elements in the circuit. ***Note that you must break the circuit and put the multimeter in series with the element to measure the current.***

- Organize your calculations and simulation results in a table for comparison. You must submit the screenshot of the circuit with all of the simulated voltages and currents shown.
- Simulate the circuit in Figure 2-3 in NI Multisim. Measure the voltage and current for each element in the circuit. Organize your calculations and simulation results in a table for comparison. You must submit the screenshot of the circuit with all of the simulated voltages and currents shown.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to build the circuits in Figures 2-1 and 2-3 and make measurements using the DMM.

2.1 Three Resistor Circuit. Construct the circuit of Figure 2-1 on your breadboard. Each vertical column of five holes in the breadboard is one node; i.e., the five holes are all connected together but are not connected to any neighbor. Before you start taking measurements organize and plan your data table(s).

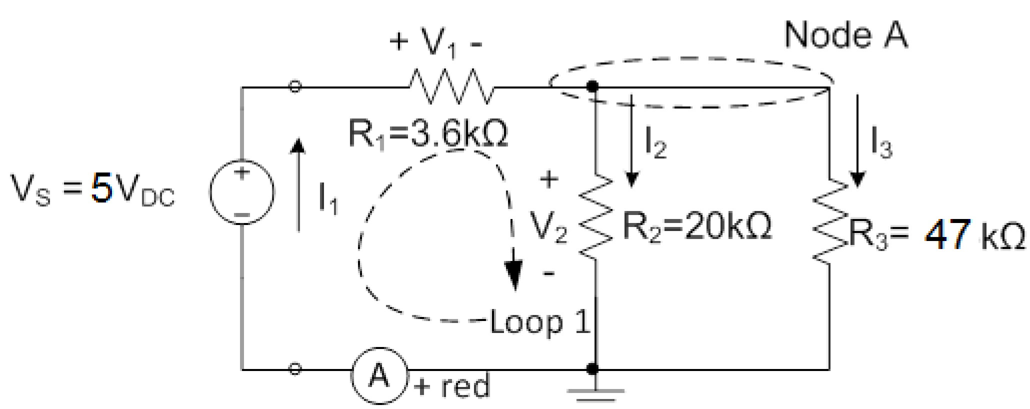

Figure 2-1: Three resistor circuit

2.1.1 Arrange the resistors on your breadboard to align with their positions in the drawing as shown in Figure 2-2. Use the +6V DC power supply to set-up V_S.

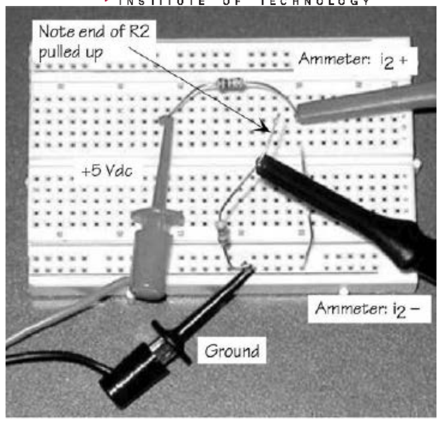

Figure 2-2: Setup to measure I_2

2.1.2 Use the DMM to measure all the labeled voltages (V_S, V_1, V_2). To measure the correct polarity of the voltage you must connect the red terminal to the "+" side of the resistors. Record the voltages on a table similar to Table 2-1, where the nominal value was found in the pre-lab.

Table 2-1: Three resistor circuit voltages

	measured	nominal	%error
V_S. V			
V_1, V			
V_2, V			

2.1.3 Compute the percent error of your measured voltages compared to the values calculated based on the nominal resistor. Use the following formula:

$$\%\ \text{error} = \frac{\text{measured} - \text{nominal}}{\text{nominal}}\ \text{x}\ 100 \qquad \text{(eq. 2.1)}$$

2.1.4 Use the DMM to measure all the labeled currents (I_1, I_2, I_3). Remember to connect the DMM in the ammeter mode such that the ammeter is in series. Figure 2-2 shows how the meter leads are placed to measure I_2. Compute the percent error of your measurements compared to the nominal values. Record your data on a table similar to Table 2-1.

Comment in your lab book on what is important to do when using the ammeter to measure current?

2.1.5 Use the DMM to measure the resistance of each resistor, call this value the measured value. Using Ohm's Law to calculate the resistance of each resistor based on the voltage and current measured. Call this value the predicted value. For example, $R_2 = V_2/I_2$ and should be close the ohmmeter measurement of resistance. Compute the percent difference of your ohmmeter measurements of resistance to your voltage and current measurements using the following formula:

$$\%\ \text{error} = \frac{\text{Predicted} - \text{Ohmmeter measured}}{\text{Ohmmeter measured}}\ \text{x}\ 100 \qquad \text{(eq. 2.2)}$$

Record this data on a table similar to Table 2-1.

Comment on what is important to do when using the ohmmeter to measure resistance.

2.1.6 Verify Kirchhoff's Voltage Law with your voltage measurements around Loop 1 and Kirchhoff's Current Law with your current measurements at Node A.

2.2 Current Source Circuit. Your goal is to verify that the total power absorbed in the circuit is equal to the total power generated in the circuit, by the principle of conservation of energy. Remember that in order to measure the current in the branch, you must place the ammeter in series and you will have to break the circuit to do this.

2.2.1 Construct the circuit of Figure 2-3 on your breadboard. Use the current limiting function of the DC power supply to create a current source by connecting the +25V port (red lead at the top and black lead at the bottom). Set the display limit function to set the voltage limit to +25V (higher than you need) and the current limit to **500 mA** before turning the output on. (Note the power supply displays the current in units of Amps. 20mA = 0.020A). Use the +6V port to set the voltage source $V_S = 5V_{DC}$. Make sure the current limit of the 5V voltage source is set to at least **500mA** (higher than you need). Make the rest of the connections to the resistors as shown in the circuit.

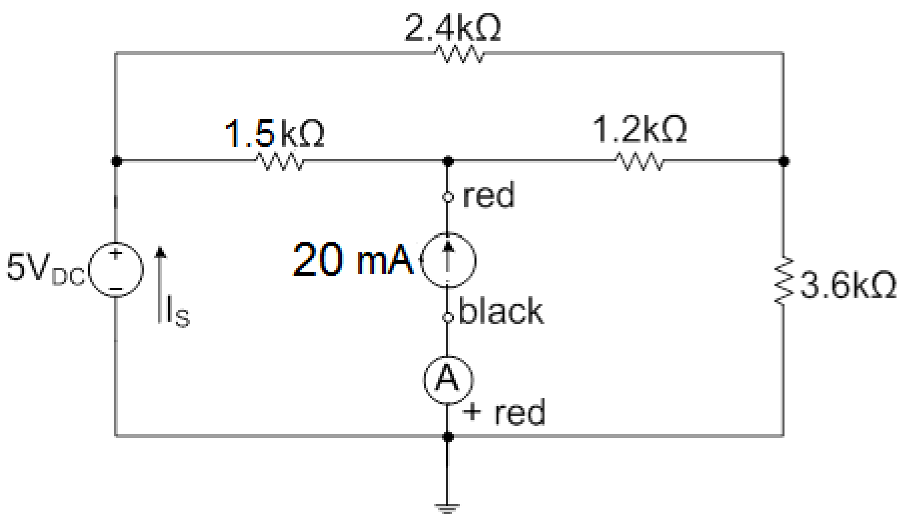

Figure 2-3: Circuit with a current source.

2.2.2 For each circuit element (resistors and sources) measure the voltage and current. Create a separate data table for voltage and current. The tables should be similar to Table 2-1. The tables should include measured, nominal and calculate percent error using equation (2.1). By convention we label all resistors in the passive sign convention and we label all sources in the active sign convention.

2.2.3 For each circuit element, calculate the magnitude of the power using measured voltage and current. Compare this data to the nominal power calculated in the pre-lab. Organize the power analysis in a data table with measured, nominal and percent error. Also include an additional column to note whether the power is being absorbed or delivered.

2.2.4 Verify that the total power absorbed is equal to the power delivered.

2.2.5 *What would happen to the 20mA current source if you limited the power supply's voltage to 10 V instead of 25V? Try it and explain your results*?

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab

- ☐ Title, name, partner, date, room , station
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct pre-lab if necessary

2.1 Three resistor circuit

- ☐ Procedure
- ☐ Circuit of Figure 2-1 with all components labeled
- ☐ Table of Measured data: I_1, I_2, I_3, % error
- ☐ Table of Measured data: V_s, V_1, V_2, % error
- ☐ Table of Measured data: R_1, R_2, R_3, comparison with Ohm's law, % error
- ☐ Analysis – Verify Kirchhoff's Voltage Law with your measurements around Loop 1
- ☐ Analysis – Verify Kirchhoff's Current Law with your measurements at Node A
- ☐ Comment – what's important when using the ammeter, when using the ohmmeter

2.2 Current source circuit

- ☐ Procedure
- ☐ Circuit of Figure 2-3 with all components labeled with nominal values
- ☐ Table of Measured data (voltage, current, resistance and % error) for each circuit element including sources
- ☐ Table of power data (power and % error, absorbed or delivered) for each circuit element including sources
- ☐ Analysis – Verify the conservation of energy principle
- ☐ Comment – what would happen if you reduce the voltage limit on the current source?

Ensure that all team members sign and date the last page.

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Lab 3 Voltage and Current Dividers

The objective of this lab is to investigate the properties of voltage and current dividers, and to observe the application of voltage dividers to the Wheatstone bridge.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of the lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 In order to prepare for lab watch the video ***Intro_to_Lab 3***. This video should give you an idea of what you will do in the lab. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will use the Digital Multimeter (DMM) to measure voltage and current. Review your work in Lab 1 and or the ***How_to*** videos if you forgot how to do this.

1.3 Apply the ***voltage and current divider techniques*** presented in the lectures and sections 3.3 and 3.4 of the Nilsson textbook to make predictions for the measurements that will be taken in parts 2.1 and 2.2.

Your written pre-lab work should include the following:

- Copy Figure 3-1 in your lab book.
- Use the measured values of the resistors in your kit and calculate the predicted values of the voltages ($V_1 – V_5$) in Figure 3-1. Summarize the results in a table in your lab book.
- Copy Figure 3-2 in your lab book.
- Use the measured values of the resistors in your kit and calculate the predicted values of the currents (I_1-I_5) in Figure 3-2. Summarize the results in a table in your lab book.
- Check your work by building the circuit in Figure 3-1 in NI Multisim. Use the multimeter set to a voltmeter to measure ($V_1 – V_5$). Organize your calculations and simulation results in a table for comparison. You must submit the screenshot of the circuit with the simulated values shown.
- Check your work by building the circuit in Figure 3-2 in NI Multisim. Use the multimeter set to an ammeter to measure ($I_1 – I_5$). Organize your calculations and simulation results in a table for comparison. You must submit the screenshot of the circuit with the simulated values shown.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to verify the relationships for voltage and current dividers and then apply them to show how the Wheatstone Bridge is used to improve the accuracy of difficult measurements.

2.1 **Voltage Divider:** Select the following resistors: 15 kΩ, 20 kΩ, 51 kΩ, 47 kΩ, and 100 kΩ then measure and record their values using the digital multimeter (DMM). Connect them in series. You can get the measured values from Lab 1.

2.1.1 Refer to your notes in Lab 1 to set-up the dual power supply as shown in the schematic of Figure 3-1.

2.1.2 Set-up one DMM to measure the voltage across the dual supply (shown at left in Figure 3-1). If you set up the supply correctly you should measure an output of 30 V. Connect this supply to the resistors in series keeping one voltmeter across the supply, while using the other voltmeter to measure and record the voltage across each resistor. In Figure 1, the second DMM is used to measure the voltage across the 51 kΩ resistor.

2.1.3 Record the measured value of the voltage across each resistor as $V_{measured}$.

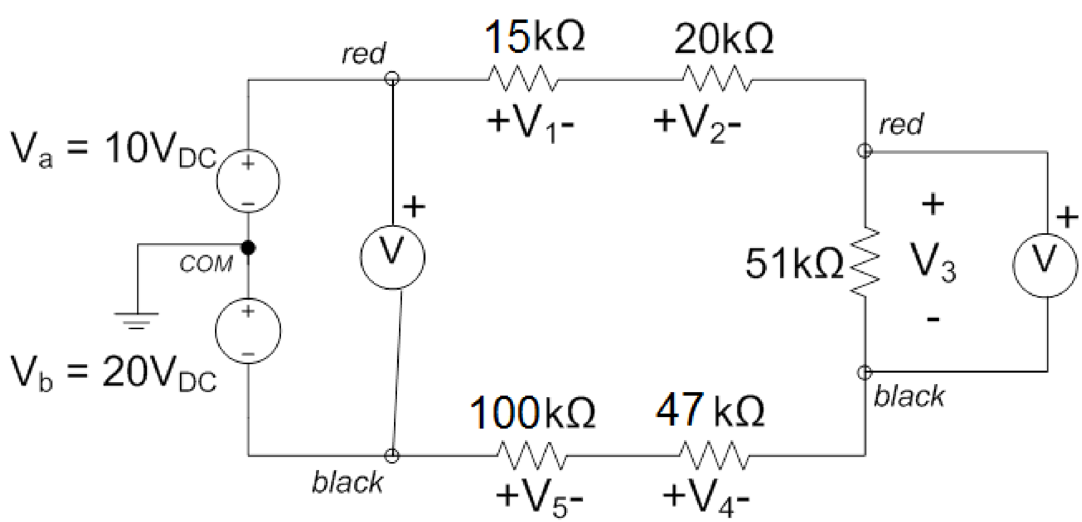

Figure 3-1: Circuit Diagram for *Voltage Division*

2.1.4 Apply voltage division to re-calculate the results of step 1.3 in the pre-lab using the measured values for the resistors and the actual supply voltage. Call these values $V_{predicted}$. Organized your data into a table like Table 3-1 and compute the percent error from the predicted value for each resistor using the following formula:

$$\%\ \text{error} = \frac{\text{measured} - \text{predicted}}{\text{predicted}}\ \text{x}\ 100 \qquad \text{(eq. 2.1)}$$

Table 3-1: Voltage Divider Results (Sample)

Resistor [kΩ]	Voltage [Volts] predicted	Voltage [Volts] measured	% error
1.2	0.0196	0.019587	0.04
15	0.2453	0.24516	-1.52
47	0.7730	0.77028	-0.35
100	-1.6382	-1.6092	-1.77
750	-12.3239	-12.175	-1.21

2.2 **Current Divider:** Switch the supply off. Re-connect the resistors in parallel and re-configure both DMMs to measure current as shown in Figure 3-2, where once again the current through the 51 kΩ resistor (I_3) is being measured.

2.2.1 Use the 25 V power supply with the current limit set to 3 mA and the voltage turned up high enough to get the 3 mA source. Put the ammeter in series with the voltage source and adjust the 25V to get exactly 3 mA. Then use the ammeter to measure the current through each resistor, call this value is $I_{measured}$.

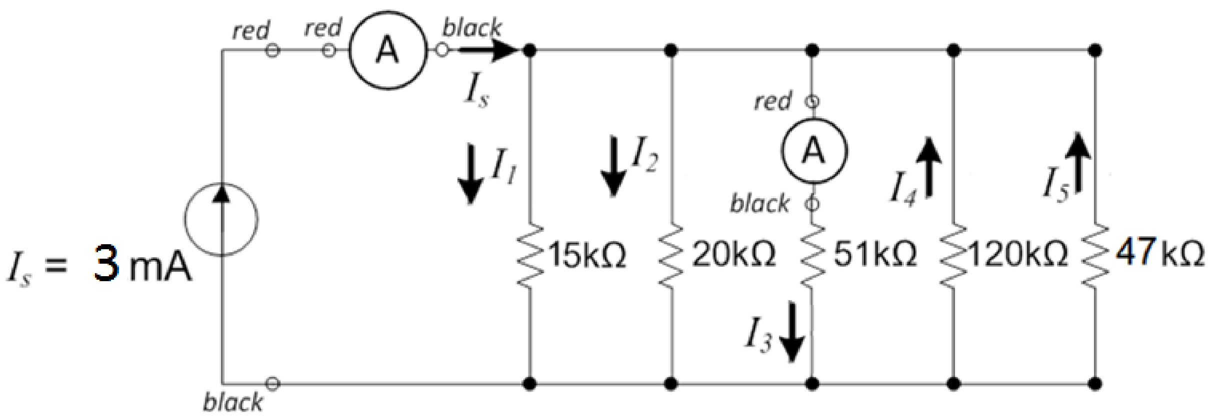

Figure 3-2: Circuit Diagram for *Current Division*

2.2.2 Apply current division to re-calculate the results of step 1.3 in the pre-lab using the measured values for the resistors and the actual supply current ***i***. Call these values $I_{predicted}$.

2.2.3 Organize your data into a table, like Table 3-2 and compute the percent error from the predicted value for each resistor using equation 2.1.

Table 3-2: Current Divider Results (Sample)

element Resistance [kΩ]	Current [mA] predicted	Current [mA] measured	% error $(I_m - I_p)/I_p \times 100$
1.2	10.727	11.109	3.56
15	0.856	0.883	3.14
47	0.272	0.2803	3.17
100	0.128	0.1335	4.13
750	0.0170	0.0174	2.10

2.3 **Wheatstone Bridge:** The next part of the lab is concerned with how voltage dividers in the form of a Wheatstone Bridge are used to accurately measure extremely large or extremely small resistances. Note that simply placing such extreme resistances across an ohmmeter will only give approximate readings, e.g. resistors much less than 1 Ω cannot be measured accurately because the ohmmeter terminals and leads have resistance that may be of the same order as the resistance being measured. A circuit diagram for a Wheatstone Bridge is shown in Figure 3-3.

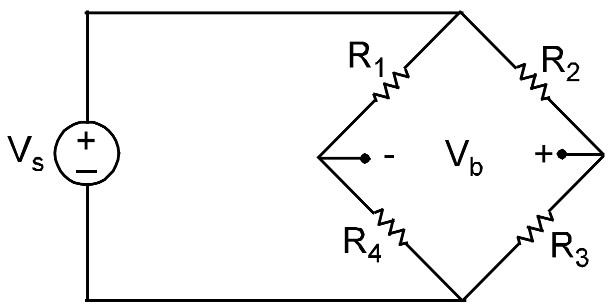

Figure 3-3: Circuit Diagram for a *Wheatstone Bridge*

Notice that the Wheatstone Bridge is two voltage dividers in parallel. By subtracting the outputs of the voltage dividers, we have:

$$V_b = \left(\frac{R_3}{R_2 + R_3} - \frac{R_4}{R_1 + R_4} \right) V_s \qquad \text{(eq 2.2)}$$

The bridge is "balanced" (that is, Vb = 0), for

$$V_b = 0 \quad \text{for} \quad \frac{R_4}{R_1} = \frac{R_3}{R_2} \qquad \text{(eq. 2.3)}$$

Let us suppose that R_1 is an extreme resistor whose value is unknown and difficult to measure accurately with an ohmmeter. However, if the ratio of R_2 to R_3 is known and if the value of R_4 is also known, then R_1 is easily determined using the following expression.

$$R_1 = R_4 \frac{R_2}{R_3} \qquad \text{(eq. 2.4)}$$

2.3.1 You are going to measure the resistance of a wire. Select a standard ***blue*** wire (see Figure 3-4) from your kit and measure its resistance with the ohmmeter. This will be on the order of 100mΩ. Call the ohmmeter measurement of the resistor R_{2w}.

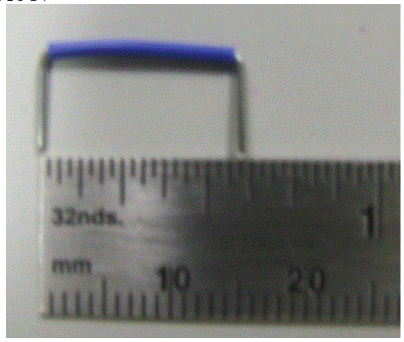

Figure 3-4: Standard blue wire

2.3.2 Set-up the Wheatstone Bridge, making R_2 = 1.2 kΩ and R_3 = 750 kΩ, R_4 a resistance substitution box (potentiometer or variable resistor) and R_1 being the blue wire. Calculate the ratio of R_2/R_3 accurately using your measured resistance values (it should be close to 1/625, but will vary because of tolerances). Power the Wheatstone Bridge using 5 V for V_S with the current limit set to 10 mA.

2.3.3 Balance the bridge by adjusting the value of R_4 until V_b is very small and changes polarity when you adjust R_4. Measure the value of R_4 with the ohmmeter (make sure that R_4 is removed from the circuit). Use the measured values of all three resistors and the following formula to calculate the value of R_1. This will be on the order of 1 mΩ. Call this value R_{Bridge}, the nominal resistance of the blue wire. Now calculate the error between the measured resistance and the nominal value by using the following formula. Create a table that summarizes the data including the nominal, measured and % error of the resistance.

$$\% \text{ error} = \frac{R_{2w} - R_{Bridge}}{R_{Bridge}} \times 100 \qquad \text{(eq. 2.5)}$$

2.3.4 Comment on why you think the error between the measured and nominal value is so large. How does the resistance of the ohmmeter leads compare to the resistance of the blue wire?

2.4 **Ohmmeter using the 4-wire technique:** There is a more precise technique for using the ohmmeter to measure small resistances. This is to use the 4-wire technique on the ohmmeter. The 4-wire technique compensates for the resistance of the leads which is so close to the resistance of the wire.

2.4.1 Put the first set of leads in the right terminals of the ohmmeter as you did in part

2.3.1 to measure resistance. Connect a 2nd set of leads to the left pair of red and black jacks marked "Ω 4W Sense". Put the red and black leads from the "Ω 4W Sense" terminal across the blue wire. Put the leads from the right terminal outside the first set on the wire with the red outside the red and the black outside the black. On the DMM, press "Shift" then "Ω 2W" which yields the 4-wire resistance measurement. Call this value R_{4w}. This will be on the order of 1 mΩ.

2.4.2 Now calculate the error between this measured resistance and the nominal value. Create a table that summarizes the data including the nominal, measured and % error of the resistance.

$$\% \text{ error} = \frac{R_{4w} - R_{Bridge}}{R_{Bridge}} \times 100 \qquad \text{(eq. 2.6)}$$

2.4.3 Comment on how this value compare to the result for the 2-wire resistance measurement. Do you think that the Wheatstone Bridge is a valid method for precise small resistance measurement?

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab

- ☐ Title, name, partner, date, room , station
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct pre-lab if necessary

2.1 Voltage divider

- ☐ Procedure
- ☐ Circuit of Figure 3-1 with all components labeled with nominal values
- ☐ Table of measured resistance values
- ☐ Table of Measured data
- ☐ Formulas used

2.2 Current divider

- ☐ Procedure
- ☐ Circuit of Figure 3-2 with all components labeled with nominal values
- ☐ Table of Measured data
- ☐ Formulas used

2.3 Wheatstone Bridge

- ☐ Procedure
- ☐ Circuit of Figure 3-3
- ☐ Table of data recorded
- ☐ Analysis – Determine the resistance of the blue wire and quantitatively compare with the ohmmeter measurement
- ☐ Comment on why you think the error between the measured and nominal value is so large. How does the resistance of the ohmmeter leads compare to the resistance of the blue wire?

2.4 Ohmmeter using the 4-wire technique

- ☐ Procedure
- ☐ Schematic of set-up
- ☐ Table of data recorded
- ☐ Analysis – Determine the resistance of the blue wire and quantitatively compare with the ohmmeter measurement
- ☐ Comment on how this value compare to the result for the 2-wire resistance measurement. Do you think that the Wheatstone Bridge is a valid method for precise small resistance measurement?

Ensure that all team members sign and date the last page

Lab 4 Node-Voltage Method

The objective of this lab is to verify the method of node-voltage to solve a circuit. You will also reinforce the laboratory skills: measuring voltage, measuring current, and systematically debugging the wiring of a circuit.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of the lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 In order to prepare for lab watch the video ***Intro_to_Lab 4***. This video should give you an idea of what you will do in the lab. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will use the Digital Multimeter (DMM) to measure voltage and current. Review your work in Lab 1 and/or the **How_to** videos if you forgot how to do this. Also you will be required to plot your data on semilog paper. You may find it useful to watch the video **How_to_plot_logscale** (http://bit.ly/22mIGWd)**.**

1.3 Make predictions for the measurements that will be taken in parts 2.1 and 2.2. Your written pre-lab work should include the following:

- Copy Figure 4-1 into your lab book. Use the measured values of the resistors in your lab kit and apply circuit analysis symbolically to Figure 4-1 to find a formula for the node-voltage, V_X, the current, I_X, and the power absorbed by resistor R as a function of R.
- Use your formulas to predict the value of V_X, I_X, and power when R = 10kΩ. Remember, a *node-voltage* is defined as the voltage rise at a node with respect to the reference node or the circuit ground.
- Use NI Multisim to check your work by building the circuit in Figure 4-1 with R = 10kΩ and use the multimeter to measure V_x, I_x, and P_x. View the following video to learn how to use the wattmeter in NI Multisim to measure power: http://goo.gl/qupJK . Now use the wattmeter to measure the power delivered to R. Submit the results of the NI Multisim simulation with the values shown on the printout. Create a table to compare the calculated and simulated results.
- Copy Figure 4-3 into your lab book. Use the measured values of the resistors in your circuit and apply circuit analysis symbolically to find two formulas for V_X and I_X as a function of V_S in Figure 4-3.
- Use your formulas to predict the values of V_X and I_X when V_S = 10V.
- Use NI Multisim to check your work by building the circuit in Figure 4-3 with V_s = 10 V. Use the multimeter to measure the voltage V_x and I_x and compare the results to your hand calculations.
- Submit the results of the NI Multisim simulation with the values shown on the print out.
- Copy Figure 4-4 into your lab book. Simulate the circuit in NI Multisim and use the DMM to measure all of the labeled voltages and currents (V_1, V_3, I_A, I_B, I_C, I_D, I_S, I_X). Submit the results of the NI Multisim simulation with the results shown on the print

out.

- Finally, you will create two Excel spreadsheets that will help you with data collection during the lab session.
  - o Create a spreadsheet with headings: R, V_x, I_x, and P. Then make rows under R from 100 to 100 kΩ in steps of 1, 2, 4, and 7 (i.e. 100, 200, 400, 700, 1000, 2000, 4000, …). Put the formulas you derived for Figure 4-1 in the spreadsheet and calculate V_x, I_x, and P for all of the resistor values. These are the predicted values for the measurements you will make during lab. Submit the spreadsheet as part of your pre-lab submission.
  - o Create a spreadsheet with headings V_s, V_x, and I_x. Then make rows under V_s from -10 to +10 V in steps of 2. Put the formulas you derived for Figure 4-3 in the spreadsheet and calculate V_x and I_x for all of the voltage values. These are the predicted values for the measurements you will make during lab. Submit the spreadsheet as part of your pre-lab submission.

Note, a formula is a concise way of expressing information symbolically. Algebraically separate your variables so that the value you want to predict is on the left-hand side of the equation and the right-hand side of the equation consists of numerical quantities and dependent variables. For example, $V_x(R) = \frac{6.5R}{R+8{,}500} Volts$, where R is in kΩ.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to use the techniques you learned in the earlier labs to make the following measurements.

2.1 **Variable Resistor Circuit.** Build the circuit of Figure 4-1, with R being a resistance substitution box. Set-up two DMMs: one to measure the voltage across the resistor and the other one to measure the current through the resistor. Before you take a lot of data, check your set-up by measuring the values for R = 10KΩ. Compare this measurement to your pre-lab values.

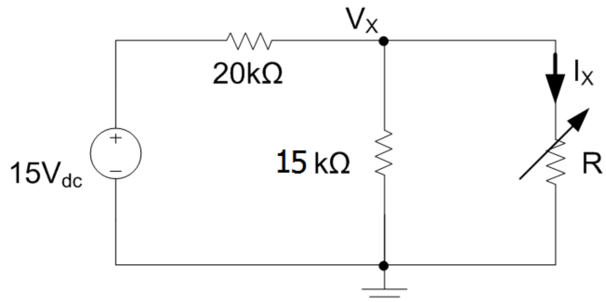

Figure 4-1: Variable resistor circuit

2.1.1 Measure the resistance of the 20kΩ and 15kΩ resistors. Re-compute your formulas to predict the values of V_x, I_x, and the power absorbed by the resistor (R) based on your measured values. Call these values "predicted"

2.1.2 Measure the node-voltage (V_X) and the current through R (I_x) as you vary the resistor (R) from 100Ω – 100kΩ in increments that are linear on a log scale. For example, step by 1, 2, 4, 7 in each of the decades (hundreds, thousands, and ten-thousands). Compute the power absorbed by the resistor (R) using your measured values of voltage and current. Organize your data in a table that contains the measured value, the predicted value and the percent difference between this measured value and the predicted values. State the formulas used. It may be helpful to use Excel in order to create the table.

2.1.3 Plot the value of V_X, I_X, and power as a function of R on the semilog paper provided. See the example semilog plot in Figure 4-2. Note the orientation of the graph paper. Properly attach the graph to your lab journal when you turn it in. It may be helpful to use Excel to create the graph.

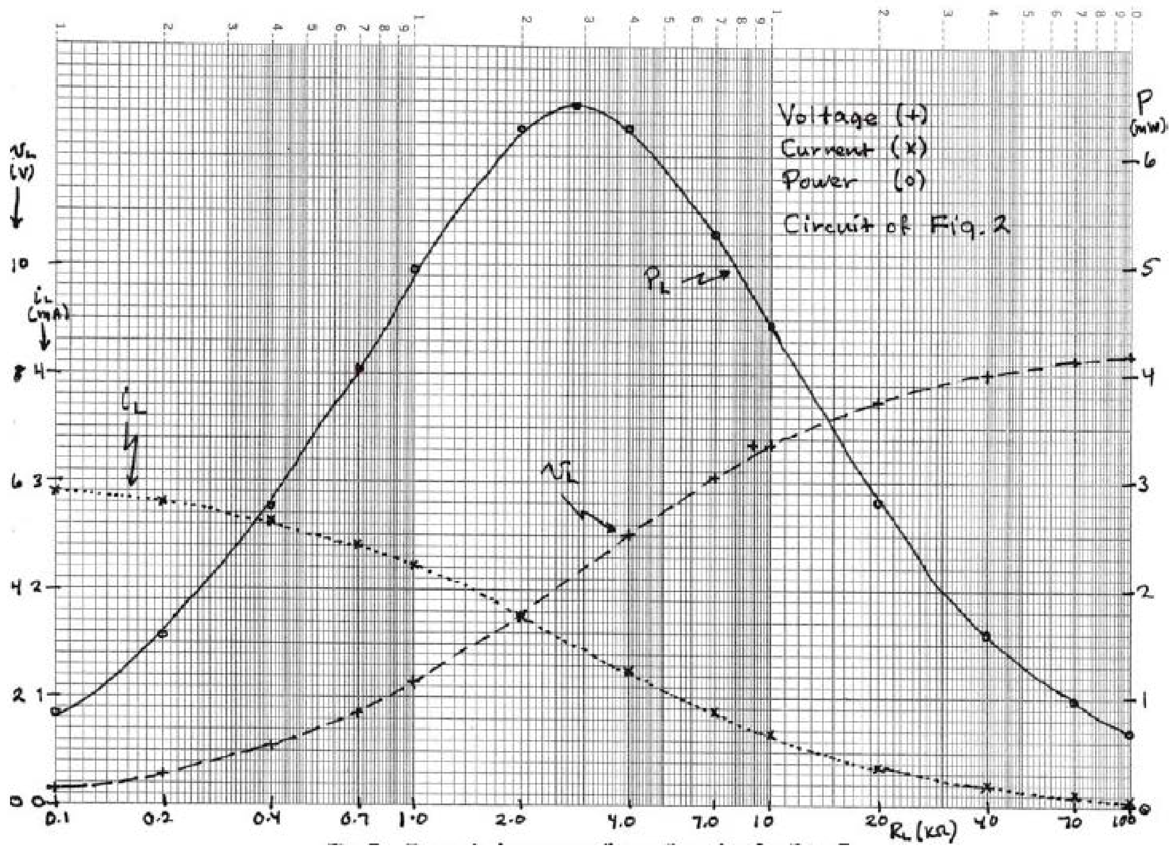

Figure 4-2: Example (not actual) semi log plot

2.2 **Variable Voltage Source Circuit.** Build the circuit of Figure 3. Before you take a lot of data, check your set-up by measuring the value of V_X and I_X for V_S = 10V. Compare this measurement to your pre-lab values.

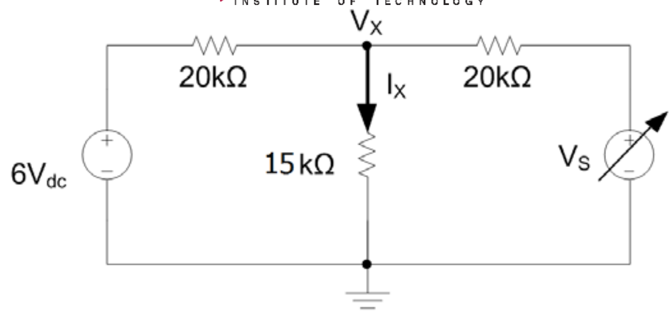

Figure 4-3: Variable voltage source circuit

2.2.1 Measure the node-voltage V_x and I_x as you vary the voltage source (V_S) from -10V to +10V in increments of 2V. It may be helpful to use Excel to create a table of this data.

2.2.2 Recalculate the formula for V_x and I_x using your measured resistance values. Call these values the predicted values. Compute the percent difference (error) between the measured value and the predicted values.

2.2.3 Plot the value of I_X (ordinate) as a function of V_S (abscissa) in a linear plot in your notebook. Then plot the value of V_x versus V_s on a linear plot in your lab book. Follow the guidelines for good graphing techniques discussed in the preface of your lab manual. It may be helpful to use Excel to create the graph.

2.3 **Supernode Circuit.** Build the circuit of Figure 4-4 and measure the node voltages V_1, V_2, and V_3. Measure the branch currents I_A, I_B, I_C, and I_D. Be careful to measure the currents in the direction indicated in the circuit and record both the magnitude and sign of the currents that you measured. Label and measure the current through the 3V source (I_S). Also measure the voltage over the 20 kΩ resistor (V_1-V_2) and the voltage over the 15 kΩ resistor (V_3-V_2). Organize and record your measurements in a data table.

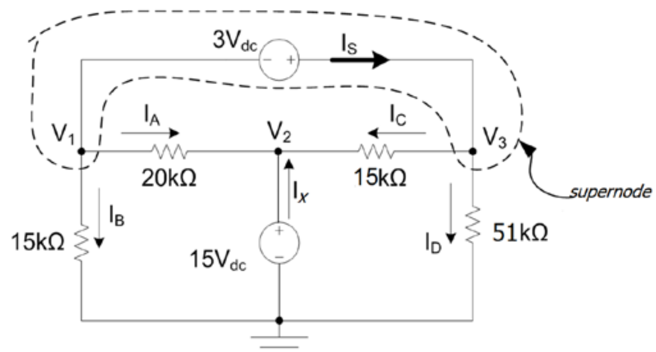

Figure 4-4: Supernode circuit

2.3.1 Perform the following analysis based on your measurements:

- Verify that the measured currents leaving the supernode sum to zero (Kirchhoff's current law).
- Verify Kirchhoff's voltage law around the three loops using your measured voltages.
- Verify the law of conservation of energy by using the measured voltages and currents.

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab

- ☐ Title, name, partner, date, room , station
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct pre-lab if necessary

2.1 Variable Resistor Circuit

- ☐ Procedure
- ☐ Circuit of Figure 4-1 with components and test points properly labeled
- ☐ Table of measured data: R and V_x, I_x, P_x and % error
- ☐ Semilog graph of V_x, I_x, and power vs. R with proper title and axes labeled with units

2.2 Variable Voltage Source Circuit

- ☐ Procedure
- ☐ Circuit of Figure 4-3 with components and test points properly labeled
- ☐ Table of Measured data: V_S, I_X, V_x, % error
- ☐ Linear graph of I_X vs. V_S with proper title and axes labeled with units
- ☐ Linear graph of V_X vs. V_S with proper title and axes labeled with units

2.3 Supernode Circuit

- ☐ Procedure
- ☐ Circuit of Figure 4-4 with components properly labeled
- ☐ Table of Measured V_1, V_2, V_3, I_A, I_B, I_C, I_D, I_S, and I_X; also V_1-V_2 and V_3-V_2
- ☐ Analysis – Verify KCL at the supernode at V_1 and V_3
- ☐ Analysis - KVL around the three loops using measured values
- ☐ Analysis - Verify law of conservation of energy for the circuit

Ensure that all team members sign and date the last page.

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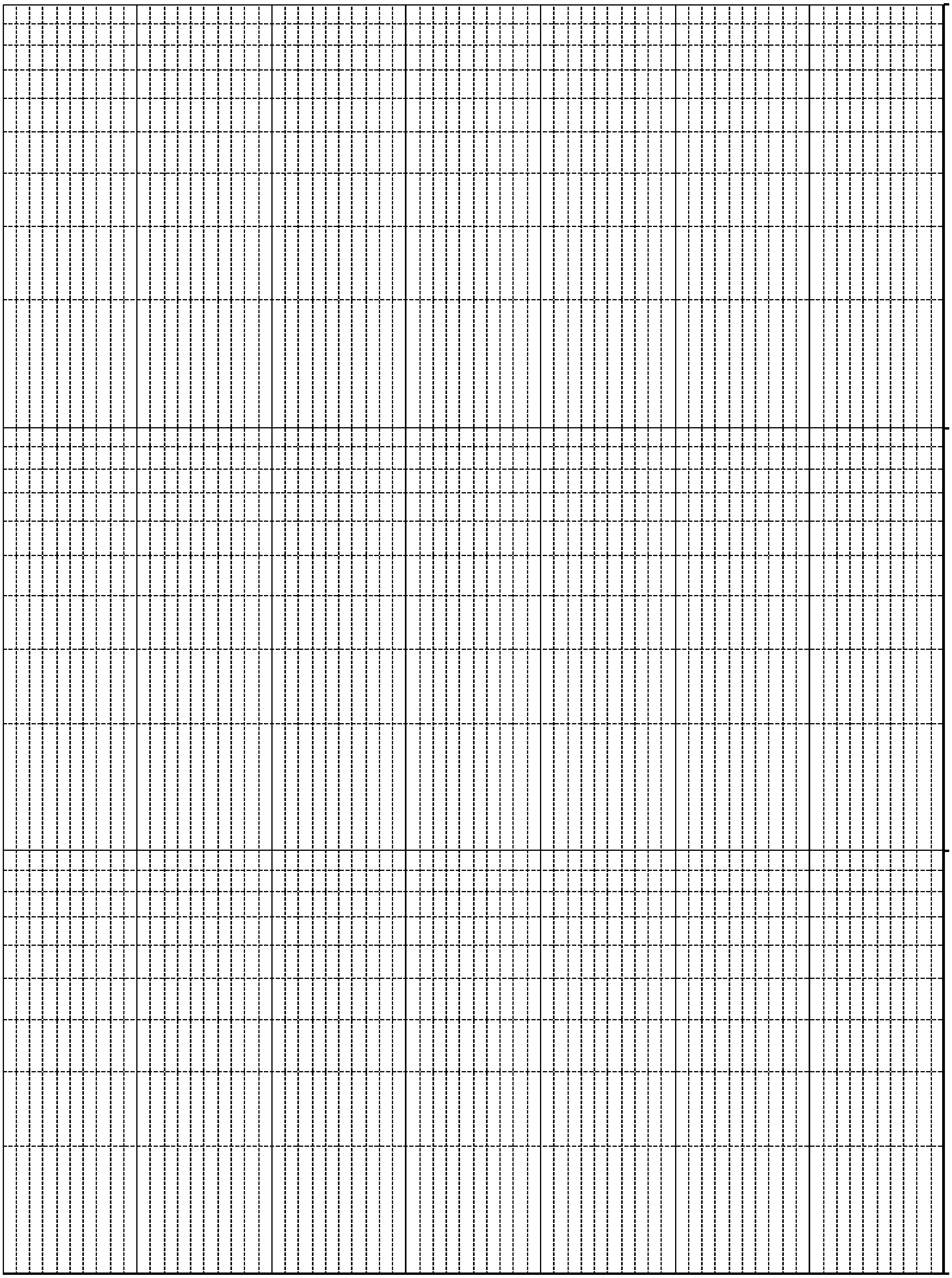

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Lab 5 Lab Practical Test 1

This lab is a test to make sure that you have developed the skills necessary to do well in future labs. This test will count one lab grade.

Because this test constitutes a significant part of your overall lab grade, you may want to review what you have been doing for the past few weeks before coming to this test. You are permitted to use the following: course textbook, the lab manual, both lab composition books, and a calculator, but not your laptop computer.

You will be making measurements on a circuit similar to the one shown in Figure 5-1. Each partner will need to be able to build the circuit because you will not work together during the practical. During the practical, you will be given a sheet with instructions for the measurements you will be taking and a data form for entering the results.

Half of the class, i.e. one member of each team, will come to the lab at the beginning of the lab period. The other team member will come 25 minutes into the second period of the lab. You each will have one hour and fifteen minutes to complete the test. Your instructor will assign the time of your test.

You will be making measurements that are similar to those you have been making in the previous labs. Review the procedures for setting up the +6V power supply and the +/-25V power supply. Your grade will be based entirely on the data you take. You are finished when you hand-in the completed data form.

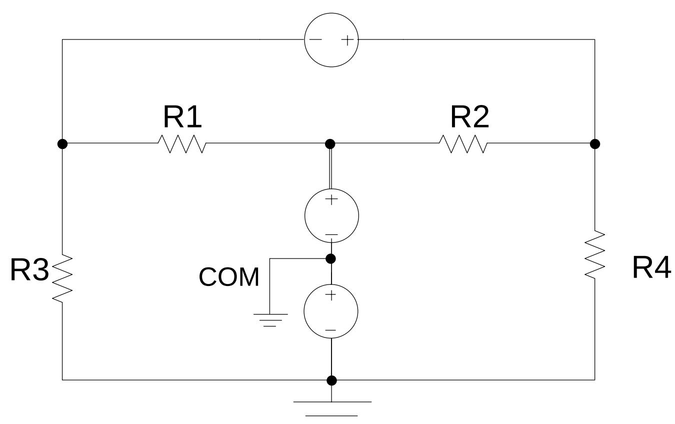

Figure 5-1: Lab Test Circuit

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Lab 6 Mesh-Current Method

The objective of this lab is to verify the method of mesh-current to solve a circuit. You will also reinforce the laboratory skills: measuring voltage, measuring current and the systematically debugging the wiring of a circuit.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of the lab session.

1.1 In order to prepare for lab watch the video **Intro_to_Lab6**. This video should give you an idea of what you will do in the lab. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will use the Digital Multimeter (DMM) to measure voltage and current. Review your work in Lab 1 and or the **How_to** videos if you forgot how to do this.

1.3 Apply the technique of mesh-current method presented in the lectures and Sections 4.5-4.7 of the Nilsson textbook to make predictions for the measurements that will be taken in parts 2.1 and 2.2. Your written pre-lab work should include the following:

- Copy Figure 6-1 in your lab book.
- Use the mesh-current method to find the four mesh currents I_a, I_b, I_c, I_d and the node-voltage V_X. Remember to use the measured values of your resistors in your calculations. Summarize the results in a table in your lab book.
- Simulate the circuit in Figure 6-1 in NI Multisim and use the multimeter to find the mesh-currents and node voltage, V_x. Summarize the results of your calculations and simulation in a table for comparison.
- Copy Figure 6-2 in your lab book.
- Use the mesh-current method to find the three mesh currents I_1, I_2, and I_3. Compute the magnitude of the power associated with the two independent sources and indicate whether the source delivers or absorbs power. Remember to use the measured values of the resistors in your calculations. Summarize the results in a table in your lab book.
- Simulate the circuit in Figure 6-2 in NI Multisim and use the multimeter to find the mesh-currents and node voltage, V_B. Also use the wattmeter to find the power associated with each of the independent sources. Organize the results of your calculations and simulation in a table for comparison.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to use the techniques you learned in the earlier labs to make the following measurement of mesh-currents and node-voltages.

2.1 **Mesh-Current Circuit.**

Measure the values of the resistors used in the following circuit and re-calculate the values of the mesh-currents and node voltage (V_x). Note the unusual position for the ground or reference node. Call these values the predicted values.

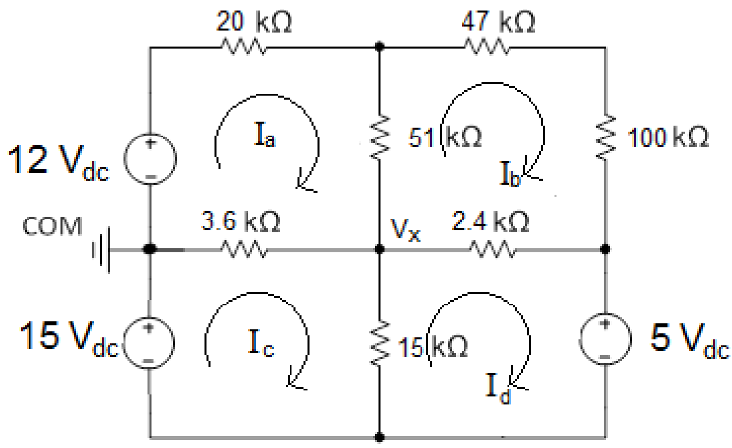

Figure 6-1: Mesh-current circuit

2.1.1 Build the circuit of Figure 6-1. Measure each of the four mesh currents I_a-I_d. Since a mesh-current is a current that exists only in the perimeter of a mesh you need to set the ammeter in series with an outside branch of the circuit.

2.2.2 Measure the node-voltage V_X. Note the position of the ground symbol defines the reference point for the node-voltage.

2.2.3 Organize your measurements and predicted quantities in a data table. Quantitatively compare your measurements to the predicted values.

2.2.4 Devise and carry-out one test to verify your measurements are correct, for example you can verify KVL, KCL, Ohm's law, or conservation of energy.

2.2 Supermesh Circuit. Measure the values of the resistors used in the following circuit and re-calculate the values of the mesh-currents and voltage V_B. Call these values the predicted or nominal values.

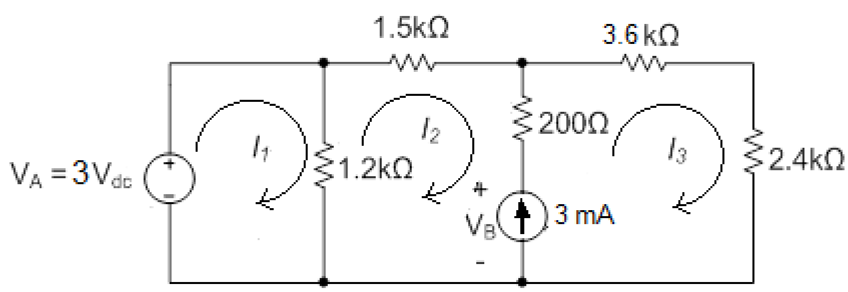

Figure 6-2: Supermesh circuit

2.2.1 Build the circuit of Figure 6-2. Use the 25 V DC power supply to create the 3mA source by setting the voltage and current limits appropriately. Measure each of the three mesh currents and quantitatively compare your measurements to the predicted values. Since a mesh-current is a current that exists only in the perimeter of a mesh you need to set the ammeter in series with an outside branch of the circuit.

2.2.2 Quantitatively compare these measurements to the predicted values. Organize and report your measurements and analysis in a data table.

2.2.3 Measure the voltages V_A and V_B and use your measurements to compute the magnitude of the power associated with the two independent sources. Determine if the source delivers or absorbs power.

2.2.4 Comment on how you can determine whether an independent voltage or current source is actually delivering or absorbing power.

2.3 Dummy Resistors In the circuit in Figure 6-2, there are two "dummy resistors". A "dummy element is an element that when removed has no effect on the predicted behavior of the circuit. Remove the 1.2kΩ dummy resistor, in parallel with the 3V voltage source, and replace the 200Ω dummy resistor, in series with the 3mA current source, with a wire. Repeat your measurements of the voltage V_B and mesh currents I_2 and I_3.

2.2.3 Measure the power associated with the independent sources in Figure 6-2 both before and after the dummy elements have been removed. Analyze your results and explain the difference between the measurements of voltage, current, and power with and without the 'dummy elements'. How can you recognize a dummy resistor in a circuit schematic?

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab

- ☐ Title, name, partner, date, room number, station number
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct pre-lab if necessary

2.1 Mesh-Current Circuit.

- ☐ Procedure
- ☐ Circuit of Figure 6-1 with all components labeled
- ☐ Table of Measured data: I_a-I_d, V_X with error analysis
- ☐ Analysis and comment - Devise and carry-out one test to verify your measurements are correct, for example you can verify KVL, KCL, Ohm's law, or conservation of energy.

2.2 Supermesh Circuit.

- ☐ Procedure
- ☐ Circuit of Figure 6-2 with all components properly labeled
- ☐ Table of Measured data: I_1 - I_3, V_A & V_B, Power with error analysis
- ☐ Comment on how you can determine whether an independent voltage or current source is actually delivering or absorbing power.

2.3 Dummy Resistors

- ☐ Procedure sentence
- ☐ Circuit of Figure 6-2 with 20kΩ resistor removed and 150Ω resistor replaced with a wire with all components properly labeled
- ☐ Table of Measured data for the modified Figure 2
- ☐ Analysis and comment – explain measurements when dummy elements are removed.

Ensure that all team members sign and date the last page.

Lab 7 Thévenin and Norton Equivalents

The objective of this lab is to investigate the properties of Thévenin and Norton equivalent circuits, and to predict their application to multiple loads.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of the lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 In order to prepare for lab read section 4.10 through 4.12 on Thévenin and Norton equivalents in your textbook. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will use the Digital Multimeter (DMM) to measure voltage and current. Review your work in lab 1 and or the **How_to** videos if you forgot how to do this.

1.3 Apply the ***Thévenin and Norton techniques*** presented in the lectures and section 4.10 of Nilsson for the circuit of Figure 1 and calculate the nominal values that you will measure in parts 2.1 and 2.2. Your written pre-lab work should include the following:

- Copy the circuit in Figure 7-1 into your lab book.
- Use the measured values of the resistors in your kit and determine the Thévenin equivalent voltage, Thévenin equivalent resistance, and Norton equivalent current, with respect to terminals a—b.
- Use NI Multisim to check your work. Build the circuit in Figure 7-1 in NI Multisim and use the multimeter to run two separate simulations to measure the current through and voltage across terminals a and b. These values represent the Thevenin voltage and Norton current. You will also use the ohmmeter setting on the voltmeter to measure the open circuit resistance across terminals a and b. This value represents the Thevenin resistance. Note that you will have to disable the voltage source for this measurement. Submit the 3 screenshots of the simulated circuit with the values. Organize a table with your calculated and simulated values for comparison.
- Copy the circuit in Figure 7-2 into your lab book.
- Use the Thévenin equivalent circuit to predict the load resistor (connected across a-b as shown in Figure 7-2) that will absorb maximum power. Compute the maximum power. Also find the formula that predicts the value of the power that can be delivered to the load as a function of R_{load}.
- Use NI Multisim to check your work. Build the circuit in Figure 7-2 in NI Multisim with the load resistor you selected in the prior step. Use the wattmeter to find the power delivered to the load resistor. Submit the screenshot of the simulated circuit with the values. Organize a table with your calculated and simulated values for comparison.
- Next you will create an Excel spreadsheet to help with data collection during the lab session. Create the column headings: R_{Load}, V_{Load}, I_{Load}, P_{Load}. Under the R_{Load} column, put the resistor values from 0 to 100 kΩ in 10 kΩ increments

and also resistor values from 100 kΩ to 1 MΩ in 100 kΩ increments. There should be 20 data points total for the resistance. Next, use the formulas derived to calculate the load voltage, current, and power on the spreadsheet. These are the predicted values for the measurements you will make during lab. Submit the spreadsheet as part of your pre-lab submission.

- Next, you will create 4 graphs: V_{LOAD} vs R_{LOAD}, I_{LOAD} vs R_{LOAD}, P_{LOAD} vs R_{LOAD} and V_{LOAD} vs I_{LOAD}.
- On the V_{LOAD} vs I_{LOAD} graph, you should extrapolate and mark V_{th}, on the I_{LOAD} vs R_{LOAD} graph, you should extrapolate and mark I_N, on the P_{LOAD} vs R_{LOAD} graph you should mark P_{MAX} and the resistance at P_{MAX}, on the V_{LOAD} vs I_{LOAD} graph you should mark V_{TH} and I_N.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to measure the Thévenin and Norton equivalents for the circuit shown in Figure 7-1 and use them to verify the Maximum Power Transfer Theorem.

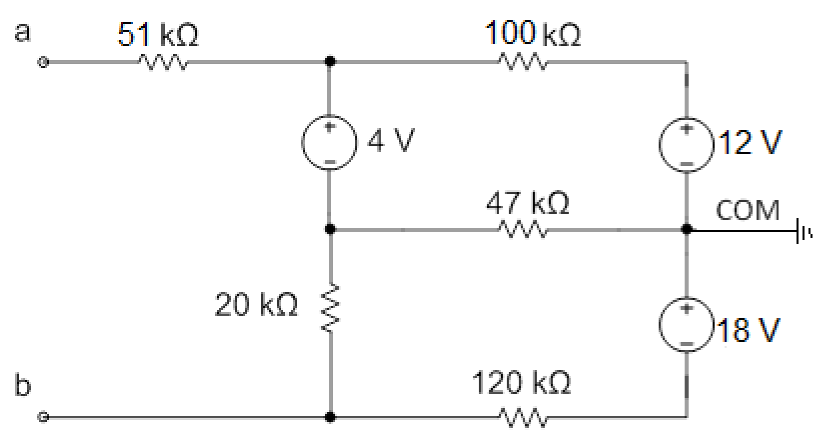

Figure 7-1: Circuit Diagram for *Thévenin & Norton Equivalents*

2.1 **Measure the Thévenin and Norton equivalent values directly** Measure the values of the resistors used in the following circuit and re-calculate the Thévenin and Norton equivalent values. Call these values the predicted values.

2.1.1 Measure the Thévenin equivalent resistance directly. Connect the resistors as shown in Figure 7-1. Do not connect the voltage sources for the time being. Instead of connecting the voltage sources, replace them with short-circuits, then place a DMM ohmmeter across the terminals a—b and measure the Thévenin Resistance (open-circuit resistance). Call this $R_{thMeasured}$. Record R_{th} measured and nominal values in a data table and compute the percent error.

2.1.2 Measure the Thévenin equivalent voltage directly. Remove the short circuits and connect the voltage power supplies. Adjust the 6 V power supply to give an output of 4

V. Then set the +25 V power supply to give an output of +12 V, while the -25 V supply is set to -18 V. Place a DMM voltmeter across the terminals a—b and measure the Thévenin Voltage (open-circuit voltage), call this $V_{thMeasured}$. Record V_{th} measured and nominal values in the same data table as the previous part and compute the percent error.

2.1.3 Measure the Norton Current directly. Place a DMM ammeter across the terminals a—b and measure the Norton Current (short-circuit current) and call this $I_{Measured}$. Record I_N in the same data table as the previous parts and compute the percent error.

2.2 **Maximum Power Transfer:** Thévenin equivalents are particularly useful when circuits have multiple loads, because you do not have to re-calculate the output voltage, current and power from scratch each time. Simulate multiple loads by placing a resistance substitution box across terminals a—b, as shown in Figure 7-2. Set up the both DMMs and set one to measure the voltage across the load and the other to measure the current through the load.

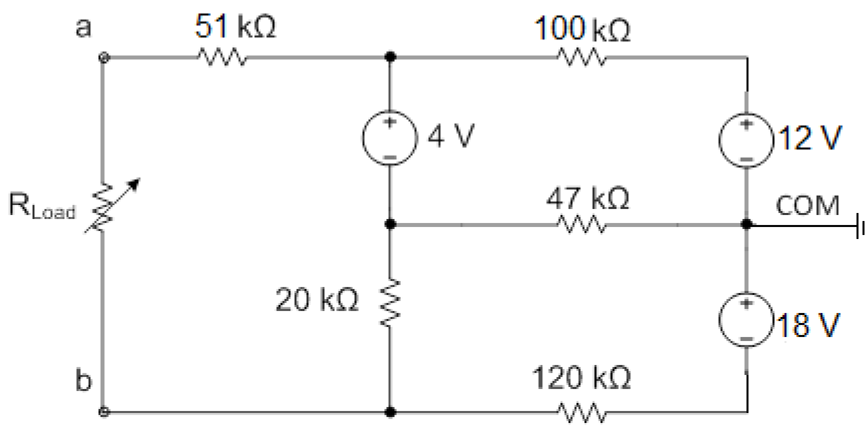

Figure 7-2: Circuit Diagram for *Multiple Loads*

2.2.1 Vary the load from zero to 100 kΩ in 10 kΩ steps and from 100 kΩ to 1 MΩ in 100 kΩ steps and measure the voltage across and the current through R_{Load}. Record these values in the data table you created on the Excel spreadsheet in the prelab. Use measured load voltage and current to calculate P_{Load}. Next, create three graphs in Excel or Logger Pro: P_{Load} vs. R_{Load}, V_{Load} vs. R_{Load} and I_{Load} vs. R_{Load}.

2.2.2 Estimate the maximum value of the power from the P_{Load} vs. R_{LOAD} graph and call this $P_{Max\ Measured}$. Estimate from your graph the value of load resistance that corresponds to maximum power and call this $R_{Max\ Measured}$. Mark these values on the printout of the graph. Record these values on a data table and compute the percent error compared to the predicted value.

2.2.4 Estimate the Thevenin voltage from the V_{Load} vs. R_{Load} graph and call this value $V_{th\ Measured}$. You may have to extrapolate beyond the end of your graph. Mark this value on the printout of the graph. Record this value in a data table and compute the percent error compared to the predicted value.

2.2.5 Estimate the Norton current from the I_{Load} vs. R_{Load} graph and call this value $I_{N\ Measured}$. Mark this value on the printout of the graph. Record this value in a data table and compute the percent error compared to the predicted value. Your graphs should look similar to Figure 7-3, this is not your data.

2.3 **Measure the Norton Current indirectly:** The Norton Current was measured directly by applying a short circuit in part 2.1. This worked because the current was small and did not damage the DMM when placed in series. This is not always the case and the Norton Current often must be found indirectly. We will now exercise an alternative way to measure the Norton Current, based on the high resistance load measurements taken in part 2.2 (high resistance loads give small currents). Plot a graph of voltage (ordinate) vs. current (abscissa) for the following values of R_{load}: 10 kΩ, 100 kΩ, and 1 MΩ. This should give you a straight line, with a negative slope. Note on your graph where the Thévenin Voltage and Norton current points are located. You may have to extrapolate beyond the end of your graph for these values.

2.3.1 Use your graph to estimate the values of V_{TH} and I_N, then calculate the percent error of these values compared to the predicted values found in part 2.1. Organize your results in a table. Your graph should be similar to Figure 7-4, note this is different data.

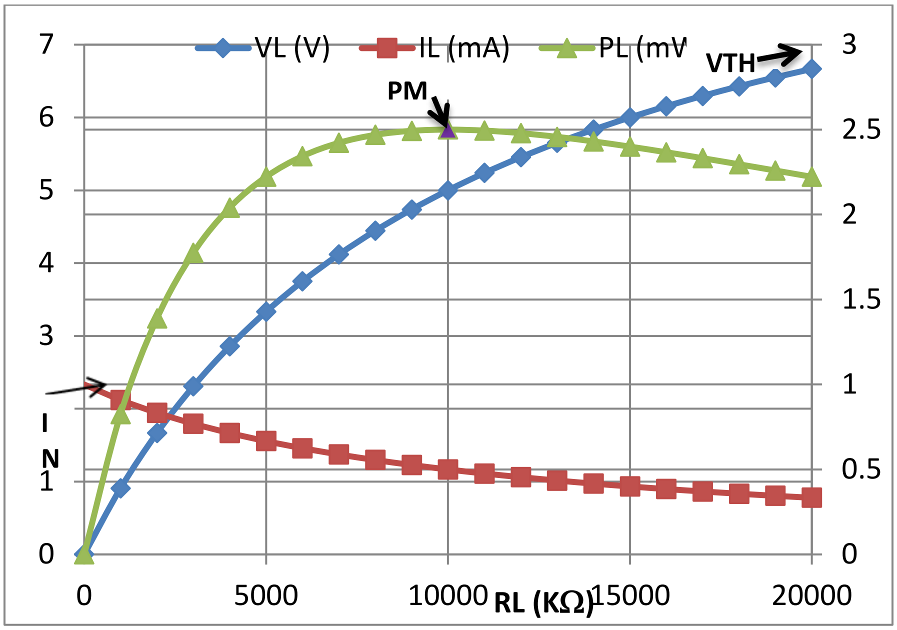

Figure 7-3: Estimate P_{max}, V_{TH}, I_N from a graph (V_{TH} = 10V, I_N = 1 mA, R_{th} = 10 kΩ)

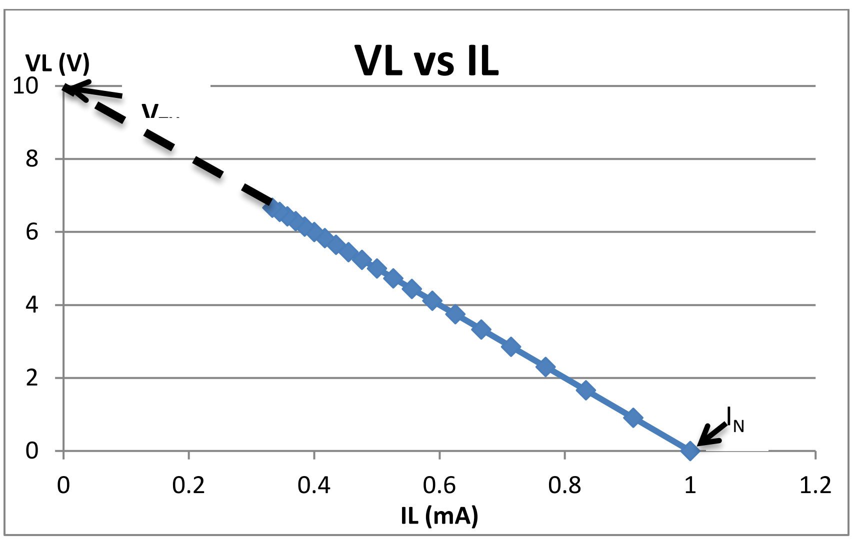

Figure 7-4: V_{LOAD} vs I_{LOAD} (V_{TH} = 10V, I_N = 1 mA, R_{th} = 10 kΩ)

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab

- ☐ Title, name, partner, date, room number, station number
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct pre-lab if necessary

2.1 Measure the Thévenin and Norton equivalent values directly.

- ☐ Procedure
- ☐ Circuit of Figure 7-1 with all components labeled
- ☐ Table of Measured data: V_{TH}, I_N, and R_{TH} with error analysis

2.2 Maximum Power Transfer.

- ☐ Procedure
- ☐ Circuit of Figure 7-2 with all components properly labeled
- ☐ Table of Measured data: R_{load}, V_{load}, I_{load}, and power with error analysis
- ☐ 3 graphs for P_{LOAD}, I_{LOAD} and V_{LOAD} versus R_{load}
- ☐ Analysis – estimate and quantitative comparison of P_{max}, R_{max}, V_{th} and I_N. Mark these values on the respective graphs.

2.3 Measure Norton current indirectly

- ☐ Procedure
- ☐ Graph of load voltage vs. load current; label V_{TH} and I_N on the graph.
- ☐ Analysis – estimate and quantitative comparison of V_{TH} and I_N. Mark these values on the graph.

Ensure that all team members sign and date the last page.

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Lab 8 Operational Amplifiers

The objectives of this lab are to investigate the properties of an operational amplifier (op-amp) integrated circuit (IC). We will also introduce the function generator (FG) and digital oscilloscope (Scope) instruments.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of the lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 In order to prepare for lab this week watch the video **Intro_to_Lab8**. This video should give you an idea of what you will do in the lab. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will need to learn how to operate the oscilloscope and function generator. You will use an operational amplifier (op-amp) in an integrated circuit (IC) 8-pin package. You are also encouraged to watch the instructional videos both before and during lab:

- How_to_use_function_generator (http://bit.ly/1QXK4JV)
- How_to_adjust_scope_display (https://youtu.be/LsaA8aps9vY)
- How_to_power_op_amp (https://youtu.be/wBg2fI3hDCs)
- How_to_FG_HighZmode (http://bit.ly/1U7VptM)

These videos will show you the correct way to set-up the function generator and adjust the scope display to make some basic measurements. Alternately you can read through the instruments' user manual and the op-amp specification data sheet which are available on-line and a printed copy is available in the lab.

1.3 Read sections 5.1-5.3 in your textbook. For the circuit shown in Figure 8-1, assume the op-amp is ideal and use Node Analysis to calculate the following:

- Copy the circuit in Figure 8-1 in your lab book. Use the measured values of the resistors in your kit and determine the gain formula of the circuit V_o/V_i in terms of variables R_i and R_f. Calculate the numeric value of the gain.
- Calculate the current, I_{out} in Figure 8-4 for V_i = 1V.
- The formula for decibel [dB] gain is $20 \log_{10} |V_o/V_i|$, find the numeric value of the gain in dB.
- Specify the range of V_i such that the op amp does not saturate.
- Use Excel or Logger Pro to create a plot of V_o versus V_i for a range of V_i between -6 and +6 V.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to build the circuit of Figure 8-1 and make some measurements using the DMM and the oscilloscope.

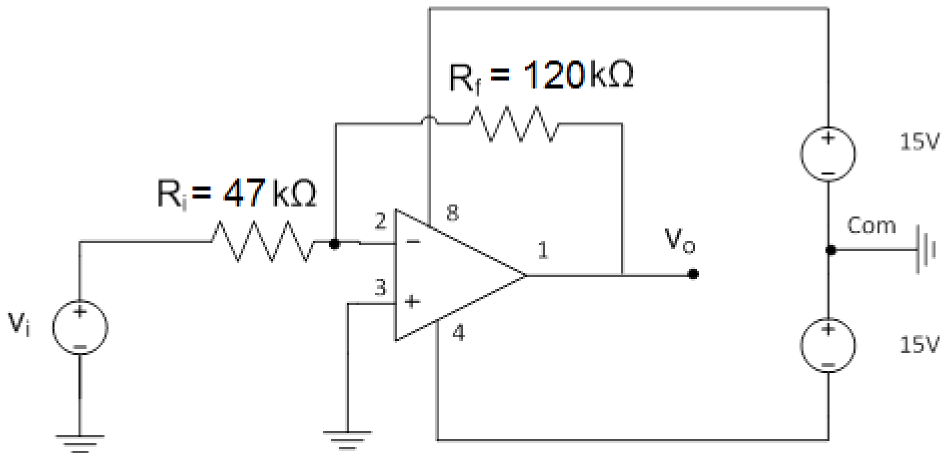

Figure 8-1: Inverting amplifier circuit

2.1 Power the Op-amp. Construct the circuit of Figure 8-1 on your breadboard. You will use the IC chip TL072 which contains two op-amps. Before removing your IC chip from the ESD container, you should touch the ground terminal of a power supply that is powered "on" with one hand, while handling the chip with the other hand. This will ensure that any electrical charge on your body has been discharged before you touch the chip.

2.1.1 Place the op-amp chip across the center 'gutter' with pin 1 on the lower left as shown in Figure 8-2. The pin numbers of the TL072 IC package are labeled on the circuit. When working with the TL072, you should follow the pin-out diagram in Figure 8-3.

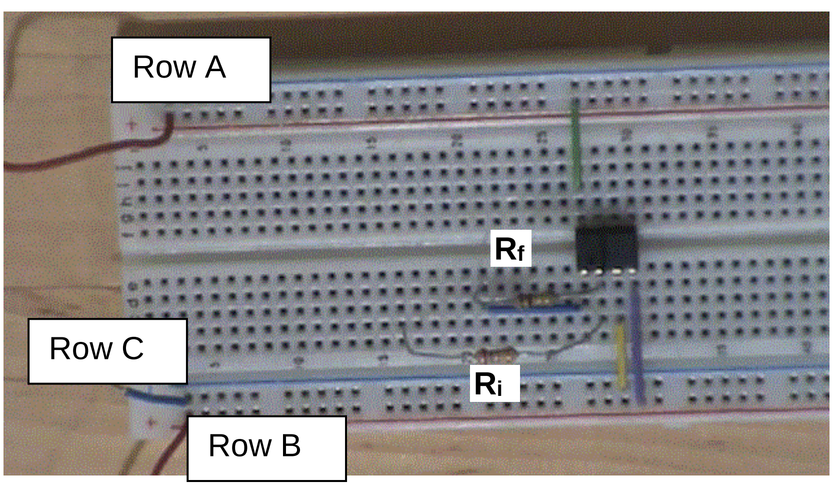

Figure 8-2: Proper layout of the inverting op-amp circuit of Figure 8-1. Pin 1 has a dot in the corner of the chip.

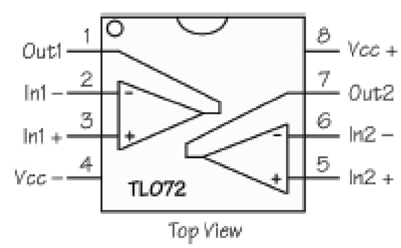

Figure 8-3: TL072 pin diagram. Both op-amps are powered through pin 4 and 8 (V_{CC-} = -15V and V_{CC+} = 15V)

2.1.2 Set the +25 V power supply to give an output of +15 V and connect the red lead to row A, as shown in Figure 8-2. Then row A should be connected to pin 8 (VCC+). Set the -25 V supply to -15 V and connect the red lead to row B, and row B should be connected to pin 4. It is important to set the current limit to 100mA on both inputs. The common terminal (black lead) is the common ground of the circuit and should be connected to row C on the bottom of the breadboard.

2.1.3 Connect the feedback resistor (R_f) between pins 1 and 2, and connect the input resistor (R_i) to pin 2. Pin 3 should be connected to ground. As shown in Figure 8-2.

2.1.4 Verify that the op amp is powered correctly by measuring the node-voltages at the point they are used in the circuit, i.e., the supply pins 4 and 8 with respect to the common ground.

2.2 Measure the DC Gain and saturation of an op amp circuit.

2.2.1 Set the input to $1V_{DC}$ using the +6V DC power supply.

2.2.2 Use the DMM to measure V_i and V_o then use these values to calculate the absolute gain. Create a table to compare the predicted to the measured value of the gain by calculating percent error. If this value is not close to your predicted value for the gain then debug your circuit to correct the error.

2.2.3 Create a table to record the output voltage of the op amp circuit as you vary the input voltage from -6 V to +6 V in steps of 0.5 V, you may have to use smaller steps at the saturation point to get see corner. Note that to get the negative voltage you will have to reverse the leads on the +6V supply. Compare these results to the predicted value found in the pre-lab.

2.2.4 Use Excel or Logger Pro to create a graph of the measured V_o versus V_i and make it clear where the output becomes non-linear due to saturation.

2.2.5 At what output voltage did the op amp saturate? Is this consistent with what you learned in class regarding saturation? Does the op amp saturate at the same voltage for the positive and negative input? Is this consistent with what you learned in class?

2.3 Measure the DC Gain of an op amp circuit in dB

2.3.1 Set the input to $1V_{DC}$ using the +6V DC power supply.

2.3.2 Use the DMM to measure V_i and V_o then use these values to calculate the dB gain. Create a table to compare the measured to the predicted value for the gain.

2.3.3 So, far, we've been comparing predicted and measured values by stating percentages. However, decibels are a logarithmic relationship, so division becomes subtraction. Therefore on the data table compare dB results by stating that the measured value is some number of dB larger (or smaller) than theory predicts. An acceptable statement could be, "The voltage V_X is 2dB larger than the predicted value," or "The output of the circuit is within ± 1 dB of the predicted value over the entire range tested." dB has a meaning of its own. A difference of 1 dB, whether from 60 to 61 dB or 100 to 99 dB, is considered the "just barely noticeable difference." Hence a circuit that conforms to the design within 1 dB is an excellent design. When computing the error of gain measured in dB use the following formula:

$$Voltage\ Gain\ error = Gain_{Measured}[dB] - Gain_{Nominal}[dB]$$

2.4 Node Analysis.

1. Using the circuit that you just constructed, with the input set to **4V$_{DC}$**, verify that the sum of the currents entering the super-node encompassing the five terminals of the op amp equal zero. The supernode is represented by the dashed line in Figure 8-4 below) equal 0. Use the DMM to measure each of the currents labeled on the circuit shown in Figure 8-4. That is, measure currents labeled: I_n, I_p, I_4, I_8, and I_{out}. Remember that you need to place the ammeter in series. By convention all currents are labeled as directed into the chip, even if positive current is actually flowing out of the chip. Verify that KCL holds for the supernode. Create a data table to compare the measured and predicted values for the current, I_{out}. There should be an error analysis for I_{out}.

2. When analyzing op-amp circuits you should never assume that the output current (I_{out}) is zero. Even though its value might seem 'small', it is not small when you compare the value to the input currents. If the input current is approximately zero and the output current is not zero, where does the "extra" current come from?

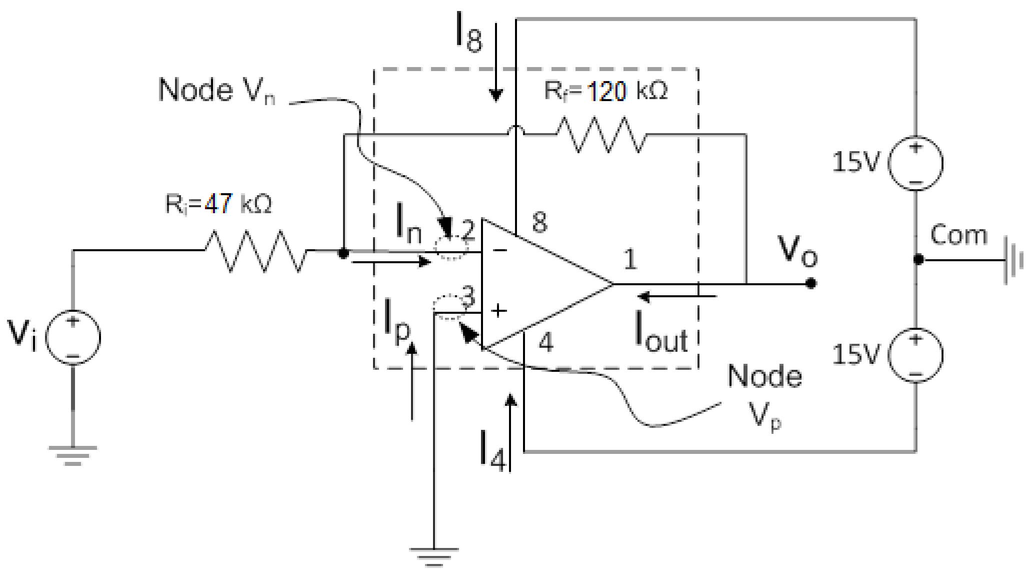

Figure 8-4: Circuit of Figure 1, with the op-amp super-node depicted inside the dashed lines.

2.5 Inverting op-amp – ideal assumptions.

1. The *virtual short circuit condition* states that $V_p = V_n$ when an ideal op-amp is wired for negative feedback. Measure V_n and V_p for the circuit in Figure 8-4 to verify the veracity of this ideal op-amp assumption. Make sure to measure the input voltages with respect to the common ground. According to the manufacturer's data specification sheet for this part, $|V_p - V_n|$ should be less than 6mV and is typically 3mV. How does your data compare?

2. The *infinite input impedance condition* states that the input current (I_n and I_p) are essentially zero. According to the manufacturer's data specification sheet for this part, I_n and I_p should be less than 200nA and is typically 65nA. How does your data compare? What is the smallest current that you can measure with the DMM?

2.6 Inverting op-amp –AC Output: In this part you will use the Function Generator (FG) to generate a time-varying signal with a sinusoidal shape. This will be the input, V_i, to the op amp circuit.

- Remove the 6V power supply from the circuit, you won't need this one anymore
- Turn on the function generator and set it to the "high-Z" mode by accessing the utility functions.
  For the Function Generator model in room ***B105*** follow the instructions below:
  - Push shift and then the enter button
  - Push the right arrow button 3 times – the display should read D.SYS MENU
  - Push the down arrow button 2 times – the display should read 50 OHM
  - Push the right arrow once – the display should read HIGH Z
  - Push enter

  For the Function Generator model in room ***C115*** follow the instructions below:
  - Push UTILITY
  - Push SETUP
  - Push HIGH Z

2.6.1 Connect the output of the FG to the input of the op-amp circuit of Figure 8-1. Using a BNC-to-clips lead, connect BNC end to the port labeled "output" and the clips end the input resistor (red clip) and the black clip to the common ground of your circuit (which is the bottom row A in Figure 8-2). Set the frequency of the FG to 1 kHz. Set the amplitude of the Function Generator to 1 Vpp.

2.6.2 You will use the digital oscilloscope (scope) to measure the input and output of the op-amp circuit. Use the standard scope probes located in the drawer of your bench (gray leads). These leads are 10:1 attenuated probes. The scope should automatically set the probe setting to 10:1. If not you will have to manually set the scale factor to 10:1.

2.6.3 Set up the scope to measure the input signal of your circuit to the port labeled "1" by connecting the positive lead (the hook) to the input resistor and connect the ground (black) to the common ground of your circuit. Set up the scope to measure the output signal of your circuit to the port labeled "2" by connecting the positive lead (the hook) to pin 1 and connect the ground (black) to the common ground of your circuit (bottom row A). Double check that all grounds are connected to the same point (all black leads should be connected to the bottom row A). The set-up is shown in Figure 8-5.

2.6.4 When all these connections are made, turn the output "on" for the DC power supply. If you are in room C115, you must push the "***output***" button on the FG to turn it on. Push the "***auto-scale***" button on the scope and observe the input and output signal.

2.6.5 To measure the input and output, push the quick measure button on the oscilloscope. Then use the buttons at the bottom of the window on the scope to set the source to channel 1, set the measurement to peak to peak, and click the measure peak to peak button. Repeat this step for channel 2 of the scope. Use the scope measurements to determine the AC gain and compare this measurement to the DC gain measurement. Do an error analysis between the AC and DC gain where the DC is nominal.

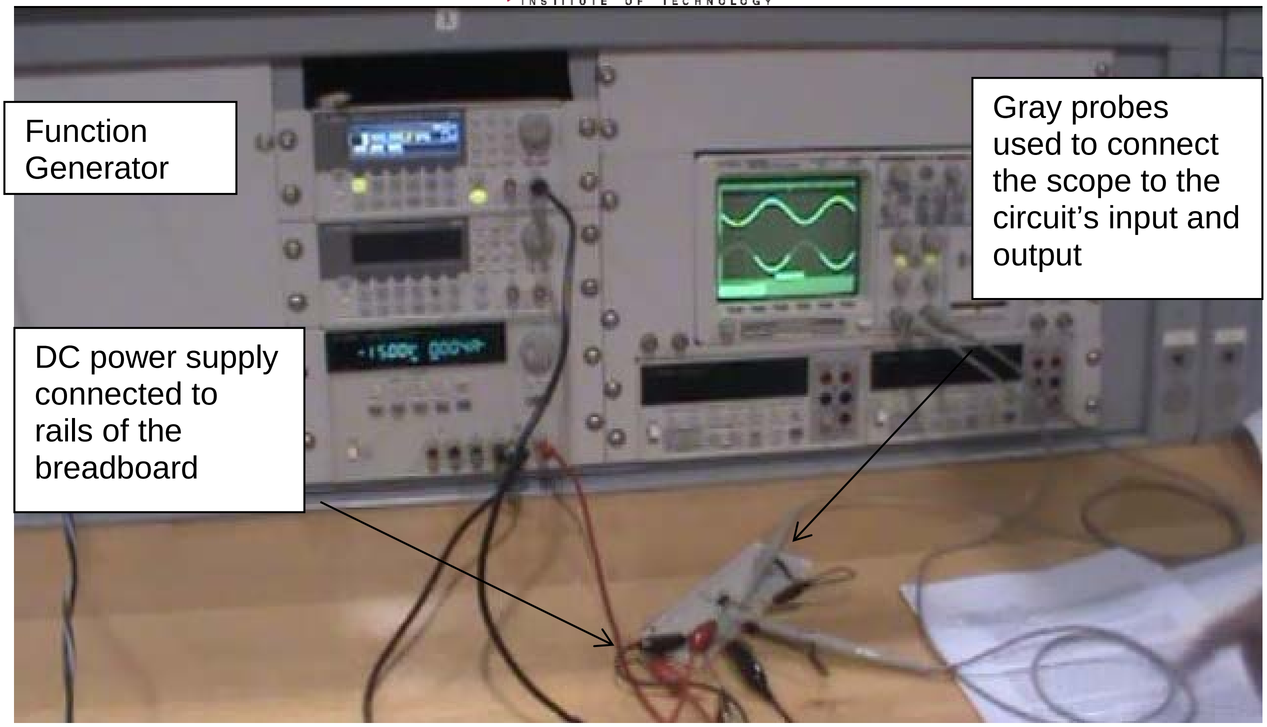

Figure 8-5: Set-up of inverting op amp circuit with an AC input

2.6.5 Use the grid in your journal to create scale model sketch of the input and output of op amp circuit shown on the oscilloscope. Your graph should be at least half of the page in order to adequately see the detail. Make sure to label the axis of your sketch in units of time on the x-axis and volts on the y-axis. Notice the voltage scale factor is displayed for each signal on the scope screen in the upper left corner as e.g., "1 1.00V/" which means each vertical division represents 1.00 V. The voltage scale factor will most likely not be the same for Channel 1 and Channel 2. The time scale factor should be 200 microseconds per division (200μs/). Try adjusting the horizontal and vertical scale using the knobs. Explain why the input and output signals are inverted or out of phase 180°. Alternately, you can take a picture of the oscilloscope screen and tape it into your lab book. Make sure that there is adequate detail shown on the image.

2.6.6 Next, slowly increase the input voltage, V_i, on the function generator until you observe distortion on the output, V_o, on channel 2 of the oscilloscope. At what input voltage did this occur? What was the output voltage at this value? What do you think causes this phenomenon? Is this result consistent with the Vi range for linearity that you found in the pre-lab? Make a sketch of the oscilloscope for inclusion in your lab book. Alternately, you can take a picture of the oscilloscope screen and tape it into your lab book. Make sure that there is adequate detail shown on the image.

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab
- ☐ Title, name, partner, date, room number, station number
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct the pre-lab if necessary

2.1 Power the Op-amp
- ☐ Procedure
- ☐ Circuit of Figure 8-1 with all components labeled, including the pin numbers of the TL072 IC chip

2.2 Measure the DC Gain and saturation of an op-amp circuit
- ☐ Procedure
- ☐ Table of measurement & comparisons: V_i, V_o, linear gain
- ☐ Graph of V_o versus V_i label saturation point, axes with units, title

2.3 Measure the DC Gain of op-amp circuit in dB
- ☐ Procedure
- ☐ Table of measurement & comparisons, Gain in dB

2.4 Inverting op-amp – Node Analysis
- ☐ Procedure
- ☐ Label the currents on the circuit in Figure 8-4 on the circuit you drew in part 2.1
- ☐ Table of measured currents: I_n, I_p, I_4, I_8, I_{out}, with error analysis for I_{out}
- ☐ Analysis - Verify KCL
- ☐ Analysis - Where does the extra current for I_{out} come from?

2.5 Inverting op-amp – ideal assumptions
- ☐ Procedure
- ☐ Label the voltages on the circuit in Figure 8-4 on the circuit you drew in part 2.1
- ☐ Table of measured voltages: V_n, V_p and I_n, I_p
- ☐ Analysis – comment on how data verifies ideal op-amp assumptions
- ☐ Analysis – what is the lowest current that the DMM can measure?

2.6 Inverting op-amp –AC Output.
- ☐ Procedure
- ☐ Table of measurements V_i, V_o, AC Gain, and comparison
- ☐ Sketch of scope output for the inverting op-amp circuit with proper title and axes labeled with units
- ☐ Analysis - Explain why the input & output signals are out of phase
- ☐ Analysis - AC gain measurement compared to the DC Gain measurement
- ☐ Answer questions about Vi and Vo,
- ☐ Sketch of scope output for non-linearity with proper title and labels

Ensure that all team members sign and date the last page.

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Lab 9 Design and Application of Op Amp Circuits

The objective of this lab is to design and construct a non-inverting operational amplifier that will enable the output of a microphone to be heard on a set of earphones.

1.0 PRE-LAB

Submit the results of the pre-lab on engineering paper at the beginning of the lab session. Make a copy of your pre-lab in the library before submission in case you need it during the lab session.

1.1 To prepare for lab his week watch the video **Intro_to_Lab9**. This video should give you an idea of what you will do in the lab. During the lab you should follow the instructions written in this lab manual. If you do not understand anything in the lab procedure, go and ask your instructor.

1.2 You will build an op-amp circuit and use the function generator and scope. Review your work in lab 8 and or the **How_to** videos if you forgot how to do this.

1.3 Apply the techniques presented in the lectures and section 5.5 in your book. You may also want to review the **Design_NonInverting** video. Your written pre-lab work should include the following:

- Use the circuit in Figure 9-1 to design a non-inverting amplifier that will take a signal in the range of 10 to 20 mV and produce an output in the range of 200 to 500 mV.
- Set the power supply voltage so that an input signal of 0.5 V can be amplified without causing saturation. Remember that distortion will occur when the output voltage is roughly 1.5 Volts before the power supply limit. In other words if the power supply is set to +/-15 Volts expect the op-amp will actually saturate for outputs less than -13.5 and more than 13.5, approximately.
- Predict the maximum value of input voltage (Vi) that can be amplified without saturation occurring.
- Draw a circuit diagram of your design showing the resistor nominal values. Be sure to pick standard resistors in the kΩ range with 5% tolerance, these are listed in Appendix H (Chapter 13) of your textbook and on page 12 of the lab manual. You can purchase the needed standard resistors from the Instrument Room or you can use parts that are in your lab kit. The Instrument Room has most 5% values of resistors available, especially in the decades from 100Ω to 100kΩ. Resistors cost 5¢ each.

- Use Excel or Logger Pro to create a plot of V_o versus V_i for a range of V_i between

-1.0 and +1.0 V.

1.4 Be sure you are familiar with the ECE Department's Writing Standards, with regard to laboratory notebooks. These are outlined in the beginning sections of this lab manual. You will be expected to finish the lab and have it properly recorded in the lab notebook within three class periods. All books will be collected at the end of the lab period and incomplete books will receive reduced grades.

2.0 LAB PROCEDURE

You are going to construct the circuit designed in the pre-lab and use it to drive a set of earphones.

2.1 Build the Circuit: Select the resistors you determined from the pre-lab. Measure the resistors with the ohmmeter and use their values to calculate the nominal gain for the op-amp circuit. Build the circuit shown in Figure 9-1. Double check your connections before powering the circuit and limit the current to 100mA. A wrong connection or too much current can destroy the op amp. Verify that the op amp is powered correctly. The 6 V DC source will be V_i and it should be set to 0.5V. Measure the output of the op-amp and calculate the gain to confirm that the circuit is working correctly. Record the measured and nominal values for the gain on a data table and perform an error analysis.

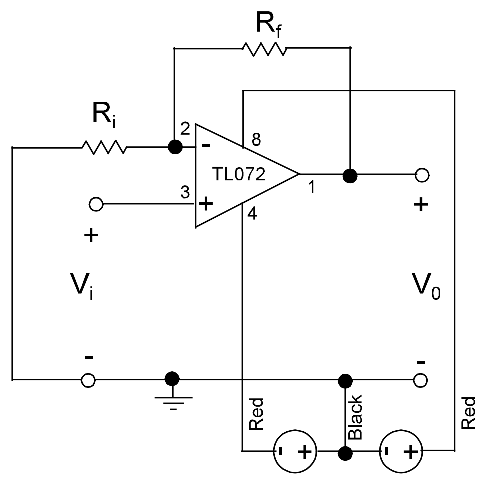

Figure 9-1: Circuit Diagram for *Non-inverting Amplifier*

2.2 Voltage Measurements of Linear Range: Observe the DC gain of the op-amp by plotting a graph of V_0 vs. V_i as V_i is varied from -1.0 to 1.0 V. Be sure to take enough data to show the effect of saturation, especially at the “corner” of the curve. Comment on how this graph compares to your prediction in the pre-lab and the ideal saturation curve? Make sure to do an error analysis for the gain and saturation point.

2.3 Scope measurements of Linear Range: Turn off the output of the power supplies and disconnect the 6 V DC source.

2.3.1 Set the function generator (FG) to “high-Z” mode as you did in Lab 8. Set the FG to produce a sine wave output of 500 mV (peak-to-peak) at a frequency of 1 kHz, use channel 1 of the oscilloscope to confirm this is correct. When you have confirmed the FG output is correct, connect the FG and channel 1 of the scope to V_i. Turn on the power supplies and observe V_0 on channel 2 of the oscilloscope.

2.3.2 Increase the output amplitude of the FG until you observe the onset of saturation in the amplifier’s output, note the corresponding value of V_i. On the scope, push Quick Measure and select the Channel and Peak-Peak in the window to see the voltage. Make a sketch of the scope output in your lab book and comment on the characteristics of the graph that indicate the op-amp is saturated. If you prefer, you can take a picture of the oscilloscope screen to insert in your lab book. Make sure it shows all of the required details including s/div and v/div.

2.3.3 Compare the scope's measurement of the saturation range to your prediction in the pre-lab by doing an error analysis.

2.4 Amplify a Microphone Signal: You are going to use your amplifier to strengthen the output signal from a microphone, so that it is audible in the earphone. The microphones that are available in the lab have an internal resistance of about 600 Ω, so model it as a voltage source in series with 600 Ω. Typical speech produces an output below 25 mV, which is much too weak to drive the earphones because they need signals in the order of hundreds of mV.

2.4.1 Remove the function generator and connect the output of the microphone to the input of your op-amp using the jack provided, as shown in Figure 9-2. Be sure that the wire from the outer shell of the microphone goes to the ground of your circuit.

2.4.2 Connect your earphone to your op-amps output, also shown in Figure 9-2, using the jack provided. Which lead goes to ground is not important here. Observe V_i on channel 1 of the oscilloscope and V_0 on channel 2. Set channel 1 to 20 mV, channel 2 to 100 mV, with the time-base at 5 msec.

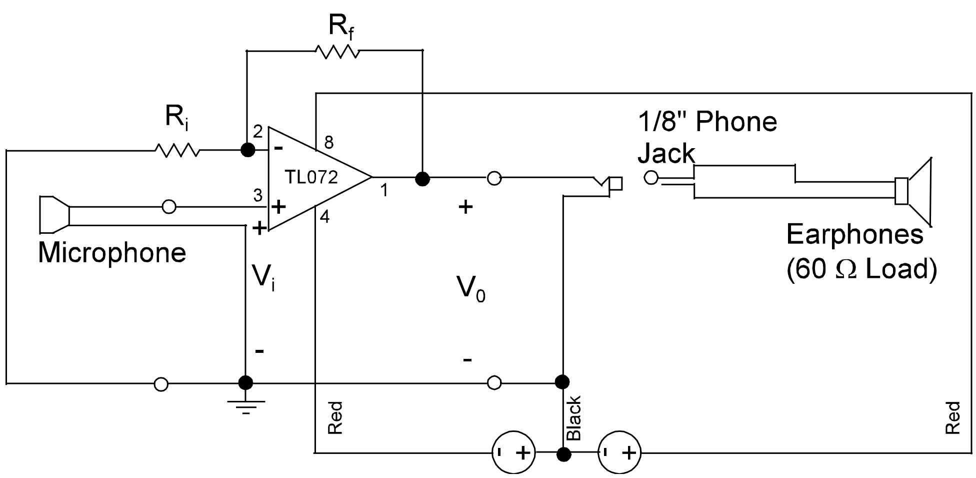

Figure 9-2: Circuit Diagram for *Op-amp Driving Earphones*

2.4.3 Be sure the power supplies are on. Test the circuit by having one team member speak into the microphone while the other team member is wearing the earphones.

2.4.4 The partner with the microphone should make high and low pitch, loud and soft tones into the microphone. Explain in your lab book what you hear in the earphones and what you see happen on the oscilloscope as the sound is varied. Can you hum loud enough to make the amplifier output clip? Describe qualitatively how the scope signal (amplitude and frequency) is correlated to the frequency and intensity of your voice.

2.4.5 Demonstrate your amplifier operation to your lab instructor and have the instructor initial your journal.

3.0 CHECKLIST

The lab-work is finished; now make sure your lab notebook is properly completed, in particular make sure the following is done:

1.0 Pre-lab

- ☐ Title, name, partner, date, room number, station number
- ☐ Any formulas that apply to the whole lab that you will reference later
- ☐ Page numbers, table of contents
- ☐ Correct the pre-lab if necessary

2.1 Power the Op-amp

- ☐ Procedure and required formulas
- ☐ Circuit that you designed like Figure 9-1 with all components labeled, including the pin numbers of the TL072 IC chip. If you changed your design from the pre-lab work note what you changed and why.
- ☐ Analysis - Data table of measured resistor values with error
- ☐ Analysis - Data table of op amp gain with error

2.2 Voltage Measurements of Linear Range

- ☐ Procedure
- ☐ Table of measurement & comparisons: V_i, V_o, linear gain
- ☐ Graph of V_o, V_i showing the linear range and the saturation point
- ☐ Analysis - error analysis saturation point for V_i and V_o.
- ☐ Comment on how this graph compares to your prediction in the pre-lab and the ideal saturation curve

2.3 Scope measurements of linear range

- ☐ Procedure
- ☐ Sketch of scope output clearly showing V_i, V_o, the saturation region
- ☐ Analyze - compare the scope's measurement of the saturation range to your prediction in the pre-lab.
- ☐ Comment on the characteristics of the a saturated op amp on the scope output

2.4 Amplify a Microphone Signal

- ☐ Procedure
- ☐ Circuit like Figure 9-2
- ☐ Comment - describe qualitatively how the scope signal is correlated to the frequency and intensity of your voice.
- ☐ Demonstrate your amplifier operation to your lab instructor and have the instructor initial your journal.

Ensure that all team members sign and date the last page.

Lab 10 Lab Practical Test 2

This lab is a test to make sure that you have developed the skills necessary to do well in future labs and future classes.

You may want to review what you have been doing for the past few weeks before coming to this test. You are permitted to use the following: course textbook, the lab manual, both lab logbooks, and a calculator, but not your laptop computer.

You will be making measurement on a circuit similar to the one shown in Figure 10-1. Your instructor will give you the resistor values in the class before the test. Each partner must be able to build the circuit on a breadboard because you will not work together during the test. In the test you will be given a sheet with instructions for the measurements you will be taking and a data form for entering the results.

Half of the class, i.e. one member of each team, will come to the lab at the beginning of the lab period. The other team member will come 25 minutes into the second period of the lab. You each will have one hour and fifteen minutes to complete the test. Your instructor will assign the time of your test.

You will be making measurements that are similar to those you have been making in the previous labs. Your grade will be based entirely on the data you take. You are finished when you hand-in the completed data form.

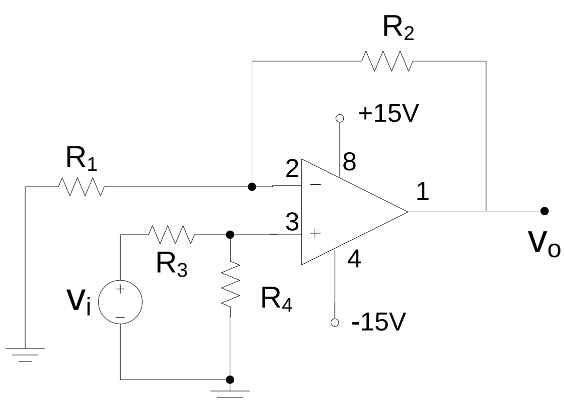

Figure 10-1: Op-amp circuit