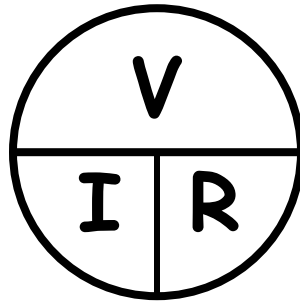**Allan Hancock College**

Engineering Program

Electric Circuits Laboratory Manual
ENGR 171

Spring 2019

Dominic J. Dal Bello

2019

On the cover: The graphic is a traditional way of remembering Ohm's Law.

Need the equation for voltage?   Cover *V* ....$V = IR$

Need the equation for current?   Cover *I* ....$I = \dfrac{V}{R}$

Need the equation for resistance?   Cover *R* ....$R = \dfrac{V}{I}$

Always record as many digits from the measurement device as possible.
Deal correctly with significant figures.

(In lab, it is <u>not</u> an automatic three significant figures).

CONTENTS

LAB COMPONENTS

The following components are included in the **ENGR 171 Lab Kit.**

Students will assemble their own kit from components provided by the AHC Engineering Program (effective Fall 2009; previously, students had to purchase kits from the bookstore).

Kits will be kept in zip-lock baggies in the lab room.

The kit includes one (1) of each component, unless noted.

Component	Value		
Proto-board (Bread board)	n/a		
Resistors (1/4 watt, 5%) see: *Appendix A: Resistor Color Codes*	470 Ω	2.2 kΩ	4.7 kΩ
	680 Ω	2.7 kΩ	10 kΩ
	1.0 kΩ (2)	3.0 kΩ	33 kΩ
	2.0 kΩ (2)		
Capacitors see: *Appendix B: Capacitor Codes*	0.1 µF ceramic disk (or polyester film)		
Inductor	33 mH	(distributed as needed)	
	4–6 H	(distributed as needed)	
Operational Amplifier	LM741 N	(distributed as needed)	
Potentiometer	10 kΩ	(distributed as needed)	

PRIMARY REFERENCE TEXTS:

C.K. Alexander and M.N.O. Sadiku, *Fundamentals of Electric Circuits*, 5th ed., New York: McGraw Hill, 2013.

C.K. Alexander and M.N.O. Sadiku, *Fundamentals of Electric Circuits*, 4th ed., New York: McGraw Hill, 2009.

C.K. Alexander and M.N.O. Sadiku, *Fundamentals of Electric Circuits*, 3rd ed., New York: McGraw Hill, 2007.

J.G. Tront, *PSpice for Basic Circuit Analysis*, 2nd ed., New York: McGraw Hill, 2007.

Electrical Engineering Laboratory
Allan Hancock College

LABORATORY SAFETY RULES

1. Arrive to your laboratory section on time. Instructions on the experiment and pertinent safety issues are discussed during the first few minutes of lab.

2. No horseplay or running will be tolerated in the laboratory.

3. No bare feet or open sandals are permitted while working in the laboratory.

4. Food and beverages are not allowed in the laboratory.

5. Never energize a circuit or piece of equipment without complete knowledge of its purpose and the resulting actions.

6. Do not energize any equipment without first observing that no one is in a position to be injured by your actions.

7. Examine carefully all line cords and test leads before using them. Never plug in an AC power cord that is frayed or has a loose or otherwise defective plug.

8. Report all defective or questionable tools and equipment to the instructor.

9. Rings, watches and other metal jewelry are electrical conductors. They may come in contact with live circuits and cause serious shocks or burns. Remove these items while working in the lab.

10. Avoid contact with any voltage source. Turn off the power before working on a circuit. Voltages as low as 30 volts have been fatal!

11. Do not make circuit connections by hand while circuits are energized. This is especially dangerous with high current circuits.

12. Never work in the laboratory alone.

13. Wear safety glasses, gloves and protective clothing when required.

14. Report all injuries, no matter how slight, to your instructor.

15. Keep your work area neat and clean. At the end of each lab session, return all leads, wires, components, equipment, etc., to where you found them. Power off all equipment.

16. Make sure your equipment is placed in a secure and stable position on the workbench.

17. Know the locations of the fire extinguishers, first aid kits, and emergency AC power shut off switches. Be sure to know how to use these items in case of an emergency.

18. When working with exposed 120-volt AC power in your circuit, have the instructor check your wiring before applying power.

19. Many precautions are required when soldering. Be sure you have detailed instruction in this area before you do any soldering in the laboratory.

20. Chemicals located in the laboratory can present a health hazard if proper safety precautions are not observed. Get approval from your instructor before using any chemicals.

21. Keep all exterior exit doors and aisles clear of any obstructions.

I (print name) _____, have read, understand, and agree to follow the above mentioned safety rules, and any other directions given to me in writing or verbally by my instructor, or any other Allan Hancock Engineering or Electronics instructor.

Signed: _____ Date: _____

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Signed: _____   Date:_____

INTRODUCTION

COURSE GOALS

Like most engineering circuits laboratory courses, the goals of this course are to:

1. Provide students with hands-on experiences constructing, testing and analyzing electronic circuits that:
   - reinforce concepts studied in the lecture course, and
   - introduce students to additional concepts not necessarily covered in the lecture course.

2. Familiarize students with the laboratory setting, electronic measurement equipment, and electronic hardware.

3. Teach students good experimental technique.

4. Teach students proper experimental documentation methods and form.

5. Involve students in physical applications of electrical/electronic engineering.

6. Challenge students with thought-stimulating and creative problems.

7. Expose students to experimental considerations sometimes omitted from textbook treatments.

LABORATORY PROCEDURES

1. Students will generally work in teams of two (2).

2. **Do not eat or drink in the lab**. Spilled liquid in the lab is dangerous. A surface near the lab entrance is typically designated for drinks, etc.

3. **Each student is <u>expected to read the lab instructions,</u> and review any references cited in the lab instructions or by the instructor, <u>BEFORE</u> coming to the laboratory**. Each student should be ready to proceed confidently with the experiment upon arrival. Be sure to understand what is to be done **before** starting the experiment.

4. In performing experiments and making computations, team members should **share responsibilities and rotate activities** so that all group members gain experience in wiring circuits, verifying circuits, operating equipment, etc. **All reports, however, are to be written <u>individually</u>** (unless otherwise instructed) **and are to be the student's original work.**

5. Team members should **rotate "leadership"** of the group (from experiment to experiment), so that each member of the group may have that experience. **<u>Do not just watch</u>** others do the work. **You need to know how to build and measure basic circuits to pass the course.**

6. The equipment used in an electronics laboratory is sensitive and expensive. Each piece of equipment should be treated with care to assure that it will provide useful service to many future students.

7. Report any unsafe, non-working, malfunctioning or damaged equipment to the instructor. Do not return non-functioning leads (cables) to the lab drawers; they need to be either fixed or removed from inventory.

8. Do not write on, mark up, drop, or throw any laboratory equipment.

9. Connecting leads (cables/wires) and instrument probes are subject to heavy use. Be careful when using them; e.g., do not disconnect banana-plug leads by just yanking on the wire.

10. Before dismantling an experimental setup, the results should be checked by the student team for any apparent inconsistencies in the data. Despite what it may seem like, the results are not random or magic; you should be able to predict – at least roughly – the output.

11. **At the end of each lab session, each laboratory device must be powered off and all lab equipment must be returned to its storage location**. Cables and test leads should be rolled-up, rubber-banded, and put neatly back in drawers. If something is needed or missing, inform your instructor. **Your work area should be clean when you leave**.

LAB NOTE BOOK (do not purchase)

<u>Do not</u> purchase a lab notebook for ENGR 171. All required papers are included in this manual. In short, the tables, etc., that you would typically have to create on your own have been provided for you.

LAB WRITE-UPS

In ENGR 171, **each student will submit an individual lab write-up for each experiment**, unless instructed otherwise. **While students collect data in teams (of two), the reports are expected to be individual and original.**

In general, the basic form and order of each write-up will be either:

A. (1) Typed answers to given questions;
   (2) Plots and Graphs;
   (3) Original Data Sheets; and
   (4) Support Calculations.

B. (1) Data Sheets;
   (2) Hand-written answers to questions;
   (3) Plots and Graphs.

The underlying goal is that your responses should have the quality of formal reports or technical memoranda, without having to put a formal and lengthy report together.

Students should consider written responses as final drafts; i.e., as excerpts or "snippets" from formal reports. **Each answer should consist of well-written and complete sentences, and be correct in form, grammar and content, etc.**

The answers should also "stand on their own"; i.e., the reader (grader) should not need to have read the actual question to know what the answer is addressing. **Assume that the reader is familiar with the general experiment, but not with the question you are answering.**

You might be tempted to write "Yes" as an answer. However, "Yes" is neither a complete sentence, nor does the reader know what the question is.

As an example, an answer to *Question 5, Experiment 1* might be: "5. The 470 Ω and 2.7 kΩ resistors were both within 5% of their nominal value. The 4.7 kΩ was not within tolerance, but was 6.7% above nominal." <u>Do not</u> just write: "5. No. 4.7kΩ was 6.7% off."

As the answers are intended to be **excerpts** of a formal report, use the appropriate voice and tense. For AHC Engineering labs, **when writing about what <u>was</u> done**, use the **traditional lab report passive voice**: *3rd person, past tense*. Thus, in the answers:

- **Do not use "I," "we," "you", etc**. The text is about the experiment, not about "us".
  Write "The current through the series combination of resistors was measured…".
  <u>Do not</u> write "We measured the series combination...".

- Do not speak directly to the reader.
  Write "Table 2 shows…"
  <u>Do not</u> write "As you can see in Table 2...".

- The experiment happened in the past. Use the *past tense* when describing *what was done* in the experiment.
  Write: "The current was measured…".
  <u>Do not</u> write "The current is measured…".

When referring to tables, figures and equations in the report itself, use the *present tense*.

- Write "The voltage-current response for the unknown resistor is plotted in Figure 1...".
  <u>Do not</u> write "The voltage-current response was plotted in Figure 1."

FORMAT OF WRITE-UPS

Each experiment has specific instructions for how to prepare the write-up, under the heading "WHAT TO TURN IN". As an example, the instructions for *Experiment 1* are given in the inset (textbox) on Page *ix*.

The format of the first page of the typed write-up is given in *Figure 1*.

For clarity, number the answers to correspond to the question numbers.

No cover sheet is necessary or desired.

Use only one side of a sheet of paper, except for Data Sheets.

Single-space the answers. Leave one line between paragraphs, and two lines between numbered answers.

WHAT TO TURN IN

***Each student* will turn in an individual and original report.** Each report will be **typed, single-spaced, stapled,** and in the **following order:**

1. Answers to the Questions.

On a new sheet of paper:

- In the upper right-hand corner, type:

> your name
> your partner's first name
> Engr. 171
> date of experiment

- Two lines below the date and centered, type:

Experiment 1: Ohm's Law

-- Answer the ***Post-Lab Questions***.

- Answer the questions in complete sentences, and in such a way that the reader does not need to see the actual questions to understand what you are writing about. Each answer should stand on its own; some repetition between answers may be necessary.

- Always introduce a table (or a figure) with words (text) before it appears in the document; e.g., "Table 1 is …"; "The voltage-current response…is given in Figure 1…".

- For clarity, number each answer, and leave two blank lines between answers.

- Use **tables** and **Microsoft Equation (Editor)** as appropriate. Number and title each table in your report. Do not just insert a table, figure or equation without some narrative introducing or describing it, its significance, etc.

- The write-up is intended as a much reduced technical "report", or a set of snippets from a report. As such use ***3rd person*** (the passive voice), and ***past tense*** when describing *what was done in the experiment*. **Do not use "I," "we," "you", etc.**

> ***Present tense*** may be used when referring to tables, etc., in the report; e.g., "The voltage-current data for … is given in *Table 2*."

2. Excel plots of the *v-i* curves for the 470-Ω and 2.7-kΩ resistors. Title and label each figure. Excel plots may be shared within a group.

3. Original *Data Sheets*, <u>completely</u> filled in.

4. Hand-plots (one original hand-plot per student), **support calculations**, etc. Items 3 and 4 serve as the "**Appendix**."

Use only <u>one side</u> of each sheet (except for the Data Sheets). Again, leave at least two blank lines between answers.

Do not include a separate cover sheet. A separate cover sheet is not necessary, nor desired.

Again, you do not have to retype the questions, but **answer each question so that a reader (grader) can figure out the topic that you are addressing, even if he/she has not read the question.** Assume your audience is someone else besides the instructor, but who is familiar with the experiment you performed. Write answers in complete sentences.

For example, an answer to Question 5 might be: "5. The 470 Ω and 2.7 kΩ resistors were both within 5% of their nominal value. The 4.7 kΩ was not within tolerance, but was 6.7% above nominal." <u>Do not</u> just write: "5. No. 4.7kΩ was 6.7% off."

TABLES and FIGURES

Tables and ***figures*** are great ways to present data, and you are to use them in ENGR 171 write-ups. Tables and figures should be numbered and titled as if you are writing a formal report; e.g., "Table 1. Voltage-Current response of a 4.7-kΩ resistor."

Tables present numerical information in a grid-form, typically with a *header row* at the top, and a *header column* at the left. In reports, a great amount of information can be effectively summarized in a table. Thus, the writer need not (and should not) write (excruciating) paragraphs listing out the data when the data would be easier to read and understand in a table. In the text of a report, numerical values called out from a table should be those that are the most significant (e.g., the primary results of the experiment), or those that the writer wants to draw attention to (such as unexpected or questionable data). Do not repeat all of the tabular data in the text.

If there are only a few numerical values to report, is a table necessary? is a one-row table effective? A few values can be reported within the text.

Look for opportunities to combine tables. I once received a materials science report with three one-row tables, one for each material, but with columns for the same material properties. This report was difficult to read (text/table/text/table), and comparing the different materials was near-impossible (the tables were not all on the same page). Only one table was necessary, with a row for each material. Of course, do not get too carried away; not all data can be put into one huge table.

Tables are numbered in the order in which they appear (Table 1, Table 2, …so it can be referred to easily) **and titled**. <u>**The table title goes above the table**</u> (see this manual and your textbooks). The title should be descriptive of the data. It should be clear to the reader what the table is about. Tables are often extracted from reports, so the title and any notes should allow the table to stand on its own. A terrible title is: "Table 1. Data"; "Table 1. Resister 1 Measurements" is not much better. "Table 1. Voltage-current response of a 4.7-kΩ resistor." says a lot.

Note the form of the title: a name (Table #), and a brief descriptive phrase. <u>Do not</u> write a title as if it were part of the narrative; i.e., do not write: "Table 1 shows the voltage…" or "Table 1. This table shows…" (we know it is a table).

Tables are not figures.

Figures are graphical elements: graphs, pictures, drawings, schematics, etc. In circuits, the most important figures are schematics, and in most lab reports, you would need to draw circuit schematics, pc. In ENGR 171, the most common figures for write-ups with be graphs (e.g., voltage vs. current graphs in Expt. #1). Please refer to the section on *Creating Graphs*, below.

Figures are numbered, and generally titled, as *Figure 1* is as right. Note **the figure title is below the figure**. While it is said a picture is worth a thousand words, figures often need context, as they may be extracted from reports and must stand on their own.

Introduce Tables and Figures

Each table (or figure) is to be proceeded by a brief narrative explaining it. A table by itself is not a complete answer; the table needs to be introduced with text and given context. The reader has no clue what is going on if a table suddenly appears in a report without introduction. The table is but one of the elements in effectively communicating your results.

For example, write: "Table 1 gives the voltage-current response for the 4.7 kΩ resistor. … ." After referring to and introducing the table in the text, place the table in the write-up, as illustrated in *Figure 1*. Text after the table may discuss the data.

Do not just write "See Table 1" or "See Figure 2" for the text of an answer. Write "Figure 2 shows the voltage-current response… ." Answers need to stand alone; they should be clear, concise, correct and complete.

Table and Figure Titles

- **A table's title is <u>above the table</u>**.
- **A figure's title is <u>below the figure.</u>**

Please see the tables and figures in this manual, and in your Engineering textbooks. *Figure 1* illustrates both of these concepts… the figure's title is below the graphic, while there is "table" within the graphic itself.

When numbers are used as a name or designator, use the numeral: "Table 1", Figure 3". Do not write "Table One", etc. The *quantity* is written out as a word e.g., "There are three figures."

Figure 1. Sample format of first page for typed responses in Engr 171. Note in "Question 2", Table 1 is introduced in the text before it appears. The table title is above the table.

EQUATIONS

Use Microsoft Equation (Equation Editor) in Word when creating equations in the typed responses. Remember, **variables are italicized, units are not**.

When there are many equations, you should number them so they can be referenced. For example, writing "Substituting Equation 2 into …" is much clearer and less problematic than "Substituting the equation four paragraphs above…"

Center the equation and right-align the equation number (use the center-tab and right-tab) like this:

$$p = vi \tag{2}$$

In this manual (and the textbook), there are several experiments (chapters), so the equations are given two indices: expt.eqn (ch.eqn). Here, *Equation 4.3* is the third numbered equation in Expt. #4.

Short reports – such as lab write-ups – are not long enough to be broken into sections. **Just use a single index** … use "Equation 2" for the second equation of Expt. #3; <u>do not</u> write "Eqn. 3.2".

Again, it is <u>not</u> "Equation Two". When a number is used as a name or designation, use the numeral (2), not the word (two).

CREATING GRAPHS

An engineering graph illustrates relationships between changing quantities in visual form. The advantages of a graph over a table are that (1) graphs allow variations in magnitude, slope and direction to be readily observed, and (2) a large amount of data can be efficiently displayed. Graphs are also more "friendly."

Since **graphs are used to present information**, the primary emphasis when creating them (besides being correct) should be on **clarity**. **Graphs should be easily understood and quickly read**. Frequently, a graph or chart that was originally part of a report is reproduced and circulated separately, so graphs should be self-explanatory and well-annotated.

The following are general rules for creating good graphs. While these guidelines were originally developed for hand-drawn graphs in a lab-notebook, they are valid for computer-generated graphs. Only the tools have changed.

1. To create graphs by hand, use engineering paper, graph paper, or log-paper. For computer work, use Excel, MATLAB or a graphing software.

2. **Determine the type of scale** that will most clearly illustrate the relationship between the variables.

   - With a *proportional scale* (a linear axis), distances along the axes are directly proportional to the variable values.

   - Sometimes it is better to plot one axes (or both) using a *logarithmic scale*. The log scale allows plotting a large range of values, and has the advantage that a given percentage change in a variable is represented by the same physical distance in different decades. Learning how to read and use a log scale is important in engineering and science.

3. **Use decimal scales that are easy to read** (thus it is easy to read the coordinates of a data point). For linear scales, **the smallest division should be 2, 5 or 10**:

   - "0, 2, 4, 6, 8…"
   - "0, 5, 10, 15..."
   - "0, 10, 20, 30..."

   or their multiples of 10^n, e.g.:

   - "0, 200, 400, 600…",
   - "0, 0.05, 0.10, 0.15, 0.20",
   - "0, 1, 2, 3,…",
   - "0, 0.1, 0.2, 0.3…", etc.

   <u>Do not</u> use other increments. We live in a decimal world.

   The number of decimal places of the numbers on the axis should have the same precision.

   - use: "…0.10, 0.15, 0.20"
   - <u>do not</u> use: "…0.1, 0.15, 0.2"

   Avoid excessive zeroes; "…0.2000, 0.3000…" implies you can read the graph to ±0.00005!

   Avoid excessive zeroes, both in-front of, and in-rear of, non-zero digits. Use the S.I. prefixes for what they were intended:

   - write 80,000,000 Pa as 80 MPa.
   - write 0.0035 A as 3.5 mA.

   "Life is too short to be writing a lot of zeroes." – DJD.

4. Include tick marks on the axes. This allows data points to be easily read off the graph.

   Numbered tick-marks should be regularly spaced (e.g., "0, 5, 10, 15…").

   Do not number tick-marks such as "7, 14, 21…"; even through these values are evenly spaced, how can coordinates be read off the graph with these numbers on the axis? Use divisions of 2, 5 or 10, or their decimal multiples (see Item 3).

5. To avoid distortion, start all axes from zero unless another origin is required for clarity.

6. Label each axis with the variable being plotted, and include units.

7. **Variables are italicized,**

   units are in plain text; e.g., i = 12 mA.

8. **Plot the independent (control) variable** on the horizontal (x-) axis. When only one quadrant is needed, place the origin near one corner of the page (usually the lower-left corner), allowing room for graph title, axes, axes titles and labels, variables, units, and adequate margins between the graph and the edge of the paper.

   The horizontal (x-axis) is called the ***abscissa***, the vertical (y-axis) is called the ***ordinate***.

CAUTION: In Excel, use ***x-y scatter plots***; <u>do not</u> use *line plots*. Line plots take the *x*-data and plot it as if they are categories that are equally spaced on the horizontal axis. Thus, if the *x*-values of the data points are 2, 3, 7, 15, then "2", "3", "7" and "15" will all be equally spaced on the axis; it is not a true mathematical graph. Line plots are useful when the *x*-data are categories (e.g., "Monday, Tuesday…", months, Item #, etc.).

CAUTION 2: Make sure your axes have ***tick marks*** on them; some default settings of Excel do not include them. Tick marks allow the coordinates of data points on the graph to be determined.

9. **Use as much of the page as possible –** consistent with the scaling of the axes – so that the proper scale multiples are obtained (see Item 3 above). **<u>DO NOT squeeze a plot into a small area</u>; someone should be able to <u>easily read points</u> off the graph.**

10. **Data tables for graphs**. **In a lab notebook**, when there are a lot of data points, the graph should be placed on the page *following* the data table (a graph is made from the data; the data comes first). When there are only a few data points, a data table can be placed on the same page as the graph.

    In reports, if a large quantity of data is used to create a graph, put the data table in an appendix. A huge table in the middle of a report gets in the way. It should be clear from the graph itself what is going on. The narrative paragraphs that describe the graph should discuss/highlight significant values from the graph (maxima, large changes, etc.). Readers interested in the details will look at the appendix.

11. When plotting both *experimental* and *theoretical data points* on the same graph, **Indicate *experimental* points by small distinct dots in the center of an enclosing circle**, or with another distinctive symbol/marker. This enables a clear separation between data points that are *experimental*, and any data points that are *theoretical*.

12. If it is expected that the usual *continuous relationship* between the variables exists, **<u>a smooth curve</u> should be drawn through the experimental points** with minor variations due to experimental errors being disregarded. If a hand-plot, carefully sketch in a smooth curve, or use an irregular curve (e.g., a French Curve tool) to draw a smooth line.

    A smooth curve that models the trend of the data will not necessarily go through each and every experimental point (real measurements have error, etc.) "Through the experimental points" implies the curve is a best-fit through the points.

    Many engineering systems are linear. If the data is expected to be linear, draw the best <u>line</u> through the experimental points. The line will not necessarily pass through each point.

    With **discontinuous** data, such as points on a *calibration curve*, connect neighboring points by straight lines. Straight lines would be used to connect points on a graph that plots, say, a football team's points by game (the data is not continuous). **Straight lines should <u>not</u> be used to connect data points of a data set that is expected to be <u>continuous</u>,** such as the data in most experiments.

13. In Excel, when a ***scatter-plot*** is created, you have the choice to have:

    (1) markers and no lines;
    (2) markers and a smooth curve through each point;
    (3) markers and straight lines between neighboring points;
    (4) no markers with a smooth curve through each point; and
    (5) no markers with straight lines between points.

    In science and engineering, you will primarily use one of the following:

    - **markers and no lines** – especially when you will subsequently apply a curve-fit (an Excel ***trendline***); an automatically plotted line through each point will "get in the way" of the fit (trendline).

    - **no markers with a smooth curve** – especially when there are a lot of data points; a graph with too many markers looks like a thick line, which is not easy to read.

- **markers with a smooth curve through them** – assuming there are few markers. However, since the curve will be forced through each point, the curve's waviness may look odd; a linear or non-linear curve fit (trendline) might show the trend better.

14. A curve-fit in Excel is called a ***trendline***; the equation of the curve-fit can be displayed on the plot, as can the residual R-value.

    The trendline can also be forced to go through the origin.

    When placing a trendline, use an appropriate form of equation from the theory that the data is expected to follow. Typically, the equation is **linear** (e.g., Ohm's Law), **quadratic** (free-fall), or **exponential** (decay of voltage in an RC-circuit).

15. If possible, plot related curves on the same set of axes (but do not force too much data onto one graph).

    The points for one curve should be made distinct from those of other curves by using different-shaped ***markers*** (square, diamond, etc). Curves can also be differentiated with different ***line styles*** (solid, dashed, etc.). **Avoid using only color to distinguish different data sets**.

16. **Is a *legend* necessary?** Consider identifying each curve with a short description next to it (even a variable, e.g., use labels v_1 and v_2 for the voltage across R_1 and R_2). By labeling each curve, no legend is necessary. Legends take up space, and the reader must look at the graph, then at the legend, then back to the curve to read it; it can be a distraction.

17. When related plots are created on a single page, and have the same horizontal axis and scale, align the plots horizontally so that any vertical line drawn through their x-axes passes through the same x-value. Aligning the graphs makes it easy to compare the graphs at any particular x.

18. **Make all graphs self-explanatory by including adequate titles, annotations, etc.**

    Especially in lab note-books, the title, text boxes, annotations, etc., should describe the curves and designate the material, apparatus or equipment being tested by make, model or rating. Indicate any special conditions of the test; include the date(s) of the test. The data taken in lab will be incorporated in reports, so the more detailed the information, the more legitimate the data.

    Graphs in reports may be extracted and presented on their own or in other contexts. Graphs within reports should also be self-explanatory and well-annotated.

19. **The "*x*-axis" of the graph should be located either:**

    - **at the bottom of the page, or**
    - **along the right-hand side of the page**

    as shown in ***Figure 2***. Arrange all lettering to read from the bottom or right-hand side of the page.

    Why? Think about how graphs (or tables) would look if the bottom of each graph was at the left side of the page in a book. If such graphs appeared on facing pages, when you rotate the book to look at them, the graph that comes second (right-hand page) would be above the one that comes first (left-hand page); in other words, out-of-order.

    Although reports are usually one-sided, the format should be consistent (what you do practice, you will do in "the game"). The document (report or book) will always be rotated 90° clockwise to view the rotated graphs, etc. It should be noted that more printers are capable of duplex printing.

    Also, the "*x*-axis" of a graph is placed at the right side of a page, the staple will not interfere with the origin.
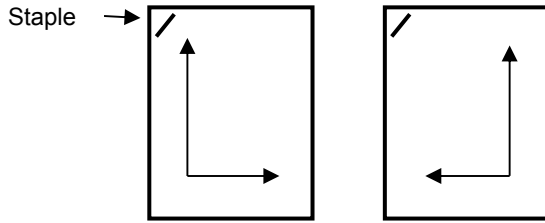
Figure 2. Place the "*x*-axis" of a graph towards the bottom of the page, or towards the right side of the page.

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20. **Do not distinguish or refer to different curves by color alone.** Colors are helpful in discerning between data sets/lines of the graph, especially on a computer monitor. However, light colors print faintly. When graphs are reproduced, the copies are usually black-and-white/grayscale. ***Which gray curve is the "orange curve" that the text is referring to?***

    Even with colored printing, how does this help readers who are color-blind?

    Distinguish data sets with different shaped markers (circles, squares, diamonds, etc.), and **curves with different line styles** (solid, dashed, dotted, dash-dot, thick, etc.). If you use colors, also use symbols and/or line styles to distinguish different sets of data.

    In hand-drawings, use dark pencil or black/blue ink so that graphs can be readily reproduced.

21. **A graph is but one *type* of figure**. Other figures include: photographs, drawings, schematics, etc. **Graphs should be titled as *Figures***. For example: "Figure 1 Voltage-current response of a 10-kΩ resistor." **<u>Do not</u> label a graph, "Graph 1. Voltage-current response….**"

The foregoing are general rules for creating graphs. They may be modified to best present the data at hand. Consistency in format throughout a report is important since it is one less thing the reader has to decipher. The decision on what procedure to follow should always be based on the answer to the following question:

> **How can this set of data be presented most clearly and usefully?**

ELECTRICAL CIRCUITS LABORATORY TIPS   Rev.: 1/08/17, DJD

Your first circuits lab course can at times be frustrating. It was for me. You may be studying circuits for the first time. The conventions used in engineering are different than those used in physics and in electronics. The schematics do not look like real circuits. It is hard to "see" what is going on. The equipment is new to you and confusing, etc.

The purpose of the next few pages is to give you some hints on **wiring** and **checking circuits**. Other tips are included in each experiment. You should also study the background materials in the *Appendix* of this manual, such as "Resistor Color Codes," "The Proto-board," etc., and any other sources referenced in the experiments.

Resist the temptation to blindly follow the steps in the lab manual. Try to figure out what each step means. The goal of labs is to understand what is going on. Pre-, In- and Post-Lab Questions that ask "*why*", etc., are there to make you think about what is physically going on. You should develop your own questions. Questions you might ask yourself are: "Why is the voltmeter connected this way?" "What current should I expect through this resistor?" "What happens if this resistor is replaced by a larger one?" etc. Discuss such questions with your lab partner – he or she should be just as interested in learning, but may be afraid to ask. If you want to test your ideas, make sure they are safe (ask your instructor if in doubt).

Read the entire experiment, do the pre-lab assignment and review reference material BEFORE coming to lab – even when not specifically reminded to do so. **Read the lab procedures so you know how to set up the experiment. Read the theory and do pre-lab calculations so you know what results to expect**.

Students who do the pre-labs and analyze the circuits beforehand understand the lab concepts better. Prepared students finish the lab sooner. It quickly becomes obvious when a student is not giving sincere and sufficient effort on pre-lab work and experiments; this suspicion is usually confirmed in the lab practicum/exam.

Come prepared. You owe it to your lab partner, to your instructor, and to yourself .

Prevention: Check Circuit Elements

An important step in any circuit experiment is to check your equipment, components, wires, etc., for proper operation *before* placing them in a circuit. This is one of the easiest and most effective practices to ensure a smooth, headache-free lab session. It is relatively easy to find a faulty component before it is placed in a circuit. It can be very difficult to find a faulty component after the circuit has been built.

Some basic checks:

- **Check each *lead* (*cable*, *jumper wire*) with an ohmmeter for (near-) zero resistance**. If the digital multimeter (DMM) selected as an ohmmeter displays "OL" (over limit), then the lead is *open* (has "infinite" resistance) and should not be used (it should have a very small resistance).

- **Check (measure) each resistor** to ensure that you have selected the right one, and that it is within tolerance. Resistors that have been subjected to power beyond their power rating for an extended period will have burned and cannot be relied on. **Always measure resistors. Use the *measured* values for in-lab and post-lab calculations,** unless instructed otherwise.

- **Check (measure) voltage sources**. A DC power supply can be checked with a DMM in DC voltmeter mode. An AC power supply can be checked with an oscilloscope.

  Always measure the input voltage; <u>do not</u> trust the display of the power supply as it is not necessarily accurate. In addition, a DMM generally gives better resolution (precision) than a power supply's display.

- **Check potentiometers**. The resistance across the outer terminals should be the full value of the potentiometer's resistance. The resistance between the middle and either outer terminal should vary as the pot's dial is turned.

- **Check capacitors and inductors**. These, as well as resistors, can be measured on the Philips PM 6303 RCL Meter in the lab.

- **Check diodes** using the DMM in diode mode, or measure the forward (small) and reverse (large) resistances of the diode with the DMM in ohmmeter mode.

Building the Circuit

When building a circuit, try to keep it neat (*Figure 1*). Consider the following hints:

- **Keep the power off when wiring your circuit** and when changing out components. Accidentally creating a *short* with the power on may create an excessive current, or cause a large voltage discharge, either of which may damage components and/or **YOU**!

- Always start with a well-drawn schematic of the circuit. Do not build from memory.

- Check-off completed circuit connections on the schematic as you go. This reduces the likelihood of using more wires than necessary, minimizes redundancy, reduces the chance of error, and produces a neater circuit.

- Color-code circuit connections. Use red leads from the power supply's positive terminal. Use black leads to the supply's negative terminal, and to *ground* (**COMmon**) when it is connected to the supply's negative. Or use green for *ground*. Other colors are available. Color-coding generally makes it easier to check the circuit for proper wiring.

- **Ground the circuit** – this will keep the voltages in your circuit close to *earth ground* $V = 0$. Circuits that are not grounded are *floating* (the voltage is not fixed with respect to ground).

- Connect electrical components directly to each other via the proto-board.

- Keep the circuit flat, near the surface of the *proto-board* (bread board). Wires can be cut and then bent at 90° with pliers.

- Use as few extra wires (*jumper wires*) as possible. The more connections, the more things can go wrong (wiring errors, connections coming lose, etc.).

- *Jumper wires* are pre-cut/pre-bent to length to fit in 0.1" proto-boards. The insulation color indicates the length per the color code for resistors; e.g., a red jumper is 0.2" (or 2"). Selecting efficient lengths helps keep the circuit flat and the connections short.

- Use connections that are as short as possible. This makes for a neater circuit. Also, long wires can contribute to extraneous capacitance, inductance and electromagnetic interactions (interference).

- Do not cross wires or components over each other. Crossed components make the circuit
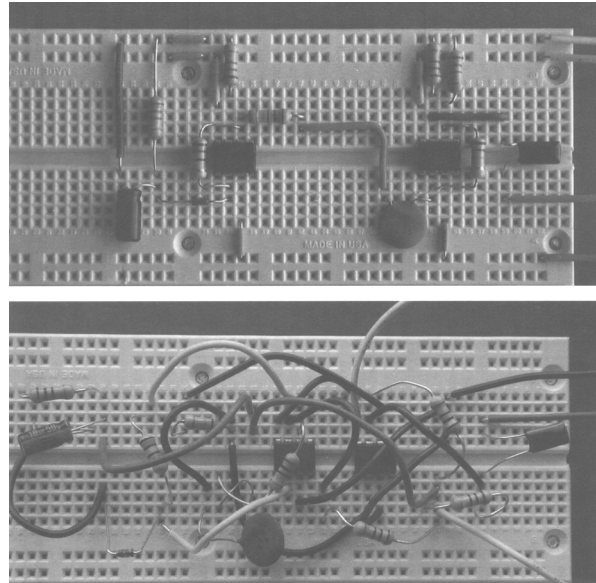

Figure 1. These circuits should do the same thing. Keep it neat. [Tsividis, Figure 2, p. 4].

difficult to understand, and make changes difficult to perform. Bare wires that touch can create short-circuits.

- **When the circuit is constructed, check the wiring to ensure connectivity. Then have your partner check the wiring.**

- Plug in integrated circuits (ICs) – such as *op-amps* – **across** the proto-board *trough* so that each pin is in a different 5-hole set.

- Be sure the pins of ICs are straight (use pliers to straighten) so that they fit into the appropriate proto-board sockets.

- Unplug ICs carefully to avoid bending the pins. Use an *IC extractor* if available (a large tweezer-like tool to pull out ICs).

- Use the "+" and "–" lines of the proto-board as *buses* (an electrical interface that can supply the same voltage to several components). For example, connect the power supply's positive voltage to the top "+" line; all the sockets along the line will be at the same voltage, and any device that requires that voltage can be connected to any of the sockets.

- If your circuit has distinctive "blocks" of components that have different functions, try to group the components of each block together in the same area of the board.

- Make sure the resistors have high enough power ratings, and the capacitors have high enough voltage ratings.

- Connect electrolytic capacitors (the ones in cylindrical cases) with the proper polarity, or else they may explode.
- Discharge capacitors (to $V_c = 0$) before plugging them into a circuit. Do this by placing a resistor across their leads for a short amount of time. Small capacitors with small voltages can be zeroed by simply short-circuiting their leads.
- When measuring voltages or currents, or when applying voltage to the circuit, connect the probe leads (often having alligator clips) to short leads (jumper wires) which in turn can be inserted into the proto-board sockets. Be careful that these jumpers cannot be accidentally pulled out of the board.
- Only connect *oscilloscope probes* to the oscilloscope input. These probes are only to be used for measurements. **<u>Do not</u> use the scope probes to apply voltages; you will damage them.**
- The green socket on the DC power supply, and the ground (negative) on the oscilloscope are at "absolute ground," or $V = \mathbf{0}$. If you connect these anywhere on your circuit, that point will have zero voltage (whether you want it to or not).

Troubleshooting or Debugging

Your circuit may not work on the first try, despite the care you took in building it. This may be due to defective parts or an incorrect design. Often, it is due to a loose or incorrect connection, a wrong component, bent IC pins, an accidental short, etc. These errors are sometimes difficult to see, especially in a large circuit. Here are some tips in helping to find the cause of the trouble:

- **Turn off the power**. If you continue to power the circuit as you move the components, you may cause a short circuit or rapid discharge that could damage parts or **you**!
- **Understand the connection pattern of your proto-board**; check that your components are properly connected (they may be shorted, not-connected, connected to the wrong 5-hole set, etc.). Use the proto-board effectively; there is no need to crowd your circuit during lab (manufacturing is another matter).
- A circuit may have overheated components (you might be able to smell them) which need replacement. Be careful – they may be hot.

- If your power supply displays current (AHC's DC Triple Output does), watch it as the circuit is energized. If it is zero, there is likely an open connection. If the supply current is higher than expected, there may be a short in the system.
- The current from the DC Triple Output Power Supply can be limited to avoid large currents that may damage components (AHC's supplies can output up to 2 A). The **Current Control** dial is used to set the limit. Do not set the limit too low or the circuit may not get enough current to properly operate. See "Setting the Current Limit" in *Appendix F*.
- When the circuit is energized, use a voltmeter to ensure the voltages at various nodes (and across various elements) are as expected.
- If the circuit large and/or complicated, do not try to check it all at once. Check the behavior of different components or blocks (sets of components) to ensure each is behaving properly. You may need to isolate different blocks and test them separately. This approach is called the "Divide and Conquer" method.
- If the overall system can be built by breaking it into several blocks of components with distinct functions, **test each block as you build it**, *then* connect them together.
- If you need to change-out components, do so one at a time, and recheck. **Changing more than one thing at a time will not tell you what the problem is/was.** While you think you might be saving time by "multi-tasking," you will likely be more confused by changing several things at once.
- Be careful for interference from outside sources (lights, other electromagnetic equipment, etc.). Use short connections and wires; ground the circuit.
- If you cannot find the error, clear the board and **start from scratch**. This is necessary if your wiring is sloppy and it is difficult to follow what is going on. Avoid having to start over by building the circuit neatly the first time.
- **A big tip**: If the circuit is not working as you expect, **make sure you have a closed circuit**, and that the components and jumper wires are connected together properly. You will likely hear me say something like this in lab:

  "**Follow the current flow. ... does it agree with the current flow in the schematic?"**

Running Experiments

- **Always read each step completely before acting.** Do not read the step half-way and start working on the circuit. There may be important information at the end of the step.
- Try to figure out the result of each step before performing it. This will save you time. The results of undergraduate labs can generally be calculated ahead of time (do the Pre-Lab).
- Make hand-plots as you run the test (even rough plots). It is often difficult to see trends from data tables, but plots show relationships between data, and can be used to determine what may be wrong with your circuit.
- Do not take your circuit apart until you are sure you have <u>correctly</u> completed your measurements.
- Try to make measurements as accurately and precisely as possible. Remember that they are never exact (what might the sources of error be?). DMM readings may even *drift* with time.
- **Record display readings as far out as possible**. If the DMM displays 5 digits, write all 5 digits. If the last digits drifts, write 4.
- Use proper ranges (scales) on measuring equipment (DMM's and oscilloscopes) to get the best resolution (see ***Appendix E***).
- Be careful when obtaining small quantities by subtracting two larger quantities. For example, $1.254 - 1.249 = 0.006$. If you measure/record data to only three significant digits, $1.25 - 1.25 = 0$.
- **Learn about your test equipment**. Resist the temptation to randomly push buttons. Have some idea of which buttons are used to measure which quantities.
- **Share the work equally with your lab partner**. If you do no work, you are being unfair to your partner. **Learn by doing**, not by watching. On the other hand, do not take over and do all the work yourself; you are cheating your partner out of the learning process. Take turns in doing the tasks. A good idea is for one partner to build the circuit, and the other to verify it and take measurements. Switch tasks for the next experiment.

Tips when Using a Multimeter

(see *Appendix E* on the Fluke 45 DMM)

- **When measuring voltage or current**, always start with the highest *scale* (*range*) first, and then select lower (smaller) scales until the best scale is found. This is especially important when using analog (needle/dial) meters. Using too small of a scale will "peg" the meter since you are trying to measure a value larger than the display (the needle/dial is forced against the far right of the display, hitting the *peg stop*). *Pegging* the needle can damage it. In both digital and analog circuits, the DMM's circuitry can be damaged.
- **When using a multimeter as an *ohmmeter*, make sure the power to the circuit is off**. An ohmmeter has a calibrated voltage source that sends current through the resister being measured. Based on the value of that current, an analog meter's needle (dial) deflects to indicate resistance. If an ohmmeter is connected to a "live" (powered) circuit, the calibrated voltage source can be damaged in both digital and analog meters, and the needle can be pegged in analog meters.

  Even if not damaged, the ohmmeter will read an incorrect value since a different current is flowing than otherwise.
- **Always measure the resistor removed from the circuit** to ensure the resistance of the resistor itself is measured, and not the resistance of a set of resistors in parallel.

Miscellaneous Tip

- When operating a circuit that has a *potentiometer* in it, take care when you turn the dial of the pot all the way clockwise or counterclockwise (to zero ohms between the middle and one of the outer terminals). Depending on how the circuit is built, there is a possibility of drawing an excessive current through the pot, and cause its fuse to blow. A blown fuse acts as an open circuit; no current will flow.

Sources:

Electrical Engineering Department Staff, *Electric Circuits Laboratory EE 251*, Cal Poly San Luis Obispo, Winter 2004.

Tsividis, Yannis, *A First Lab in Circuits and Electronics*. J. Wiley & Sons, 2002, pp. 3-10.

KEY TO FIGURES

Some of the components used in lab, along with their standard symbolic representations, are shown in *Table 1*. Electronic components in *schematic drawings* do not look like their real-life counterparts. A schematic drawing – or *schematic* – is a symbolic representation of the actual system, making the circuit easier to draw and understand. It is important to be able to build real circuits from their schematic drawings, as well as to create schematic drawings from existing circuits. A schematic circuit and a pictorial of its as-built circuit are shown in *Figure 1*.

Table 1 Schematics and Pictures of Electronic Components and Equipment generally used in this manual.
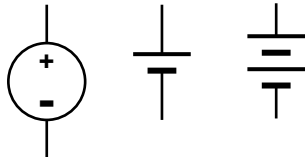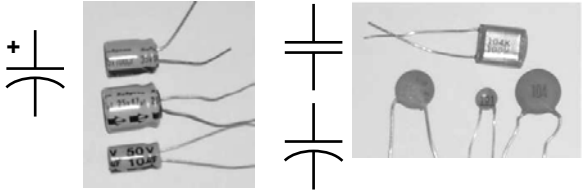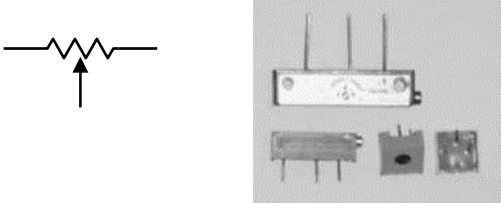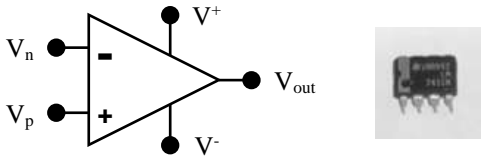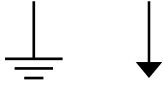
Resistor	**DC Voltage Source (DC Power Supply)**
Capacitor (*left*: **Electrolytic (+),** *right*: **Polyester , Ceramic Disk)**	**Variable DC Voltage Source**
Inductor (Coil)	**AC Voltage Source (Function Generator)**
Potentiometer (Pot)	**Operational Amplifier (Op-Amp)**
Ground	

Table 1, continued

(a) Schematic representation

(b) Pictorial representation

V_s reading

Wire connected to positive (red) terminal of power supply

Wire connecting negative (black) terminal to ground (green) terminal

$- V_s +$

Bus line (nodes with same voltage)

R_1

5-hole (5-socket) set, (nodes with same voltage)

Trough

Connected to negative (black) terminal of power supply

R_2 R_3

Proto-board

Figure 1 Converting a Schematic (a) into a Real Circuit (b). A DC voltage source V_s and resistor R_1 in series with the parallel combination of R_2 and R_3 .

EXPERIMENT 1

Ohm's Law

GOAL

To understand Ohm's Law, the voltage-current relationship in a resistor.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Read resistor color codes.
- Construct a basic circuit on a proto-board and apply a voltage with a DC power supply.
- Measure unknown resistance directly with the Digital Multimeter (DMM).
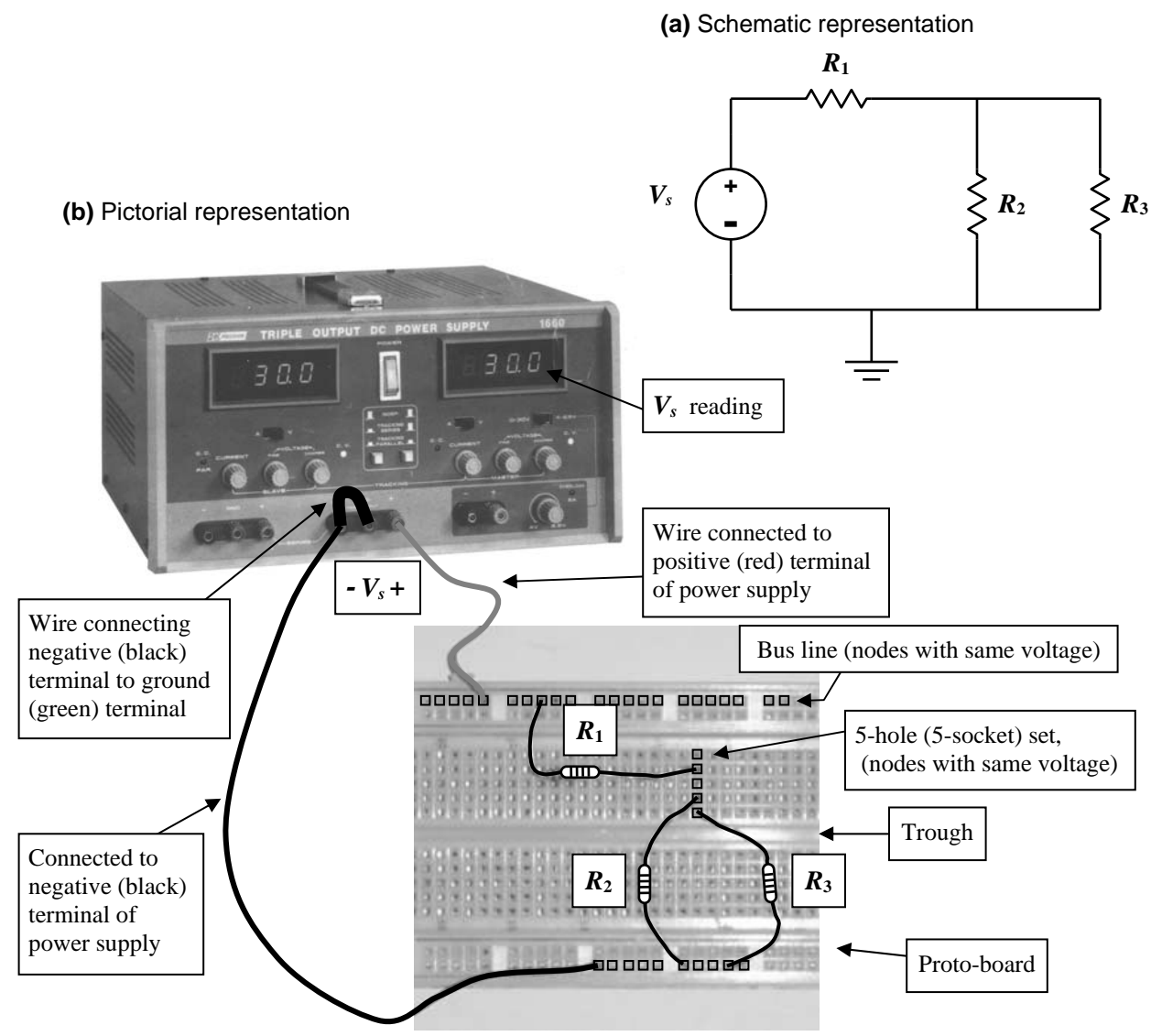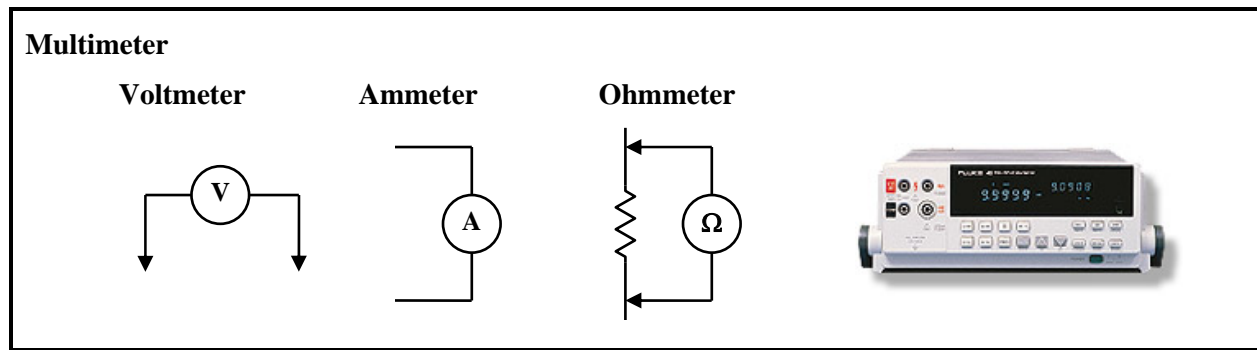- Measure voltages and currents with the DMM and calculate unknown resistances.
- Verify Ohm's Law through experiment.

BACKGROUND

Read: • Alexander and Sadiku, 3e, 4e or 5e: Ch. 1, Ch. 2.1–2.2
 • "Electrical Circuits Laboratory Tips" (see introduction material to this manual)
 • "Key to Figures" (introduction to this manual)
 • "Resistor Color Codes" (***Appendix A***)
 • "The Proto-Board (Bread board)" (***Appendix C***)
 • "Fluke 45 Digital Multimeter (DMM)" (***Appendix E***)
 • "Triple Output DC Power Supply" (***Appendix F***, up to, but not including, 'Series Tracking Operation')

Resistors

The most common electronic component used in this course is the ***resistor***. The principal property of a resistor is its electrical ***resistance***. "The resistance R of an element denotes its ability to resist the flow of electric current; it is measured in ohms (Ω)" [Alexander & Sadiku, 5e, p. 31].

The ***nominal***[1] ***value*** of a resistor is read from the resistor's color bands (see ***Appendix A***). The ***actual value*** of a resistor will be within a certain percentage of its nominal value; this percentage is the resistor's ***tolerance***. The tolerance is usually 5% for standard resistors. To determine the actual value of a resistor, measurements must be taken.

In this experiment, you will determine the value of three "unknown" resistors using the three measurement techniques discussed below. You will also verify ***Ohm's Law*** in the process.

---

[1] *Nominal*: in name only.

1. *Direct Measurement*
(Ohmmeter Method)

In the first method, the Fluke 45 DMM is used as an *ohmmeter* to directly measure unknown resistance R_x (*Figure 1.1*).

Before coming to lab, review Appendix E: "Fluke 45 Digital Multimeter."

2. *Ohm's Law - Voltage-Current Ratio*
(Voltmeter-Ammeter Method)

Ohm's Law is the basis of the second method. "*Ohm's Law* states that the voltage [drop] v across a resistor is directly proportional to the current i flowing through the resistor" [Alexander & Sadiku, 5e, p. 31]:

$$v = iR \tag{1.1}$$

Thus, if the current through a resistor is doubled, the voltage across the resistor is also doubled. Said another way, the voltage-to-current ratio is constant (and equal to the resistance $R = v/i$).

Here, the DMM is used as a *voltmeter* to measure voltage drop v_x across unknown resistor R_x, and then as an *ammeter* to measure current i through the resistor (*Figure 1.2*). With voltage and current measured, the unknown resistance R_x is:

$$R_x = \frac{v_x}{i} \tag{1.2}$$

Note: This is actually how an ohmmeter works… a known voltage is applied to the resistor and the current measured; the voltage-to-current ratio is then calculated and displayed as the resistance.

3. *Ohm's Law - Voltage Ratio*
(Single-Voltmeter Method)

Ohm's Law is also the basis of the third method. Consider placing two resistors in series: **known** R_1 and **unknown** R_x (*Figure 1.3*). The current through two resistors in series is the same. The voltages across the resistors, v_1 and v_x, are:

$$v_1 = R_1 i \quad \text{and} \quad v_x = R_x i \tag{1.3}$$

Since the current is the same in both resistors:

$$i = \frac{v_1}{R_1} = \frac{v_x}{R_x} \tag{1.4}$$

Rearranging *Eqn. 1.4*, for resistors in series, the ratio of their resistances equals the ratio of their voltage drops:

$$\frac{R_x}{R_1} = \frac{v_x}{v_1} \tag{1.5}$$

Solving for unknown resistance R_x:

$$R_x = \frac{v_x}{v_1} R_1 \tag{1.6}$$

With R_1 known, only voltages are measured. Measuring voltage is much easier than measuring current.
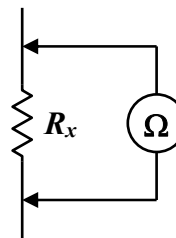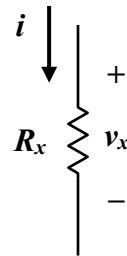

Figure 1.1

Figure 1.2

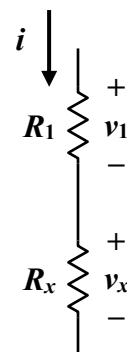**Figure 1.3**

MATERIALS AND EQUIPMENT

1   470 Ω, 1/4 watt, 5% resistor
1   2.0 kΩ, 1/4 watt, 5% resistor
1   2.7 kΩ, 1/4 watt, 5% resistor
1   4.7 kΩ, 1/4 watt, 5% resistor
1   Triple Output DC Power Supply
1   Fluke 45 Digital Multimeter (DMM)
1   proto-board (bread board)
-       various cables and test leads (e.g., banana plug-to-alligator clip cables; power supply switch)
-       various wires (jumpers)
-       engineering paper (for hand plots).

PROCEDURE

You will determine the resistances of three "unknown" resistors: 470 Ω, 2.7 kΩ and 4.7 kΩ. The 2.0-kΩ resistor is taken as "known."

Ohmmeter Method (Direct Measurement)

1. From the lab kit, select the following resistors: 470 Ω, 2.7 kΩ and 4.7 kΩ.

2. Using the DMM as an *ohmmeter* (***Figure 1.1***), measure the value of each resistor and record the results in ***Table 1-1*** of the ***Data Sheet***. Record **all** digits displayed on the DMM (the DMM's in the lab should read 4 or 5 digits). **Make sure the values are within tolerance as given by the resistor's tolerance band.** If a resistor is out of tolerance, it might be the wrong resistor or it has broken down.

Voltmeter-Ammeter Method (Ohm's Law)

3. With the DC power supply **not connected** to the circuit, **turn the supply on**, and set it up so that it will control and display the **MASTER supply** voltage (see ***Appendix F***). Set the voltage to 0.0 V by turning the MASTER supply COARSE CONTROL all the way counterclockwise (to minimum); set the FINE CONTROL at mid-range (halfway, "12 o'clock") or as needed. Make sure you use the MASTER Supply (learn the tool you are using).

    Set the CURRENT CONTROL knob to "10 o'clock" (this limits the current to less than 1 A). See "Setting the Current Limit" on page F.6 of ***Appendix F***. A current limit of 100 mA is sufficient for all experiments in this manual.

    Take this opportunity to investigate how the voltage responds to its COARSE and FINE CONTROLS without the power supply being connected to a circuit.

    Set the voltage to 0.0 V. **Turn off** the power supply.

4. Using the proto-board, jumper wires, leads (e.g., banana-to-alligator cables), and the DC power supply (still **turned off**), build the circuit shown in ***Figure 1.4a***. Use the 4.7 kΩ resistor for "unknown" resistor R_x.

    For the voltage source, connect a red lead from the MASTER supply's positive (red) terminal to the circuit, and a black lead from the (black) negative terminal.

    Ground the supply's negative terminal by connecting it to the supply's **GND** (green) terminal. While the color of the leads does not affect the circuit's performance, *color coding* is helpful to visualize what is going on.

    Set up the DMM in *voltmeter* mode and connect it *in parallel* with R_x (***Figure 1.4b***). Use a red lead from the positive (red) terminal of the DMM, and a black lead from the negative/COM (black) terminal.

    DO NOT TURN ON THE POWER SUPPLY yet.
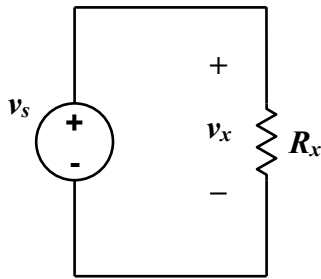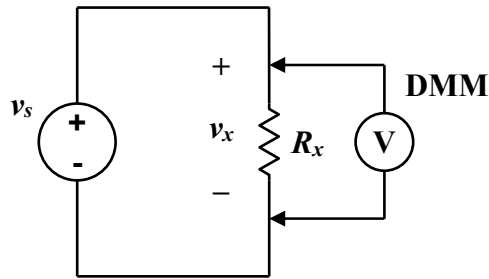
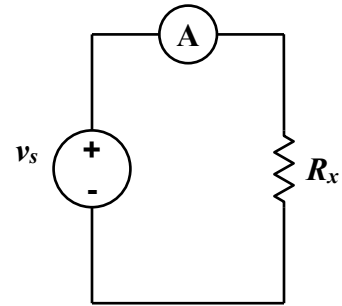**Figure 1.4a**   **Figure 1.4b** DMM as a voltmeter.   **Figure 1.5** DMM as an ammeter.

5. Ask your instructor to ensure that you have set up the circuit correctly (**Figure 1.4b**) before going on to the next step. Ask your instructor initial **Table 1-2**.

6. **Turn on** the power supply, and increase the voltage so that the voltage across the 4.7-kΩ resistor (as measured on the DMM) $v_s = v_x = 6.00$ V. The voltage displayed on the power supply is likely different than that measured with the DMM. **Always MEASURE voltages with the DMM** (do not trust the power supply's display).

   Record the measured voltage in **Table 1-2** on **Line 7a** (include all digits displayed on the DMM).

7. Using the voltage measured in **Step 6**, and the resistor's <u>nominal value</u>, **calculate the current** that should be flowing through the 4.7-kΩ resistor. Record in **Line 7a**.

   Repeat the calculation using the resistor's <u>measured value</u> from **Step 2**. Record your results in **Table 1-2, Line 7b**.

8. **Turn off** the power supply without changing the voltage level. Reconfigure the circuit as shown in **Figure 1.5**, with the DMM as an **ammeter** (do not forget to change the positive lead of the DMM to the appropriate current port).

9. **Turn on** the power supply without changing the voltage. Measure the current, and record its value in **Table 1-2, Line 9**).

   From the <u>measured voltage</u> (**Step 6**) and the <u>measured current</u>, *calculate the resistance* and record it in **Table 1-2, Line 9**.

   Make sure that the power supply display does not change its voltage reading (~6.0 V) significantly. If it changes, there is something wrong with the set-up. Verify the voltage source with the DMM and reset if necessary.

10. **Turn off** the power supply. Reconfigure the circuit for voltage measurements (**Figure 1.4b**).

11. **Turn on** the power supply. Increase the voltage across the resistor to 12.00 V (as measured on the DMM). Record in **Table 1-2, Line 13**.

12. **Turn off** the power supply. Reconfigure the circuit for current measurements (**Figure 1.5**).

13. **Turn on** the power supply. Measure the current and record in **Table 1-2**. *Calculate the resistance* (from the measurements of **Steps 11** and **13**) and record in **Table 1-2, Line 13**.

14. **Turn off** the power supply. *As a "progress check," answer the questions under Table 1-2*.

15. Rebuild the circuit in **Figure 1.4**, using the 470-Ω resistor for R_x. Using the methods described above, vary the voltage from 2.0 to 12.0 V in 2.0-V steps (measure with the DMM). Take the current at 0.000 V to be 0.000 A. For each voltage step, use the DMM to measure the voltage and corresponding current and record them both in **Table 1-3**.

    <u>**CAUTION**</u>**: Do not change the voltage until its current is measured** (voltage is the input, current is the output).

16. Repeat **Step 15** using the 2.7 kΩ resistor.

17. Using the voltages and currents measured at the 12.0-volt level, *calculate the resistance of the* 470-Ω *and* 2.7-kΩ *resistors and record them* in the last row of *Table 1-3*.

18. Using the data from *Table 1-3* **hand-plot** *voltage vs. current* graphs, one for the each resistor (470 and 2.7k). Voltage *v* should be on the vertical axis, and current *i* on the horizontal. See 'Creating Graphs' in the "Introduction" of this manual.

    • Use one page of engineering paper per graph – one page for each resistor.

    • **Each student will draw <u>one</u> hand-plot**, either for the 470-Ω or for the 2.7-kΩ resistor). If a group has three students, one of the resistors will be plotted twice.

    • Title the plot (e.g., "*v* vs. *i* for ___".

    • Make the linear scale appropriate so that you use most of the paper (i.e., do not crowd your graphs into a corner).

    • Use a straight edge to draw the axes. Correctly label the axes with title (variable) and units.
      Include tick marks on each axis.

    • Include the point (0,0) in your data set.

    • **For each set of data**, draw a *straight line* that best approximates its trend. The slope of this line is the *resistance*. Consider how well the data falls on the line.

    Ask you instructor to initial your plot.

    After the experiment, use Excel – on the lab computers or later outside of lab – to plot the data from *Table 1-3*. Use an *x-y scatter plot*. In Excel, a linear *trendline* can be superimposed on each set of data that automatically gives the best-fit line and its equation. Force the line to go through the origin (0,0) – it is an option in Excel. The slope of this line is the resistance. Use a separate sheet of paper for each plot.

    Students will submit their own individual reports, but may share Excel graphs.

Single-Voltmeter Method (Voltage Ratio)

19. Set the power supply to zero, and **turn it off.**

20. Select the 2.0-kΩ resistor from the lab kit. The 2.0-kΩ resistor will be used as the "known" R_1. Directly measure R_1 on the DMM (ohmmeter mode). Record R_1 in the title of *Table 1-4*; include units.

21. Build the circuit shown in *Figure 1.6*. For the "unknown," use $R_x = 470$ Ω.

22. **Turn on** the power supply and increase the voltage to $v_s = 12.0$ V. Measure the voltage across the power supply with the DMM to ensure that it is at 12.0 V.

23. Measure the voltage across known resistor R_1, and then across the "unknown" resistor $R_x = 470$ Ω (*Figure 1.6*). Record the values in *Table 1-4*.

24. Repeat **Steps 21** through **23** for "unknown" resistor $R_x = 2.7$ kΩ and then for $R_x = 4.7$ kΩ.

25. Using the measured values of R_1, V_1 and V_x, *calculate the values of R_x for each* "unknown" (*Equation 1.6*) and record in *Table 1-4*.

26. Summarize the data in *Table 1-5*. Ask your instructor to initial the data sheet.

27. Turn the voltage down to 0.0.V. **Turn off** the power supply and DMM. Disconnect the circuit and put your components away. Clean up your work area. Return cables to drawers, wrap them with rubber bands, etc.
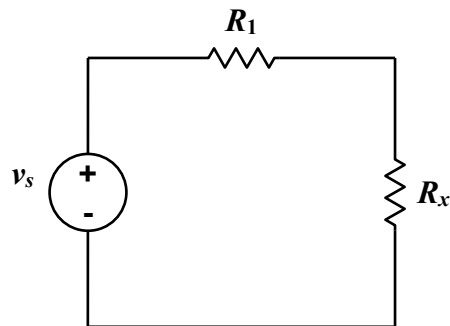

Figure 1.6 Known resistor R_1 in series with "unknown" resistor R_x.

WHAT TO TURN IN

Each student **will turn in an individual and original report.** Each report will be **typed, single-spaced, stapled,** and in the **following order:**

---

1. Answers to the Questions.

On a new sheet of paper:

- In the upper right-hand corner, type:

> your name
> your partner's first name
> Engr. 171
> date lab was completed

- Two lines below the date and centered, type:

> **Experiment 1: Ohm's Law**

- Answer the *Post-Lab Questions*.

- Answer the questions in complete sentences, and in such a way that the reader does not need to see the actual questions to understand what you are writing about. Each answer should stand on its own; some repetition between answers may be necessary.

- Always introduce a table (or a figure) with words (text) before it appears in the document; e.g., "Table 1 is …"; "The voltage-current response…is given in Figure 1…".

- For clarity, number each answer, and leave two blank lines between answers.

- Use **tables** and **Microsoft Equation (Editor)** as appropriate. Number and title each table in your report. Do not just insert a table, figure or equation without some narrative introducing or describing it, its significance, etc.

- The write-up is intended as a much reduced technical "report", or a set of snippets from a report. As such use *3rd person* (the passive voice), and *past tense* when describing *what was done in the experiment*. **Do not** use **"I," "we," "you",** etc.

Present tense may be used when referring to tables, etc., in the report; e.g., "The voltage-current data for … is given in *Table 2*."

2. Two Excel plots of the *v-i* curves for the 470-Ω and 2.7-kΩ resistors. Title and label each figure. Excel plots may be shared within a group.

3. Original *Data Sheets*, completely filled in.

4. One hand-plot (one original hand-plot per student – the one you did in lab), any support calculations, etc. Items 3 and 4 serve as the "Appendix."

Use only one side of each sheet (except for the Data Sheets). Again, leave at least two blank lines between answers.

Do not include a separate cover sheet. A separate cover sheet is not necessary, nor desired.

Again, you do not have to retype the questions, but **answer each question so that a reader (grader) can figure out the topic that you are addressing, even if he/she has not read the question.** Assume your audience is someone else besides the instructor, but who is familiar with the experiment you performed. Write answers in complete sentences.

For example, an answer to Question 5 might be: "5. The 470 Ω and 2.7 kΩ resistors were both within 5% of their nominal value. The 4.7 kΩ was not within tolerance, but was 6.7% above nominal." Do not just write: "5. No. 4.7kΩ was 6.7% off."

Note: For all write-ups, unless specified, each student will turn-in an individual and original report. While data is collected as a group, you interpretation and presentation should be your own.

POST-LAB QUESTIONS

1. Redo **Table 1-5** (in Word) as part of the answer; number it as *Table 1*, and title it appropriately (tables are numbered <u>and</u> titled). Compare the resistances found using each method. Use the resistances measured directly in **Step 2** as the *actual values*. The "%error" of a *calculated (experimental) value* compared to the *actual* (or *accepted*) *value* is:

$$\%error = \frac{\left[\text{calculated}\right] - \left[\text{actual}\right]}{\left[\text{actual}\right]} \times 100\%$$

   Do not just put the table down as the answer, but introduce it with text. For example, start the answer something like this: "The resistance values for each resistor determined by the three methods are given in Table 1. …" followed by a brief discussion on the meaning and/or significance of the data, etc. Then include the table.

2. Using Excel, plot the voltage vs. current data for the 470-Ω resistor from **Table 1-3** using an *x-y scatter plot*.

   The first data point should be (0.0, 0.0).

   From the Excel plot, determine the resistance using a linear curve-fit (an Excel trendline). Force the fit to go through the origin. Properly title the graph, label the axes, and annotate the *v-i* curve (label the slope and its units), etc.

   In the written response, report the resistance using the trendline method, and the *%error* using the trendline method with respect to the directly measured resistance.

   Do not just write "See graph" as the written part of the answer. Rather, start the answer something like: "2. Figure 1 is a graph of the voltage-current response of…"

   <u>Note 1</u>: the curve-fit (trendline) is actually a *fourth* method to determine resistance. The trendline extends the second method by considering several experimental points.

   <u>Note 2</u>: a "voltage vs. current" graph has voltage on the vertical axis and current on the horizontal.

3. Repeat **Question 2** for the 2.7-kΩ resistor.

4. Do the graphs from *Questions 2* and *3* confirm Ohm's Law? *Clearly explain* how they do, or do not.

   Considered together, do **Steps 9** and **13** (**Table 1-2**) confirm Ohm's Law? *Clearly explain* how they do, or do not.

5. The resistors are all rated at **1/4 watt** (the maximum power they can dissipate for some period of time without failing). At any time during the experiment, did any of the resistors exceed their rated power capacity? Explain/justify/verify the answer with calculation(s).

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<u>DATA SHEET, pg. 1/2</u>	Name
Expt. #1 Ohm's Law, Resistance	Lab Partner

Table 1-1 Direct Measurement of Resistor R_x (Step 2). *Do not forget to include units.*

Nominal Value	470 Ω	2.7 kΩ	4.7 kΩ
Measured Value			
%Difference with respect to (w.r.t.) *Nominal Value*			

Table 1-2 Calculated and Measured Current through 4.7 kΩ resistor. Instructor: ☐

Step #. Current	Nominal Voltage (V)	Measured Voltage (V)	Resistance	Current (mA)	Calculated Resistance (kΩ)
7a. Calculated Current	6.00 V		Nominal, 4.7 kΩ calc		
7b. Calculated Current	6.00 V		Measured, from **Table 1-1** calc		
9. Measured Current	6.00 V			meas	
13. Measured Current	12.00 V			meas	

Are the current values in Steps 7a and 7b within 5% of each other?   YES   NO   (circle one)

Are the current values in Steps 7a and 9 within 5% of each other?   YES   NO   (circle one)

Table 1-3 Voltage and Current Measurements: 470 Ω and 2.7 kΩ. *Include units.*

Nominal Voltage across R_x (V)	Measured Voltage and Current			
	470-Ω resistor		2.7-kΩ resistor	
	v_x (V)	i ( )	v_x (V)	i ( )
0.0*	0.00000	0.00000	0.00000	0.00000
2.0				
4.0				
6.0				
8.0				
10.0				
12.0				
Calculated Resistance at 12.0 V	$R_x =$		$R_x =$	

* Include the point (0,0) in the graphs.

DATA SHEET, pg. 2/2	Name
Expt. #1 Ohm's Law, Resistance	Lab Partner

Table 1-4 Measured Voltages and Calculated Resistances for Single Voltmeter Method.

Measured value of known resistor (nominally 2.0 kΩ), R_1 = _____.

Nominal Value, of "Unknown" R_x	v_1: Voltage across known resistor R_1 (V)	v_x: Voltage across "unknown" resistor R_x (V)	Calculated R_x *Include units.*
470 Ω			
2.7 kΩ			
4.7 kΩ			

Summary

Table 1-5 Comparison of Resistance Values for Three Methods. *Include units*.

	Direct Measurement	Calculated from Measurements			
Nominal Value	Ohmmeter	Voltmeter-Ammeter Method (at v = 12.0 V)		Single-Voltmeter Method	
R_x	R_x	R_x Value	% Error*	R_x Value	% Error*
470 Ω					
2.7 kΩ					
4.7 kΩ					

* %Error with respect to ***directly measured value*** (or *actual value*)

$$\%Error = \frac{[\text{calculated}] - [\text{directly measured}]}{[\text{directly measured}]} \times 100\%$$

Instructor Initial:

EXPERIMENT 2

Series and Parallel Resistive Circuits

GOAL

To understand Kirchhoff's Laws and series and parallel resistive circuits.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Measure voltages and currents with the DMM.
- Determine equivalent series and parallel resistances.
- Verify Kirchhoff's Laws.
- Compute power supplied by a source and dissipated by resistors.

BACKGROUND

Read: • Alexander and Sadiku, 3e, 4e or 5e: Ch. 2

Kirchhoff's Laws

In Experiment 1, we studied how *Ohm's Law* relates the voltage drop v across a resistor R to the current i through it: $v = iR$. If a circuit is very simple, Ohm's Law is sufficient to solve for the currents and voltages.

For a general configuration of sources and resistors, **Kirchhoff's Laws** are also needed to solve for the voltage drops across (and thus currents through) each resistor.

Kirchhoff's Laws may be summarized as follows:

Kirchhoff's Voltage Law (KVL)

The algebraic sum of all voltage changes around any **closed loop** (closed path) is zero. Physically, the total voltage drop (e.g., across resistors, and possibly across sources) must equal the total voltage rise (e.g., across voltage sources), around any closed loop.

Recall that voltage is energy per charge, so KVL is an energy concept.

Kirchhoff's Current Law (KCL)

The algebraic sum of all currents entering a **node** is zero. Physically, the total current entering a node must equal the total current leaving the node (conservation of charge).

Ohm's Law and Kirchhoff's Laws are the fundamental ideas of circuit analysis. "Everything" is based on these three laws.

In this experiment, you will investigate resistors configured **in series** and **in parallel**.

Equivalent Series Resistance

Figure 2.1 shows three resistors **in series**. KCL requires that the total current entering each *node* (the joint between components) be equal to the total current leaving that node. With only one loop, all components are in series, and the current must be the same through each component.

KVL requires that the algebraic sum of the voltage changes around a closed loop equal zero. Taking voltage drops as positive, and rises as negative, and moving clockwise around the loop:

$$-v_s + iR_1 + iR_2 + iR_3 = 0 \tag{2.1}$$

$$v_s = i(R_1 + R_2 + R_3) \tag{2.2}$$

Ohm's Law states that resistance is the ratio of the voltage across a resistor to the current through it. Applying this idea to **Equation 2.2**, the **equivalent resistance** of the three resistors **in series** is:

$$R_s = \frac{v_s}{i} = R_1 + R_2 + R_3 \tag{2.3}$$

The three resistors can be replaced with one resistor R_s, and the current will not change; R_s is equivalent to the original three resistors.

For *N* resistors **in series**:

$$R_{s,N} = \sum_{k=1}^{N} R_k \tag{2.4}$$

Note: Variable R_s is often used for the internal resistance of a voltage source v_s. Do no mix these two definitions.
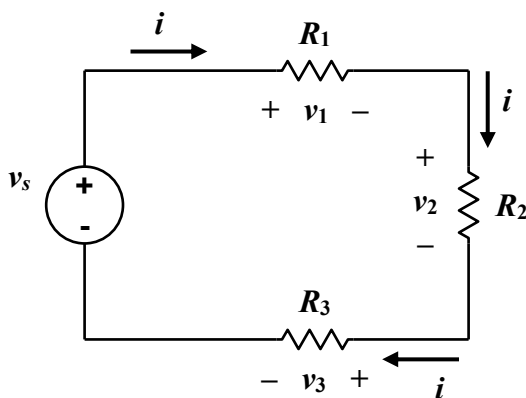
Equivalent Parallel Resistance

Figure 2.2 shows three resistors **in parallel**. KVL around each *closed loop* requires that the voltage drop across each resistor be the same and equal to v_s.

KCL at the upper node requires that the current from the voltage source equal the sum of the currents through the three resistors (the current entering the node equals that leaving the node). Applying KCL, and Ohm's Law ($i = v/R$):

$$i = i_1 + i_2 + i_3 = \frac{v_s}{R_1} + \frac{v_s}{R_2} + \frac{v_s}{R_3}$$
$$= v_s\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \tag{2.5}$$

The **equivalent resistance** of the three resistors **in parallel** is:

$$R_p = \frac{v_s}{i} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)^{-1} \tag{2.6}$$

For *N* resistors **in parallel**:

$$R_{p,N} = \sum_{k=1}^{N}\left[\frac{1}{R_k}\right]^{-1} \tag{2.7}$$

For the special case of two resistors in parallel, the *equivalent resistance* is:

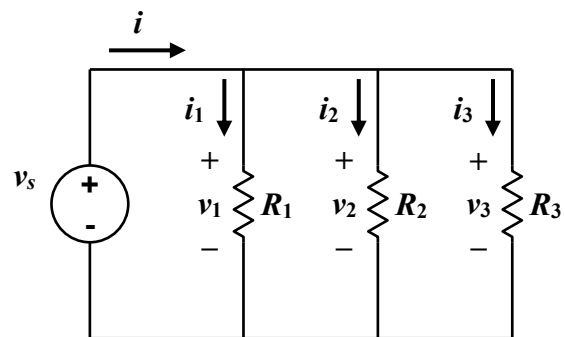$$R_{p,2} = \frac{R_1 R_2}{R_1 + R_2} \tag{2.8}$$

Figure 2.1

Figure 2.2

MATERIALS AND EQUIPMENT

1   470 ohm, 1/4 W, 5% resistor
1   680 ohm, 1/4 W, 5% resistor
1   1.0 kΩ, 1/4 W, 5% resistor
1   3.0 kΩ, 1/4 W, 5% resistor
1   DC Power Supply
1   Digital Multimeter (DMM)
1   proto-board
-    various cables and test leads (banana plug-alligator clip cables; power supply switch)
-    various wires (jumpers)

PROCEDURE, SERIES CIRCUIT

1. Select resistors 680 Ω, 1.0 kΩ and 3.0 kΩ from your lab kit. Using the DMM, measure them and record their actual values in *Table 2-1*. *Are all resistor values within tolerance?*

2. With the power supply **not connected** to the circuit, set it up so that voltage will be supplied by the MASTER supply. Set the voltage to zero. Set the current limit control knob to no more than "10 o'clock". See "Setting the Current Limit" on page F.6 of *Appendix F*.

3. Construct only the resistive part of the circuit shown in *Figure 2.3a* with $R_1 = 680\ \Omega$, $R_2 = 1.0\ k\Omega$, $R_3 = 3.0\ k\Omega$. Make sure you connect the resistors in the correct order. Do not connect the power supply yet.

4. *Using the measured resistances, calculate the equivalent series resistance* $R_{s,c} = \Sigma R_k$. Record in *Table 2-1*.

5. Connect a red lead to the positive terminal of the power supply, and a black lead to the negative terminal. Ground the negative terminal of the supply. Connect the red lead to Node *a* of the circuit, and the black lead to Node *b* (*Figure 2.3b*).

Place the DMM in voltage mode, across the voltage source (*Figure 2.3b*).

6. **Have your instructor verify your circuit** *before* **you energize it (turn on the power)**. Ask your instructor to initial the box in *Table 2-1*.
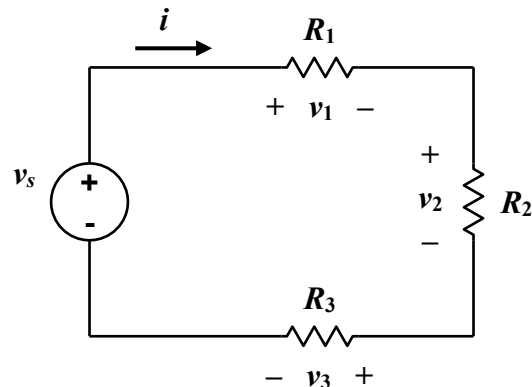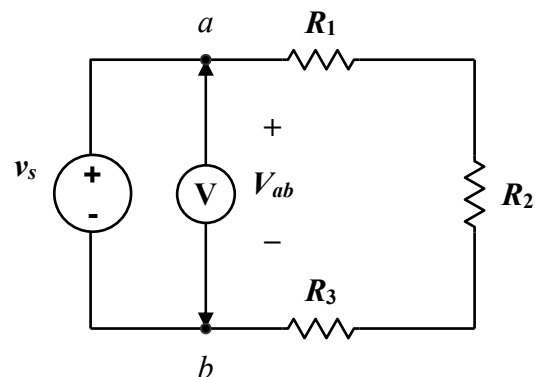

Figure 2.3a

Figure 2.3b

7. **Turn on** the power supply. Increase the supply voltage so 12.0 volts is measured by the DMM (in DC voltage mode) between Nodes *a* and *b* ($v_s = V_{ab} = 12.0$ V, **Figure 2.3b**). Record the measured value as $V_{ab,m}$ at the bottom of **Table 2-1**.

If, as you increase the voltage, the "C.C." light on the DC power supply lights up, turn the power supply off and notify the instructor. You may have a **short** in the system, drawing an excessive amount of current from the supply. Or the Current Limit may be set to low.

8. Measure the voltage v_1 across resistor R_1 (**Figure 2.3c**). Record as $v_{1,m}$ in **Table 2-1**. Repeat for voltages v_2 and v_3.

9. *Using the measured voltage across each resistor, and the measured resistances, calculate the current that should go through each resistor* (e.g., $i_{1,c}$ goes through R_1, etc.). Record them in **Table 2-1.**

10. *Using the measured voltages, calculate the total voltage drop Σv_k across the resistors.* Record as $(\Sigma v_k)_c$ in **Table 2-1.**

11. Measure the current i_1 through R_1 (**Figure 2.3d**). Record as $i_{1,m}$ in **Table 2-1**. Do not forget to reconfigure the circuit and DMM to measure current. Place the ammeter in front of R_1.

Repeat for currents i_2 and i_3 by placing the ammeter in the loop before R_2 and then before R_3.

12. **Turn off** the power supply and disconnect it from the circuit.

13. Measure the resistance R_s between Nodes *a* and *b* (**Figure 2.3e**). Record the value as $R_{s,m}$ at the bottom left of **Table 2-1.**

14. Complete **Tables 2-2** and **2-3** from the measured values in **Table 2-1**.

The "Pre-lab Calculation Values" are calculations performed using the *nominal* values of resistances and the voltage source.
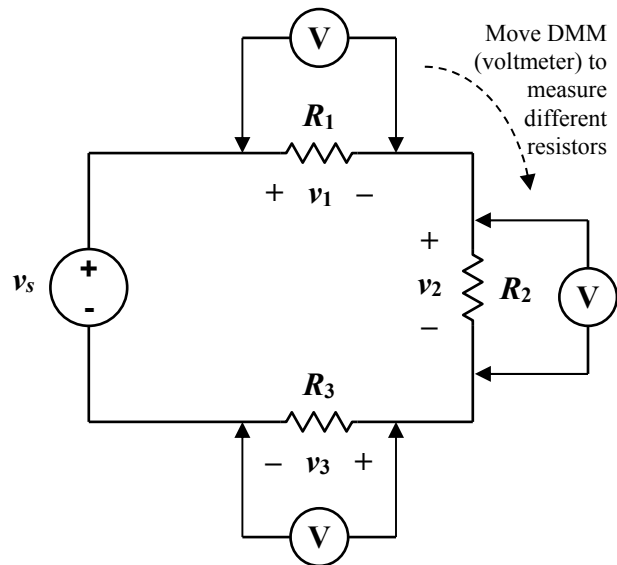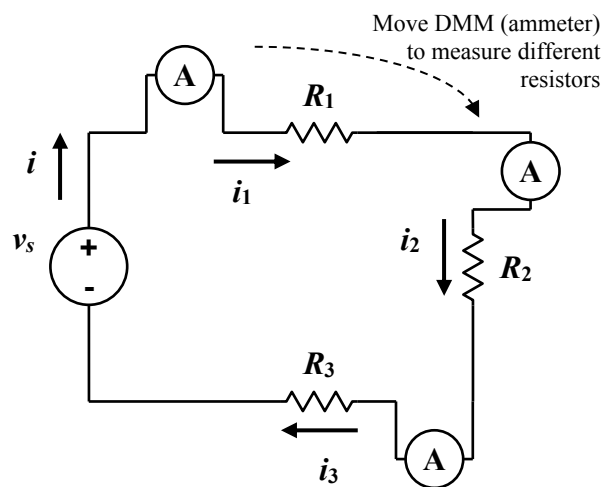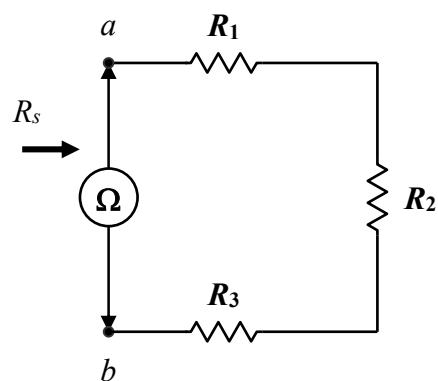

Figure 2.3c

Figure 2.3d

Figure 2.3e

PROCEDURE, PARALLEL CIRCUIT

Parallel Circuit – Three Resistors

15. With the power supply **not connected** to the circuit, set it up so that voltage will be supplied by the MASTER supply. Set the voltage to zero. Set the current limit to no more than "10 o'clock".

    Turn off the power supply.

16. Construct the circuit shown in *Figure 2.4a* with $R_o = 470\ \Omega$, $R_1 = 680\ \Omega$, $R_2 = 1.0\ k\Omega$ and $R_3 = 3.0\ k\Omega$. Resistor R_o is used to control current; you do not need an exact measurement, but use the 470-Ω resistor.

17. Transfer the measured resistance values from *Table 2-1* to *Table 2-4*. *Using the measured resistances, calculate the equivalent parallel resistance $R_{p,c}$. Record in* ***Table 2-4.***

18. **Turn on** the power supply. Increase the supply voltage so that the voltage across Nodes c and d is $v = V_{cd} = 12.0$ V (as measured by the DMM). Record the measured value as $V_{cd,m}$ at the bottom of the rightmost column of *Table 2-4*.

    CAUTION: v_s is <u>not</u> 12 V. The 12.0 V should be measured across the three parallel resistors. v_s will be should be more than 12 V.

19. Reconfigure the circuit and DMM to measure the current in each resistor. Measure the current through the voltage source, i, and the current through each resistor i_k (i_1, i_2 and i_3). Record the values in *Table 2-4* as i_m, $i_{1,m}$, $i_{2,m}$ and $i_{3,m}$.

    CAUTION: make sure the circuit is still connected so that the three parallel resistors are still part of the circuit.

20. *Using the measured currents, calculate the total current Σi_k through the resistors and record as $(\Sigma i_k)_c$ in* ***Table 2-4.***

21. *Using the measured currents and resistances, calculate the voltage drop across each resistor (e.g., $v_{1,c}$) and record in* ***Table 2-4.***

22. Measure the voltages across each resistor (e.g., $v_{1,m}$) and record in *Table 2-4*.

23. **Turn off** the power supply and disconnect it from the circuit

24. Measure the resistance R_p between Nodes c and d (*Figure 2.4b*). Record as $R_{p,m}$ at the bottom left of *Table 2-4*.

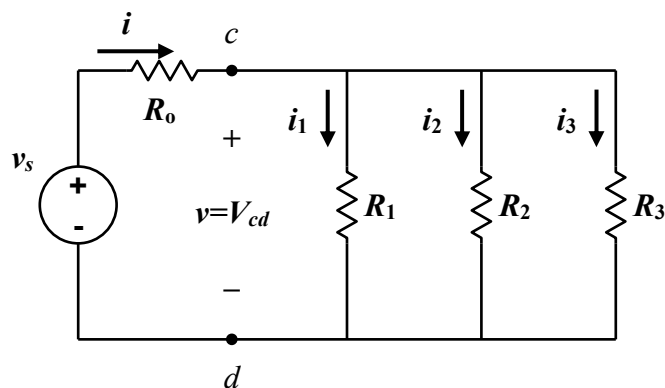25. Complete *Tables 2-5* and *2-6* from the measured values in *Table 2-4*.

Figure 2.4a
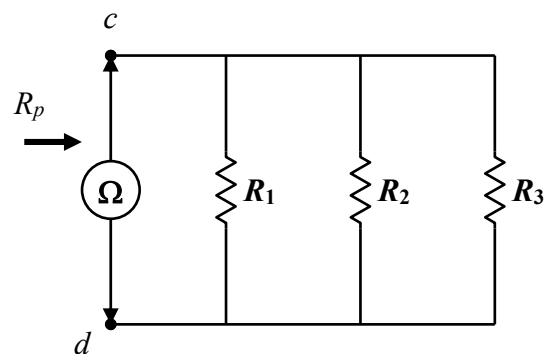
Figure 2.4b

Parallel Circuit – Two Resistors

26. Construct the circuit shown in *Figure 2.5* with $R_o = 470\ \Omega,\ \ R_1 = 680\ \Omega,\ \ \text{and}\ \ R_2 = 1.0\ k\Omega.$ With the power supply turned off and set to zero volts, connect it to the circuit.

27. Transfer the measured resistance values from *Table 2-1* to *Table 2-7*. *Calculate the equivalent resistance $R_{p,c}$*. Record in *Table 2-7.*

28. **Turn on** the power supply. Increase the supply voltage so that the voltage across Nodes *e* and *f* is $v = V_{ef} = 12.0$ V. Record the measured value as $V_{ef,m}$ at the bottom of the rightmost column of *Table 2-7*.
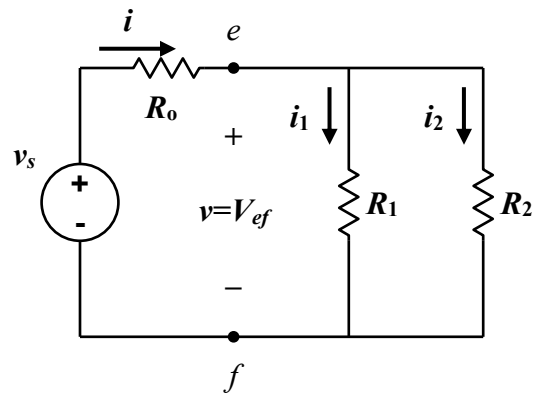
    CAUTION: v_s is not 12 V. The 12.0 V should be measured across the two parallel resistors. v_s is should be more than 12 V

29. Measure the current through the voltage source, *i*, and the current through each resistor i_k (i_1 and i_2). Record the values in *Table 2-7* as i_m, $i_{1,m}$ and $i_{2,m}$.

30. *Using the measured resistor currents, calculate the total current Σi_k through the resistors* and record as $(\Sigma i_k)_c$ in *Table 2-7.*

31. *Using the measured currents and resistances, calculate the voltage drop across each resistor* (e.g., $v_{1,c}$) and record in *Table 2-7*.

32. Measure the voltages across each resistor (e.g., $v_{1,m}$) and record them in *Table 2-7*.

33. **Turn off** the power supply and disconnect it from the circuit

34. Measure the resistance R_p between Nodes *e* and *f*. Record as $R_{p,m}$ at the bottom left of *Table 2-7*.

35. Disconnect the circuit and put the components away. Turn the power supply to 0.0 V, and turn off the power supply and DMM. Clean up your work area. Wrap cables with rubber bands, return cables to drawers, etc.

Figure 2.5

WHAT TO TURN IN

In order and **stapled**: (1) *Data Sheets*, (2) answers to the *Post-Lab Questions*, and (3) **support calculations and other appendix materials**. The Data Sheets should be first (your name is on them).

Use this sheet to answer the questions. Answers do not need to be typed.
<u>**Answer in complete sentences**</u>. Practice technical writing, e.g., use **3rd person**; use **past tense** when describing *what was done* in the experiment). **Do not use "I," "we," "us," etc., in your answers**.

POST-LAB QUESTIONS (answer on this sheet). Answer in complete sentences.

Series Circuit Questions

1. Complete *Tables 2-1, 2-2* and *2-3*, if necessary. Append any support calculations.

2. Were the resistors within tolerance (within 5% of their nominal values)? If (and only if) any resistor was not within tolerance, indicate which one, and its percent difference with respect to the nominal value.

3. Should it be expected that the sum of the voltage drops across the three resistors equals 12.0 V? *Explain* physically why or why not.

4. Referring to *Table 2-2*, are the <u>measured values</u> of the *equivalent resistance* and of the *voltages* **across each resistor** all within 5% of their nominal values (with respect to the pre-lab calculations)? If any quantity is out of tolerance, indicate which one(s) and the percent difference **with respect to the nominal value(s)**. If (and only if) a quantity is more than 5% off its nominal value, can the difference be explained? This concept/calculation should give you a small idea of the uncertainty that designers must deal with. Continue on the next page if necessary.

4., *continued, if necessary.*

5. During the experiment, did any resistor in the series circuit exceed its maximum power rating (1/4 watts). If so, which one? Justify your answer using the power calculations in *Table 2-3*.

6. How much power is being supplied to the circuit by the voltage source?

7. What is the total power dissipated by the three resistors? Show the calculation here.

8. Should the answers to **Questions #6** and **#7** be the same? Explain physically why or why not.

Parallel Circuit Questions (3 resistors)

9. Complete *Tables 2-4*, *2-5*, and *2-6*, if necessary.

10. Should the sum of the currents through the three resistors equal the supply current?
    Explain physically why or why not?

11. Is the total power supplied by the source equal to that dissipated by the resistors?
    Justify your answer using the power calculations of *Table 2-6*.

12. During the experiment, did any resistor in the parallel circuit exceed its maximum power rating
    (1/4 watts). If so, which one? Justify your answer using the power calculations in *Table 2-6*.

Parallel Circuit Questions (2 resistors)

13. Complete **Table 2-7**, if necessary.

14. When R_3 was removed to create the 2-resistor circuit, does the current from the voltage supply *increase*, *decrease*, or *stay the same*? Does this circuit response make sense? Explain physically why or why not.

15. When R_3 was removed to create the 2-resistor circuit, does the current in resistor R_1, i_1, *increase*, *decrease*, or *stay the same*? Explain physically why.

Miscellaneous Question

16. *Circle one*. In parallel-only circuits, such as the one studied in this experiment (with a constant voltage source) adding a resistor in parallel:

    (a) increases the equivalent resistance and increases the source current.
    (b) increases the equivalent resistance and decreases the source current.
    (c) decreases the equivalent resistance and increases the source current.
    (d) decreases the equivalent resistance and decreases the source current.
    (e) does not affect the equivalent resistance, nor does it affect the source current.
    (f) none of the above.

    Explain your answer.

DATA SHEET, pg. 1/3	Name
Expt. #2a 3-Resistor Series Circuit	Lab Partner

Table 2-1 Resistances, Voltages and Currents for 3-Resistor Series Circuit. *Do not forget units.*

subscripts: *m* : measured; *c* : calculated from measured values | Instructor:

Nominal Resistance	Measured Resistance	Measured Voltage (V)	Calculated Current (mA) (use measured v & R)	Measured Current (mA)
$R_1 = 680\ \Omega$		$v_{1,m} =$	$i_{1,c} =$	$i_{1,m} =$
$R_2 = 1.0\ k\Omega$		$v_{2,m} =$	$i_{2,c} =$	$i_{2,m} =$
$R_3 = 3.0\ k\Omega$		$v_{3,m} =$	$i_{3,c} =$	$i_{3,m} =$
Calculated Equivalent Resistance (from measured resistances R_i) $R_{s,c} = \Sigma R_k =$		**Calculated Total Voltage** (from measurements $v_{k,m}$) $(\Sigma v_k)_c =$		
Measured Equivalent Resistance $R_{s,m} =$		**Measured Total Voltage** (Source Voltage) $v_s = V_{ab,m} =$		

Table 2-2 Equivalent Resistance and Voltage Drop across each Resistor. *Do not forget units.*

Quantity	Pre-lab Calculations (use nominal values)	In-Lab Calculations (ΣR_i)	Direct Measurements	% Difference* (w.r.t. nominal)
Equivalent Resistance				
Voltage, v_1				
Voltage, v_2				
Voltage, v_3				

* With respect to nominal value. $(\%\ \text{difference w.r.t. nominal}) = \dfrac{(\text{measured value}) - (\text{nominal value})}{(\text{nominal value})} \times 100\%$

Table 2-3 Power Supplied or Dissipated by Components
(for *Calculated Power*, use the sign convention: "–" if power is supplied, "+" if it is absorbed)

Component	Measured Resistance (Ω)	Measured Voltage (V)	Measured Current (mA)	Calculated Power (mW)
Voltage Source				
R_1				
R_2				
R_3				

DATA SHEET, pg. 2/3	Name
Expt. #2b 3-Resistor Parallel Circuit	Lab Partner

Table 2-4 Resistances, Voltages and Currents for 3-Resistor Parallel Circuit. Do not forget units.

Nominal Resistance	Measured Resistance	Measured Current (mA)	Calculated Voltage (V) (use measured i & R)	Measured Voltage (V)
$R_1 = 680\ \Omega$		$i_{1,m} =$	$v_{1,c} =$	$v_{1,m} =$
$R_2 = 1.0\ k\Omega$		$i_{2,m} =$	$v_{2,c} =$	$v_{2,m} =$
$R_3 = 3.0\ k\Omega$		$i_{3,m} =$	$v_{3,c} =$	$v_{3,m} =$
Calculated Equivalent Resistance (from measured resistances R_i) $R_{p,c} =$	**Calculated Total Current** (from measurements $i_{k,m}$) $(\Sigma i_k)_c =$			$V_{cd,m} =$
Measured Equivalent Resistance $R_{p,m} =$	**Measured Total Current** (Source Current) $i_m =$			

Table 2-5 Equivalent Resistance and Current through each Resistor.

Quantity	Pre-lab Calculations (use nominal values)	In-Lab Calculations ($R_{p,c}$)	Direct Measurements	% Difference* (w.r.t. nominal)
Equivalent Resistance				
Total Current i				
Current, i_1				
Current, i_2				
Current, i_3				

* With respect to nominal value. $\left(\% \text{ difference w.r.t. nominal}\right) = \dfrac{\left(\text{measured value}\right) - \left(\text{nominal value}\right)}{\left(\text{nominal value}\right)} \times 100\%$

Table 2-6 Power Supplied or Dissipated by Components
(for *Calculated Power*, use the sign convention: "–" if power is supplied, "+" if it is absorbed)

Component	Measured Resistance (Ω)	Measured Voltage (V)	Measured Current (mA)	Calculated Power (mW)
Voltage Source				
R_1				
R_2				
R_3				

DATA SHEET, pg. 3/3	Name
Expt. #2c 2-Resistor Parallel Circuit	Lab Partner

Table 2-7 Resistances, Voltages and Currents for 2-Resistor Parallel Circuit.

Nominal Resistance	Measured Resistance	Measured Current (mA)	Calculated Voltage (V) (use measured i & R)	Measured Voltage (V)
$R_1 = 680\ \Omega$		$i_{1,m} =$	$v_{1,c} =$	$v_{1,m} =$
$R_2 = 1.0\ k\Omega$		$i_{2,m} =$	$v_{2,c} =$	$v_{2,m} =$
Calculated Equivalent Resistance (from measured resistances R_i) $R_{p,c} =$	**Calculated Total Current** (from measurements $i_{k,m}$) $(\Sigma i_k)_c =$			$V_{ef,m} =$
Measured Equivalent Resistance $R_{p,m} =$	**Measured Total Current** (Source Current) $i_m =$			

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EXPERIMENT 3

Superposition

GOAL

To understand the Principle of Superposition and its application in circuit analysis.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Determine the equivalent resistances of combination series/parallel circuits.
- Verify the Principle of Superposition for linear circuits.

BACKGROUND

Read: • Alexander and Sadiku, 3e, 4e or 5e: Ch. 4.3

Method of Superposition

Linear circuits with two or more independent sources (voltage and/or current sources) may be solved using standard circuit analysis techniques. However, solving such a circuit can be difficult. Also, when considering more than one source (input), the effect of an individual source on a single output is lost.

A powerful strategy used to solve a linear system with several inputs is the **Method of Superposition**. The circuit is analyzed with **only** one independent source turned on, and the rest of the independent sources *turned off* or *killed*. *Turned off* or *killed* means voltage sources are short-circuited (to ensure $v_s = 0$), and current sources are open-circuited ($i_s = 0$). A circuit analysis is performed with each independent source acting alone. For a system with three independent sources, three different single-source problems must be solved. Then, the solutions to the individual problems are combined – **superimposed** – to get the total solution.

The advantage of the **Method of Superposition** is that single-source circuits are relatively easy to solve. Another – perhaps more important – advantage is that the effect of each source can be studied alone. A disadvantage is that more total work may be involved since more (but usually easier) problems need to be solved.

It should be emphasized that the **Method of Superposition** is only applicable to *linear systems*. Fortunately, many engineering systems are linear (or nearly so). The circuits in this course are linear. For resistors, voltage is linearly proportional to current ($v = iR$). The resistance is taken as constant over all ranges of current and temperatures (not exactly true, but a very good approximation). You will learn later in the term that voltages across capacitors and inductors are taken as *linearly* proportional to the integral and derivative of the current, respectively.

Mathematically, superposition implies that for a function $f(x)$:

$$f(a+b) = f(a) + f(b) \qquad (3.1)$$

where a and b are two valid input values for $f(x)$. The solution for input $[a + b]$ is equal to the sum of the individual solutions for inputs a and b each acting alone.

If the function is *linear*, superposition is valid. Consider $g(x) = 2x$:

$$g(a+b) = 2(a+b) = 2a + 2b$$
$$g(a) + g(b) = 2a + 2b \qquad (3.2)$$
$$\therefore g(a+b) = g(a) + g(b)$$

If the function is *non-linear*, superposition is not valid. Consider $h(x) = x^2$:

$$h(a+b) = (a+b)^2 = a^2 + 2ab + b^2$$
$$h(a) + h(b) = a^2 + b^2 \qquad (3.3)$$
$$\therefore h(a+b) \neq h(a) + h(b)$$

In this lab, you will verify the ***Principle of Superposition*** using the circuit shown in *Figure 3.1*.

To distinguish when both sources (inputs) v_1 and v_2, are acting, and when they are acting alone, the following convention is used in this experiment when referring to V_x and i_x measurements and values:

- v_1 and v_2 acting: $\quad V_x, i_x$
- v_1 acting alone: $\quad V_{x'}, i_{x'}$
- v_2 acting alone: $\quad V_{x''}, i_{x''}$

When referring to the calculated sum of the values of $V_{x'}$ and $V_{x''}$, and that of $i_{x'}$ and $i_{x''}$, the summation symbol (Σ) is used:

- $\Sigma V_x = \Sigma V_{xk} = V_{x'} + V_{x''}$
- $\Sigma i_x = \Sigma i_{xk} = i_{x'} + i_{x''}$

Subscript k is used as an (implied) counting variable.

CAUTION: Be consistent throughout the experiment when making measurements. **Always measure voltage V_x using the same polarity**. **Always measure current i_x in the same direction (negative values are important)**.

In *Figure 3.1*, the current i_x is assumed to flow to the right; positive measurements mean current flows to the right; negative measurements mean current flows to the left.

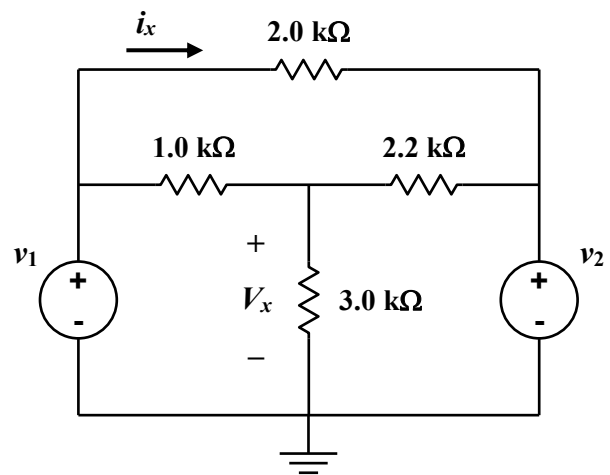**CAUTION**: i_x is NOT the current leaving the positive terminal of v_1.

Figure 3.1

MATERIALS and EQUIPMENT

- 1   1.0 kΩ, 1/4 W, 5% resistor
- 1   2.0 kΩ, 1/4 W, 5% resistor
- 1   2.2 kΩ, 1/4 W, 5% resistor
- 1   3.0 kΩ, 1/4 W, 5% resistor
- 1   DC Power Supply (use both MASTER and SLAVE supplies, **INDEPendent mode**)
- 1   DMM
- 1   proto-board
- -   various cables and test leads (banana plug-alligator clip cables; power supply switch; etc.)
- -   various wires (jumpers)

PROCEDURE

1. Using the DMM, measure the resistors and record their actual values in **Table 3-1**. Make sure the resistors are all within tolerance.

2. With the power supply **not connected** to the circuit, set it up so that it is in **INDEPendant mode**. Use the **SLAVE** (left) supply for voltage v_1, and the **MASTER** (right) supply for voltage v_2 (**Figure 3.1**). Set both voltages to zero. Set the **current limit** of both supplies to "10 o'clock". **Turn off** the power supply.

CASE I: $v_1 = 16.0$ V, $v_2 = 12.0$ V

CASE Ia: v_1 **only** ($v_2 = 0$)

3. Construct the circuit shown in **Figure 3.2**. Use the **SLAVE** supply as v_1. **Ground** the bottom node.

   Question: How is the requirement that $v_2 = 0$ put into practice?

4. **Turn on** the power supply. Increase the SLAVE voltage to $v_1 = +16.0$ V. Measure v_1 with the DMM. Record the measured value in **Table 3-2**.

5. Measure the voltage $V_{x'}$ and the current $i_{x'}$ as shown in **Figure 3.2**. Record the values in **Table 3-2**, _Row Ia_.

   Make sure the DMM leads align with the assumed polarities of the voltage and current (be consistent with measurement polarity throughout the experiment).

6. Do not turn down the voltage, but **turn off** the power supply and disconnect it (v_1) from the circuit.

7. Measure the resistance that is seen by voltage source v_1 during the test; i.e., the resistance between the source's (+) and (-) terminals. Record in **Table 3-4**.
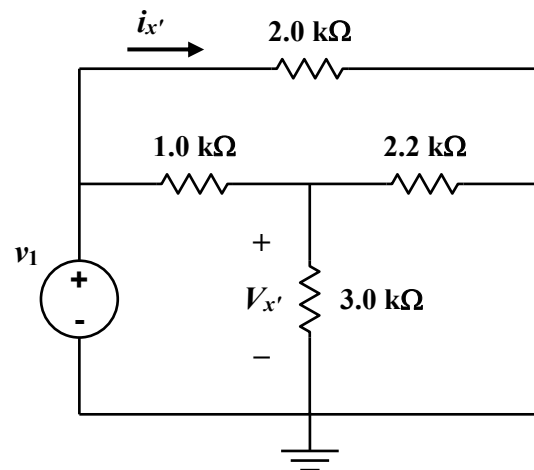
   Hint: When measuring the resistance presented to the voltage source, make sure to remove the voltage source (as instructed in **Step 6**) – otherwise you will include the effect of the voltage source's resistance in the measurement. Just replace the source with the ohmmeter.

Figure 3.2

CASE Ib: v_2 only $(v_1 = 0)$

8. Construct the circuit shown in *Figure 3.3*. Use the **MASTER** supply as v_2.

9. **Turn on** the power supply. Increase the MASTER voltage to +12.0 V. Measure v_2 with the DMM. Record in *Table 3-2, Row Ib*.

10. Measure the voltage $V_{x''}$ and the current $i_{x''}$. Make sure the DMM leads align with the assumed polarities. Record the values in *Table 3-2*.

11. Do not turn down the voltage, but **turn off** the power supply and disconnect it from the circuit.

12. Measure the resistance seen by voltage source v_2. Record it in *Table 3-4*.

13. *Calculate the sums of the voltages and the currents* from **Step 5** and **10**. In other words, **superimpose** the individual solutions. Record in *Table 3-2, Row Ia+Ib* as ΣV_{xk} and Σi_{ik} (k is the implied counting variable).

CASE Ic: v_1 and v_2 acting together

14. Construct the circuit shown in *Figure 3.1*. Use the **SLAVE** supply as v_1 and the **MASTER** supply as v_2.

15. **Turn on** the power supply. Measure v_1 and v_2 with the DMM to insure they are still at the correct values (16.0 V, 12.0 V). Record the values in the bottom row of *Table 3-2*.

16. Measure the voltage V_x and the current i_x. Record the values in *Table 3-2, Row Ic*.

17. **Turn off** the power supply.

Case II: $v_1 = 8.0$ V, $v_2 = -12.0$ V

18. Repeat **Steps 3** through **17** for:

    $v_1 = +8.0$ V and $v_2 = -12.0$ V.

    Make sure you correctly apply the negative voltage with respect to ground (see 'Different Positive and Negative Voltages with Separate Common Ground' **in *Appendix F*,**).

    Record measured values in *Table 3-3*.

It is not necessary to repeat the resistance measurements (**Steps 7** and **12**) for Case II.

Resistance Measurement

19. Construct the resistive network shown in *Figure 3.4*. Measure the resistance across the 2.2-kΩ resistor as shown. Record in *Table 3-4*.

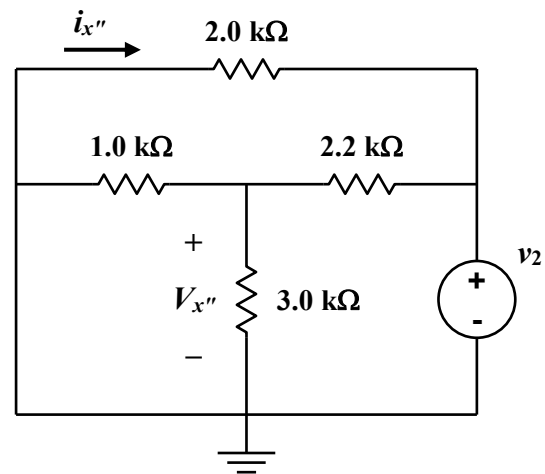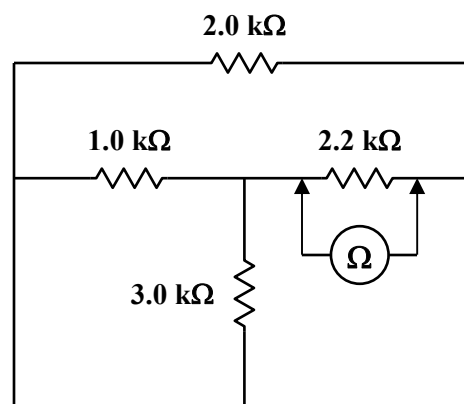20. Turn the power supply down to 0.0V, turn off the power supply and clean up.

Figure 3.3

Figure 3.4

WHAT TO TURN IN

Each student **will turn in an individual and original report.** Each report will be **typed, single-spaced, stapled,** and in the **following order:**

1. Answers to the Questions.

On a new sheet:
- In the upper right-hand corner, type:

> your name
> your partner's first name
> Engr. 171
> date lab was completed

- Two lines below the date and centered, type:

Experiment 3: Superposition

- Answer the *Post-Lab Questions*.

- Answer the questions in complete sentences, and in such a way that the reader does not need to see the actual questions to understand what you are writing about. Each answer should stand on its own; some repetition between answers may be necessary.

- Always introduce a table (or a figure) with words (text) before it appears in the document; e.g., "Table 1 is …"; "The voltage-current response…is given in Figure 1…".

- For clarity, number each answer, and leave two blank lines between answers.

- Use **tables** and **Microsoft Equation (Editor)** as appropriate. Number and title each table in your report. Do not just insert a table, figure or equation without some narrative introducing or describing it, its significance, etc.

- The write-up is intended as a much reduced technical "report", or a set of snippets from a report. As such use *3rd person* (the passive voice), and *past tense* when describing *what was done in the experiment*. **Do not use "I," "we," "you", etc.**

Present tense may be used when referring to tables, etc., in the report; e.g., "The voltage-current data for … is given in *Table 2*."

2. Original *Data Sheets*, <u>completely</u> filled in.

3. Any hand-plots, support calculations, etc. Items 2 and 3 serve as the "**Appendix**."

Use only <u>one side</u> of each sheet (except for the Data Sheets). Again, leave at least two blank lines between answers.

Do not include a separate cover sheet. A separate cover sheet is not necessary, nor desired.

Again, you do not have to retype the questions, but **answer each question so that a reader (grader) can figure out the topic that you are addressing, even if he/she has not read the question.** Assume your audience is someone else besides the instructor, but who is familiar with the experiment you performed. Write answers in complete sentences.

POST-LAB QUESTIONS

Questions on next page.

POST-LAB QUESTIONS

1. Using the **pre-lab calculations** (using the nominal resistances and voltages), and the **measured data** from *Table 3-2* (**Case I**) and *Table 3-3* (**Case II**), set up **two tables** to compare your *expected* and *actual values* of $V_{x'}$, $V_{x''}$ and V_x (both sources acting together), and $i_{x'}$, $i_{x''}$ and i_x. Prepare one table for each case studied in the experiment.

   Each table should have three data columns: *Theoretical Values* (i.e., pre-lab values); *Measured Values*; and *%difference*. There should be six rows, one each for: $V_{x'}$, $V_{x''}$, V_x, $i_{x'}$, $i_{x''}$ and i_x. Calculate the %difference *with respect to the pre-lab (nominal) calculations*.

   Introduce the tables with text before they appear; e.g., "Table 1 is…". **Number** and **title** each table.

   In the narrative, comment on how well the measured values agree with predictions (the key point). Explain in words the significance of the data.

   Note: **Question 1 is <u>not</u> about superposition**. The values to be discussed are the outputs for when v_1 only is acting ($V_{x'}$, $i_{x'}$), when v_2 only is acting ($V_{x''}$, $i_{x''}$), and when both sources are acting at the same time (outputs V_x, i_x).

   Hint: Since the text should not be very long, leave it all together in a paragraph or two above both tables. A couple of lines of text between tables can easily be overlooked by the reader.

2. From the **measurements** (*Tables 3-2* and *3-3*), demonstrate that the Principle of Superposition worked for both V_x and i_x for both cases:

   - **Case I**: $v_1 = 16.0$ V; $v_2 = 12.0$ V
   - **Case II**: $v_1 = 8.0$ V; $v_2 = -12.0$ V

   What is the *%error* using superposition for each quantity in each case? Calculate the error as follows:

$$\frac{\left[\sum(\text{Sources acting individually})\right]-\left[\text{Sources acting together}\right]}{\left[\text{Sources acting together}\right]}$$

Prob. 2, cont.,

   A table for each type of output should be used to display the information being asked for.

   The first table should be for the voltages. There should be two rows, for Case I and Case II. Data columns should be: $V_{x'}$, $V_{x''}$, ΣV_x (superposition of $V_{x'}$ and $V_{x''}$), V_x (when both sources acting together) and *%error* of the superimposed solution with respect to when both sources are acting together. Recall that $V_{x'}$, $V_{x''}$ and V_x are measured values.

   The second table should be for currents.

   Again, introduce the table(s) with text; explain what the tables mean.

3. Use a typed table to present the reduced data in this question; calculations can go in the Appendix.

   Using the *measured resistances* (**Table 3-1**), **calculate** the resistance seen by v_1 in *Figure 3.2*. Does the calculation agree with the measurement in **Step 7 (*Table 3-4*)**? What is the *%difference* of the calculated value with respect to the directly measured value?

   Repeat for the measured resistance in **Step 12**.

   Hint: You might want to redraw the resistive networks to better see the circuit for your analysis.

4. In lab, the circuit in *Figure 3.4* was built, and then an ohmmeter was placed across the 2.2-kΩ resistor. Explain why the value measured was not 2.2 kΩ **(Step 19, *Table 3-4*)**? Make a sketch to better illustrate the actual resistance being measured. Using the actual resistor values, *calculate* the value that should have been measured.

   Make sure to report the measured and calculate values (do not just say "they are different" like past students have).

   What lesson about *resistance measurements* is being illustrated here?

DATA SHEET, pg. 1/2	Name
Expt. #3 Superposition	Lab Partner

Table 3-1 Resistor Values.

Nominal Value	Measured Resistance (kΩ)	%Difference (with respect to nominal)	Within Tolerance?
1.0 kΩ			
2.0 kΩ			
2.2 kΩ			
3.0 kΩ			

Table 3-2 Measured Voltage V_x and Current i_x for Case I: v_1 = +16.0 V, v_2 = +12.0 V.

Case	Voltage Source	Measured Supply Voltage (V)	Measured Voltage (V)	Measured Current (mA)
Ia	v_1 = 16.0 V; v_2 = 0.0 V	v_1 =	$V_{x'}$ =	$i_{x'}$ =
Ib	v_1 = 0.0 V; v_2 = 12.0 V	v_2 =	$V_{x''}$ =	$i_{x''}$ =
Ia + Ib	**Sum of individual measurements** (*calculate*)		ΣV_{xk} =	Σi_{xk} =
Ic	**Supply voltages acting together** v_1 = 16.0 V; v_2 = 12.0 V	v_1 = v_2 =	V_x =	i_x =

Table 3-3 Measured Voltage V_x and Current i_x for Case II: v_1 = 8.0 V, v_2 = –12.0 V.

Case	Voltage Source	Measured Supply Voltage (V)	Measured Voltage (V)	Measured Current (mA)
IIa	v_1 = 8.0 V; v_2 = 0.0 V	v_1 =	$V_{x'}$ =	$i_{x'}$ =
IIb	v_1 = 0.0 V; v_2 = –12.0 V	v_2 =	$V_{x''}$ =	$i_{x''}$ =
IIa + IIb	**Sum of individual measurements** (*calculate*)		ΣV_{xk} =	Σi_{xk} =
IIc	**Supply voltages acting together** v_1 = 8.0 V; v_2 = –12.0 V	v_1 = v_2 =	V_x =	i_x =

DATA SHEET, pg. 2/2	Name	
Expt. #3 Superposition	Lab Partner	

Table 3-4 Circuit Resistance Measurements.

Resistance	Step	Measured Resistance (Ω)
Resistance seen by v_1 (in v_1-only circuit)	7	
Resistance seen by v_2 (in v_2-only circuit)	12	
Resistance measured across the 2.2-kΩ resistor	19	

EXPERIMENT 4

Thevenin Equivalent Circuits

1/09/17

GOAL

To understand Thevenin (and Norton) Equivalent Circuits.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Reduce a complicated circuit to its Thevenin and Norton equivalents.
- Verify Thevenin Equivalent circuits experimentally.
- Determine the load resistance to cause maximum power output of a circuit.

BACKGROUND

Read: • Alexander and Sadiku, 3e, 4e or 5e: Sections 4.5–4.8

Note: The present discussion is limited to resistive circuits only. For this discussion, a "complex circuit" is composed of one for more sources (voltage, current, independent, dependent) and several resistors. Here, "complex" does not refer to the mathematics used to analyze AC circuits.

It is often necessary to calculate currents and/or voltages that a complex circuit supplies to different **loads** (resistances) that are connected to that circuit. A *load* is a component (or separate circuit) that is to be powered by the complex circuit, e.g., a television is a *load* on a house's electrical system.

If the complex circuit is linear (composed of linear sources and linear resistors), then – as far as the load is concerned – the complex circuit can be replaced with a simpler circuit, consisting only of a single voltage source *in series* with a single resistor. This simpler circuit is the **Thevenin Equivalent Circuit** of the original circuit. Alternatively, the original circuit can be replaced with a current source *in parallel* with the same resistor; this is the **Norton Equivalent Circuit**.

Thevenin Equivalent Circuit

Figure 4.1a represents a "complex" linear circuit with output terminals *a* and *b*. The original complex circuit is composed of sources and resistors, possibly connected in a complicated manner. However, as far as we are concerned, the system is a *black box*; we only have access to terminals *a* and *b*. The "box" is to supply power to load resistor R_L.

In the laboratory, the original system's Thevenin Equivalent Circuit is determined by:

(1) measuring the *open-circuit voltage* across terminals *a* and *b*, v_{oc} (**Figure 4.1b**); and

(2) measuring the *short-circuit current* from terminal *a* to terminal *b*, i_{sc} (by inserting an ammeter between *a* and *b*, **Figure 4.1c**).
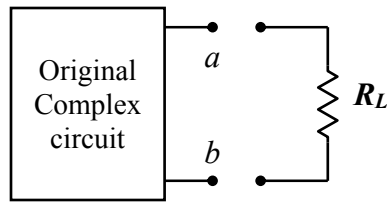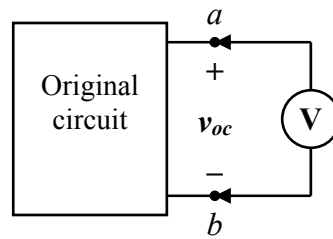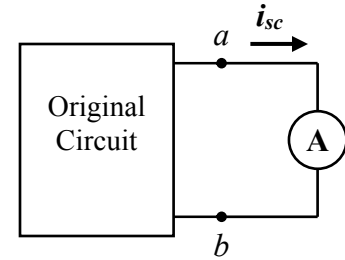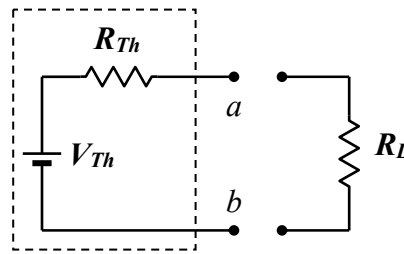
Figure 4.1a

Figure 4.1b
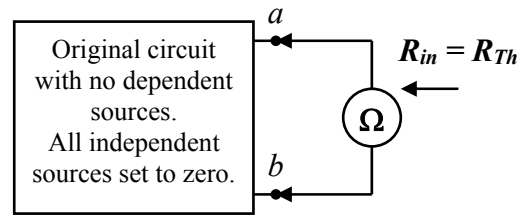

Figure 4.1c

Figure 4.1d

Figure 4.1e

From the measurements, the Thevenin Voltage V_{Th} and Thevenin Resistance R_{Th} are then:

$$V_{Th} = v_{oc} \tag{4.1}$$

$$R_{Th} = \frac{V_{Th}}{i_{sc}} \tag{4.2}$$

These quantities define the Thevenin Equivalent Circuit in the dashed box of **Figure 4.1d**.

If the original circuit has **no dependent sources**, R_{Th} can be found by setting all of the *independent sources* in the original circuit to zero (short-circuiting voltage sources, open-circuiting current sources; i.e., "killing" the sources). The resistance across terminals *a-b*, R_{in}, is then measured (**Figure 4.1e**). The Thevenin Resistance is:

$$R_{Th} = R_{in} \tag{4.3}$$

When the components and their configuration are known (i.e., the values of the sources and resistors, and how they are connected), V_{Th} and R_{Th} (and i_{sc}) can be **calculated** – as you have done in homework.

Load Resistance, Current and Voltage

When load R_L is connected to the original circuit (**Figure 4.1d**) – now defined by its Thevenin Equivalent – the current through the load is, by *Ohm's Law*:

$$I_L = \frac{V_{Th}}{R_{Th} + R_L} \tag{4.4}$$

and the voltage across the load is, by *voltage division*:

$$V_L = \frac{R_L}{R_{Th} + R_L} V_{Th} \tag{4.5}$$

The advantage of simplifying the original circuit to just V_{Th} and R_{Th} can now be appreciated. Once the Thevenin Equivalent Circuit is specified (V_{Th} and R_{Th}), then for any load resistance R_L, the output current I_L and output voltage V_L are readily determined. A new and lengthy calculation of the entire original circuit with load R_L need not be done to find the output for each new R_L.

Note that the details of the original circuit (i.e., voltages across individual resistors in the original circuit) are lost by replacing it with its Thevenin Equivalent. However, the point of creating a Thevenin Equivalent is to focus on what is going on at the load.

Power Transfer to Load

For DC circuits, the power dissipated by the resistive load (the power transferred to the load) is:

$$P_L = V_L I_L = R_L I_L^2 = \frac{V_L^2}{R_L} \qquad (4.6a)$$

or, in terms of known V_{Th}, R_{Th}, and load R_L:

$$P_L = R_L \left(\frac{V_{Th}}{R_{Th} + R_L} \right)^2 \qquad (4.6b)$$

Norton Equivalent Circuit

The Norton Equivalent is a current source I_N, such that:

$$I_N = \frac{V_{Th}}{R_{Th}} = i_{sc} \qquad (4.7)$$

in parallel with resistance $R_N = R_{Th}$, as shown in the dashed box of **Figure 4.1f**. The Norton Current I_N is simply the short-circuit current i_{sc} (**Figure 4.1c**), and the Norton Resistance is the Thevenin Resistance (**Figure 4.1e**).

The circuit of **Figure 4.1f** is equivalent to the circuit in **Figure 4.1d**, provided I_N is given by **Equation 4.7** and $R_N = R_{Th}$.
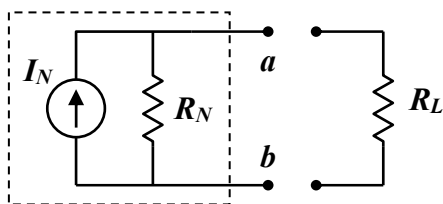

Figure 4.1f

POTENTIOMETER

The *potentiometer* or "pot" (*Figure 4.2a*) is introduced is this experiment. The schematic of the pot is shown in *Figure 4.2b*.

The potentiometer is a three-terminal device that serves as a *voltage divider*. Or, if only the center terminal (*b*) and one of the outer terminals (*a* or *c*) is used, the pot is a *variable resistor* or *rheostat*. The potentiometer can be modeled as two resistors, whose total resistance $R_{ac} = R_{ab} + R_{bc}$ is constant (*Figure 4.2c*). Total resistance R_{ac} is the constant resistance across the outer terminals *a* and *c*, but R_{ab} and R_{bc} may vary.

The position of the center terminal (*b*) – the *wiper* – controls the distribution of resistances R_{ab} and R_{bc}. The position of the wiper is changed with a screw, and you must either use the potentiometer adjustment tool or a very small screwdriver.

When current flows through the potentiometer, the pot acts as a voltage divider (*Figure 4.2d*):

$$V_{ac} = iR_{ac} = i(R_{ab} + R_{bc})$$
$$= iR_{ab} + iR_{bc} = V_{ab} + V_{bc} \quad (4.8)$$

Depending on the position of the wiper, R_{ab} varies from 0 to R_{ac} (and R_{bc} from R_{ac} to 0). Thus, V_{ab} varies from 0 to V_{ac} (and V_{bc} from V_{ac} to 0).

If only terminals *a* and *b* are used (or only *b* and *c*), the pot is a variable resistor, with R_{ab} varying from 0 to R_{ac} (*Figure 4.2e*). By varying R_{ab}, the current through the circuit can be modified.

CAUTION: When using the pot as a variable resistor, take care as its value approaches zero; you may cause excessive currents in the circuit.

Potentiometers are used in audio (stereo, radio, etc.) systems to control volume (*Figure 4.2d*). The total voltage available is V_{ac}; you can't change that (e.g., 4 stacked D batteries equal 6 V). As you turn the volume dial, you move the pot's wiper. The voltage applied to the amplifier block of the system, say V_{bc}, changes with wiper position. The change in output voltage changes the volume. A similar application is a dimmer switch.

Note that if only the outer terminals, *a* and *c*, are used, the pot is just an expensive constant-value resistor.
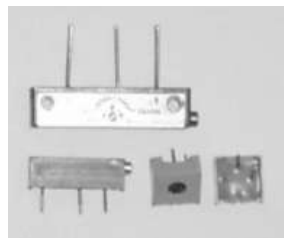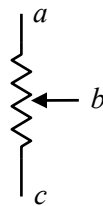

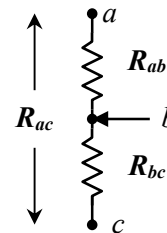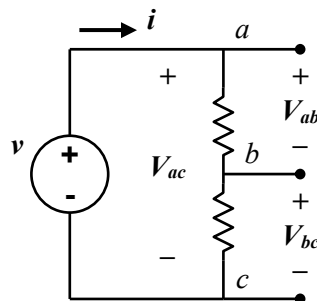Figure 4.2a   Figure 4.2b   Figure 4.2c

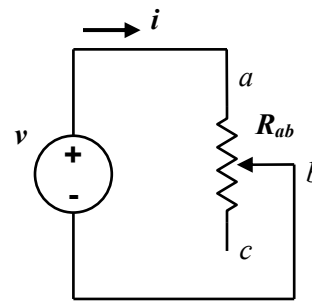Figure 4.2d   Figure 4.2e

MATERIALS AND EQUIPMENT

- 1   1.0 kΩ, 1/4 W, 5% resistor
- 1   2.0 kΩ, 1/4 W, 5% resistor
- 1   3.0 kΩ, 1/4 W, 5% resistor
- 1   10 kΩ, 1/4 W, potentiometer, 10 turn (ask instructor if it is not in the lab kit);
              it should be labeled "103", for 10×10^3 Ω (the same code as for resistors)
- 1   DC Power Supply
- 1   DMM
- 1   proto-board
- -   various cables and tests leads (banana plug-alligator clip cables; power supply switch; etc.)
- -   various wires (jumpers)

PROCEDURE

1. Measure the resistors and the potentiometer (across the pot's outer terminals), and record their actual values in **Table 4-1**. Make sure all the resistors are within tolerance, and that you have the correct potentiometer.

2. With the power supply **not connected** to the circuit, set it up so that the voltage will be supplied by either of the supplies (be sure to use the **INDEPendent** mode if using the **SLAVE supply**). Set the voltage to zero. Set the current limit to "10 o'clock". **Turn off** the power supply.

3. Construct the circuit of **Figure 4.3a**. For the load resistor R_L use the 10 kΩ potentiometer as a variable resistor (**Figure 4.3b**). Only use the center terminal (**wiper**) and one of the outer terminals of the pot (as in **Figure 4.2e**). It might be a good idea to mark the end of the pot next to the outer terminal that you are using, since you might be removing the pot from the proto-board to change its resistance.

4. Set the pot to $R_L = 200$ Ω. When measuring the pot's resistance R_L, make sure that it is removed from the circuit. To change R_L, turn the pot's screw (this changes the position of the wiper). Record the measured value of R_L in the first row of **Table 4-2**.

Hint: It is not necessary to remove the pot from the proto-board, but it is necessary to disconnect it from the circuit. With the pot in the proto-board, isolate the pot from the circuit. To measure resistance, insert jumper

wires connected to the ohmmeter leads into the appropriate proto-board sockets.

5. Place the pot (R_L) in the circuit, making sure to connect the circuit correctly so $R_L = 200$ Ω (not ~10k–200=~9800 Ω). Each terminal of the pot should be in a different 5-socket set of the proto-board.
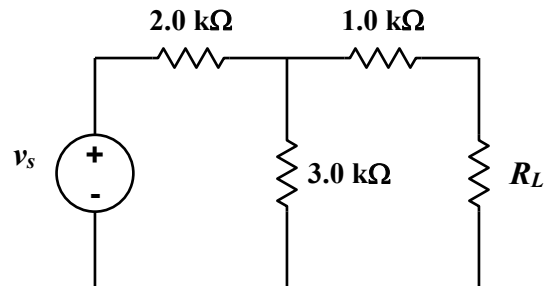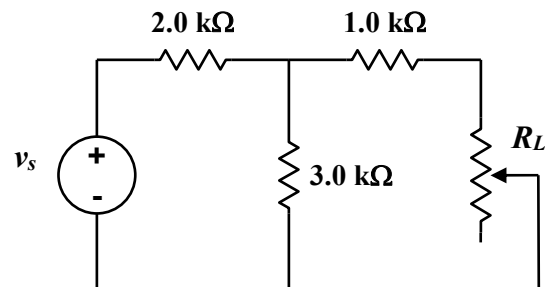

Figure 4.3a

Figure 4.3b

6. **Turn on** the power supply. Increase the voltage to 15.0 V. Measure and record the supply voltage in the title of *Table 4-2*.

7. Measure the voltage across the 2.0 kΩ resistor V_{2k}, and record it in *Table 4-2*. This value will be used to calculate the current provided by the source.

8. Measure voltage V_L across the load resistor R_L and record it in *Table 4-2*.

9. Repeat the measurements R_L, V_{2k} and V_L by varying the load (pot) resistance as follows:

   $R_L =$ 200, 300, 500, 700, 1.0k, 2.0k, 3.0k, 5.0k, 7.0k and 10k Ω.

10. Calculate the load power P_L for all load resistances and record in *Table 4-2*. You may fill out the rest of the table later to in order to determine *efficiency*.

11. **Estimate** the value of R_L that gives the maximum power transfer, i.e., the maximum power dissipated by the load, $P_{L,max}$.

12. Take **four additional sets of measurements using values of R_L near to and on either side of the resistance estimated to give maximum power transfer** (**Step 11**). These measurements are to provide a better approximation of the actual value of R_L that gives the maximum power than the set values already measured (i.e., to "bracket" the actual value).

    Think. If you estimate R_L to be 8000 Ω, do not just make measurements at 7990 Ω and 8010 Ω. This is hardly a wide enough bracket (both are essentially 8000 Ω).

    Adapt. During the measurements, adjust your estimate as necessary. For example, if the output power goes down as you increase R_L, do not keep increasing R_L. You are trying to get close to the value of R_L that gives the maximum power output, not just to do extra measurements without thinking about why you are doing them.

    Record the four sets of R_L, V_{2k} and V_L measurements and P_L calculations in the last four rows of *Table 4-2*.

Determine the Thevenin Equivalent Circuit

13. If you have not already done so, using the nominal supply voltage and nominal resistor values, **calculate** V_{Th} and R_{Th}. Record these calculated *nominal* values in the first column of *Table 4-3* as $V_{Th,n}$ and $R_{Th,n}$ (n for nominal).

14. Using the measured supply voltage and measured resistor values, **calculate** V_{Th} and R_{Th}. Record these calculated values in the second column of *Table 4-3* as $V_{Th,c}$ and $R_{Th,c}$.

15. Disconnect R_L and measure the voltage across output terminals a and b (*Figure 4.4a*). This is the open-circuit voltage, $v_{oc} = V_{Th}$. Record in the third column of *Table 4-3* as $V_{Th,m}$.

16. Place the ammeter between the output terminals and measure the short-circuit current i_{sc} (*Figure 4.4b*). Record the *measured* i_{sc} in the third column of *Table 4-3*.

17. **Turn off** the power supply and disconnect it. Replace the power supply with a short-circuit, e.g., a jumper wire (*Figure 4.4c*).

18. Measure the resistance across terminals a and b (*Figure 4.4c*). This is R_{Th}. In this circuit, it should be seen that R_{Th} is the 1-kΩ resistor in series with the parallel combination of the 2.0 kΩ and the 3.0 kΩ. Record the *measured* R_{Th} in the third column of *Table 4-3*.

19. Verify in *Table 4-3* that the ratio of the *measured* values $[V_{Th}/i_{sc}]_m$ equals the *measured* Thevenin Resistance $R_{Th,m}$.
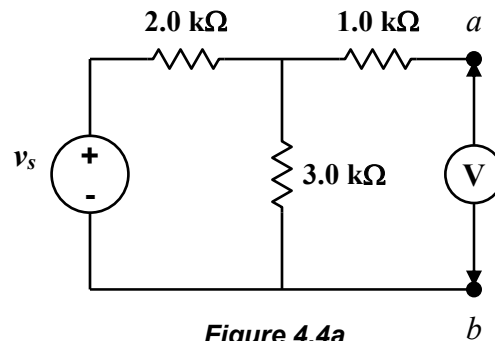
Figure 4.4a
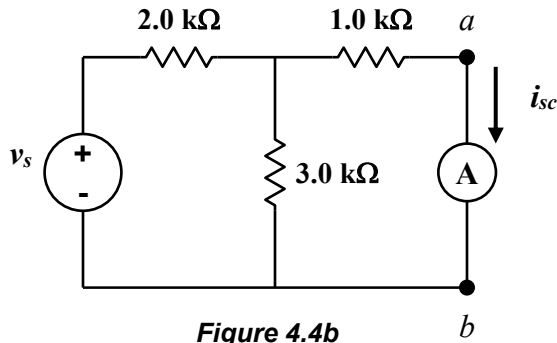
Figure 4.4b
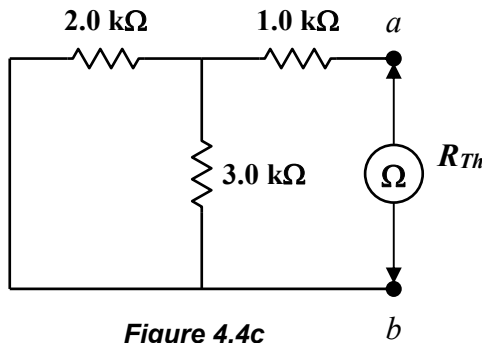
Figure 4.4c

Thevenin Equivalent Measurements

20. Reconfigure the circuit as shown in **Figure 4.5**; this is the Thevenin Equivalent Circuit of **Figure 4.3**. Use the measured value of V_{Th} for the supply voltage. The resistor set-up in the dashed box is R_{Th}. Alternatively, another potentiometer set equal to R_{Th} could be used.

    Make sure the supply voltage is changed to V_{Th}.

21. Measure the actual values of V_{Th} and R_{Th} of the new configuration. Record in the title of **Table 4-4**.

22. Repeat **Steps 4-10**, but only measure and record measured values for R_L and V_L in **Table 4-4**.

23. Take one more measurement with $R_L = R_{Th}$. Use the measured value of R_{Th} from **Step 18** (or **Step 21**). Record in the bottom row of **Table 4-4**.

24. Turn the power supply down to 0.0V, turn off the power supply and clean up.
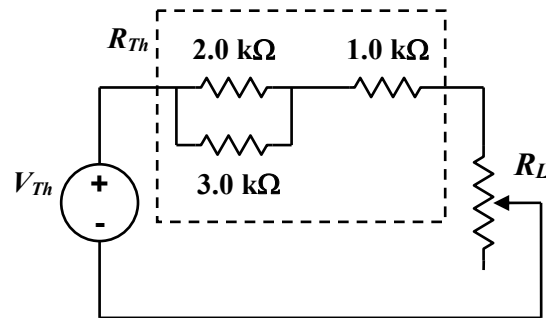
Figure 4.5

WHAT TO TURN IN

Each student **will turn in an individual and original report.** Each report will be **typed, single-spaced, stapled,** and in the **following order:**

1. Answers to the Questions.

On a new sheet:

- In the upper right-hand corner, type:

  your name
  your partner's first name
  Engr. 171
  date lab was completed

- Two lines below the date and centered, type:

  Experiment 4: Equivalent Circuits

- Answer the *Post-Lab Questions*.

- Answer the questions in complete sentences, and in such a way that the reader does not need to see the actual questions to understand what you are writing about. Each answer should stand on its own; some repetition between answers may be necessary.

- Always introduce a table (or a figure) with words (text) before it appears in the document; e.g., "Table 1 is …"; "The voltage-current response…is given in Figure 1…".

- For clarity, number each answer, and leave two blank lines between answers.

- Use **tables** and **Microsoft Equation (Editor)** as appropriate. Number and title each table in your report. Do not just insert a table, figure or equation without some narrative introducing or describing it, its significance, etc.

- The write-up is intended as a much reduced technical "report", or a set of excerpts or snippets from a report. As such **use *3rd person*** (the passive voice), and ***past tense*** when describing *what was done in the experiment*. **<u>Do not</u> use "I," "we," "you", etc.**

  Present tense may be used when referring to tables, etc., in the report; e.g., "The voltage-current data for … is given in *Table 2*."

2. Original ***Data Sheets***, completely filled in. Fill in ***Tables 4-2*** and ***4-4*** so you can calculate efficiency.

3. Support calculations, etc. Items 2 and 3 serve as the "**Appendix**."

Use only <u>one side</u> of each sheet (except for the Data Sheets). Again, leave at least two blank lines between answers.

Do not include a separate cover sheet. A separate cover sheet is not necessary, nor desired.

Again, you do not have to retype the questions, but **answer each question so that a reader (grader) can figure out the topic that you are addressing, even if he/she has not read the question.** Assume your audience is someone else besides the instructor, but who is familiar with the experiment you performed. Write answers in complete sentences.

POST-LAB QUESTIONS

Note: Four sheets of semi-log paper are provided. You only will use two (two are spares).

1. **Power Curves**. Using data from the two circuits (**Figures 4.3** and **4.5**, **Tables 4-2** and **4-4**), plot Load Power (mW) against Load Resistance (Ω):

$$P_L \text{ vs. } R_L$$

on a semi-log plot; i.e., a *proportional* (linear) *scale* for the vertical axis (power), and a *logarithmic scale* for the horizontal axis (resistance).

Construct **high-quality hand-plots** on the semi-log graph paper provided after the data sheets. <u>Do not</u> use Excel.

When plotting data, you do not need to calculate the logarithm of R_L. The log-scale automatically scales the data (note that the increments between minor grid-lines decrease as you move to the right in each decade). **Connect points together with a smooth curve**. **<u>Do not</u> draw straight lines between points.**

You should have two curves on one graph:
- P_L vs. R_L for the original circuit, and
- P_L vs. R_L for the Thevenin Equivalent

Set the scale of the vertical axis so you can plot both curves on the same graph, but still have divisions that make sense (e.g, use main divisions "0, 1, 2, 3..."; "0, 2, 4, 6...", "0, 5, 10, 15...", or decimal multiples, "0, 10, 20, 30…", etc). Look at the data carefully <u>before</u> plotting. Start the vertical axis at zero (0).

Discuss the **power curves** of the original circuit and the Thevenin circuit. <u>Some</u> topics to address include:
- Is it expected that the curves be the same or different? Explain why.
- Did the maximum power transfer occur at the same value of R_L in both circuits? Explain why maximum powers should or should not occur at the same value of R_L.
  Think. This is an experiment. Does "same" mean exactly equal?
- Was the maximum power transferred to the load the same for each circuit? Explain why the maximum powers should or should not be the same.

2. **Efficiency Curves**. Repeat **Question 1** using the efficiency data (fill in **Tables 4-2** and **4-4**). Use a new sheet for the plots of Efficiency (%) against Load Resistance (Ω):

$$\text{Efficiency vs. } R_L$$

You should have two curves on one graph.

Discuss the **efficiency curves** of the original circuit and the Thevenin circuit. <u>Some</u> topics to address include:
- Is it expected that the curves be the same or different? Explain why.
- Did the maximum efficiency take place at the same value of R_L in both circuits? Explain why the maximum efficiencies should or should not occur at the same R_L.
- Was the maximum efficiency the same for each circuit? Explain why the maximum efficiencies should or should not be the same.

3. The value of the maximum load power $P_{L,max}$ should be:

$$P_{L,\max} = \frac{V_{Th}^2}{4R_{Th}} \tag{4.9}$$

Use this equation to calculate $P_{L,max}$ from the measured values of V_{Th} and R_{Th}.

In the experiment, $P_{L,max}$ was calculated from measurements of V_L and R_L (the last entry of **Table 4-4**, where $R_L = R_{Th}$).

Report the values of $P_{L,max}$ from the experiment and from **Equation 4.9**. What is the *%difference* with respect to that of equation? (i.e., compare the values). Does the experiment confirm the equation?

4. When the load power is maximum in the <u>original circuit</u>, what is the efficiency of the power transfer? Do maximum power transfer and maximum efficiency occur at the same value of load resistance? Are the responses (shapes of the curve) the same? Why or Why not?

5. Repeat **Question 4** for the <u>Thevenin Equivalent Circuit</u>.

6. On an additional sheet of paper, starting with **Equation 4.6b** in this lab manual, **derive** the expression for R_L that gives the maximum power dissipated by the load (use calculus). Give the answer in terms of constants V_{Th} and R_{Th}. **SHOW YOUR WORK**. Perform this derivation by hand (not typed).

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DATA SHEET, pg. 1/2	Name
Expt. #4 Equivalent Circuits	Lab Partner

Table 4-1 Resistance Values.

Nominal Value	Measured Resistance (kΩ)	% Difference (%) (with respect to nominal)	Is it within Tolerance?
1.0 kΩ			
2.0 kΩ			
3.0 kΩ			
10 kΩ pot (outer terminals)			

Table 4-2 Circuit Measurements.   Source voltage: v_s = _____.

R_L	Load Resistor R_L	Voltage across 2 kΩ V_{2k}	Load Voltage V_L	Source Current i_s	Source Power P_s	Load Power P_L	Efficiency
nominal	measured	measured	measured	V_{2k}/R_{2k}	$v_s \times i_s$	$\dfrac{V_L^2}{R_L}$	$\dfrac{P_L}{P_s} \times 100\%$
Units: Ω	Ω						%
200							
300							
500							
700							
1.0k							
2.0k							
3.0k							
5.0k							
7.0k							
10k							

*Remember to take four additional measurements near and around the estimated value of R_L that gives the greatest P_L; these four measurements should give a better estimate of the R_L that gives the maximum load transfer. Do not select values that are too close together. As more measurements are taken, if possible, revise the approximation of R_L for maximum power transfer.

DATA SHEET, pg. 2/2	Name
Expt. #4 Equivalent Circuits	Lab Partner

Table 4-3 Thevenin Equivalent.

	CALCULATIONS		DIRECT MEASUREMENTS [Steps 15-17]	Calculated R_{Th} from *measured V_{Th} and measured i_{sc}* [Step 19]
	Nominal Values [Step 13]	Measured Values [Step 14]		
V_{Th}	$V_{Th,n}$	$V_{Th,c}$	$V_{Th,m}$	$R_{Th,\exp} = V_{Th,m} / i_{sc,m} =$
i_{sc}			$i_{sc,m}$	Does the calculated $R_{Th,\exp}$ (above) agree with the directly-measured $R_{Th,m}$?
R_{Th}	$R_{Th,n}$	$R_{Th,c}$	$R_{Th,m}$	

Table 4-4 Thevenin Circuit Measurements. V_{Th} = _____; R_{Th} = _____.

R_L	Load Resistor R_L	Load Voltage V_L	Source Current i_s	Source Power P_s	Load Power P_L	Efficiency
nominal	measured	measured	$\dfrac{V_{Th}}{R_{Th}+R_L} = \dfrac{V_L}{R_L}$	$V_{Th} \times i_s$	$\dfrac{V_L^2}{R_L}$	$\dfrac{P_L}{P_s} \times 100\%$
Units: Ω						%
200						
300						
500						
700						
1.0k						
2.0k						
3.0k						
5.0k						
7.0k						
10k						
$R_{Th} =$						

R_L (Ω)

$R_L \, (\Omega)$

Expt. 4

R_L (Ω)

100 1000 10000

Expt. 4

R_L (Ω)

100   1000   10000

Expt. 4

EXPERIMENT 5

The Operational Amplifier (Op-amp)

1/09/17

GOAL

To understand Operational Amplifiers and their limitations.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Build and analyze basic operational amplifier (op-amp) DC circuits.
- Identify some basic applications for op-amps.

BACKGROUND

Read: • Alexander and Sadiku, 3e, 4e or 5e: Ch. 5
      • http://cache.national.com/ds/LM/LM741.pdf   (data sheet for Op-Amp), included.
      • "The Proto-Board (Bread board)" (*Appendix C*)
      • "Triple Output DC Power Supply" (*Appendix F,* 'Identical Positive and Negative Voltages')

The ***operational amplifier*** – or ***op-amp*** – is an amplifier with a very high gain, a high input impedance, and a low output impedance (for now, think of *impedance* as *resistance*). The op-amp has many applications in electronics such as: active filters, summers, integrators, comparators, level detection devices and instrumentation amplifiers.

When working with the ***ideal model*** of the op-amp, there are only two properties that the circuit designer and analyst need to know:

(1) the currents into both op-amp input terminals are zero, and
(2) the voltage drop across the op-amp input terminals is zero.

What could be better than that?

The ideal model assumes an infinite input impedance, and a zero output impedance. In reality, the op-amp is a very complex device (see the National Semiconductor specification sheets after the data tables or online).

By knowing the limitations of an actual op-amp, and the regions for which the op-amp does perform close to ideal, simple op-amp models can be used, even in complex circuits. In this experiment, you will use the ideal op-amp model.

The three basic op-amp circuit configurations studied in this experiment are:

(1) the ***inverting amplifier circuit***;

(2) the ***non-inverting amplifier circuit***; and

(3) the ***buffer*** (*isolation amplifier*, or *voltage-follower*).

The analysis of each circuit is fairly straight-forward using the ideal op-amp model. Using basic circuit analysis, and the ideal op-amp, you should be able to derive the equations that describe the overall circuit response on your own.

Figure 5.1a is the symbolic representation of an operational amplifier. The figure shows the op-amp (the triangle), the DC *supply voltages* (positive V^+ and negative V^-), the *inverting* and *non-inverting input voltages* (v_n and v_p), and the *output voltage* (V_o). Each voltage shown represents the potential at that point with respect to the arbitrarily chosen zero potential of the reference line (i.e., $V_{ref} = 0 =$ ground).

The DC power supplies (V^+ and V^-), provide the energy to amplify signals. The output voltage V_o cannot exceed the positive DC supply voltage V^+, and cannot be more negative than the negative DC supply voltage V^-. If the output voltage reaches either DC supply voltage, it cannot get any larger in magnitude, no matter how much the input is increased. This condition is called *saturation*.

The DC power supplies are usually configured to provide **equal and opposite voltages** ($V^- = -V^+$), so that the output signal voltage V_o may swing equally above and below the reference voltage of zero volts. The magnitudes of the supply voltages are chosen to be equal so the largest undistorted output may be obtained from a sinusoidal (AC) input (although we will only use DC voltages in this experiment). The op-amp specification sheet gives the maximum permissible magnitude, or *rating*, for the supply voltages.

See *Appendix F* for hints on setting up the Triple Output DC Power Supply with equal and opposite DC voltage supplies [If you ask about this in lab, the instructor will remind you that Appendix F was mentioned three times during the instructions for this experiment].

CAUTION: In schematic diagrams, the op-amp **DC supply connections (Pins 4 and 7) are usually not shown**, but they do – and must – exist. Do not forget them when constructing your circuit. They provide the power to amplify both DC and AC input signals.

Figure 5.1b is a pictorial representation of the top of a typical op-amp package. The LM741 op-amp is an 8-pin *dual in-line package* (**DIP**). The op-amp must be set across the proto-board *trough* so that each pin is in its own 5-socket set.

The op-amp pins are numbered 1 to 8. Place the depressed (or printed) half-circle (or depressed or printed circle) to the left. Starting from below the half-circle (or circle), number the pins counter-clockwise 1 through 8.

Pins 2, 3, 4, 6 and 7 on the actual LM741 op-amp correspond to the terminals on the symbolic op-amp, v_n, v_p, V^-, V_o and V^+, respectively (*Figure 5.1a*). Pins 1 and 5 are used for balance (beyond the scope of this class), and 8 has no connection (#8 provides physical symmetry).
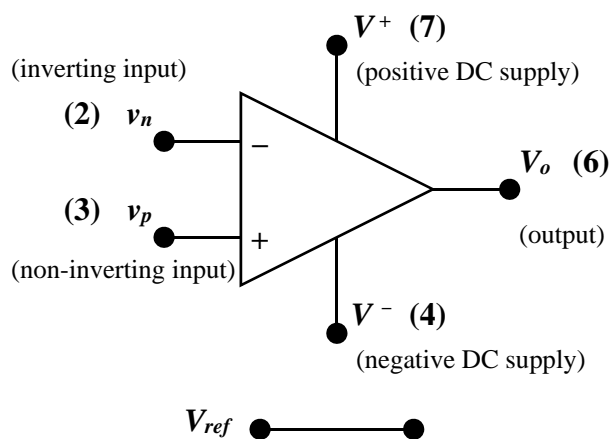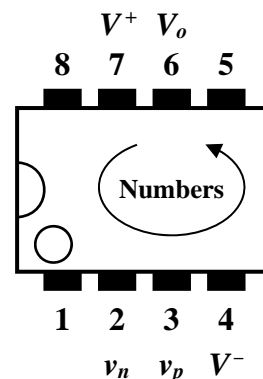

Figure 5.1a

Figure 5.1b

Figure 5.2 is a general configuration of a basic op-amp circuit. The two input signals v_1 and v_2 are not the DC Supply voltages (nor are v_1 and v_2 necessarily the same as v_n and v_p). Resistor R_2 is the *feedback resistor*.

For the circuit in *Figure 5.2*, it can be shown – i.e., **you** should be able to derive it – that the output voltage V_o as a function of the input voltages v_1 and v_2 is:

$$V_o = \left(1 + \frac{R_2}{R_1}\right)v_2 - \frac{R_2}{R_1}v_1 \qquad (5.1)$$

When $v_2 = 0$, the op-amp is a classic *inverting amplifier circuit*: it amplifies signal v_1 by R_2/R_1, and *inverts* it (as indicated by the negative sign). Inversion means that the output V_o is 180° *out-of-phase* with v_1 (with v_1 positive and $v_2 = 0$, V_o is negative; with v_1 negative and $v_2 = 0$, V_o is positive).

When $v_1 = 0$, the op-amp in a *non-inverting amplifier circuit*: it amplifies the signal v_2 by $[1+R_2/R_1]$ but does not invert it. Output V_o is *in-phase* with v_2 (they have the same sign).

Other circuit configurations are possible, giving such circuits as: *summers* (e.g., when several v_1-R_1 type signals enter the negative op-amp input terminal), *difference amplifiers* (e.g., *Figure 5.2*), *buffers* ($v_1=0$, $R_1 = R_2 = 0$), *integrators*, *differentiators*, etc. Thus the op-amp's name… it can be use to perform mathematical **operations**, and to **amplify** signals.
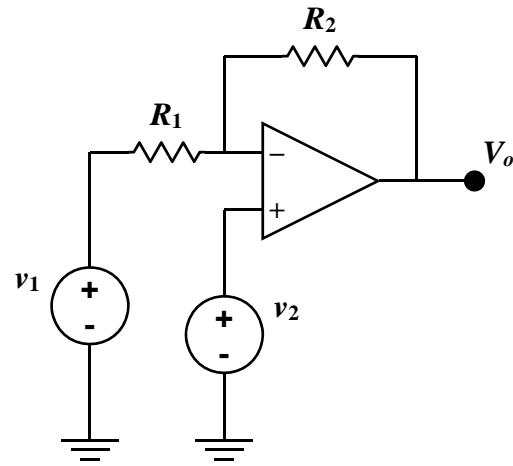
Figure 5.2

MATERIALS and EQUIPMENT

1	470 Ω, 1/4 W, 5% resistor
1	2.0 kΩ, 1/4 W, 5% resistor
1	4.7 kΩ, 1/4 W, 5% resistor
1	10 kΩ, 1/4 W, 5% resistor
1	33 kΩ, 1/4 W, 5% resistor
1	Operational Amplifier, LM741, or equivalent (see specification sheet)
1	Triple Output DC Power Supply (for V^+ and V^-),
1	a voltage source for input signal v_i (v_1 and v_2):

    - a second DC supply, or

    - a Function Generator using DC output only (see Expt. 8 for a description of the Wavetek Function Generator; see instructor if using another Function Generator), or

    - **a potentiometer connected between V^+ and ground; the wiper is used for v_1 (or v_2); this is perhaps the simplest and neatest way to provide the input signal**.

1	DMM
1	proto-board
-	various cables and test leads (banana plug-alligator clip cables; power supply switch)
-	various wires (jumpers)

PROCEDURE

1. Measure the resistors and record the actual values in *Table 5-1* and *Table 5-5*. Make sure all the resistors are within tolerance.

Inverting Op-Amp Circuit

> **Read all the instructions every step before implementing it**.

2. Construct the inverting amplifier circuit shown in *Figure 5.3a*, with $v_i = 0.50$ V, $R_1 = 10$ kΩ and $R_2 = 33$ kΩ. Before applying v_i, make sure to apply the positive and negative **supply voltages** V^+ and V^- (Pins #7 and 4, respectively). Note that the supply voltages are not shown in *Figure 5.3a*

   Set the DC supplies to provide $V^+ = +15.0$ V and $V^- = -15.0$ V (see 'Applications/ Identical Positive and Negative Voltages' in **Appendix F**).

   Measure the supply voltages with the DMM, and record them in the title of *Table 5-2*.

3. Use a second DC supply for input voltage v_i. <u>Better</u>, connect a potentiometer between V^+ and the ground, and use the wiper for input v_i. Set v_i to +0.500 V. Measure v_i and record the measured voltage in *Table 5-2*.

4. Measure the output voltage V_o (its **magnitude** and **polarity**, with the negative lead of the DMM at ground) and record it in *Table 5-2*. *Calculate the amplification of your in-lab circuit. Is the result in agreement with the pre-lab calculation (prediction)?*

5. Make sure the supply voltages are still providing the appropriate voltage. Measure and record V^+ and V^- in *Table 5-3a*.

   Copy the data for v_i and V_o from *Table 5-2* into the row below (0, 0) in *Table 5-3a*. It is assumed that the first data point is (0, 0).

   Increase v_i to 1.000 V; measure v_i and V_o and record in *Table 5-3a*. Increasing v_i by 0.500 V increments, repeat the v_i-V_o measurements until the amplifier has **saturated** (V_o becomes constant). Take enough data points to ensure saturation.

6. Estimate the value of $v_{i,sat}$ and $V_{o,sat}$ as described in **Step 7**.

   Note: $V_{o,sat}$ will not necessarily equal V^+ (or V^-); why might this be?
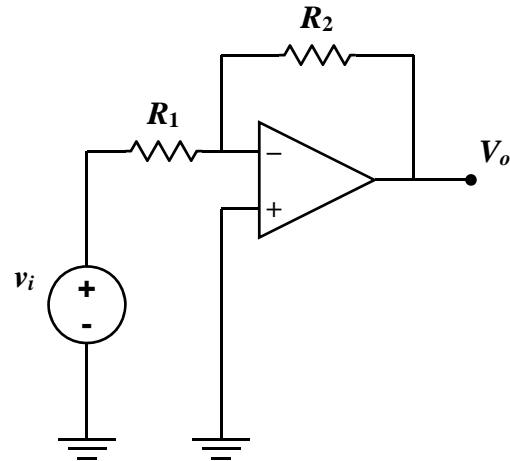
Figure 5.3a

7. <u>Using engineering paper</u>, make a **hand-plot** of the V_o vs. v_i data (v_i on the horizontal). On your graph, draw two lines that estimate:

   (1) the rising linear part of the curve, and

   (2) the horizontal part of the curve ($V_{o,sat}$).

   From the intersection of these two lines, estimate the saturation values of the input and output voltages, $v_{i,sat}$ and $V_{o,sat}$. Record in *Table 5-4*. <u>Do not</u> make the error of assuming the two lines meet at a data point.

   Note: One team member should make this hand-plot; the other team member will make the hand-plot for the non-inverting circuit.

Inverting Op-Amp Circuit with Load

8. Set v_i to zero. **Turn off** all the power. Turn off v_i before turning off the supply voltages.

9. Connect a load resistance $R_L = 470\ \Omega$ from V_o to ground (*Figure 5.3b*).

10. Turn on the DC supply voltages. Turn on the input signal v_i and set it to $v_i = 1.00$ V DC. Record its value in *Table 5-5*.

11. Measure the voltage across the load and record in *Table 5-5*. *Calculate the current through the load R_L and record in *Table 5-5*.*

12. Repeat **Steps 8-11** for $R_L = 2.0$ kΩ.

13. Repeat **Steps 8-11** for $R_L = 4.7$ kΩ.

14. Set v_i to zero. **Turn off** all the power.

Non-inverting Op-Amp Circuit

15. Construct the circuit shown in *Figure 5.4*, with $v_i = 0.500$ **V, $R_1 = 10$ kΩ and $R_2 = 33$ kΩ.** Before applying the signal v_i, make sure the positive and negative supply voltages still provide +15.0 V and –15.0 V. Make sure v_i is applied to the correct op-amp input terminal. Record its measured value in *Table 5-2*.

16. Measure and record the output voltage V_o (*magnitude* and *polarity*) and record it in *Table 5-2*. *Calculate the amplification of your in-lab circuit. Is the result in agreement with the pre-lab calculation?*

17. Make sure the supply voltages (V^+ and V^-) are still providing the appropriate voltages. Measure and record in *Table 5-3b*.

    Copy the data for v_i and V_o from *Table 5-2* into the row below (0, 0) in *Table 5-3a*. It is assumed that the first data point is (0, 0).

18. Estimate the value of $v_{i,sat}$ and $V_{o,sat}$ with a hand-plot, as described in **Step 7**.

    <u>Note</u>: The other team member should make this hand-plot. If there are three team members, the third should also make the hand-plot for the non-inverting op-amp.

19. Set v_i to zero. **Turn off** all the power.

Buffer Op-Amp Circuit

20. Construct the circuit shown in *Figure 5.5*, with $v_i = 3.00$ V. Record the measured value of v_i in *Table 5-2*. Before applying the signal v_i, make sure the positive and negative supply voltages still provide +15 V and –15 V.

21. Measure and record the output voltage V_o (magnitude and polarity) and record it in *Table 5-2*. *Calculate the amplification of the in-lab amplifier circuit. Is the result in agreement with the pre-lab calculation?*

22. Clean up.
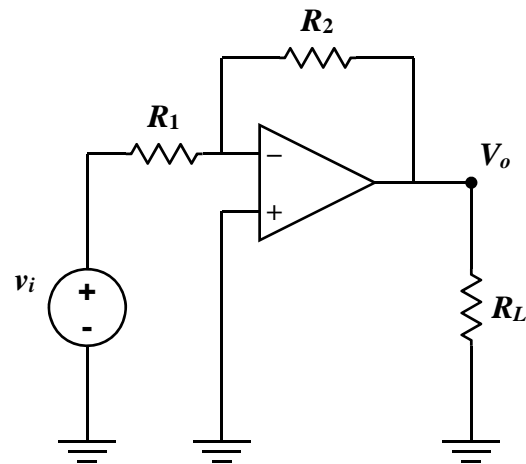
Figure 5.3b
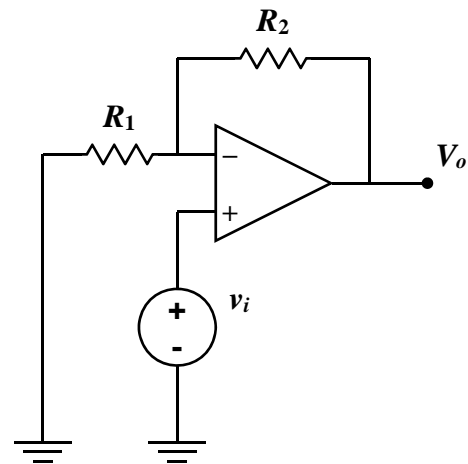
Figure 5.4
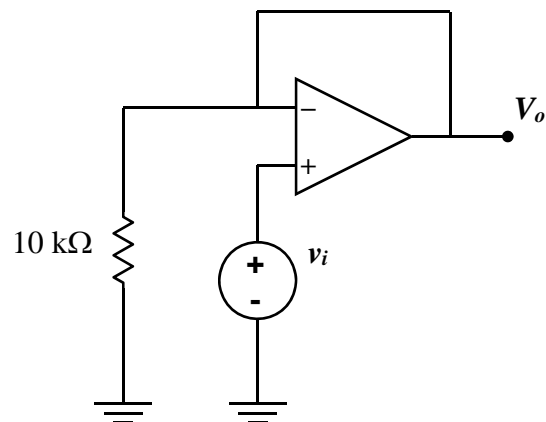
Figure 5.5

WHAT TO TURN IN

In order: (1) the **Data Sheets**, (2) **answers to the Post-Lab Questions**, and (3) **Two Excel Plots, One In-Lab Hand-Plot, supplemental calculations, etc.**

<u>Use this sheet to answer the questions</u>. Append additional sheets if necessary. You do not need to type your answers.

POST-LAB QUESTIONS

1. Complete *Tables 5-1* to *5-5*, if necessary.

2. **Using Excel**, create a revised graph of V_o vs. v_i (output voltage vs. input voltage) for each set of data – one graph for the inverting circuit (*Table 5-3a*) and on for the non-inverting circuit (*Table 5-3b*).

   Use a separate sheet of paper for each data set. Include data point (0,0) for each graph.

   <u>Do not</u> have Excel automatically fit a curve through all of the points; only plot markers for the data.

   Use the same general technique as in lab to approximate the saturation voltages $V_{o,sat}$ and $v_{i,sat}$. The intersection of the two lines using technology should be a better approximation than that made from the hand-plot in lab. The drawing tool in Excel can be used to approximate the lines. Or use Excel to plot the lines of the bilinear model (the SLOPE function is a good tool to determine the slope of a line fitted to a points).

   Do not make the error in assuming that the two lines must intersect at a data point. In reality, there is a smooth transition between the linear and saturated regions (plot the curve with a smooth-line through the data points to visualize this).

   Clearly label the values of $V_{o,sat}$ and $v_{i,sat}$ on the graph using the Text Tool. For example, using <u>fictional</u> data, your text box might have this near the intersection point: $(v_i, V_o)_{sat} = (9.3 \text{ V}, 28.3 \text{ V})$

3. *Circle one*. In **Steps 7-12** (*Figure 5.3b*) which way does current flow in resistor R_L?
   (a) down.
   (b) up.
   (c) there is no current.

   Explain your answer (explain the physics).

4. For most circuits without an op amp, when a load resistor R_L is connected, the value of the voltage across the load depends on the resistance R_L. Based on the data of **Table 5-5** (**Figure 5.3b**) does $V_o = V_L$ for an op-amp circuit depend on the value of R_L? Explain physically why or why not.

5. Consider the circuit in **Figure 5.2**. Using $v_1 = 1.5$ V and $v_2 = 1.0$ V, and using the nominal values of resistors R_1 and R_2 for this experiment, determine the value of V_o.

6. Again consider **Figure 5.2** with the nominal values of R_1 and R_2 used in this experiment, and with supply voltages $V^+ = +15$ V and $V^- = -15$ V. If $v_1 = 3.1$, determine the most positive and most negative values for v_2 without causing **saturation** if $v_1 = 2.0$ V. Assume the output can actually reach ±15.0 V.

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DATA SHEET, pg. 1/2	Name
Expt. #5 Op Amps	Lab Partner

Table 5-1 Resistance Values for Op-Amp Circuit

Nominal Value	Measured Resistance (kΩ)	% Difference (w.r.t. nominal)	Is Resistance within Tolerance?
R_1 = 10 kΩ			
R_2 = 33 kΩ			

Table 5-2 Op-Amp Circuit Amplification v_i = 0.5 V DC.

Supply Voltages (measured): V^+=_____V; V^-=_____V.

	Pre-Lab Calculations (predictions) (using nominal values)		In-Lab Measurements			
	Output Voltage V_o (V)	Amplification V_o/v_i	Input Voltage v_i (V)	Output Voltage V_o (V)	Amplification V_o/v_i	%Difference in Amplification (w.r.t. Nominal)
Inverting Op-Amp Circuit						
Non-Inverting Op-Amp Circuit						
Buffer						

Table 5-3 Input Voltage – Output Voltage Measurements (record data down left, then right column)

5-3a Inverting Op-Amp Circuit			
V^+=_____V; V^-=_____V			
v_i (V)	V_o (V)	v_i (V)	V_o (V)
0.0000	0.000		

5-3b Non-Inverting Op-Amp Circuit			
V^+=_____V; V^-=_____V			
v_i (V)	V_o (V)	v_i (V)	V_o (V)
0.000	0.000		

DATA SHEET, pg. 2/2	Name
Expt. #5 Op Amps	Lab Partner

Table 5-4 Saturation Voltages, Estimated from *In-lab Hand-plots* of V_o vs. v_i.

Measured Supply Voltages: V^+=_____V; V^-=_____V.

	Input Voltage $V_{i,sat}$ (V)	Output Voltage $V_{o,sat}$ (V)
Inverting Op-Amp Circuit		
Non-Inverting Op-Amp Circuit		

Table 5-5 Output Voltage (Load Voltage) for Various Load Resistors for Inverting Op-Amp Circuit. v_i = **1.0 V DC**.

R_L	470 Ω	2.0 kΩ	4.7 kΩ
Measured Resistance (kΩ)			
Measured Input Voltage, v_i (V)			
Output Voltage = Load Voltage $V_o = V_L$ (V)			
Load Current, i_L (mA)			

August 2000

National Semiconductor

LM741
Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0˚C to +70˚C temperature range, instead of −55˚C to +125˚C.

Features

Connection Diagrams

Metal Can Package
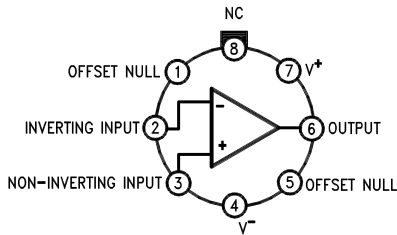
00934102

Note 1: LM741H is available per JM38510/10101

Order Number LM741H, LM741H/883 (Note 1)**,
LM741AH/883 or LM741CH
See NS Package Number H08C**

Dual-In-Line or S.O. Package
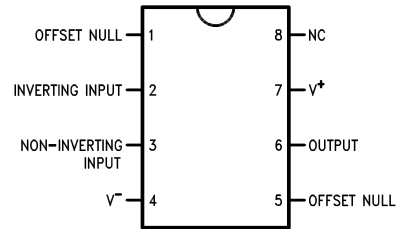
00934103

**Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E**

Ceramic Flatpak
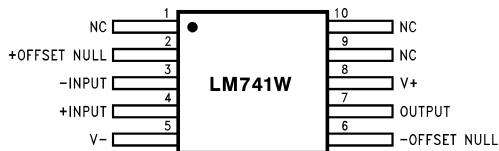
00934106

**Order Number LM741W/883
See NS Package Number W10A**

Typical Application

Offset Nulling Circuit
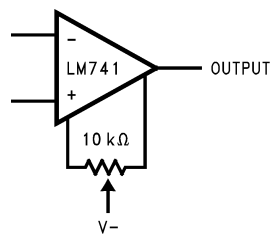
00934107

Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55˚C to +125˚C	−55˚C to +125˚C	0˚C to +70˚C
Storage Temperature Range	−65˚C to +150˚C	−65˚C to +150˚C	−65˚C to +150˚C
Junction Temperature	150˚C	150˚C	100˚C
Soldering Information			
N-Package (10 seconds)	260˚C	260˚C	260˚C
J- or H-Package (10 seconds)	300˚C	300˚C	300˚C
M-Package			
Vapor Phase (60 seconds)	215˚C	215˚C	215˚C
Infrared (15 seconds)	215˚C	215˚C	215˚C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering

surface mount devices.

| ESD Tolerance (Note 8) | 400V | 400V | 400V |

Electrical Characteristics (Note 5)

| Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25˚C$ $R_S \leq 10\,k\Omega$				1.0	5.0		2.0	6.0	mV	
	$R_S \leq 50\Omega$		0.8	3.0							mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$ $R_S \leq 50\Omega$			4.0							mV
	$R_S \leq 10\,k\Omega$						6.0			7.5	mV
Average Input Offset Voltage Drift				15							µV/˚C
Input Offset Voltage Adjustment Range	$T_A = 25˚C$, $V_S = ±20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25˚C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/˚C
Input Bias Current	$T_A = 25˚C$		30	80		80	500		80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			0.210			1.5			0.8	µA
Input Resistance	$T_A = 25˚C$, $V_S = ±20V$	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \leq T_A \leq T_{AMAX}$, $V_S = ±20V$	0.5									MΩ
Input Voltage Range	$T_A = 25˚C$							±12	±13		V
	$T_{AMIN} \leq T_A \leq T_{AMAX}$				±12	±13					V

Electrical Characteristics (Note 5)   (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	$T_A = 25°C$, $R_L \geq 2$ kΩ										
	$V_S = \pm20V$, $V_O = \pm15V$	50									V/mV
	$V_S = \pm15V$, $V_O = \pm10V$				50	200		20	200		V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$R_L \geq 2$ kΩ,										
	$V_S = \pm20V$, $V_O = \pm15V$	32									V/mV
	$V_S = \pm15V$, $V_O = \pm10V$				25			15			V/mV
	$V_S = \pm5V$, $V_O = \pm2V$	10									V/mV
Output Voltage Swing	$V_S = \pm20V$										
	$R_L \geq 10$ kΩ	±16									V
	$R_L \geq 2$ kΩ	±15									V
	$V_S = \pm15V$										
	$R_L \geq 10$ kΩ				±12	±14		±12	±14		V
	$R_L \geq 2$ kΩ				±10	±13		±10	±13		V
Output Short Circuit Current	$T_A = 25°C$	10	25	35		25			25		mA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$	10		40							mA
Common-Mode Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq 10$ kΩ, $V_{CM} = \pm12V$				70	90		70	90		dB
	$R_S \leq 50\Omega$, $V_{CM} = \pm12V$	80	95								dB
Supply Voltage Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$V_S = \pm20V$ to $V_S = \pm5V$										
	$R_S \leq 50\Omega$	86	96								dB
	$R_S \leq 10$ kΩ				77	96		77	96		dB
Transient Response	$T_A = 25°C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		µs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	$T_A = 25°C$	0.437	1.5								MHz
Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5		V/µs
Supply Current	$T_A = 25°C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25°C$										
	$V_S = \pm20V$		80	150							mW
	$V_S = \pm15V$					50	85		50	85	mW
LM741A	$V_S = \pm20V$										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	$V_S = \pm15V$										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Electrical Characteristics (Note 5) (Continued)

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100˚C/W	100˚C/W	170˚C/W	195˚C/W
θ_{jC} (Junction to Case)	N/A	N/A	25˚C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

Note 5: Unless otherwise specified, these specifications apply for $V_S = \pm 15V$, $-55˚C \le T_A \le +125˚C$ (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to $0˚C \le T_A \le +70˚C$.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(μs).

Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram
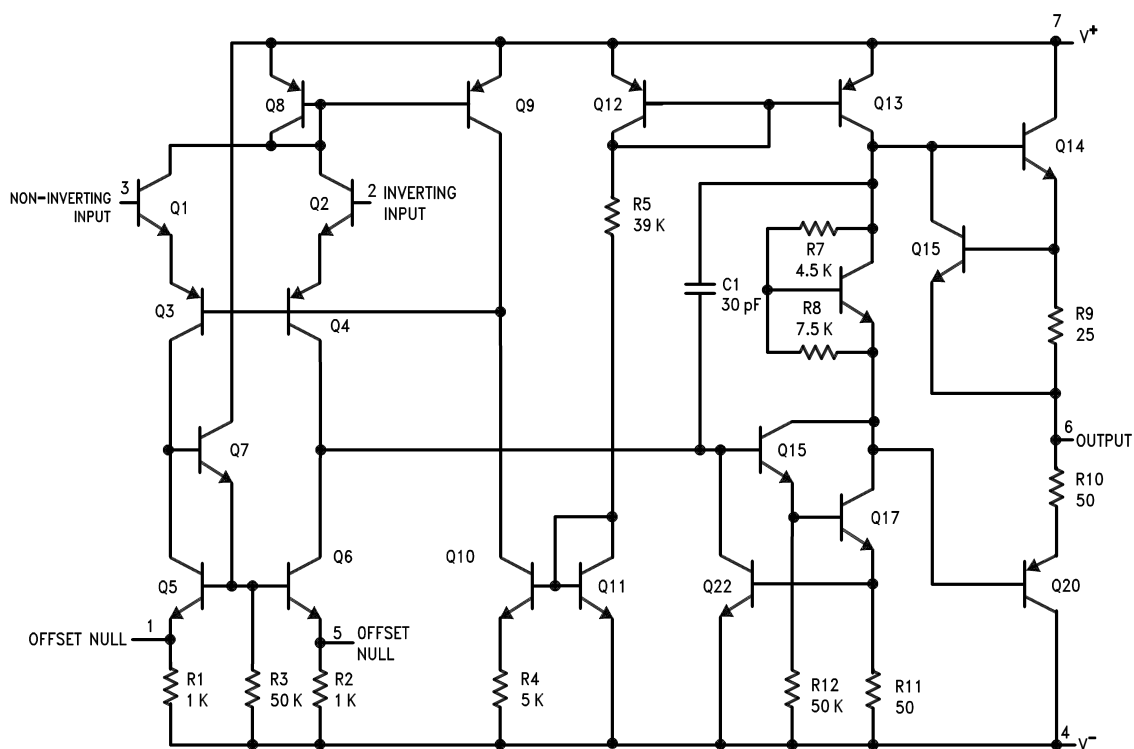
00934101

Physical Dimensions inches (millimeters)
unless otherwise noted
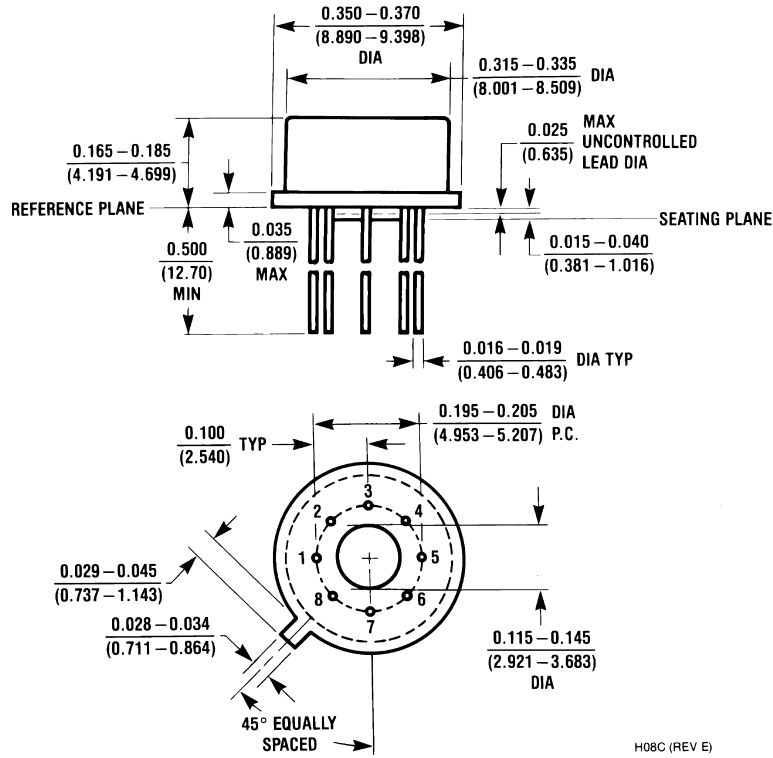
Metal Can Package (H)
Order Number LM741H, LM741H/883, LM741AH/883, LM741AH-MIL or LM741CH
NS Package Number H08C

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

0.400 MAX

R0.010 TYP

8 7 6 5

0.220
0.291

0.310 MAX
GLASS

R0.025 TYP

1 2 3 4

0.290
0.320

0.180
MAX

0.045 TYP
0.065

0.005
MIN

GLASS
SEALANT

0.200
MAX

0.020
0.060

0.150
MIN

0.125
0.200

95° ± 5° TYP

0.310
0.410

90° ± 4° TYP

0.008 TYP
0.012

0.055 MAX
BOTH ENDS

0.018 ± 0.003 TYP

0.100 ± 0.010 TYP
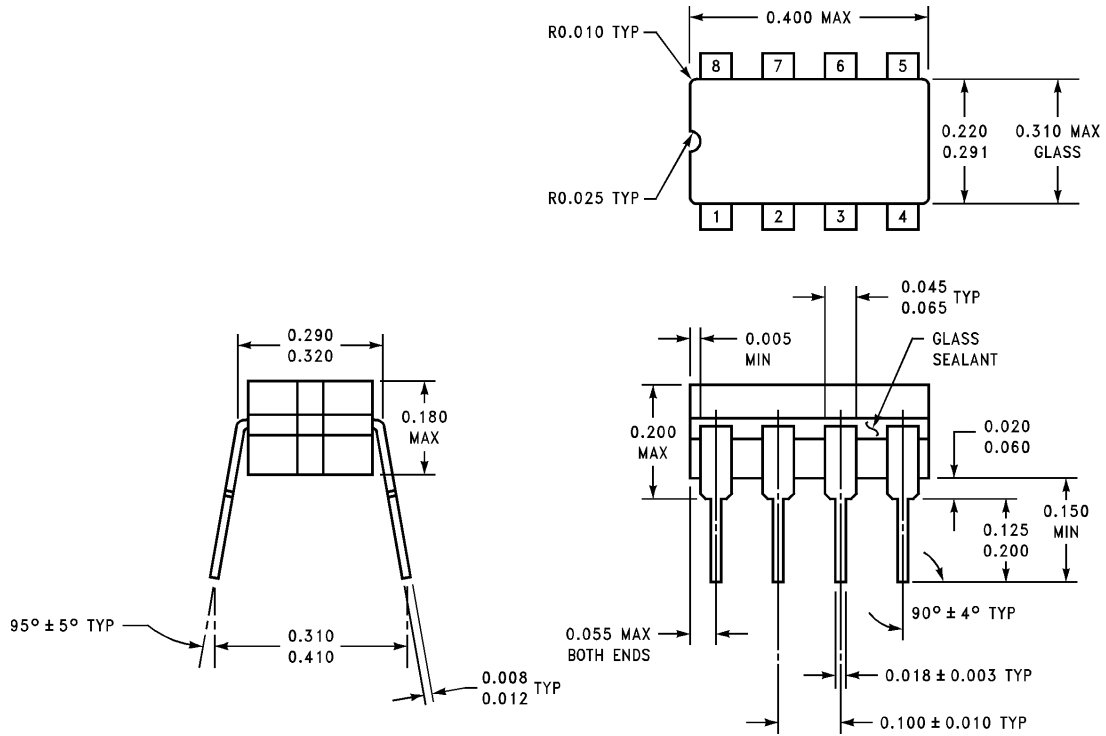
J08A (REV K)

Ceramic Dual-In-Line Package (J)
Order Number LM741J/883
NS Package Number J08A

0.373 − 0.400
(9.474 − 10.16)

0.090
(2.286)

0.092
(2.337)
DIA

8 7 6 5

0.250 ± 0.005
(6.35 ± 0.127)

0.032 ± 0.005
(0.813 ± 0.127)
RAD

8 7

PIN NO. 1 IDENT

PIN NO. 1 IDENT

OPTION 1

1 2 3 4

1

OPTION 2

0.280
(7.112)
MIN

0.030
(0.762)
MAX

0.040
(1.016)
TYP

0.039
(0.991)

0.145 − 0.200
(3.683 − 5.080)

0.300 − 0.320
(7.62 − 8.128)

20° ± 1°

0.130 ± 0.005
(3.302 ± 0.127)

95° ± 5°

0.125 − 0.140
(3.175 − 3.556)

0.020
(0.508)
MIN

0.009 − 0.015
(0.229 − 0.381)

0.125
(3.175)
DIA
NOM

0.065
(1.651)

90° ± 4°
TYP

0.325 +0.040
−0.015

0.018 ± 0.003
(0.457 ± 0.076)

8.255 +1.016
−0.381

0.100 ± 0.010
(2.540 ± 0.254)

0.045 ± 0.015
(1.143 ± 0.381)

0.060
(1.524)

0.050
(1.270)

N08E (REV F)

Dual-In-Line Package (N)
Order Number LM741CN
NS Package Number N08E

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)
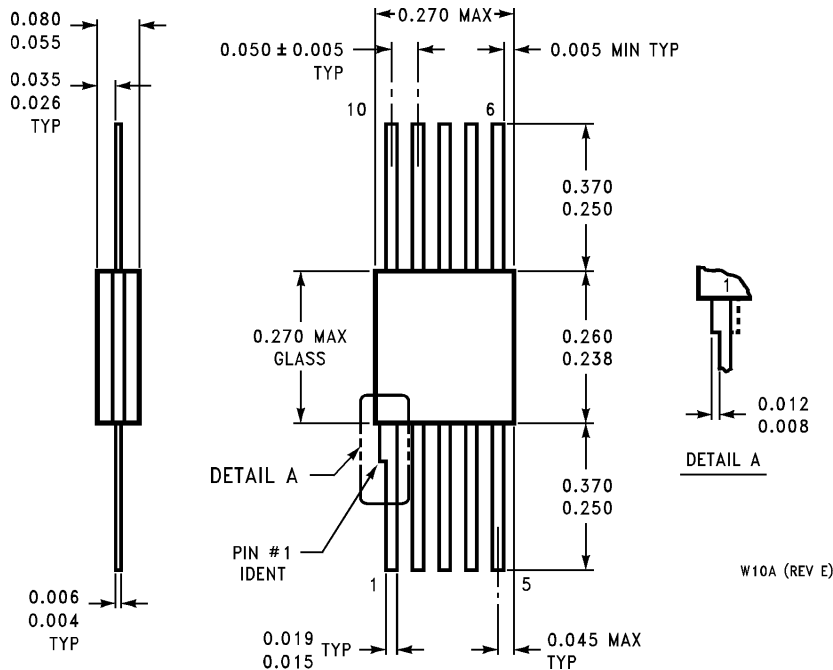
10-Lead Ceramic Flatpak (W)
Order Number LM741W/883, LM741WG-MPR or LM741WG/883
NS Package Number W10A

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

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EXPERIMENT 6

Computer Analysis

GOAL

To become familiar with the computer analysis of circuits.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to use PSpice to:

- Model and analyze DC resistive circuits.
- Model and analyze DC circuits with dependent sources.
- Determine the Thevenin Equivalent Circuit of a complex circuit.

BACKGROUND

Read: • Online tutorials of OrCAD Capture and PSpice.
- Alexander and Sadiku, 3e or 4e (not 5e): "Appendix D: PSpice for Windows" (up to and including "D.3 DC Analysis", pp. A-21 to A-28). The 5e indicates there is a PSpice tutorial online at www.mhhe.com/alexander, but I have not found it.
- The 5e's Example 4.14 shows a PSpice setup with a dependent source.
- Tront, Joseph, G., *PSpice for Basic Circuit Analysis*, Ch. 1-3.
- Experiments 2 (Parallel Circuit) and 3 (Superposition); Problems 4.57 and 5.38 (3e, 4e, 5e)

As you have discovered, large and/or complicated circuits can be difficult and time-consuming to analyze by hand. In the *design process* (actually coming up with circuits that do what you want), you may need to go through many design iterations before the design is complete and ready for production. The design process requires many rounds of analysis: from rough calculations of the overall system to detailed calculations that ensure every component is the right one so that the system can finally be mass-produced. Many lengthy but similar analyses may need to be performed.

Circuit analysis (and any engineering discipline) is based on physical laws and mathematical rules, no matter how complex the circuit may seem. Such an analysis can be automated with a computer. The computer is therefore a powerful engineering **tool**, as it can perform many calculations in a very short amount of time.

In this experiment, you will learn how to use the computer software PSpice to analyze several circuits, some that we have already studied in lab. We will also consider circuits that are more complex, with components that we would otherwise have difficulty accessing in a first undergraduate lab course (e.g., circuits with dependent sources).

WARNING! No matter how wondrous or magical computer programs may seem, they are **only tools** to help you get work done. Tools in the hands of someone who does not know how they work are not very useful, and possibly dangerous. Almost anyone can operate a computer program by reading the manual and inputting data. To properly deal with the input and output requires experience, practice and education.

As engineers, when using computing tools, we should <u>at least</u>:

(1) have an idea of how the program works (the physical and mathematical modeling behind it);

(2) have a rough idea of what values are to be expected as output; and

(3) understand the implications of various outputs; i.e.: be able to interpret the results, and understand how the results can be used to make better designs.

The first point means that the *physical* and *mathematical theories* of circuit analysis must be understood, and how both are modeled in the software (not necessarily the nuts and bolts of the programming language; that is important for other engineers and programmers to know. However, knowing how to program in general is an important skill for engineers to have.).

The *limitations* of a program must also be understood, or results achieved beyond the program's capabilities may be used to make bad, if not fatal, design decisions. While many people can be taught to use a structural analysis program, I am sure that you do not want "just anybody" to be designing and analyzing bridges, buildings and aircraft structures.

The second point implies that we should be able to estimate, even for complicated circuits, what the solution will be, even if it is just a rough *order of magnitude* calculation. In other words, we should not be too surprised by the output. If we are, something is wrong with the original circuit itself or with the computer model. Or we may need to go back and study the theory a bit more; perhaps we missed (or misunderstood) something. **Remember, a computer does what we tell it to do, not necessarily what we want it to do**.

Thirdly, once a solution is computed, at minimum, we should be able to verify that it makes sense. Often, a result that is far from the expected answer is evidence that something is wrong with the circuit or the computer model. Someone not familiar with the appropriate theory will be unable to catch such an error. From the results, engineers should be able to determine if a system is acting properly, if components are near failure, or what can be changed to make the system more safe, efficient and robust.

These three points (and more), are why an engineer's education is rigorous and continues throughout his/her career. The computer is but a tool to help gather information and perform calculations; its output must not substitute for human understanding and judgment.

MATERIAL AND EQUIPMENT

- **PC Computer** with **OrCAD Capture** program and **PSPICE Student Version** (current version). Some computers at Allan Hancock College that *should* have PSpice are:
  - Electronics Lab computers;
  - Physics Lab computers;
  - AHC Science Department's Portable Computer Lab computers;
  - MESA computers;
  - In addition, if you purchased (not required) the Tront *PSpice for Basic Circuit Analysis* book**,** the **OrCAD Capture** and **PSpice Student Version** comes with it. You may load it onto your PC or other machine that you have permission to load programs on.

- A **flash drive**, or other rewritable portable storage media to store files.
- Alexander and Sadiku's textbook (3e and 4e: Appendix D, a PSpice Tutorial, optional).
- The 5e's Example 4.14 (PSpice setup with a dependent source, optional).
- Tront's PSpice book (optional).
- Instructions for Engr 171 Experiment 2 and 3.
- Problems 4.57 and 5.38 (3e, 4e, 5e)

Download the current release of OrCAD 17.2 (Capture and PSpice) for free*

The current release of OrCAD 17.2 (and 16.6) can be downloaded here:

> http://www.orcad.com/resources/orcad-downloads

Click on "Download FREE - OrCAD PCB Designer 17.2-2016 Lite" link. A new page will appear asking for information (*Figure 6.1*) Your "Job Title" is "Student."

Or, go directly: http://www.orcad.com/buy/try-orcad-for-free

Request the following download:

- OrCAD 17.2 PSpice Designer Lite Software (Capture / PSpice only, download)
  (64-bit Windows)

OR:

- OrCAD 16.6 Lite Software (Capture / PSpice only, download)
  (32-bit Windows)

Upon submitting the form, you will receive an email from OrCad on how to download the software.

If you also want the PCB (printed circuit board) Designer, select one of the "All products" options.

Download Lite Request

Please fill out all of the fields below to submit your request for OrCAD software. Once submitted, you will receive an email with links to your requested software, so be sure to use an email address you have access to. If you do not receive your email, don't forget to check your spam/junk folders.

First Name *

[   ]

Last Name *

[   ]

Email *

[   ]

Company/University *

[   ]

Job Title *

[- Select -   ▾]

Address *

Country *

[- Select -   ▾]

Phone *

[   ]

Software requested *

☐ OrCAD 17.2 PCB Designer Lite Software (All products, download)

☐ OrCAD 17.2 PSpice Designer Lite Software (Capture / PSpice only, download)

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☐ OrCAD 16.6 Lite Software (All products, download)

☐ OrCAD 16.6 Lite Software (Capture / PSpice only, download)

☐ OrCAD 16.6 Lite Software (All products, DVD mailed)

[Submit]

Figure 6.1

Load the software onto any computer that you have permission to load software onto.

*Note: The free download is not the full version of OrCAD. There are a limited number of nodes and branches in the demo version. However, for the work we have to do in our lab, and for most undergraduate applications, there are more than enough available nodes and branches, etc.

PROCEDURE

Hint: In PSpice, always include a ground node and name it "0" (the number zero). PSpice does *nodal analysis*, so it requires a reference node that is at zero potential. The GND symbol is not automatically at zero.

1. On the **desktop** of a lab computer, create a folder named **engr171_yourname** (e.g., engr171_allanhancock). Save your files here. Better yet, use a flash drive to save files. Temporary files on school computers may be automatically deleted every evening or when the computer shuts down.

   If using your own computer, create a folder in a location that you can remember.

   PSpice creates about 10 small files per circuit model. Each file stores particular information about the circuit: the components; the schematic of the circuit; the type of analysis performed; etc.

   Once you have created and saved a model and analysis, and want to **reopen** it in OrCAD, **open the file with the extension .dsn** (design). The .dsn file will allow you to edit your circuit and perform analyses. Other files only open the circuit schematic, etc.

   It is recommended that you create a <u>new</u> **project** for each problem.

Series Circuit - Walkthrough

2. In lab, your instructor will walk you through opening the OrCAD Capture program, **creating** a 2-resistor series circuit **model**, (such as that in Chapt. 2 of Tront's book), **running a simulation**, **displaying data**, printing, etc.

3. After running the simulation, save it and print it. You should display **voltage, current, and power on the output** schematic (select the "V", "I" and "W" icon buttons).

   You should put your name, the title of the model, and the date in the *title block* in the lower right hand corner of the "page." You can do this by clicking on the text-holders <Text> in the title block and entering the required information. The page layout used in

OrCAD Capture is a typical set-up for engineering drawings – a frame around the figures, with a title block for pertinent information in the lower right corner.

The circuit schematic may be annotated by using OrCAD Capture's text and drawing tools.

Save and Print the Series Circuit. Turn in the printout to your instructor <u>during</u> the lab period.

Parallel Circuit

4. Create and analyze the three-resistor *parallel* circuit from **Experiment 2**, but without the R_o (which was used to control the current in case there was a short). The circuit is shown in **Figure 6.2**; use $v_s = 12.0$ V, $R_1 = 680$ Ω, $R_2 = 1.0$ kΩ and $R_3 = 3.0$ kΩ.

   Display the voltage, current and power results on the schematic.
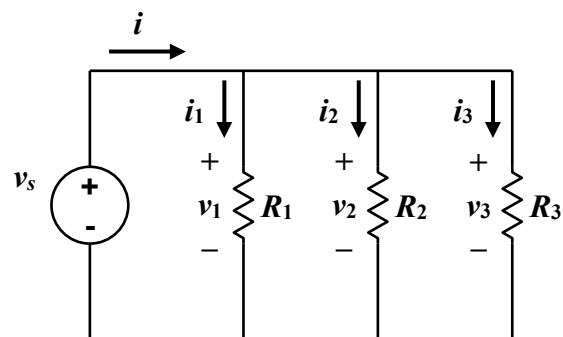
   Save and Print.

Figure 6.2

Superposition

5. Redo *Case I* of *Experiment 3* by building three circuits:

> (1) v_1 only ($v_2 = 0$),
>
> (2) v_2 only ($v_1 = 0$), and
>
> (3) both v_1 and v_2 acting at the *same* time.

Build and run all three circuits on the same screen (page) at the same time. However, make sure you name each voltage source and each resistor with a different name, and that each circuit has a ground ("0") node. If two components in the same analysis have the same name, the computer will be confused; the analysis will not be performed.

Do not just let PSpice name the resistors automatically (R_1, R_2, R_3, … R_8, R_9, …).

Rather, manually name the components systematically, as follows:

> R_{11}: circuit 1, resistor 1;
> R_{12}: circuit 1, resistor 2;
> R_{13}: circuit 1, resistor 3;
> R_{14}: circuit 1, resistor 4;
> R_{21}: circuit 2, resistor 1;
> R_{22}: circuit 2, resistor 2; etc.

In this way, the same resistor can actually be called "R_1" in three different circuits (R_{11}, R_{21}, R_{31}). (Practice presenting information clearly and logically).

Display voltage, current and power results on the schematic.

Save and Print.

Thevenin Equivalent Circuit

6. Do *Problem 4.57* in Alexander and Sadiku (3e 4 or 5e). See *Table 2* in Tront (p. 23) or *Figure D.13* in Alexander and Sadiku (3e or 4e, p. A-28) for which PSpice component to use for the dependent source. Tront *Chapt. 3* will also be useful. Example 4.14 in the 5e uses a dependent source.

The dependent sources are in PSpice's **ANALOG library**.

Use open-circuit voltage measurements and short-circuit current measurements to determine V_{Th} and I_{sc}. Like the Superposition problem, you can build two circuits (one open-circuit, one short-circuit) on the same page and simulate them simultaneously. Name the elements systematically.

Hint: In some versions of PSpice the dependent source value **must be changed in the *property tables* under the GAIN** column. Do not just change the "value" in the pop-up window that appears when you click on the graphic; this might only change the label on the schematic (unlike when clicking on resistors). Double check by looking at the property tables.

Hint: Take care to send the current the correct way (use a negative current to make current flow opposite the arrow).

Hint: PSpice may require a circuit element in a branch to display the current in that branch. For the short-circuit, use a very small resistor (e.g., $R = 0.001\ \Omega$); for the open-circuit, use a very large resistor (e.g., $R = 1\ G\Omega$. Note that PSpice interprets "M" as "milli", not "mega").

Calculate R_{Th}.

Annotate the schematic with the Text Tool to clearly list the values of V_{Th}, I_{sc}, and R_{Th}.

Save and Print.

Operational Amplifier

Do *Problem 5.38* in Alexander and Sadiku (3e, 4e or 5e). Use an ideal op-amp model. The ideal op-amp is in PSpice's **ANALOG library.**

Use the following magnitudes (the 4th and 5th editions only have variables):

$V_1 = 10$ mV	$R_1 = 25$ kΩ
$V_2 = 20$ mV	$R_2 = 20$ kΩ
$V_3 = 50$ mV	$R_3 = 10$ kΩ
$V_4 = 100$ mV	$R_4 = 50$ kΩ
	$R_5 = 50$ kΩ

Take careful notice of the **polarity** of each source.

Display voltage, current and power results.

Save and Print.

WHAT TO TURN IN

Each student **will turn in an individual and original report.** Each report will be **typed, single-spaced, stapled,** and in the **following order:**

1. Answers to the Questions.

On a new sheet:
- In the upper right-hand corner, type:
    your name
    your partner's first name
    Engr. 171
    date lab was completed
- Two lines below the date and centered, type:

    Experiment 6: Computer Analysis

- Answer the *Post-Lab Questions*.

- Answer the questions in complete sentences, and in such a way that the reader does not need to see the actual questions to understand what you are writing about. Each answer should stand on its own; some repetition between answers may be necessary.

- Always introduce a table (or a figure) with words (text) <u>before</u> it appears in the document; e.g., "Table 1 is …"; "The voltage-current response…is given in Figure 1…".

- For clarity, number each answer, and leave two blank lines between answers.

- Use **tables** and **Microsoft Equation (Editor)** as appropriate. Number and title each table in your report. Do not just insert a table, figure or equation without some narrative introducing or describing it, its significance, etc.

- The write-up is intended as a much reduced technical "report", or a set of snippets from a report. As such **use *3rd person*** (the passive voice), and ***past tense*** when describing *what was done in the experiment*. <u>**Do not**</u> **use "I," "we," "you", etc.**

2. Print-outs of the results for all four PSpice circuit simulations that you did on your own (parallel, superposition, Thevenin, Op-Amp). You have already turned in the series circuit analysis.

Make sure that *voltage*, *current* and *power* results are displayed for each component or node of each circuit.

Make sure that the *title block* of each page includes your name, the title of the analysis, and the date on all printouts.

The bottom of each layout should be at the right side of the stapled page/packet.
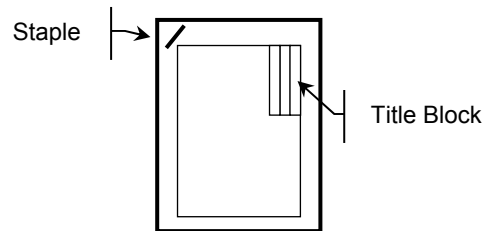
Why? Please see 'Creating Graphs' in the "Introduction" of this manual.

3. Any sheets with hand calculations, etc.

<u>Note:</u> **In your data tables and narrative, use italics and subscripts for variables. Even though PSpice cannot (R1, R2), Microsoft Word can (R_1, R_2).**

Questions on the following page.

POST-LAB QUESTIONS

1. **Parallel Circuit**. Using the analysis results, clearly demonstrate that the power supplied to the parallel circuit equals the power dissipated by its resistors (show the numbers/math in the answers).

2. **Superposition**. Show that the Principle of Superposition is confirmed for:

   2a. Voltage, at **EVERY** node.

   2b. Current, through **EVERY** resistor.

   Use a table to present the data. There should be at least five data columns:

   (1) source v_1 only;

   (2) source v_2 only;

   (3) $v_1 + v_2$ (superimposed; e.g., the numerical sum of Columns 1 and 2);

   (4) v_1 and v_2 acting together; and

   (5) %difference between the superimposed solution, with respect to when the sources are acting together.

   There are 3 node-voltages and 4 resistor currents to consider, so there should be at least 7 rows.

3. **Superposition**. Clearly demonstrate that superposition <u>does not work</u> for <u>power</u>. Consider the power dissipated by only one of the resistors (your choice). Show the math for that specific resistor in the answer.

   Explain *physically* and *mathematically* why, in general, superposition does not work for power.

4. **Thevenin Equivalent**.

   4a. Sketch and label (with calculated values) the Thevenin Equivalent Circuit determined by your analysis.

   4b. Sketch and label the Norton Equivalent Circuit.

   The sketches can be made in OrCAD Capture and copied into your Word document, drawn by hand, <u>or</u> drawn with another computer tool.

   As always, introduce each figure with text before the figure appears; explain what the figure is, its significance, etc. Do not just write "See figure" as the text part of your answer; a figure without explanation is confusing.

5. **Op-Amp Summer**. Verify, by hand, that the summer works for *Part (a)* of *Problem 5.38*. Include your hand-calculations at the end of the packet.

EXPERIMENT 8

Oscilloscope Operation

1/09/17

GOAL

To become familiar with the operation of oscilloscopes and function generators.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Make voltage measurements with an oscilloscope.
- Use the oscilloscope to display different forms and scales of voltage-time data.
- Generate periodic signals with a function generator.

BACKGROUND

See also: • Tektronix's *XYZ's of Oscilloscopes*.

  - Online: http://www2.tek.com/cmswpt/tidetails.lotr?ct=TI&cs=Primer&ci=2280&lc=EN

  - Hardcopy in lab.

  • Oscilloscope Instruction Manual (in lab).

  • Tektronix's Oscilloscope Video (possibly shown to you, or it may be borrowed).

  • Online resources:

  http://www.doctronics.co.uk/scope.htm   (*a good overview, with function generator*)

  http://www.virtual-oscilloscope.com/   (*realistic Shockwave simulation* with same scope as

  Doctronics' tutorial)

  http://www.phy.ntnu.edu.tw/java/oscilloscope/oscilloscope.html   (*a simple Java scope simulation*)

An ***oscilloscope* (scope) is used to measure time-varying electric signals** (waveforms). The standard display is voltage versus time.

In this experiment, you will be introduced to basic oscilloscope operations. It takes time to become familiar with this piece of equipment, so try not to get frustrated.

A simple pictorial of an ***oscilloscope*** is shown in ***Figure 8.1***. The oscilloscope used in lab is a Tektronix 2246A oscilloscope, the front of which is shown in ***Figure 8.6*** (p. 8.7). A scope measures the voltage at a specific circuit node with time, and so it is a valuable tool. As with any tool, the more familiar you become with its abilities and limitations, the more efficiently you will be able to use it.
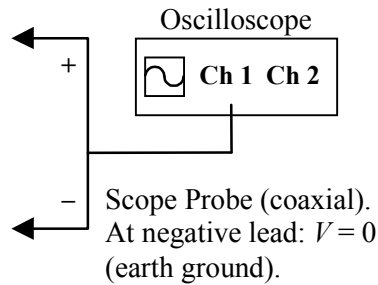
Oscilloscope

Figure 8.1 Simple pictorial of Oscilloscope.

Scopes, however, are not designed to serve as precise measuring instruments. The results can be considered as very good estimates of what is really going on in your circuit. If greater accuracy is required, use other measurement techniques and instruments.

Oscilloscopes, with their many knobs, buttons and switches (*Figure 8.6*) can be quite confusing, if not intimidating. Although there are many different models, all scopes operate on the same, relatively small, set of principles. Understanding these principles will allow you to quickly utilize any new scope.

The web resources listed in the *Background* section provide useful tutorials and simulations for practice. While the simulations do not necessarily use the exact oscilloscopes that are in our lab, the basic operation is the same.

The traditional scope display (screen) is one end of a cathode-ray tube (CRT). The display operates the same way as the picture tube in older television and computer monitors. An electron beam strikes the display, which is coated with phosphor particles. The phosphor glows momentarily when struck by the beam. The phosphor coating is fairly delicate, so **do not let the display get too bright, or you may cause permanent damage to the scope**. Reduce the intensity of the display with the intensity [INT] control knobs below the display.

Modern scopes are digital, but reading the display is the same. The scopes used in Engr 171 have CRT displays.

The operation of a scope can be divided into three basic topics: (1) the **input**, (2) the **vertical**, and (3) the **horizontal**. The input is the instantaneous voltage at a node in the circuit. Typically, the scope displays *voltage* **vs.** *time* on the vertical and horizontal axes, respectively.

The Input

A voltage signal is measured using the oscilloscope's *coaxial probe* (*Figure 8.5*, p. 8.6). **Only use oscilloscope probes with the scopes**. **Do not** use scope probes with other measuring devices, nor with power supplies. Doing so may damage the probes.

Oscilloscopes have at least two input channels, and many have four. This allows several waveforms to be measured simultaneously and compared. Also, it is sometimes useful to plot voltage vs. voltage curves, which requires two input signals.

Displaying the Input

There are three modes to view voltage vs. time on the scope (*Figure 8.2*). It is important that you know and understand the differences.

(1) **GROUND** (both AC and DC Coupling LED indicator lights off) **displays the zero voltage reference level (line)** on the scope display (screen); i.e., no signal is displayed (*Figure 8.2a*).

Since you can move the displayed signal up-and-down, the center of the physical display (screen) is usually not *zero*. The display (screen) is basically a "window" that looks onto the total graph of the signal. By selecting **GROUND**, the display plots where the $V = 0$ line is currently located. The ground reference line may or may not be visible (you may be looking at a portion of the graph not near $V = 0$). The reference line can be made visible by adjusting the **VERTICAL POSITION** [↕] knob. This feature allows you to set where on the display will be $V = 0$. It is usually a good idea to align the reference line with one of the horizontal lines printed on the screen.

(2) **AC COUPLING** (AC Coupling indicator on) displays **<u>ONLY</u>** the *time-varying* (periodic) *part of the signal*; the DC (average) component of the signal is removed (*Figure 8.2b*).

(3) **DC COUPLING** (DC Coupling LED indicator on) displays the *total signal*. The total signal is the average signal (the DC part), plus the time-varying signal (the AC part) (*Figure 8.2c*).

Any periodic signal can be expressed as a constant (DC) part plus a time-varying (AC) part. As an everyday example, if someone asked you for the temperature at noon on the first day of every month in Santa Maria, you might say that *on average*, it is $T_{ave} = 70°F$ (a good estimate); **this is the DC part**. Temperature varies from the average with time: higher in the summer, lower in the winter, and is periodic with a period of 1 year. **The variations are the "AC part."** If the actual temperature is plotted against time to give a *T* vs. *t* curve, this would be **DC Coupling** (the constant plus time-varying signals). If only *the variation of the temperature from average* against time is plotted to give a ΔT vs. *t* curve (where $\Delta T = T - T_{ave}$), this would be **AC Coupling** (only the varying part is plotted).

In electrical circuits, **AC signals** are *periodic*, such as a sine wave (or combination of sine-waves), a square-wave, a saw-tooth wave, etc. In general, any periodic signal can be reconstructed as an (infinite) sum of sines and cosines using the *Fourier Series*.

The Display (the Screen)

The CRT (Cathode Ray Tube[1]) display shows a voltage vs. time graph of the incoming signal. Most oscilloscopes can also display voltage on both axes. In a CRT display, an electron beam hits the screen, which is coated with phosphor. The phosphor glows briefly when hit by the beam. The vertical deflection of the beam is caused by – and is thus a measure of – the incoming voltage signal.

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[1] For a brief summary of CRT displays, see:
http://electronics.howstuffworks.com/tv3.htm

(a)

(b)

(c)
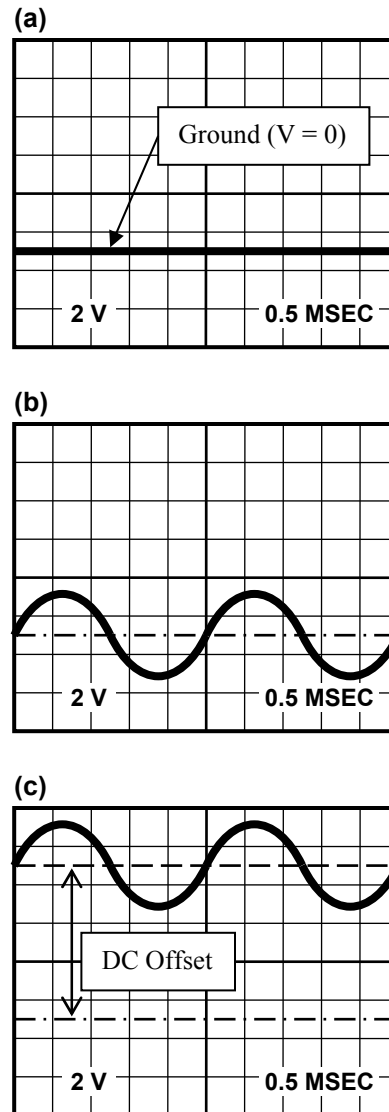
Figure 8.2 Displaying a signal. Vertical and horizontal scales (sensitivities) are displayed at lower left and lower right of the display (screen). Here, each vertical division (square) is 2 volts (2 V/div); each horizontal division is 0.5 msec.

(a) GROUND only. No signal; only the V=0 reference line is displayed. Here, the reference line is positioned in the lower part of the display (2.5 divisions below the bottom).

(b) AC Coupling displays only the time-varying part of signal; the signal oscillates about zero. The amplitude of this sine wave is 1 division or 2 V (since the sensitivity is 2 V/div.).

(c) DC Coupling displays the total signal – the constant (DC) part <u>and</u> the time-varying part. The <u>DC offset</u> of this signal is 4 divisions, or 8 volts. Thus the total signal is $v(t) = 4 + 1\sin\omega t$ divisions, or in real units, $v(t) = 8 + 2\sin\omega t$ V;

The beam moves across the screen from left to right with time.

The typical oscilloscope display is an 8×10 rectangle – 8 *divisions* (squares) tall by 10 *divisions* (squares) wide (*Figure 8.2*). Each division (square) is further divided by tick marks into fifths. Depending on the *vertical scale setting* or *sensitivity* (volts per division), the total height of the display may represent 8 V (1 V/div), 16 V (2 V/div), 4 V (0.5 V/div), etc. Depending on the *horizontal scale setting* or *sensitivity* (time per division), the total width may represent 1.0 seconds (0.1 sec/div), 5 msec (0.5 msec/div), etc. The scales (sensitivities) are shown in the lower corners of the display (*Figure 8.2*).

Note that although the center lines printed on the display screen are thicker than the others, they do not represent the zero point (origin) of the signal. The display is simply a "window" onto the entire voltage-time graph.

By knowing the scale settings you should be able to determine voltage values, the period and frequency of signals, etc., just by reading the display graphically.

The Vertical Axis ("y-axis" or ordinate)

The vertical displacement of the electron beam on the display (screen) depends on the input voltage and the *vertical sensitivity setting* (*scale*). If the sensitivity setting is 1 volt/division, then a 1.0 V signal will displace the electron beam 1 division from the reference level. The screen, being 8

divisions tall, would be 8 V from top to bottom. If the sensitivity is 0.5 V/div (i.e., 1 V per 2 div), then a 1.0 V signal will displace the electron beam 2 divisions from the reference level; the display would be 4 V tall (8 divisions, 0.5 V/div).

The vertical sensitivity is set with the **VOLTS/DIV knob**, and its value is displayed in the lower left corner of the screen (*Figure 8.3a*, "1V"). By rotating the **VOLTS/DIV knob**, you can *zoom in* or *zoom out* on the actual signal. When you change the vertical sensitivity, you change how you see the signal through the display window. If you *zoom in* (e.g., from 1V/div to 0.5V/div), you double the height of the signal as it appears on the display (illustrated in *Figure 8.3b*). Zooming in helps to see details (e.g., a pick-off-point, where the signal intersects a printed line on the display), but you might end up looking at nearly-vertical lines if the new setting grows the signal's appearance beyond the display.

You may vertically reposition the signal on the display by using the **VERTICAL POSITION [↕]** knob.

Important Note: When you adjust the scope settings, you are <u>not</u> changing the signal (waveform); you are only changing its appearance, i.e., how/where you are viewing the signal (you are changing/moving the "window" that looks onto the waveform). The oscilloscope <u>measures</u> the signal; it does not create the signal.
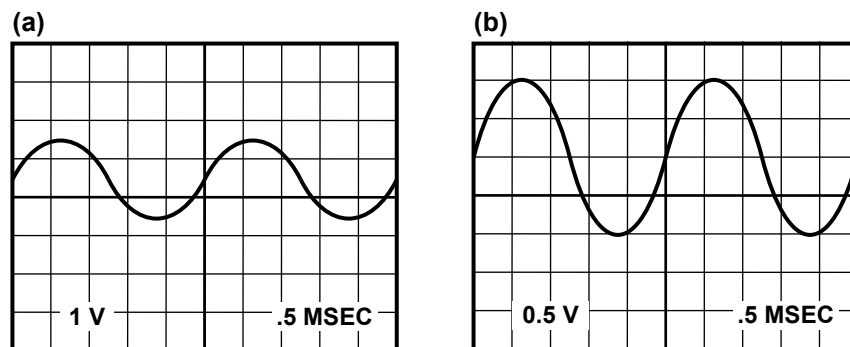

Figure 8.3. By rotating the VOLTS/DIV dial, you can zoom in (out) on a signal. Representation of *zooming in* by changing the voltage scale (vertical sensitivity) from: **(a)** 1V/div. to **(b)** 0.5 V/div.
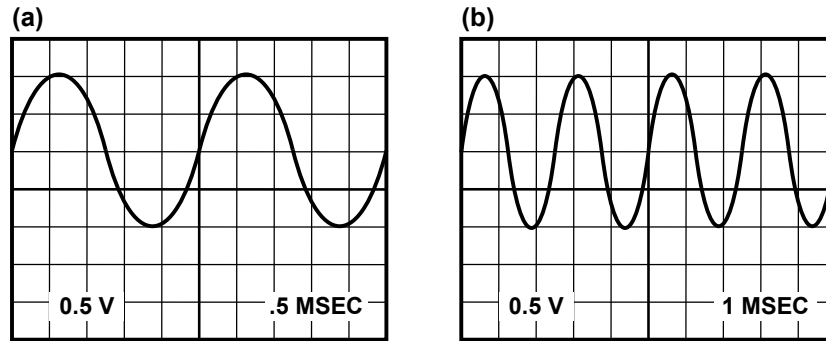
Figure 8.4. By rotating the SEC/DIV dial, you can stretch or compress the signal. Representation of compressing the display by changing the time scale from **(a)** 0.5 msec/div to **(b)** 1.0 msec/div.

You will sometimes display two input **CHANNELS** (signals) on the screen at once. The channels can be set to the **same** or **different scales**. **A different reference line** (ground) can be set/displayed for each channel. **Take care that you know the scales and where the zero of each channel is located**.

When first looking at two signals, make sure to use the same scale for both channels (so you can clearly interpret their relative sizes). You do not want to mistake a smaller signal for a larger one. When you know which signal is which, then you can change their scales to better view each signal.

The **VERTICAL POSITION** knob for each channel can be used to move two signals away from each other so you can see each individually. Or, you can display two signals on top of each other – with coincident zero-reference lines – for direct comparison (although it may be difficult to tell them apart on a CRT display; modern LED/digital displays have different colors for each channel).

The Horizontal Axis ("x-axis" or abscissa)

The scope provides internal circuitry that plots the vertical deflections of the electron beam as a **function of time**. The scope must move the electron beam horizontally at a selectable steady rate, while deflecting the beam vertically proportional to the signal voltage. The horizontal rate is controlled by the *horizontal sensitivity setting*.

The scope scans the beam from left to right on the display repeatedly. The scope must therefore restart the electron beam at the left of the display at the same spot on the waveform **every time** it scans, otherwise the display would be a confusing blur. This is referred to as *triggering*. The beam is triggered – caused to begin – at the same place on the waveform.

The *horizontal sensitivity* is set with the **SEC/DIV knob**, and its value is displayed in the lower right corner of the screen (**Figure 8.4a**, 0.5 msec per division). Like the vertical scale, the horizontal scale can be set, e.g., 10 msec per division, 5 msec per division, etc. The appearance of the signal can then be stretched or compressed horizontally (**Figure 8.4**).

You may also reposition where the signal starts on the display by using the **HORIZONTAL (TIME) POSITION** [↔] knob.

The time scale is the same for all displayed signals.

Hint: Perhaps the best way to look at a periodic signal is to display more than one but less than two periods. Thus, the time scale is as large as possible while still allowing observation of the entire waveform. If you try to display too many periods, it will be difficult to discern the details of the waveform.
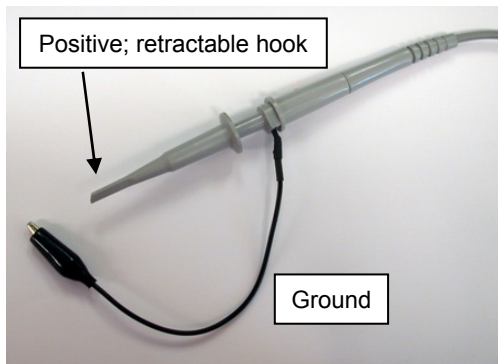
Figure 8.5 Oscilloscope probe. Only use this probe for scope measurements.

WARNING: The negative terminal of any scope probe is at the same potential (voltage) as earth (ground, V = 0). Wherever you attach the negative lead of a probe to the circuit, that point in the circuit will be at V = 0. If you attach the negative leads of two different oscilloscope probes to two different nodes in your circuit, BOTH those nodes will be forced to zero volts (ground)! You have likely shorted out part of the circuit. You probably do not want that to happen.

Be especially careful when measuring the voltage across an internal component – a component where neither of its nodes is supposed to be at the circuit's ground. Two channels are needed to measure the voltage across such a component.

Probes

The scope uses specially designed probes (*Figure 8.5*) that minimize the effect the scope has on the circuit being measured. **Only use the oscilloscope probes with the scope.**

CAUTION: Do not use the oscilloscope probes with other measurement equipment, or to supply power to a circuit; you will damage the probes.

Grounding

Oscilloscopes are internally grounded (earth grounded). The negative lead of the probe is at earth ground (V = 0). Thus, the *reference* or *ground connection* of one scope probe is also the reference for any other probe. Scopes often have two or more channels that can be displayed simultaneously. It is only necessary to use one probe's ground connection to establish the zero reference voltage in the circuit.

The oscilloscope's grounding set-up is unlike that of a digital multimeter. The DMM voltage measurements are *floated* – it is the voltage drop across a component that is being measured, not the absolute voltage. Oscilloscope measurements are made with respect to a fixed reference – earth ground (V = 0); all negative leads of a scope are grounded; the positive lead measures the "absolute" voltage at a node. Do not ground two different nodes in a circuit with two scope leads.

Numerical Display Tools

The scope can provide graphical data and numerical data. You should be able to read the signal *graphically* to measure a period of about 10 msec, or you can press a few buttons to display that the period is, more precisely, "10.125 msec". The oscilloscopes in the lab can display *numerical* values for: DC (average) voltage, positive-peak (V_p, most positive) voltage, negative peak ($-V_p$, most negative/least positive) voltage; Peak-to-Peak Voltage (V_{p-p}, the difference between positive and negative peaks), etc. Numerical values can also be displayed for period, frequency, phase angle, etc.

Numerical displays will be part of the experimental procedure of this experiment. Explore these.

NOTE: Every Engr. 171 student should be able to read the voltage and time data from the *graphical* display.

Display and Control Areas

Figure 8.6 identifies some of the common oscilloscope knobs, buttons, etc., that you will use in lab.
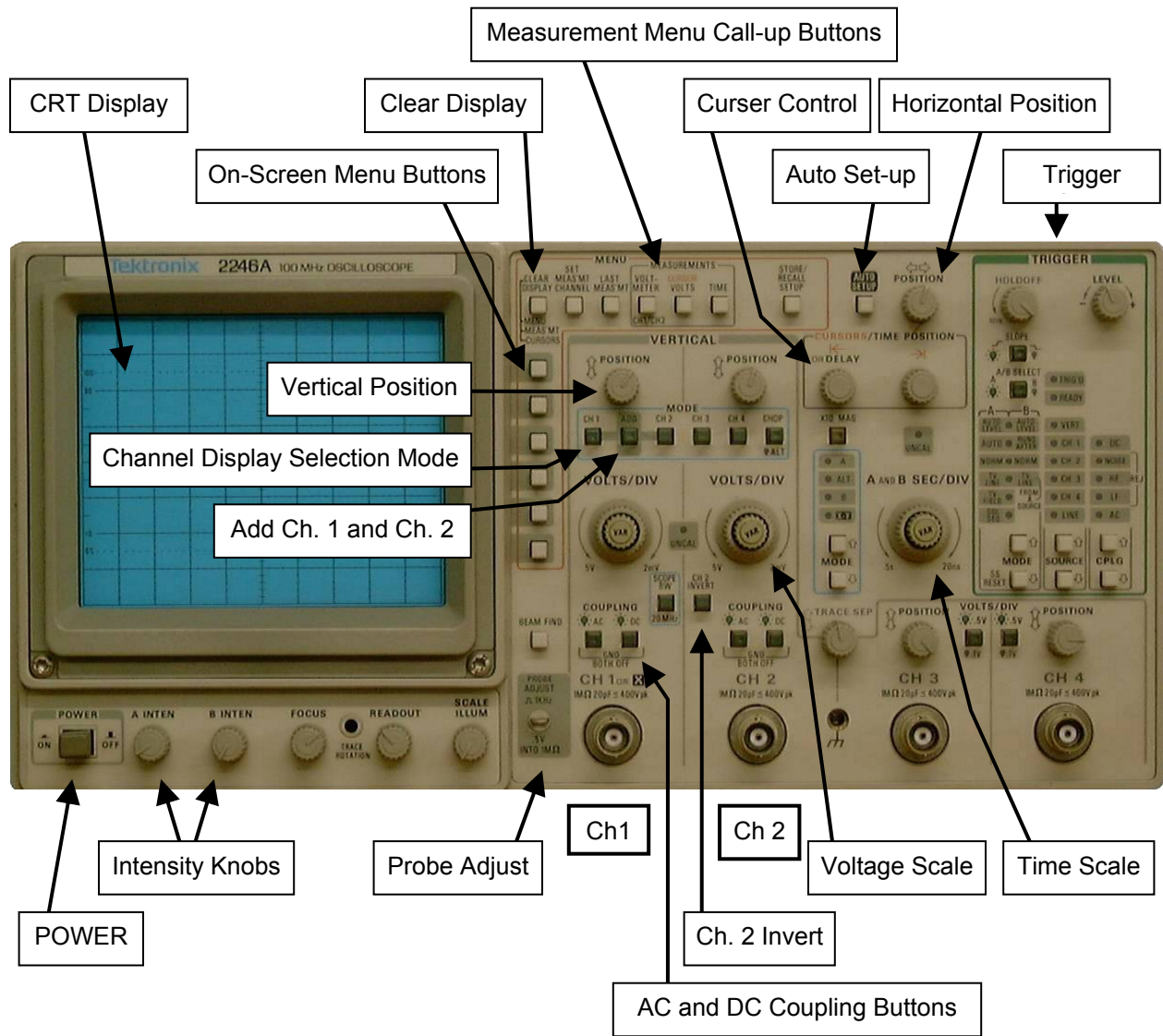

Figure 8.6 Tektronix 2246A 100MHz Oscilloscope: Knobs, buttons, etc. This is the scope used in ENGR 171.

Picture from: http://www.mb-radio.co.uk/frames/oscilloscopes/hires/tek_2246a.jpg   Accessed July 23, 2008.

NOTE: **AHC has new Function Generators which will be explained during lab, if needed**. They do not have LED displays. However, read this page as an intro to what function generators do.

FUNCTION GENERATOR: Wavetek Synthesized Function Generator Model 23

WARNING: For the output of a function generator, use the coaxial-to-mini/easy-grabber (or alligator) test leads with the **"50 Ω" label** on them. If such leads are not available, the function generator may be supplying about twice the voltage that it is displaying. In either case, **ALWAYS MEASURE** signals with an oscilloscope or a DMM.

Figure 8.7 Wavetek Synthesized Function Generator Model 23.

Function generators (FG) provide periodic signals such as sine waves, square waves, sawtooth waves, etc. They can also provide constant (DC) signals, etc.

DC (constant) and AC (periodic) signals may be applied simultaneously. The DC signal is referred to as the *DC Offset*, of just *Offset*. The *DC Offset* is the *average value* of the signal. An AC-only signal oscillates around zero (its *average* value). The DC Offset moves the AC signal up or down. The total signal is the sum of the DC and AC parts.

There is only so much power available to the FG. You will not be able to "max-out" the DC output and the AC amplitude at the same time.

The circular frequency f (in Hz) of a signal can be varied from several cycles per second (e.g., 50 Hz, where 1 hertz = 1 Hz = 1 cycle/sec), to many millions of cycle per second (e.g., 10 MHz). For best measurements, keep the output between 100 Hz and 50 kHz.

Angular frequency (rad/sec) is $\omega = 2\pi f$. The period is $T = 1/f$.

The four main buttons on the Wavetek Function Generator Model 23 (*Figure 8.7*) are: "**Freq/Period**," "**Amplitude**" "**Mode-Func**" and "**Offset**." The **knob** at the upper right of the FG is used to change the values of these different quantities. The **arrow buttons** below the Mode-Function button can also be used to change values.

Buttons

Freq/Period:

Toggles between *Period/Frequency* of signal. Change the signal's frequency (or period) by rotating the knob or pressing the arrow buttons.

Amplitude:

Magnitude of alternating (AC) signal. Press button to scroll through: *Vpp* (Peak-to-Peak), *Vp* (max positive voltage, i.e., amplitude); *Vrms* (root-mean-square), and *Vdb* (decibels). Change value by rotating the knob or pressing the arrow buttons.

Mode-Function:

Select waveforms with the knob or arrow buttons (sine, square, sawtooth, DC, etc.).

Offset:

Select DC Offset (average voltage) by rotating the knob or pressing the arrow buttons. For pure AC signals, the DC output must be set to zero.

Output

The signal output is taken from the coaxial terminal at the lower right hand corner of the FG. Use the coaxial cables labeled "50Ω". The FG assumes a 50Ω load will be connected to it. If you do not have a 50Ω cable (or a faulty one), your actual output will be roughly twice that on the FG display. **Always measure** the FG output with the oscilloscope or DMM.

MATERIALS and EQUIPMENT

- 1   Oscilloscope (scope), Tektronix 2246A
- 1   Function Generator (FG) (e.g., Wavetek 12 MHz Function Generator Model 23, or alternate)
- -   various cables and test leads (banana plug-alligator clip cables, oscilloscope probe, FG coaxial lead)
- -   various jumper wires

PROCEDURE

Every step in this experiment is meant to help you learn to use the oscilloscope. Do not skip steps. Think about what's going on with every action. You should have a good idea of the basic operation of a scope when you leave the lab. *Experiment*. If you are unsure about what you are doing, ask your instructor for guidance.

> **CAUTION**: If, on the oscilloscope **VOLT/DIV** knobs, an **orange UNCAL (uncalibrated) light** is on, you will get incorrect readings. Turn the "VAR" knob all the way clockwise (until it "clicks" and the UNCAL light goes off).

1. Turn on the oscilloscope and display a *horizontal trace* (voltage-time image) on **Channel 1**. The only **Mode button** that should be lit is "**CH 1**".

2. Connect a *scope probe* to the scope's **CHANNEL 1** co-axial cable input port. Hook the *positive* tip (retractable hook) of the probe onto the metal **PROBE ADJUST** tab on the scope (a small tab with a hole near the lower right of the scope display). Be careful not to damage the scope probe.

3. Adjust the scope settings so that you see a *trace* (curve) that looks like a square wave that fits in the display. Adjust the vertical sensitivity with the **CH 1** "**VOLTS/DIV**" knob. Adjust the horizontal sensitivity with the **"A and B SEC/DIV**" knob. The volts per division setting appears on the lower left of the display; the time per division setting appears on the lower right. Use the **VERTICAL POSITION** [↕] knob to move the signal up and down as needed.

4. Use the **FOCUS** and **INTEN** knobs under the display to focus and reduce the screen's intensity (glow). **Turn down the intensity of the display so that it is not too bright.**

5. Describe the *shape* of the signal. Align the bottom of the signal with one of the horizontal lines printed on the screen. From the *scales* (volts/division and sec/division sensitivities), and the printed divisions on the display, determine the *peak-to-peak voltage* (total height) of the signal and its *period*. Calculate the *frequency*. Record the values in *Table 8-1*.

   Hint: count the number of divisions (squares) tall the signal is, including decimal divisions, and multiply it by the **volts/div setting**. Count the number of divisions wide that one period is, and multiply it by the **sec/div setting**. The signal can be moved up/down and left/right using the **VERTICAL POSITION** [↕] and **HORIZONTAL POSITION** [↔] knobs. This lets you start a measurement at one of the printed lines on the display.

   Note: the lowest point of the actual PROBE ADJUST signal is at V = 0 (ground).

6. Remove the probe from the PROBE ADJUST tab.

7. Next, try touching the positive probe tip with your finger(s). Your body acts like an antenna – the strongest incoming signal is usually from the building's 60 Hz AC power (e.g., the lights, wall plugs, etc.). People will get different readings depending on how good an antenna they are. Record the *shape*, *peak-to-peak voltage*, *period* and *frequency* of the signal in *Table 8-1*.

Note: The human antenna signal is not very stable. To make it more stable, in the TRIGGER area at the right side of the scope, select LINE in the SOURCE column.

8. Connect a coaxial cable with two output leads (and a 50Ω label, if available) to the output of the **Function Generator** (FG). Connect the positive lead of the scope probe to the positive (red) lead of the FG. Connect the negative (black) leads together.

   For the FG, use the leads labeled 50 Ω. If these leads are not available (and even if they are), the output may be twice as large as the FG display reports. **Always** use the scope to verify the FG output. **Always measure**.

9. Experiment with different settings on the FG and the scope to familiarize yourself with the FG and scope. The FG can output various periodic signals (sine waves, square waves, sawtooth waves, etc.), with various amplitudes and frequencies, with or without a DC offset (non-zero average value).

   Create different signals with the FG. Observe the various signals with the scope at various display settings (**GND**, **AC Coupling**, **DC Coupling**), and different scales. Recall that earth ground **GND** is the V = 0 reference line.

10. Using the FG, replicate the signal from the PROBE ADJUST tab, and display it on the scope.

11. Ask your instructor to verify that you have replicated the Probe Adjust signal with the FG. **The instructor to initial the appropriate box in *Table 8-1***. The instructor may also ask you to create other signals (so experiment, as discussed in **Step 9**).

Exploring Oscilloscope Control Knobs

12. Consider the mathematical function:

$$v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right] \text{ V} \qquad (8.1)$$

   From the equation for $v(t)$, determine v_{max} and v_{min}. Record them in ***Table 8-2a***.

13. Attach scope **CHANNEL 1** ("**Ch 1**") to the FG, and perform the following steps and answer the following questions in ***Table 8-2***.

14. Using the function generator, generate the electric signal (the function):

$$v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right] \text{ V} \qquad (8.1)$$

   The value of "2.0" is the DC Offset. The value of "3.0" is V_p (the maximum positive voltage) for the AC signal. Equivalently, use 6.0 V$_{pp}$ (*peak-to-peak*).

   The frequency of the signal is 500 Hz (hertz). In the equation, 500 Hz is multiplied by 2π to get radians/sec. The FG automatically does that for you (the FG frequency is in Hz).

15. On the scope, set the **VOLT/DIV** sensitivity to 2.0 V/DIV. For this set-up, *how many divisions equal 1 volt*? Record in ***Table 8-2a***.

16. Set the **SEC/DIV** sensitivity to 0.5 mSEC/DIV. For this set-up, *how many divisions equal 1 second*? Record in ***Table 8-2a***.

17. Select **GROUND Coupling** (both AC and DC coupling LED lights off). This displays a horizontal line representing **V = 0**. Turn the VERTICAL POSITION [↕] knob so that the horizontal line is aligned with the center horizontal line **printed** on the display.

18. Press **AC Coupling**. This displays the time-varying part of the signal. Using the FG, if necessary, adjust the amplitude of the signal so that it is 3.0 V$_p$ or 6.0 V$_{pp}$. *How many divisions tall (from top to bottom) is the signal*? *How many volts*? Record in ***Table 8-2a***.

19. *What is the period of the signal measured in divisions? Measured in milliseconds*? Record in ***Table 8-2a***.

20. Press **DC Coupling**. Using the FG, adjust the offset to 2.0 V (the constant term of **Equation 8.1**). As you increase the DC component from zero to 2.0 V, the signal should move up 2.0 V on the display compared to AC Coupling.

    DC Coupling displays the total signal: the DC part (2.0 V) plus the AC part ($3.0\cos\left[2\pi(500)t\right]$ V).

21. **Ask your instructor to verify that you have generated the signal** in **Step 14** and then to initial **Table 8-2a**.

22. Make sure that the sensitivities of the scales are still at 2.0 V/DIV and 0.5 mSEC/DIV.

23. Turn the **VOLT/DIV** knob one click clockwise. *Describe what happened to the appearance of the signal. What is the new VOLTS/DIV setting*? Record in **Table 8-2b**.

24. Return the sensitivities of the scales to 2.0 V/DIV and 0.5 mSEC/DIV.

25. Turn the **VOLT/DIV** knob one click counterclockwise. *Describe what happened to the appearance of the signal. What is the new VOLTS/DIV setting*? Record in **Table 8-2b**.

26. Press **AUTO SET-UP**. This should reposition the signal in the display. The scope will automatically chose appropriate VOLTS/DIV and SEC/DIV settings.

27. Select **GROUND Coupling**. Turn the **VERT. POSITION** knob [↕] so that the ground signal is 2 divisions from the bottom of the display (6 divisions from the top). This is your new zero. Moving the reference line allows you make effective use of the display.

28. Set the voltage scale to 1.0 V/DIV and the time scale to 0.5 mSEC/DIV. Note the new voltage sensitivity.

29. Select **DC Coupling** to view the entire signal.

30. Turn the **SEC/DIV** knob one click clockwise. *Describe what happened to the appearance of the signal. What is the SEC/DIV setting*? Record in **Table 8-2b**.

31. Return the sensitivities of the scales to 1.0 V/DIV and 0.5 mSEC/DIV.

32. Turn the **SEC/DIV** knob one click counterclockwise. *Describe what happened to the appearance of the signal in the display. What is the new SEC/DIV setting*? Record in **Table 8-2b**.

33. Repeat **Steps 27** and **28**, if necessary (ground, 1.0 V/DIV, 0.5 mSEC/DIV).

Exploring Scope Menus/Measurements

We will now use the scope to display numerical values. **You should still be able to read the signal graphically** (e.g., if the voltage sensitivity is 5 V/DIV and the signal is 2.4 divisions peak-to-peak, then you should be able to say that the signal is 12 V peak-to-peak).

Voltage Measurements

34. In the **MENU/MEASUREMENT AREA** at the top center of the scope itself, press **VOLTMETER**. A menu will come up on the display. Menu choices are selected with the **MENU SELECT** Buttons just to the right of the display. The choices are :

Menu Selection	Variable	Description
DC	V_{DC}	Measures DC (average) voltage of signal.
+PEAK	$+V_p$	Measures most positive voltage of <u>displayed</u> signal w.r.t. ground (it displays different values if DC or AC Coupling is selected).
–PEAK	$-V_p$	Measures most negative voltage of display.
PK-PK	V_{pp} $=+V_p-(-V_{p})$	Measures peak-to-peak height of signal (i.e., highest to lowest point).
SELF-CAL	-	Voltmeter calibrates itself.
(TO-GATED MEASMT MENU)	-	Beyond scope of course.

35. To clear the numerical data, press **CLEAR DISPLAY**; pressing more than once might be necessary.

36. The settings should still be at 1.0 V/DIV and 0.5 mSEC/DIV. Select **GROUND** and move the reference line to 2 divisions above the bottom.

37. Make sure the FG continues to supply the signal of **Step 14**, repeated here:

$$v(t) = 2.0 + 3.0\cos[2\pi(500)t] \text{ V} \qquad (8.1)$$

38. Select **DC Coupling**. Verify with the scope that the FG is supplying the correct signal.

39. Select **VOLTMETER/DC**. Record the value in *Table 8-3*.

40. Select **VOLTMETER/+PEAK**. This should be the largest value that the signal reaches. Record in *Table 8-3*.

41. Select **VOLTMETER/–PEAK**. Record in *Table 8-3*.

42. Select **VOLTMETER/PK-PK**. Record in *Table 8-3*.

43. Turn the **VOLT/DIV** knob so that graph of the signal is now too large for the display (e.g., turn to 0.2 V/DIV). *What message does the scope display*? Record in *Table 8-3*.

44. Select **AC Coupling**, and repeat **Steps 39 to 42**. To view the signal in on the screen, you may need to select **GROUND** and move the reference line towards the center of the display, and reselect **AC Coupling**.

Voltage Cursors

45. Press **MENU/MEASUREMENT/CURSOR VOLTS**. A menu appears with choices:

Menu Selection	Description
│←VOLTS→│	Brackets signal with horizontal cursors at +*Vp* and –*Vp*. Cursors may be moved vertically using the two TIME POSITION knobs. Position both cursors with time position knob "│← OR DELAY". Position right cursor with "→│" knob.
╥ VOLTS →│	Brackets signal with horizontal cursors at ground and +*Vp*. Cursors may be moved using TIME POSITION knobs.

46. The sensitivities should still be at 1 V/DIV and 0.5 mSEC/DIV. Select **GROUND** and move it to 2 divisions from the bottom.

47. Select **DC Coupling**.

48. Select **CURSOR VOLTS/│← VOLTS →│.** Experiment with the **Time Position** knobs.

49. Select **CURSOR VOLTS/ ╥ VOLTS →│.** Experiment with the **Time Position** knobs.

Time Cursors

50. Press **MENU/MEASUREMENT/TIME**. A menu appears with choices:

Menu Selection	Description
│←SEC→│	Measures time between vertical cursor lines (the default is one period). Position both cursors with time position knob "│← OR DELAY". Position right cursor with "→│" knob.
│←1/SEC→│	Measures frequency of vertical cursor lines (inverse of period). Position cursors with TIME POSITION knobs.
│←PHASE→│	Calls up lower level menu for phase measurements. 360° is one period, and must be "set." Position cursors with TIME POSITION knobs. Very valuable when finding the *phase difference* between two signals.
(TO RISE/ FALL MENU)	Beyond scope of course.
(TO PROP DELAY MENU)	Beyond scope of course.
(TO TIMER CONTROL MENU)	Beyond scope of course.

51. Select **TIME/│← SEC →│**. Experiment with time position knobs. By moving only the right cursor, you can measure the time that an incident occurs after the left (start) cursor.

52. The display should still be showing the equation:

$$v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right]\ \text{V} \qquad (8.1)$$

Using the cursors, measure the time between a *maximum* and the next *minimum* of the signal – the *half-period*. Record in *Table 8-4*.

53. Select **GROUND**, and position the reference line on one of the display's **printed horizontal graph lines**. This printed line is – for now – the level for V = 0 (ground).

Select **AC Coupling**. The displayed signal should oscillate evenly about the selected horizontal line (ground).

Select **TIME/│← SEC →│**.

Move both cursors at the same time so that the left cursor passes through the intersection of the ground line (the printed horizontal line corresponding to V = 0) with the increasing sine wave. Next, move only the right cursor so that it passes through the sine wave's next intersection with the ground line (the sine wave is decreasing). Measure and record this time in *Table 8-4*.

54. *Which measurement technique –* **Step 52** *or* **Step 53** *is, in general, a better method to measure time differences*? *Explain why or why not.*

55. Select **TIME/│← 1/SEC →│**. Experiment with the time position knobs.

56. Select **TIME/│← PHASE →│**. To ensure that a full period is set to 360° as it should be, display at least one period of the signal, and select "Set 360°". Experiment with the time position knobs.

57. Repeat **Step 53**, but for the **PHASE** angle. Measure and record the phase angle in *Table 8-4*.

Time Measurements

58. Press **COUNTER/TIMER**. A menu appears with choices:

Menu Selection	Description
FREQ	Measures frequency of selected signal.
PERIOD	Measures period of selected signal.
WIDTH	Measures width of selected signal.
TOTALIZE	Beyond scope of course.
FREQ RATIO	Measures the frequencies of two input channels and displays their ratio. If only one signal is displayed, value is 1.
(TO GATED MEASMT MENU)	Beyond scope of course.

59. Select **COUNTER/TIMER/FREQ** on the scope; this will measure the frequency of the signal. With the FG, modify the signal's frequency. What happens to the value on the scope display? Does the frequency automatically update?

60. Set the frequency on the FG to 900 Hz. Measure the frequency using the scope, and record it in *Table 8-4*. From the frequency, *calculate the period* and record in *Table 8-4*.

61. Select **COUNTER/TIMER/PERIOD**. Record the period in *Table 8-4*. Does it agree with your calculation in **Step 60**?

62. Clear the numerical values on the oscilloscope's display by pressing the CLEAR DISPLAY button (you may need to press this button more than once to clear the display). The scales at the bottom of the screen should still be showing.

63. Turn off all equipment, disconnect cables and test-leads, and clean up work area.

WHAT TO TURN IN

Completed **Data Sheets.**

POST-LAB QUESTIONS

None other than those included in Data Sheets.

DATA SHEET, pg. 1/4	Name
Expt. #8: Oscilloscope	Lab Partner

Table 8-1 PROBE ADJUST and HUMAN ANTENNA Signals.

	Shape of Signal	Peak-to-Peak Voltage, $V_{p\text{-}p}$ (V)	Measured Period, T ( )	Calculated Frequency, f (Hz)	Replicated Probe Adjust Signal?
Probe Adjust					Instructor Init.:
Human Antenna					

Table 8-2a Sine wave with DC Offset: $v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right]$ V .

Step	Question	Answer	
12	What is $v(t)_{max}$? What is $v(t)_{min}$?	V_{max}:	V_{min}:
15	For 2.0 V/DIV, how many divisions equal 1.0 volt?		
16	For 0.5 mSEC/DIV, how many divisions equal 1.0 second?		
18	**AC Coupling measurement**. How many divisions tall is the signal (from top to bottom)? How many volts tall is it (top to bottom)?	Divisions:	Volts:
19	**AC Coupling measurement**. What is the period of the signal in divisions? What is the period T in milliseconds?	Divisions:	T (msec):

Step 21
Instructor Initial:

DATA SHEET, pg. 2/4	Name
Expt. #8: Oscilloscope	Lab Partner

Table 8-2b Sine wave with DC Offset: $v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right]$ V .

Step	Question	Answer	
Each step below (#23, 25) should start at **2.0 V/DIV** and **0.5 mSEC/DIV**.
CW: Clockwise, CCW: counter-clockwise.
23	What happens to the appearance of the signal when the VOLT/DIV knob is turned 1 click <u>CW</u>? What is the new VOLT/DIV setting?		New VOLTS/DIV
25	What happens to the appearance of the signal when the VOLT/DIV knob is turned 1 click <u>CCW</u>? What is the new VOLT/DIV setting?		New VOLTS/DIV
Each step below (#30, 32) should now start at **1.0 V/DIV** and **0.5 mSEC/DIV**.
Note the <u>new</u> volts/div setting.
CW: Clockwise, CCW: counter-clockwise.
30	What happens to the appearance of the signal when the SEC/DIV knob is turned 1 click <u>CW</u>? What is the new SEC/DIV setting?		New SEC/DIV
32	What happens to the appearance of the signal when the SEC/DIV knob is turned 1 click <u>CCW</u>? What is the new SEC/DIV setting?		New SEC/DIV

DATA SHEET, pg. 3/4	Name
Expt. #8: Oscilloscope	Lab Partner

Table 8-3 Voltage Measurement Exploration: $v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right]$ V .

Step	Question	Answer
38: DC Coupling		
39	VOLTMETER/DC (V)	
40	VOLTMETER/+PEAK (V)	
41	VOLTMETER/–PEAK (V)	
42	VOLTMETER/PEAK-PEAK (V)	
43	What is the scope message when the signal is zoomed so it no longer fits on the display?	
44: AC Coupling (repeat above measurements) – record displayed values in AC mode-only.		
39	VOLTMETER/DC (V)	
40	VOLTMETER/+PEAK (V)	
41	VOLTMETER/–PEAK (V)	
42	VOLTMETER/PEAK-PEAK (V)	

Explain the difference between DC and AC coupling measurements in words – why are they different? Do the answers of **Table 8-3** make sense with regards to **Equation 8.1**? Explain why or why not? (attach a separate sheet if necessary).

DATA SHEET, pg. 4/4	Name
Expt. #8: Oscilloscope	Lab Partner

Table 8-4 Time Measurement Exploration: $v(t) = 2.0 + 3.0\cos\left[2\pi(500)t\right]$ V .

Step	Question	Answer
COURSOR and COUNTER MEASUREMENTS. Use AC Coupling.		
52	Half-period cursor measurement, maximum to minimum.	
53	Half-period cursor measurement: intersection of waveform with printed horizontal line corresponding to ground (V = 0).	
54	Which measurement technique will give a more precise measurement, **Step 52** or **Step 53**. Explain why (think about the <u>best</u> way to determine where a point is).	
57	Phase Angle half-period cursor measurement.	
60	Scope frequency measurement of FG 900 Hz signal.	
60	*Calculated period* for 900 Hz (use frequency measured in **Step 60**).	
61	*Measured period* for 900 Hz signal. Does it agree with your calculation?	

EXPERIMENT 9

Root-Mean-Square Measurements

7/19/13

GOAL

To understand root-mean-square calculations and oscilloscope measurements.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Measure sine and square wave voltages and currents with a digital multimeter (DMM).
- Measure sine and square wave voltages with an oscilloscope.
- Calculate and convert between V_p, V_{p-p} and V_{rms} for a sinusoidal signal.
- Calculate V_{rms} for a square wave, with and without a DC offset.

BACKGROUND

See also: • Alexander and Sadiku, 3e, 4e or 5e, Ch. 11.4
• Tektronix's *XYZ's of Oscilloscopes*
• Oscilloscope Instruction Manual (in lab)

The sine wave, $v(t) = V_p\sin(\omega t)$, is the most common waveform (signal) in electricity and electronics (***Figure 9.1***). A voltage sinusoid has amplitude V_p (or V_m), peak-to-peak amplitude V_{p-p}, period T, circular frequency $f = 1/T$, and angular frequency $\omega = 2\pi f = 2\pi/T$.

When a digital multimeter (DMM) is set to measure **DC voltage**, the value displayed is the *average value* of the waveform, regardless of its shape. The average value of a periodic function $v(t)$ over one period T is:

$$V_{DC} = \frac{1}{T}\int_0^T v(t)\,dt \qquad (9.1)$$

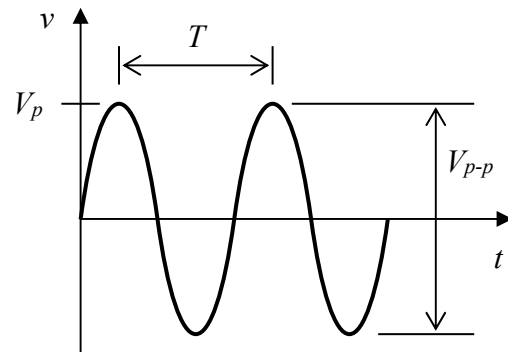For a pure sine wave, the average value is $V_{DC} = 0$.

Figure 9.1

When set to measure an **AC signal**, a DMM generally gives the **root-mean-square (r.m.s.)** value. The **r.m.s. value** or **effective DC value** of periodic function $v(t)$ is:

$$V_{rms} = \left\{ \frac{1}{T} \int_0^T [v(t)]^2 \, dt \right\}^{1/2} \qquad (9.2)$$

The right side is the **square root** of the **mean** (average) value of the **square** of $v(t)$; thus the name.

For a pure sine wave, the r.m.s. value is:

$$V_{rms} = 0.707 V_p = \frac{V_p}{\sqrt{2}} \qquad (9.3)$$

Equation 9.3 is **only valid for a pure sine wave**. Do not blindly use it for another signal.

The physical meaning of the r.m.s. voltage is as follows. **The energy transferred during one period T by periodic voltage $v(t)$ equals the energy transferred during the same amount of time by a constant (DC) voltage of value V_{rms}.**

Alternatively, since the same energy is transferred over the same time (one period of $v(t)$, or an integer multiple thereof), **the average power of the periodic signal $v(t)$ equals the average power of a DC signal of magnitude V_{rms}.**

The r.m.s. value of a periodic voltage is therefore also called the **effective DC voltage**.

Let us derive **Equation 9.2** by considering the power dissipated by a resistor R. When subjected to periodic voltage $v(t)$, the **instantaneous power** dissipated by the resistor is:

$$p(t) = v(t)i(t) = v(t)\frac{v(t)}{R} = \frac{[v(t)]^2}{R} \qquad (9.4)$$

The total energy dissipated in one period T is found by integrating $p(t)$ from 0 to T. Dividing by T gives the **average power** over one period:

$$p_{AC} = \frac{1}{T} \int_0^T p(t)dt = \frac{1}{T} \int_0^T \frac{[v(t)]^2}{R} \, dt \qquad (9.5)$$

Now consider a DC voltage V_{rms} across the same resistor R. Since V_{rms} is constant, its *instantaneous* and *average powers* are the same:

$$p_{DC} = \frac{V_{rms}^2}{R} \qquad (9.6)$$

For the two systems to transfer the same *energy* or the same *average powers* $p_{AC} = p_{DC}$, Equating **Equations 9.5** and **9.6**, and solving for V_{rms} gives:

$$V_{rms} = \left\{ \frac{1}{T} \int_0^T [v(t)]^2 \, dt \right\}^{1/2} \qquad (9.7)$$

Equation 9.7 can be used for any periodic function (not just voltage). Integrate carefully.

In electrical systems, we are usually concerned with the **total energy** transferred; i.e., the product of *average power* and *time*. Since it is easier to think in terms of DC (a single constant value), it is very useful to give a time-varying (AC) signal an effective DC value, e.g., V_{rms}, I_{rms}, etc.

CAUTION: **DMM Measurements**. If there is a DC offset (i.e., the average value of $v(t)$ is <u>not</u> zero), the Fluke DMM can give <u>two</u> r.m.s. values:

(1) for the *total signal* (AC+DC), and

(2) for the *AC-only signal*.

The user needs to know how to measure each r.m.s. value (see "**Appendix E: The Fluke 45 DMM**").

A disadvantage of using only r.m.s. values is that the details of the signal are lost. The **oscilloscope** must be used to display the waveform as a function of time.

Of the two devices, the AC voltmeter (DMM) is generally more accurate. However, the oscilloscope lets us see the total signal, including any noise, distortion, or interference. Typical DMMs have a restricted upper frequency limit, usually 1 to 10 kHz; a scope usually can measure signals into the MHz region.

The DMM can be used to measure *r.m.s. current* by inserting the DMM into the circuit in series. The scope can be used to measure current *indirectly* by measuring the voltage across a resistor, then dividing by the resistor value.

MATERIALS and EQUIPMENT

- 1   Digital Multimeter (DMM)
- 1   Oscilloscope (scope), with 2 oscilloscope probes.
- 1   Function Generator (FG)
- 1   1.0 kΩ, 1/4 W, 5% resistor
- 1   2.0 kΩ, 1/4 W, 5% resistor
- 1   2.2 kΩ, 1/4 W, 5% resistor
- 1   proto-board
- -   various cables and test leads (banana plug-alligator clip cables, scope probe, FG coaxial lead)
- -   various jumper wires

PROCEDURE

1. Before starting the experiment: *calculate the r.m.s. voltages V_{rms} for the signals described in **Steps 3, 9, 10** and **11** using the nominal values provided*. Only use **Equation 9.3** for pure sinusoids; otherwise, use **Equation 9.2** (integrate carefully).

   Record these pre-lab/nominal calculations in the second data column of **Tables 9-1**, **9-2**, **9-3** and **9-4**, respectively.

2. Turn on the scope and prepare to make voltage-time measurements with **Channel 1**.

3. Turn on the function generator (FG), and supply a sine wave of frequency $f = 1.0$ kHz. Connect the scope to the FG output and display a stable signal (**Figure 9.2a**). Adjust the FG output for an output of 4.0 V_{p-p} with no DC Offset, as measured <u>on the scope</u>. Make sure the DC Offset is zero. Record the measured value of V_{p-p} in the title of **Table 9-1**.

4. Record the frequency and period <u>displayed on the FG</u> in the first data column of **Table 9-1**. Write "n/a" (*not applicable*) if there is no display on the FG you are using.

5. Measure the frequency <u>with the scope</u>. Record in the third data column of **Table 9-1**.

6. Measure the period T <u>with the scope</u> and record in **Table 9-1**.

7. Measure the r.m.s. voltage <u>with the DMM</u> (**Figure 9.2b**) and record in the fourth data column of **Table 9-1**. *Compare the pre-lab and DMM-measured values*. Record in **Table 9-1**.
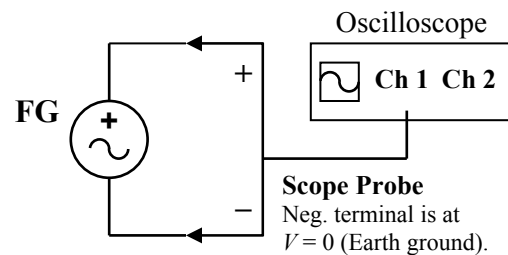
Figure 9.2a
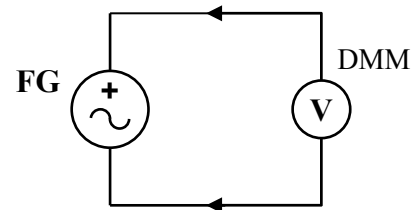
Figure 9.2b

8. Measure the frequency <u>with the DMM</u>. Record in **Table 9-1.**

9. Repeat **Steps 3–5** and **7–8** for a 3.00 V_{p-p} sine wave, with no DC Offset, at 500 Hz. Record in **Table 9-2.**

10. Repeat **Steps 3–5** and **7–8** for a 6.0 V_{p-p} square wave with no DC Offset, at 2.0 kHz. Record in **Table 9-3**.

11. Repeat **Steps 3–5** and **7–8** for a 6.0 V_{p-p} square wave with a +1.0 V DC Offset at 2.0 kHz. **DC Couple** the scope to show the entire signal). Make sure to **measure the r.m.s. value of the <u>total signal</u>** (see "**App. E**: The Fluke 45 DMM"). Record in **Table 9-4**.
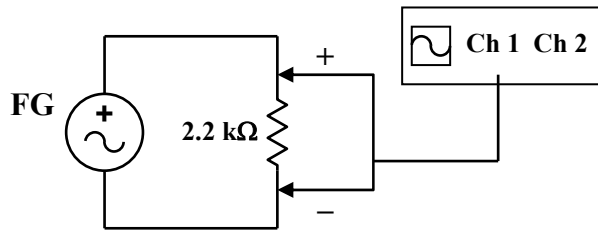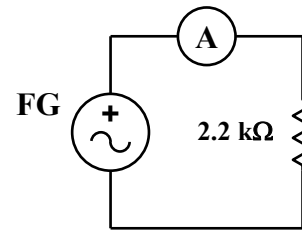
Figure 9.3a   Figure 9.3b

For **Steps 12–24**, the FG should provide a 9.0 V$_{p-p}$ sine wave with no DC Offset at 200 Hz.

R.M.S. Current (*Table 9-5*)

12. Connect the FG output across the 2.2 kΩ resistor (*Figure 9.3a*). Monitor the voltage with the oscilloscope. Record V_{p-p} in the title of *Table 9-5*.

13. From the <u>scope measurement of voltage</u> (V_{p-p}) and the <u>nominal resistor value</u>, *calculate the r.m.s. voltage and then the r.m.s. current*. Record the current in *Table 9-5*.

14. Measure the *r.m.s. current* with the DMM (*Figure 9.3b*). Record in *Table 9-5*, and compare with the result of **Step 13**.

Scope Measurements (*Table 9-6*)

15. Build the circuit shown in *Figure 9.4a*. Use **Channel 2** to measure the voltage across the 2.0 kΩ resistor. <u>From the graph on the scope display</u>, determine V_{p-p}. *Is this what you would expect using voltage division*? Record in *Table 9-6*.

16. <u>Do not display scope **Channel 1**</u>, but connect **Ch. 1's** probe across the 1.0 kΩ resistor with **Ch. 2** still across the 2.0 kΩ, as shown in *Figure 9.4b*. *Describe what happens to* **Channel 2's** *display. Explain why.* (<u>hint</u>: where is electric ground?).

17. The 1.0 kΩ resistor's voltage could be measured by switching the resistors. However, this would not be practical in a more complex circuit, nor in a circuit with permanent connections.

To measure BOTH resistor voltages without having to reconfigure the components, connect **Channel 1's** probe across <u>both</u> resistors so that it measures the entire FG signal – the voltage across both resistors (*Figure 9.4c*). Since the negative terminal of all scope probes are grounded, only the positive lead of **Ch. 1** actually needs to be connected – between the FG and 1.0 kΩ resistor (*Figure 9.4d*). **Ch. 2** should now display the same signal as it did in **Step 15**.

Follow the next few steps.

18. Display only **Channel 1** (only **Ch. 1**'s LED should be lit). This is the voltage across the FG (and across both resistors). Record $V_{p-p,1}$ in *Table 9-6*.

19. Display only **Channel 2** (only **Ch. 2** should be lit). This is the voltage across the 2.0 kΩ resistor. Record $V_{p-p,2}$ in *Table 9-6*.

20. *Perform the following calculation: Subtract* $V_{p-p,2}$ *from* $V_{p-p,1}$. Record in *Table 9-6*.

21. ***Measure*** the voltage across the 1.0 kΩ resistor by <u>using the scope</u> to subtract **Ch. 2** from **Ch. 1** (**Ch. 1** *minus* **Ch. 2**):

    First display both **Ch. 1** and **Ch. 2** using the same voltage scale. Next, press **INVERT Ch. 2** and then press **ADD** to combine the two signals (**Ch. 1** *plus* **inverted Ch. 2** = **Ch. 1** + [**–Ch. 2**]). Turn off the individual signals to display only the ADDed signal.

    Graphically read the ADDed signal $V_{p-p,2-1}$ on the display, and record in *Table 9-6*. Compare the measured value with that found using the hand-calculation in **Step 20**.

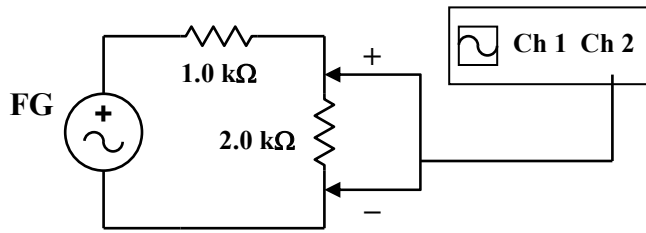   <u>Note</u>: you cannot use the numerical display to measure $V_{p-p,2-1}$; read the values <u>graphically</u>.
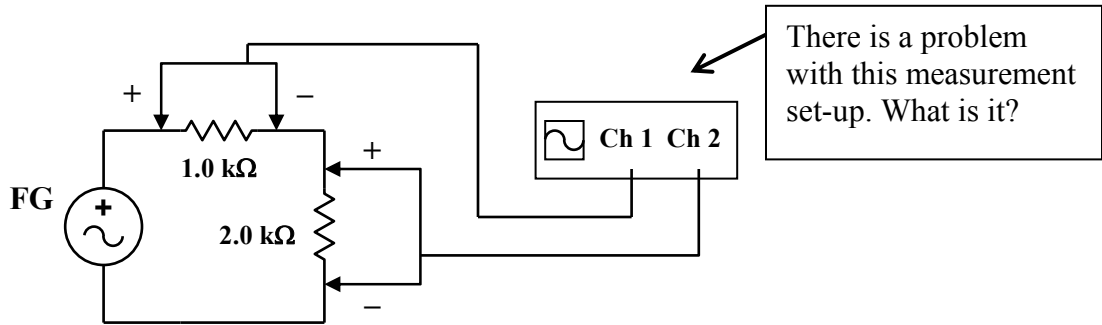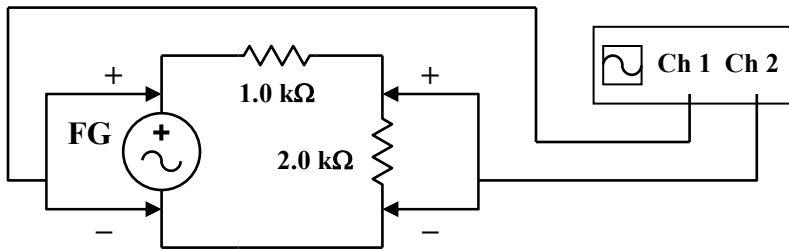
Figure 9.4a

There is a problem with this measurement set-up. What is it?
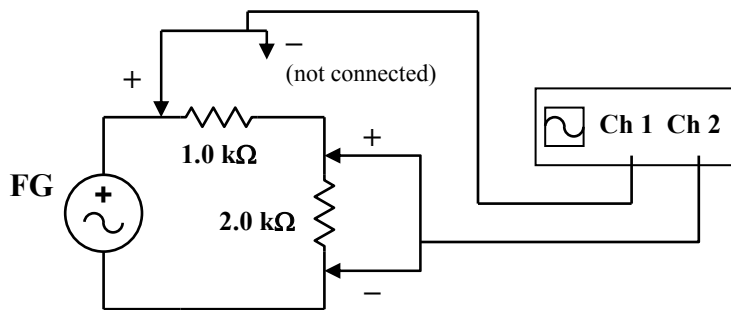
Figure 9.4b

Figure 9.4c

Figure 9.4d

DMM Measurements (*Table 9-7*)

22. Using the DMM, measure the V_{rms} across both resistors (across the FG), and then across each resistor individually (***Figure 9.5***). Record in ***Table 9-7***.

23. Sum the r.m.s voltages across each resistor from **Step 22**. *Compare with the value measured across both resistors*.

24. *Do the measured values agree with what you would expect from standard* voltage division *calculations? Explain why or why not.*
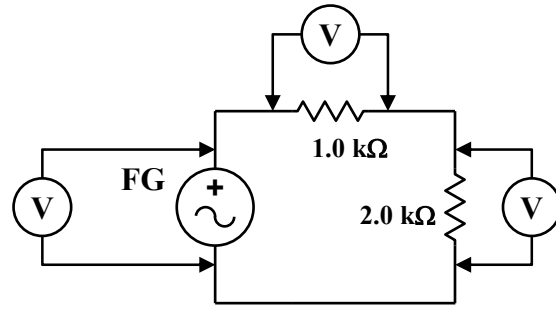
25. Turn off all power. Clean up.

Figure 9.5

Using the scope to measure the voltage across a component anywhere in a circuit

In general, to use the oscilloscope to measure the voltage across any component that is away from ground, use the following procedure:

- Connect the positive of **Ch. 2** to the node just below the component, and the negative of **Ch. 2** to the circuit ground (reference node).

- Connect the positive of **Ch. 1** to the node just above the component. The negative of **Ch. 1** need not be connected to anything since all negative leads of the scope are grounded.

- Display both **Ch. 1** and **Ch. 2**. **Ch. 1** displays the voltage just above the component, **Ch. 2** displays the node voltage just below.

- **Invert Ch. 2**.

- **ADD** the two signals: **Ch. 1 plus the inverse of Ch. 2**, or **Ch. 1 + (–Ch. 2)**

- Deselect **Ch. 1** and **Ch. 2**, if necessary, to display only their difference (**Ch. 1** *plus* inverted **Ch. 2** = **Ch. 1** *minus* **Ch. 2**).

  The difference between Ch.1 and Ch.2 is the voltage across the component in question.

WHAT TO TURN IN

In order: (1) **Data Sheets**, (2) answers to the **Post-Lab Questions** below, and (3) all calculation sheets. You do not need to type answers.

---

1. In **Step 16**, why did the voltage measured across the 2.0 kΩ resistor drop to zero?

2. In **Step 22**, V_{rms} voltage measurements were take across each resistor. What is the peak voltage experienced by each resistor, $V_{1k,p}$ and $V_{2k,p}$?

3. For a pure sine wave voltage signal, convert 50.0 V_p to *r.m.s.*

4. For a pure sine wave voltage signal, convert 75 mV_{p-p} to *r.m.s.*

5. For a pure sine wave current signal, convert 20 μA *r.m.s.* to peak-to-peak.

6. A digital multimeter usually gives AC readings in:
   - (a) peak values
   - (b) peak-to-peak values
   - (c) average values
   - (d) *r.m.s.* values
   - (e) none of the above

7. An oscilloscope can directly measure current.
   - (a) True
   - (b) False

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DATA SHEET, pg. 1/3	Name
Expt. #9 R.M.S. Measurements	Lab Partner

Table 9-1 Voltage and Frequency Measurements: **4.0 V$_{pp}$, 1.0 kHz sine wave**.

Measured source signal: V_{pp} = _____ V (on scope).

	Function Generator Display*	Predicted Values (pre-lab; nominal)	Scope Measurement	DMM Measurement	% Difference in V_{rms} (DMM w.r.t. pre-lab values)
V_{rms} **(V)**					
f **(Hz)**					
Period (msec)					

   * Write "n/a" (*not applicable*) in this column if there is no display on the function generator.

Table 9-2 Voltage and Frequency Measurements: **3.0 V$_{pp}$, 500 Hz sine wave**.

Measured source signal: V_{pp} = _____ V.

	Function Generator Display*	Predicted Values (pre-lab; nominal)	Scope Measurement	DMM Measurement	% Difference in V_{rms} (DMM w.r.t. pre-lab values)
V_{rms} **(V)**					
f **(Hz)**					

   * Write "n/a" (*not applicable*) in this column if there is no display on the function generator.

Table 9-3 Voltage and Frequency Measurements: **6.0 V$_{pp}$, 2.0 kHz square wave**.

Measured source signal: V_{pp} = _____ V.

	Function Generator Display*	Predicted Values (pre-lab; nominal)	Scope Measurement	DMM Measurement	% Difference in V_{rms} (DMM w.r.t. pre-lab values)
V_{rms} **(V)**					
f **(Hz)**					

   * Write "n/a" (*not applicable*) in this column if there is no display on the function generator.

DATA SHEET, pg. 2/3	Name
Expt. #9 R.M.S. Measurements	Lab Partner

Table 9-4 Voltage and Frequency Measurements:
6.0 V$_{pp}$, 2.0 kHz square wave, +1.0 V DC Offset.

Measured source signal: V_{pp} = _____ V, V_{DC} = _____ V.

	Function Generator Display*	Predicted Values (pre-lab; nominal)	Scope Measurement	DMM Measurement	% Difference in V_{rms} (DMM w.r.t. pre-lab values)
V_{rms} **(V)**					
f **(Hz)**					

 * Write "n/a" (*not applicable*) in this column if there is no display on the function generator.

Table 9-5 R.M.S. Current Calculation and Measurement:
9.0 V$_{pp}$, 200 Hz sine wave; 2.2 kΩ resistor.

Measured source signal: V_{pp} = _____ V.

	Calculated Value from Scope Reading	DMM Measurement	% Difference w.r.t. value calculated from scope measurement
i_{rms} **(mA)**			

DATA SHEET, pg. 3/3	Name
Expt. #9 R.M.S. Measurements	Lab Partner

Table 9-6 Oscilloscope Voltage Measurements:
9.0 V_{pp}, 200 Hz sine wave; 1.0 kΩ and 2.0 kΩ resistors in series.

Step	Reading	$V_{p\text{-}p}$ (V)	Remark
15	**Ch. 2** (probe across 2.0 kΩ, Ch. 1 not connected)		
16	**Ch. 2** (with Ch. 1 probe across 1.0 kΩ)		
18	**Ch. 1** (across both resistors)		
19	**Ch. 2** (across 2.0 kΩ)		
20	**Calculated** Ch. 1 *minus* Ch. 2		
21	**Measured** Ch. 1 *minus* Ch. 2		

Table 9-7 DMM V_{rms} Measurements:
9.0 V_{pp}, 200 Hz sine wave; 1.0 kΩ and 2.0 kΩ resistors in series.

Voltage	V_{rms} (V)	Does the distribution of V_{rms} between the 1.0 and 2.0 kΩ resistors agree with voltage division? Explain why the voltage distribution should or should not agree.
Measured across 1.0 kΩ		
Measured across 2.0 kΩ		
Sum of individual measurements (calculate)		
Measured across both resistors		
% Difference (sum of individual voltages w.r.t. direct measurement)		

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EXPERIMENT 10

AC Circuits and Phasor Diagrams

1/09/17

GOAL

To understand phasor representations of electric signals, and the complex representation of impedance.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Measure phase differences between two sinusoidal signals.
- Calculate magnitude and phase of impedances for real inductors and RC (and RL, RLC) circuits.
- Determine voltage and current in an AC circuit due to a sinusoidal input.
- Construct Phasor Diagrams.

BACKGROUND

See also: • Alexander and Sadiku, 3e, 4e or 5e: Ch. 9 and Ch. 10
    • Oscilloscope Instruction Manual (in lab)
    • Experiment 8 of this manual

PHASORS

When analyzing AC circuits, it is convenient to represent sinusoidal signals in *phasor* form. Consider a sinusoidal voltage across an element (or network), and a sinusoidal current through the element (network) as shown in *Figure 10.1*:

$$v(t) = V_m \cos(\omega t + \phi_v) \qquad (10.1)$$

$$i(t) = I_m \cos(\omega t + \phi_i) \qquad (10.2)$$

where V_m and I_m are the amplitudes (magnitudes) of the signals, ω is the frequency (rad/sec), and ϕ_v and ϕ_i are the phase angles of the signals.

The voltage and current as *phasors* are:

$$\mathbf{V} = V_m \angle \phi_v = V_m e^{j\phi_v} \qquad (10.3)$$

$$\mathbf{I} = I_m \angle \phi_i = I_m e^{j\phi_i} \qquad (10.4)$$

The form $V_m \angle \phi_v$ is called **polar form** since the phasor is given by its magnitude and direction (angle). In **rectangular form**, a phasor is given in terms of its *real* and *imaginary* components, e.g.:

$$\begin{aligned} \mathbf{V} &= V_m(\cos\phi_v + j\sin\phi_v) \\ &= V_m \cos\phi + jV_m \sin\phi_v \end{aligned} \qquad (10.5)$$

Phasors **V** and **I** are represented on the **real-imaginary** axes as shown in *Figure 10.2*.

Figure 10.1
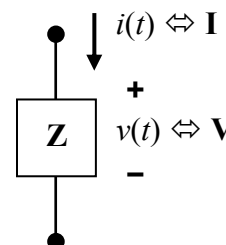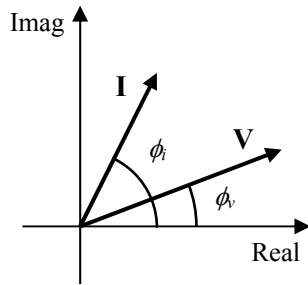
Figure 10.2 Phasors **V** and **I**.
Here, **I** leads **V** by $\phi_i - \phi_v$.

A *phasor* represents the *magnitude* and *phase angle* of a sinusoid. A phasor does not indicate the frequency of the sinusoid; nor is a phasor a function of time.

As a point of information, a *sinor* is the product of the phasor **V** and $e^{j\omega t}$:

$$\mathbf{V}e^{j\omega t} = \left(V_m e^{j\phi_v}\right)e^{j\omega t} = V_m e^{j(\omega t + \phi_v)} \qquad (10.6)$$

Using Euler's Formula, this gives:

$$\mathbf{V}e^{j\omega t} = V_m\left[\cos\left(\omega t + \phi_v\right) + j\sin\left(\omega t + \phi_v\right)\right] \qquad (10.7)$$

The sinor can be thought of as a rotating phasor with time – it has magnitude V_m, and phase angle $\omega t + \phi_v$. The real part of the voltage sinor is the voltage as a function of time: $v(t) = V_m\cos(\omega t + \phi_v)$.

IMPEDANCE

The *impedance* **Z** of an element (or several elements in combination) is the ratio of its phasor voltage to its phasor current (*Figure 10.1*). The impedance in *polar form* is:

$$\mathbf{Z} = \frac{\mathbf{V}}{\mathbf{I}} = \frac{V_m \angle \phi_v}{I_m \angle \phi_i} = \frac{V_m}{I_m}\angle\left(\phi_v - \phi_i\right) = |\mathbf{Z}|\angle\phi_Z \qquad (10.8)$$

where $|\mathbf{Z}|$ is the magnitude of the impedance, and ϕ_Z is the phase angle.

Impedance is a *complex number* with units of ohms (Ω). Impedance is <u>not</u> a phasor (a phasor represents a sinusoid, which is a time-varying signal; impedance does not represent a sinusoid; impedance does not change with time).

The impedance in *rectangular form* is:

$$\mathbf{Z} = R + jX \qquad (10.9)$$

where:

$$R = |\mathbf{Z}|\cos\phi_Z \quad \text{and} \quad X = |\mathbf{Z}|\sin\phi_Z \qquad (10.10)$$

The **real part** R is the **resistance**, and the **imaginary part** X is the **reactance**. The reactance depends on the frequency of the applied signal $\omega = 2\pi f$ (ω in rad/sec, f in Hz), and the value of the inductance L and/or capacitance C of the network, as discussed below.

The magnitude and phase of the impedance is:

$$|\mathbf{Z}| = \sqrt{R^2 + X^2} = \frac{V_m}{I_m} = \frac{V_{rms}}{I_{rms}} \qquad (10.11)$$

$$\phi_Z = \tan^{-1}\left(\frac{X}{R}\right) = \phi_v - \phi_i \qquad (10.12)$$

For a pure sinusoid $V_{rms} = 0.707V_m$ and $I_{rms} = 0.707I_m$, so the amplitude ratio and the r.m.s. ratio are equal (*Equation 10.11*). For a pure sinusoid, either the amplitudes or the r.m.s. values can be used to specify the magnitudes of voltage or current. For example:

$$\mathbf{V}_1 = 10\angle 30° \text{ V} \quad \text{and} \quad \mathbf{V}_2 = 7.07\angle 30° \text{ V}_{rms}$$

are both phasors that represent: $v(t) = 10\cos\left(\omega t + 30°\right)$ V. Note the subscript *rms* on the unit of $\mathbf{V}_2$, indicating the magnitude of 7.07 is the r.m.s. value.

Resistor Impedance

The *impedance* of a resistor is:

$$\mathbf{Z}_R = R \qquad (10.13)$$

Unless the resistor's wire is formed into a coil (an inductor), its reactance is negligible. The phase angle of the resistor's impedance is 0°; i.e.: $\mathbf{Z}_R = R\angle 0°$.

Inductive Reactance

The *reactance* of an inductor is:

$$X_L = \omega L \tag{10.14}$$

While the impedance of an inductor is often assumed to be purely reactive (as in textbook problems), there are no ideal inductors since the inductor wire has some resistance. The impedance of a practical inductor is (***Figure 10.3***):

$$\mathbf{Z}_L = R_L + jX_L = R_L + j\omega L \tag{10.15}$$

where R_L is the internal (DC) resistance of the inductor. The magnitude of R_L is generally small compared to other resistances in the circuit; however, R_L should be accounted for in a detailed analysis.

The value of an inductor's impedance depends on signal frequency ω. **As frequency increases, the magnitude of the impedance increases**. The inductor responds with high voltage to rapid changes (high frequency); recall that $v_L = L(di/dt)$. When di/dt is large (e.g., a high frequency signal), voltage is large, so the voltage-to-current ratio v_L/i is large.

The magnitude and the phase of the inductor's impedance are:

$$\left|\mathbf{Z}_L\right| = \sqrt{R_L^2 + X_L^2} \;\; ; \;\; \phi_{ZL} = \tan^{-1}\left(\frac{X_L}{R_L}\right) \tag{10.16}$$

Since R_L is generally small compared to X_L (especially for large values of ω), the phase of the inductor's impedance is close to 90°.

In polar form, the inductor impedance is:

$$\mathbf{Z}_L = \left|\mathbf{Z}_L\right|\angle\phi_{ZL} = \sqrt{R_L^2 + (\omega L)^2} \angle \tan^{-1}\left(\frac{\omega L}{R_L}\right) \tag{10.17}$$
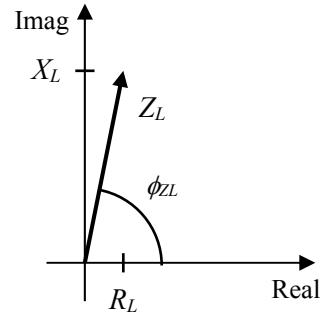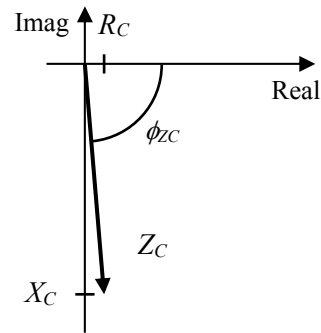

Figure 10.3

Figure 10.4

Capacitive Reactance

The *reactance* of a capacitor is:

$$X_C = -\frac{1}{\omega C} \tag{10.18}$$

While a capacitor is often assumed to be purely reactive, there is some internal resistance to AC signals. The impedance of a capacitor is (***Figure 10.4***):

$$\mathbf{Z}_C = R_C + jX_C = R_C - j\frac{1}{\omega C} \tag{10.19}$$

R_C is the internal resistance of the capacitor, which is generally negligible (the wire in the cap is short, so $R_C = 0$).

The value of a capacitor's impedance depends on signal frequency ω. **As frequency increases, the magnitude of the impedance decreases**. The capacitor responds with high current to rapid changes, approximating a short circuit; recall that: $i_C = C(dv/dt)$. When dv/dt is large (high frequency), current is large, so the voltage-to-current ratio v/i_C is small; i.e., $|Z_c|\rightarrow 0$.

The magnitude and the phase are:

$$|\mathbf{Z}_C| = \sqrt{R_C^2 + X_C^2} \;\; ; \;\; \phi_{ZC} = \tan^{-1}\left(\frac{X_C}{R_C}\right) \quad (10.20)$$

In polar form, the capacitor impedance is:

$$\mathbf{Z}_C = |\mathbf{Z}_C| \angle \phi_{ZC} = \sqrt{R_C^2 + \left(\frac{1}{\omega C}\right)^2} \; \angle \tan^{-1}\left(\frac{-1}{\omega C R_C}\right)$$
$$(10.21)$$

Since R_C is generally negligible compared to X_C (i.e., $R_C = 0$) and X_C is negative, the phase is essentially $-90°$:

$$\mathbf{Z}_C = \frac{1}{\omega C} \angle -90° = -j\frac{1}{\omega C} \quad (10.22)$$

In lab, R_C will be taken as zero.

Elements in Series

In this lab, you will investigate a couple of circuits with components placed *in series*. When components are placed *in series* (or *in parallel*) their impedances combine just like resistors do in DC circuit analysis. For N elements *in series*:

$$\mathbf{Z}_{total} = \sum_{k=1}^{N} \mathbf{Z}_k \quad (10.23)$$

In DC analysis, impedance is simply resistance; the impedance values are real numbers. In AC analysis, impedances are complex numbers. When adding impedances, add them in rectangular form.

Lab Experiment

In this lab, you will:

I.   Experimentally determine the value of inductance *L*, and the current response, of an inductor when powered by a sinusoidal voltage input. Since the inductor will be the only passive component in the circuit, its resistance R_L will be included.

II. Determine the total impedance and voltage response of an RC circuit. You will determine the voltage amplitude across each component, and construct phasor diagrams.

MATERIALS and EQUIPMENT

1	Digital Multimeter (DMM)
1	Oscilloscope (scope)
1	Philips 6303 RCL Meter (for capacitance and inductance measurements)
1	Function Generator (FG)
1	2.0 kΩ, 1/4 W, 5% resistor
1	33 mH inductor
1	4 to 8 H inductor (get this large inductor from the instructor)
1	0.1 µF capacitor (ceramic disk)
1	proto-board
-	various cables and test leads (banana plug-alligator clip cables, scope probe, FG coaxial lead)
-	various jumper wires

PROCEDURE

Part I: Inductor subjected to a Sinusoid

1. Using the DMM, measure the resistance of the resistor, and the DC resistances of the inductors R_L. Record in ***Table 10-1***.

2. Using the Philips 6303 RCL Meter, measure the inductors and the capacitor and record in ***Table 10-1*** (use RCL Auto mode unless instructed otherwise).

3. *Calculate the predicted (expected) magnitude of the total impedance $|\mathbf{Z}_L|$ of the 33 mH inductor at a frequency of $f = 400\ Hz$. Assume the value of R_L does not change with frequency. Record in* ***Table 10-2***.

CAUTION: Be careful when working with inductors. Like capacitors, inductors store energy. Change the voltage across an inductor <u>slowly</u> to prevent electric shock and/or damage to the equipment. <u>Make sure that the Function Generator (FG) is at 0 volts before connecting it to the inductor</u>. When measuring current, make sure the <u>DMM is first set to current mode</u>.

4. Connect the FG to the 33 mH inductor (***Figure 10.5***). Adjust the FG output for a purely sinusoidal signal of 4.0 V_{p-p} (2.0 V_p) at 400 Hz, <u>as measured on the scope</u>, and record the actual values in the title of ***Table 10-2***. **Make sure the DC Offset of the FG is zero**.
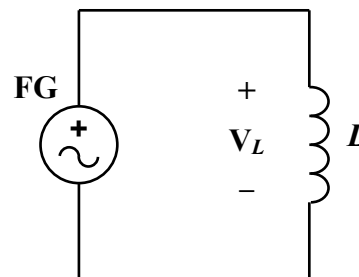

Figure 10.5 $Z_L = R_L + j\omega L$

5. Set the DMM to voltage mode. Measure the r.m.s. voltage across the inductor V_{rms} and record in **Table 10-2**. With the scope, make sure the FG is still providing 4.0 V_{p-p}. After you verify your measurement, reduce the input voltage to 0 V.

6. Remove the DMM, and set it to measure the current through the inductor.

7. Reconfigure the circuit and DMM to measure the r.m.s. current through the inductor I_{rms}. Increase the signal voltage to its previously measured value. Verify the voltage with the oscilloscope. Record the r.m.s. current in **Table 10-2**.

Note: The oscilloscope cannot measure current; it only measures $v(t)$. The DMM can only display a single value; it can measure the r.m.s. value of an AC signal. For a pure sinusoid, the r.m.s. value is directly proportional to its amplitude.

*Why are we **measuring** voltage <u>and</u> current? Why cannot you just divide voltage by resistance R_L to get the inductor's current?*

8. From your measured values of V_{rms} and I_{rms}, *calculate* the magnitude of the inductor impedance $|\mathbf{Z}_L|$ and record in **Table 10-2**. Compare this to your expected result from **Step 3**.

9. From your experimentally determined value of $|\mathbf{Z}_L|$ (**Step 8**) and measured R_L, *calculate* the inductance L and record in **Table 10-2**. Compare with the directly measured value of L (**Step 2**).

<u>CAUTION</u>: For **Step 10**, the larger inductor (~6 H) can store much more energy than the smaller one. Change the voltage across the inductor <u>very slowly</u> to prevent electric shock and/or damage to the equipment. **Make sure that the Function Generator (FG) is at 0 volts before connecting it to the inductor**. When measuring current, make sure the <u>DMM is first set to current mode</u>.

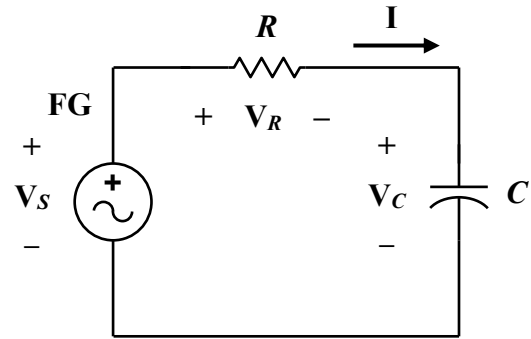10. Repeat **Steps 3–9** for the larger inductor.

Figure 10.6

Part II: RC Circuit

For the RC circuit (*Figure 10.6*), assume:

- the internal capacitor resistance is negligible, $R_C = 0$.

- the voltage source has a zero phase angle, i.e.: $\mathbf{V_S} = V_S\angle0°$. The phases ϕ of the other voltages are measured with respect to the source.

Predictions: $f = 600$ Hz

11. Consider – but do not construct – the RC circuit in *Figure 10.6* using $R = 2.0$ kΩ and $C = 0.1$ μF, and $f = 600$ Hz. From the **measured values** of the resistance and capacitance, *calculate* the **rectangular** <u>and</u> **polar forms** of the total impedance of the circuit, $\mathbf{Z}_{total} = \mathbf{Z}_R + \mathbf{Z}_C$. Record in *Table 10-3*.

12. For source voltage $\mathbf{V_S} = 5.00\angle0°$ V and total impedance $\mathbf{Z}_{total}$, *calculate* the expected phasor current $\mathbf{I}$ (in polar form). Record in *Table 10-3*.

13. From the calculated current $\mathbf{I}$, and the capacitor impedance $\mathbf{Z}_C$, *calculate* the phasor voltage $\mathbf{V}_C$ (in polar form). Record in *Table 10-3*.

14. From the calculated current $\mathbf{I}$, and the resistor impedance $\mathbf{Z}_R$, *calculate* the phasor voltage $\mathbf{V}_R$ (in polar form). Record in *Table 10-3*.
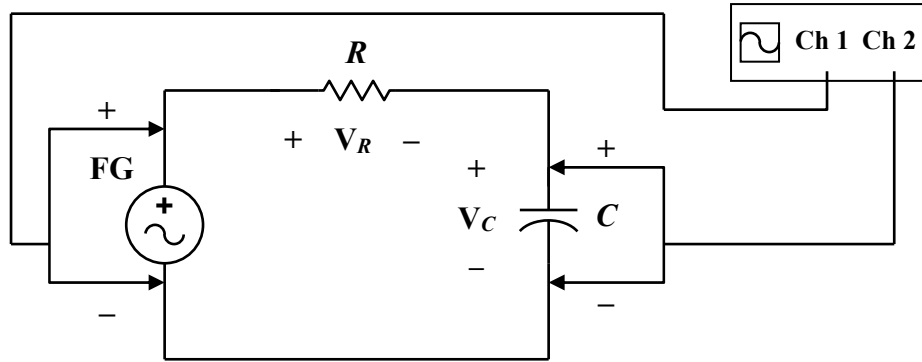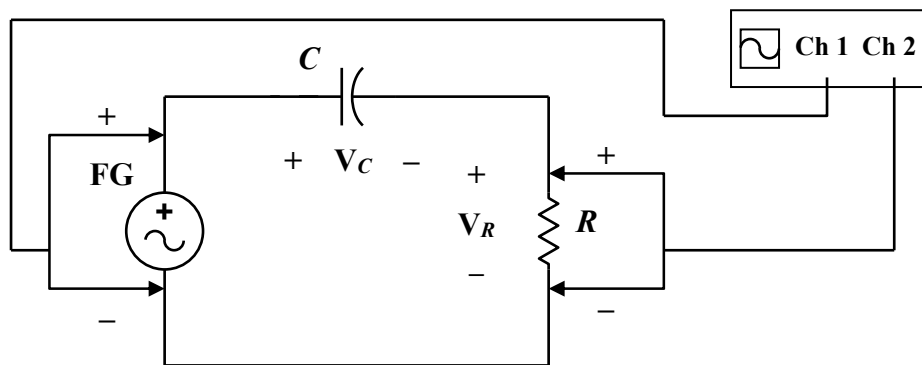
Figure 10.7

Figure 10.8

Measurements: $f = 600$ Hz

15. With the Function General (FG) **not connected** to the circuit, construct the RC circuit shown in *Figure 10.6* using $R = 2.0$ kΩ and $C = 0.1$ μF.

16. Connect the FG to the circuit. Adjust the FG output for a sinusoidal signal of 10.0 V_{p-p} at 600 Hz, as measured on the scope. Record measurements in the title of *Table 10-4*. Make sure the DC Offset of the FG is zero.

Hint: One way to ensure that the DC Offset is zero using the scope is to measure both the peak-to-peak voltage, V_{p-p}, and the maximum positive voltage, V_p. If there is no DC offset, then the double amplitude V_{p-p} will equal twice V_p (the maximum positive value), and V_p is the amplitude.

17. Measure the **peak voltage** across the FG, across the capacitor and across the resistor. Record in *Table 10-4*. *Convert the scope measurements into their r.m.s. values.*

18. Using the DMM, measure the r.m.s. voltage across the FG, across the capacitor and across the resistor. Record in *Table 10-4*. Continue to monitor the FG with the scope.

19. Using two channels on the oscilloscope, measure the phase ϕ_C of the output (capacitor) voltage with respect to the input (FG) voltage (*Figure 10.7*). Record in *Table 10-5*. *Does the capacitor voltage **lead** or **lag** the input voltage?*

Note: In *Figure 10.7*, the FG and capacitor share the same ground.

Hint: Display the reference (ground) line of each signal and align each reference line with one of the horizontal lines printed on the display (using a different printed line for each ground line visually separates the signals on a CRT display, making it easier to tell them apart). With only the source signal displayed, "Set 360°" on the scope. Then display the output signal and determine its phase shift with respect to the input signal (see *Expt. 8*).

20. Switch the positions of the resistor and capacitor so that the resistor is the output (**Figure 10.8**). Using two channels on the oscilloscope, measure the phase ϕ_R of the output (resistor) voltage with respect to the input (FG) voltage. Record in **Table 10-5.** *Does the resistor voltage* **lead** *or* **lag** *the input*?

Note: In **Figure 10.8**, the FG and resistor share the same ground.

Predictions and Measurements: $f = 1000$ Hz

21. Reconfigure the circuit (**Figure 10.6**) and repeat **Steps 11–20** for a 10.0 $V_{p\text{-}p}$, 1000 Hz sinusoid. Use **Tables 10-6** through **10-8** to record the data.

Equating R and X

22. For the RC circuit, calculate the frequency $f = f_o$, in Hz, when the magnitude of the reactance equals the real part (resistance) of the total impedance $|X_C| = R$. Record in **Table 10-9**.

23. Set the frequency of the 10.0 $V_{p\text{-}p}$ sinusoid to the calculated value of f_o (**Step 22**). Measure the r.m.s. voltage and the frequency across the FG, across the capacitor, and across the resistor. Record the values in **Table 10-9**.

    Why should the r.m.s. values, $V_{C,rms}$ *and* $V_{R,rms}$, *be the same or different*?

24. *Calculate* the ratio of $V_{R,rms}$ to $V_{S,rms}$, and record in **Table 10-9**. Square the voltage ratio and record; $(V_{R,rms}/V_{S,rms})^2$ is the *power ratio*.

25. Turn off all power. Clean up.

Note: The frequency calculated in **Step 22** is called the **half-power frequency** because the resistor dissipates 50% of the average supplied power during one period (see the power ratio calculation, **Step 24**).

WHAT TO TURN IN

Turn in (1) the ***Data Sheets***, (2) answers to the ***Post-Lab Questions*** below, and (3) ***Plots*** (one graph per page).

Page order: Data sheets, answers, plots, any calculation sheets. You do not need to type answers.

POST LAB QUESTIONS

For multiple-choice questions: *Circle* the letter corresponding to the correct answer.
   Show your work. Justify/explain you answers. Just circling a letter does not show your thought
   process. Experience shows that those who do not show their work are those who do not really think
   about the problem; they tend to get more answers incorrect than those who do.

General Inductor Questions

1. Increasing the frequency of the AC signal applied to an inductor causes its reactance to:
   (a) increase
   (b) decrease
   (c) remain the same

2. Decreasing the value of inductance in a circuit causes its reactance to:
   (a) increase
   (b) decrease
   (c) remain the same

3. Decreasing the DC resistance of an inductor causes its impedance to:
   (a) increase
   (b) decrease
   (c) remain the same

4. The unit of inductive reactance is:
   (a) henries
   (b) farads
   (c) watts
   (d) ohms

5. (Show your work). An inductor has a DC resistance of 120 Ω. When a 24-V (r.m.s.) sinusoidal signal at 60 Hz is applied, a current of 100 mA (r.m.s.) flows.
Determine the inductance.

General RC Circuit Questions

6. Increasing the frequency of the AC voltage source (but keeping the magnitude of the supplied voltage the same) to a series RC circuit causes the voltage across the capacitor to:
   (a) increase
   (b) decrease
   (c) remain the same
   (d) drop to zero

7. Decreasing the capacitance in a series RC circuit (but keeping the magnitude of the supplied voltage the same) will cause the circuit current to:
   (a) increase
   (b) decrease
   (c) remain the same
   (d) drop to zero

8. (Show your work). In a series RC circuit subjected to a sinusoidal voltage source, the peak voltage across the resistor is 5.0 volts. The peak voltage across the capacitor is 12.0 volts. The peak voltage across the source is:
   (a) 7 volts
   (b) 8.5 volts
   (c) 13 volts
   (d) 17 volts

9. (Show your work). In a series RC circuit subjected to a sinusoidal voltage source, the r.m.s. voltages across the components are: $V_R = 5.0$ V_{rms} and $V_C = 4.0$ V_{rms}. The resistor value is 1.5 kΩ. The frequency is 2 kHz. What is the capacitor value?
   (a) 0.018 µF
   (b) 0.047 µF
   (c) 0.066 µF
   (d) 0.075 µF

Questions Regarding the Experiment

10. From the predicted values (**Table 10-3** and **10-6**), and the measured values (**Tables 10-4**, **10-5**, **10-7** and **10-8**), summarize the phasor voltages for the capacitor and the resistor in **Table 10-10**. Give the voltages in terms of their amplitudes (peak values). Note that the angle difference is <u>not</u> a percent difference.

Table 10-10. Calculated and Measured Phasors for RC Circuit: **10.0 V$_{p-p}$ sine wave**.
Assume the source voltage has zero phase shift: $\mathbf{V_S} = V_S \angle 0°$.

Capacitor	600 Hz	1000 Hz
Predicted (calculated) Phasor Voltage $\mathbf{V_C}$ (polar)		
Measured (from scope) Phasor Voltage $\mathbf{V_C}$ (polar)		
Percent difference in magnitude of Phasor Voltage (predicted magnitude w.r.t. measured magnitude)		
Difference in magnitude of Phase Angle (degrees) (predicted – measured)		
Does the $\mathbf{V_C}$ lead or lag $\mathbf{V_S}$?		
Resistor		
Predicted (calculated) Phasor Voltage $\mathbf{V_R}$ (polar)		
Measured (from scope) Phasor Voltage $\mathbf{V_R}$ (polar)		
Percent difference in magnitude of Phasor Voltage (predicted magnitude w.r.t. measured magnitude)		
Difference in magnitude of Phase Angle (degrees) (predicted – measured)		
Does the $\mathbf{V_R}$ lead or lag $\mathbf{V_S}$?		

Phasor Diagrams

11. For the RC Circuit, with the **10.0 V$_{p-p}$, 600 Hz sine wave**

    (a) On ***engineering paper***, on a complex (real-imaginary) set of axes, draw the three phasors: $\mathbf{V_S}$, $\mathbf{V_C}$ and $\mathbf{V_R}$, found from ***measurements***. Use the ***measured*** amplitude V_p and the measured phase angle ϕ for each voltage phasor.

    All of the phasors should start from the origin of the axes. Recall that the source voltage has zero phase shift ($\mathbf{V_S} = V_S \angle 0°$).

    Use a ruler and a protractor. **Draw the phasor lengths and angles *to scale.*** Use a reasonable amount of space on the paper. Do not crowd the drawings into a corner of the paper. For example, since $\mathbf{V_S} = 5 \angle 0° \text{V}$, set 1 V equal to 1 inch (5 small squares on engineering paper).

    (b) Also, show *graphically* that $\mathbf{V_S} = \mathbf{V_C} + \mathbf{V_R}$. In other words, also construct a phasor ("vector") triangle.

12. For the RC Circuit, with the **10.0 V$_{p-p}$, 1000 Hz sine wave**

    On a new sheet of ***engineering paper***, repeat **Question 11** for the 1000 Hz sine wave.

*** End of Questions***

DATA SHEET, pg. 1/4	Name
Expt. #10 AC Circuits/Phasors	Lab Partner

Table 10-1 Resistor, Capacitor and Inductor Values. *Include units.*

Element	Measured Value	% Error (w.r.t. nominal)
2.0 kΩ resistor	R =	

33 mH Inductor
  inductance and DC resistance
  DC is when f = 0 Hz
	R_L =	n/a

	L =	
Large Inductor inductance and DC resistance	R_L =	n/a
	L =	n/a
0.1 µF Capacitor	C =	

Table 10-2 Voltage and Current Measurements, Calculation of Impedance and Inductance.

4.0 V$_{p\text{-}p}$, 400 Hz sine wave. *Include units.*

Measured source signal: V_{pp} = _____ V, f = _____ Hz.

	33 mH Inductor	Large Inductor
Predicted Magnitude of Total Impedance, $|\mathbf{Z}_L|$		
V_{rms} across inductor (measured)		
I_{rms} through inductor (measured)		
$|\mathbf{Z}_L|$, calculated from measured r.m.s. values		
% difference in $|\mathbf{Z}_L|$ with respect to predicted value		
L, calculated from measured r.m.s. values		
% difference in L w.r.t. directly measured value		

DATA SHEET, pg. 2/4	Name
Expt. #10 AC Circuits/Phasors	Lab Partner

Table 10-3 Calculated Impedance, Current, Voltage: RC Circuit, **10.0 V$_{p\text{-}p}$, 600 Hz sine wave.**

Nominal values: R = 2.0 kΩ, C = 0.1 μF

Assume the voltage source has zero phase: $\mathbf{V_S} = V_S \angle 0°$.

Quantity	Value and Units
$\mathbf{Z}_{total}$, *rectangular form* (calculated from measured values)	
$\mathbf{Z}_{total}$, *polar form* (calculated from measured values)	
Phasor Current, $\mathbf{I}$ (polar form, calculated from $\mathbf{V_S} = 5\angle 0°$ V and $\mathbf{Z}_{total}$)	
Phasor Voltage, $\mathbf{V_C}$ (polar form, calculated from $\mathbf{I}$ and $\mathbf{Z}_C$)	
Phasor Voltage, $\mathbf{V_R}$ (polar form, calculated from $\mathbf{I}$ and $\mathbf{Z}_R$)	

Table 10-4 Measured Voltages: RC Circuit, **10.0 V$_{p\text{-}p}$, 600 Hz sine wave.**

Assume the voltage source has zero phase: $\mathbf{V_S} = V_S \angle 0°$.

Measured source signal: $\boldsymbol{V_{pp}}$ = _____ V, $\boldsymbol{f}$ = _____ Hz.

Quantity	Scope, V_p (V) (measured)	Scope, V_{rms} (V) (calculated)	DMM, V_{rms} (V) (measured)
Source Voltage, V_S			
Capacitor Voltage, V_C			
Resistor Voltage, V_R			

Table 10-5 Measured Phase Angles: RC Circuit, **10.0 V$_{p\text{-}p}$, 600 Hz sine wave.**

Assume the voltage source has zero phase: $\mathbf{V_S} = V_S \angle 0°$.

Give angle as positive or negative, depending on if it leads or lags.

Quantity	Value and Unit
Capacitor Phase Angle, ϕ_C (measured, with respect to $\mathbf{V_S}$)	
Resistor Phase Angle, ϕ_R (measured, with respect to $\mathbf{V_S}$)	
Does $\mathbf{V_C}$ lead or lag $\mathbf{V_S}$?	
Does $\mathbf{V_R}$ lead or lag $\mathbf{V_S}$?	

DATA SHEET, pg. 3/4	Name
Expt. #10 AC Circuits/Phasors	Lab Partner

Table 10-6 Calculated Impedance, Current, Voltage: RC Circuit, **10.0 V$_{p-p}$, 1.0 kHz sine wave.**

Nominal values: R = 2.0 kΩ, C = 0.1 μF

Assume the voltage source has zero phase: $\mathbf{V_S} = V_S \angle 0°$.

Quantity	Value and Units
$\mathbf{Z}_{total}$, *rectangular form* (calculated from measured values)	
$\mathbf{Z}_{total}$, *polar form* (calculated from measured values)	
Phasor Current, $\mathbf{I}$ (polar form, calculated from $\mathbf{V_S} = 5 \angle 0°$ V and $\mathbf{Z}_{total}$)	
Phasor Voltage, $\mathbf{V_C}$ (polar form, calculated from $\mathbf{I}$ and $\mathbf{Z}_C$)	
Phasor Voltage, $\mathbf{V_R}$ (polar form, calculated from $\mathbf{I}$ and $\mathbf{Z}_R$)	

Table 10-7 Measured Voltages: RC Circuit, **10.0 V$_{p-p}$, 1.0 kHz sine wave.**

Assume the voltage source has zero phase: $\mathbf{V_S} = V_S \angle 0°$.

Measured source signal: $\mathbf{V_{pp}}$ = _____ V, f = _____ Hz.

Quantity	Scope, V_p (V) (measured)	Scope, V_{rms} (V) (calculated)	DMM, V_{rms} (V) (measured)
Source Voltage, V_S			
Capacitor Voltage, V_C			
Resistor Voltage, V_R			

Table 10-8 Measured Phase Angles: RC Circuit, **10.0 V$_{p-p}$, 1.0 kHz sine wave.**

Assume the voltage source has zero phase: $\mathbf{V_S} = V_S \angle 0°$.

Give angle as positive or negative, depending on if it leads or lags.

Quantity	Value and Unit
Capacitor Phase Angle, ϕ_C (measured, with respect to $\mathbf{V_S}$)	
Resistor Phase Angle, ϕ_R (measured, with respect to $\mathbf{V_S}$)	
Does $\mathbf{V_C}$ lead or lag $\mathbf{V_S}$?	
Does $\mathbf{V_R}$ lead or lag $\mathbf{V_S}$?	

DATA SHEET, pg. 4/4	Name
Expt. #10 AC Circuits/Phasors	Lab Partner

Table 10-9 RC Circuit for Equal *Resistance* and *Reactance* **10.0 V$_{p-p}$, ? Hz sine wave.**

Nominal values: R = 2.0 kΩ, C = 0.1 μF

	Quantity and Unit
Calculated frequency $f = f_o$ for $R = |X_C|$	
Measured frequency f_o	
Source Voltage, $V_{S,rms}$ at f_o	
Capacitor Voltage, $V_{C,rms}$ at f_o	
Resistor Voltage, $V_{R,rms}$ at f_o	
Ratio of Resistor Voltage to Source Voltage, $\dfrac{V_{R,rms}}{V_{S,rms}}$	
Square of Voltage Ratio = Power Ratio, $\left(\dfrac{V_{R,rms}}{V_{S,rms}}\right)^2$	

EXPERIMENT 11

Resonance in Series AC Circuits

1/09/17

GOAL

To understand resonance in electrical circuits, and its causes and effects.

STUDENT LEARNING OUTCOMES

After completing this experiment, you should be able to:

- Calculate the resonant frequency of an RLC series circuit.
- Measure and plot the voltage vs. frequency response of an RLC series circuit due to a sinusoidal input.
- Draw and analyze a phasor diagram of an RLC circuit.

BACKGROUND

See also: • Alexander and Sadiku, 3e, 4e or 5e: Ch. 9, 10, and Section 14.5

Consider the basic RLC series circuit of **Figure 11.1** subjected to a sinusoidal source having frequency ω (rad/sec); e.g., $v_S(t) = V_S\cos\omega t$.

The resistor **dissipates** power (**removes** energy) from the system; e.g., the resistor can model a heater, a light, a fan, a speaker, etc. The inductor and capacitor **store** energy in the circuit.

The total *impedance* is:

$$\mathbf{Z}_{total} = \mathbf{Z}_L + \mathbf{Z}_C + \mathbf{Z}_R = j\omega L - \frac{j}{\omega C} + R$$

$$= R + j\left(\omega L - \frac{1}{\omega C}\right) \qquad (11.1)$$

Note that the reactance is composed of inductive and capacitive parts: $X_{total} = (\omega L - 1/\omega C)$.

The amplitude of the total impedance is:

$$\left|\mathbf{Z}_{total}\right| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \qquad (11.2)$$

and its phase is:

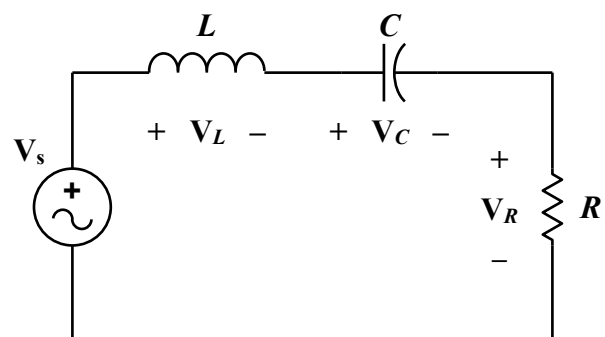$$\phi_z = \tan^{-1}\left(\frac{\omega L - 1/\omega C}{R}\right) \qquad (11.3)$$

Figure 11.1 *RLC Circuit.*

When subjected to voltage $\mathbf{V_s} = V_s \angle 0°$ V, the phasor current is:

$$\mathbf{I} = I_m \angle \phi_i = \frac{\mathbf{V_S}}{\mathbf{Z}_{total}} = \frac{V_S \angle 0°}{|\mathbf{Z}_{total}| \angle \phi_z} \quad (11.4)$$

with amplitude:

$$I_m = \frac{V_S}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}} \quad (11.5)$$

and phase $\phi_i = -\phi_z$.

The phasor voltage across the resistor is:

$$\mathbf{V_R} = \mathbf{IZ}_R = (I_m \angle -\phi_z)(R \angle 0°) \quad (11.6)$$

with amplitude:

$$V_R = \frac{R V_S}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}} \quad (11.7)$$

and phase $\phi_R = -\phi_z$ since $\mathbf{V_R}$ and $\mathbf{I}$ are in phase.

The voltage amplitudes across the inductor and capacitor are:

$$V_L = \frac{(\omega L) V_S}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}} \quad (11.8)$$

$$V_C = \frac{(1/\omega C) V_S}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}} \quad (11.9)$$

with phases $\phi_L = 90° - \phi_z$ and $\phi_C = -90° - \phi_z$, respectively.

Frequency Response and Resonance

The frequency response is a quantity's magnitude and phase angle as the source (driving) frequency is changed. For example, the voltage amplitude across resistor V_R depends on the source frequency ω (*Equation 11.7*). The phase of $\mathbf{V_R}$ also depends on ω (here $\phi_R = -\phi_z$ since $\mathbf{V_R}$ is in phase with $\mathbf{I}$).

Since the resistor models output from the circuit, we are usually most interested in the frequency response of $\mathbf{V_R}$: its magnitude and phase as functions of frequency.

Consider *Equations 11.7–11.9* and *Figure 11.1*. If the frequency is small, i.e., $\omega \to 0$, or DC, the amplitudes of the voltages across the components are:

$$V_R \to 0, \quad V_L \to 0, \quad V_c \to V_s \quad (11.10)$$

If the frequency is very large, i.e., $\omega \to \infty$, then the amplitudes are:

$$V_R \to 0, \quad V_L \to V_s, \quad V_c \to 0 \quad (11.11)$$

As ω is increased from zero, the amplitude of V_R must increase (take on non-zero values), eventually reaching a maximum before returning to zero for large values of ω. Studying *Equation 11.7*, since the numerator is constant, V_R is maximum when the denominator is minimum, which occurs when the total reactance of the circuit is zero:

$$\omega L - \frac{1}{\omega C} = 0 \quad (11.12)$$

In other words, V_R is maximum when the inductive impedance is equal and opposite the capacitive impedance. This condition is known as *resonance*.

When *Equation 11.12* is true, the total impedance of the circuit is resistive; i.e., $\mathbf{Z}_{total} = R$. The voltage amplitudes across each element becomes:

$$V_R = V_s, \quad V_L = -V_c, \quad V_c = -V_L \quad (11.13)$$

At *resonance*, the amplitude of the output voltage V_R is as large as it can be for all values of ω. In the simple series circuit of *Figure 11.1*, $V_{R,max} = V_s$. In general, the resistor is part of a larger system, so $V_{R,max}$ is not generally equal to the amplitude of the source.

The value of ω at resonance is the *angular resonant frequency* ω_o (rad/sec). Solving for the frequency in *Equation 11.12*:

$$\omega_o = \frac{1}{\sqrt{LC}} \quad (11.14)$$

The *circular resonant frequency* f_o (Hz), is:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (11.15)$$

Note that the amplitudes of the inductor and capacitor voltages do not go to zero (remember the voltages of the components are out of phase). The

amplitudes of the voltages across the inductor and capacitor for this circuit at resonance are:

$$V_L = \frac{(\omega_o L)V_S}{R} = -V_C \quad ; \quad V_C = \frac{V_S}{\omega_o CR} \qquad (11.16)$$

Half-Power Frequencies

The output – the voltage across the resistor – of an RLC circuit is not simply "full voltage" or "zero," but varies continuously between those two values as ω changes (***Equation 11.7***). It is therefore necessary to determine/discuss when the output of a system is significant or not significant. The standard measure is the ***half-power frequency***.

When the voltage across the resistor is at its maximum, $V_{R,max}$, the power dissipated by the resistor is:

$$P_{R,\max} = \frac{\left(V_{R,\max}\right)^2}{R} \qquad (11.17)$$

Half of that power corresponds to a voltage of:

$$V_{R,half-power} = \frac{V_{R,\max}}{\sqrt{2}} = 0.707 V_{R,\max} \qquad (11.18)$$

For the basic RLC circuit of ***Figure 11.1***, V_R equals $0.707 V_{R,max}$ when the denominator of ***Equation 11.7*** equals $\sqrt{2}$. This occurs when the resistance and magnitude of the reactance are equal:

$$R = \left|\omega L - 1/\omega C\right| \qquad (11.19)$$

Solving for ω gives the two half-power frequencies:

$$\omega_1 = \frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\omega_o\right)^2}$$

$$\omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\omega_o\right)^2} \qquad (11.20)$$

The quantity $|\omega_2 - \omega_1|$ is the ***bandwidth***.

The V_R-ω curve for the simple RLC circuit is given in ***Figure 11.2***. Amplitude V_R has been normalized (divided) by $V_{R,max}$ so that the maximum value on the vertical axis is 1.0, which occurs at the resonant frequency ω_o. The frequency ω is plotted on a log-scale.
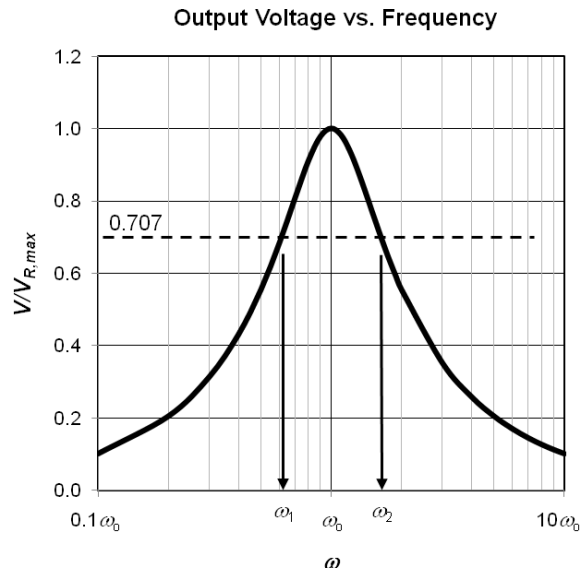

Figure 11.2 Normalized resistor output voltage vs. frequency ($V_R/V_{R,max}$ vs. ω) of a basic RLC series circuit. Frequency ω plotted on a log scale.

Application of the Resonant Response

Resonance circuits are used as electronic filters. A classic example is a radio. A very simple model of a radio is a RLC circuit with a **variable capacitor**. Radio waves are broadcasted from their station at unique frequencies; e.g., 1280 AM broadcasts at 1280 kHz, 90.7 FM broadcasts at 90.7 MHz. Your radio receives input signals from "all" stations (frequencies). As you rotate the tuning dial, you change the capacitance, which changes the *resonant frequency* of the radio (***Equations 11.14*** and ***15***).

The radio's output (speaker response), is maximum at the resonant frequency (the station you are tuned too), and less at other frequencies, so that you only hear the station you want. When you hear two stations at once, either the stations have very similar frequencies, or the ***quality factor*** (a measure of the narrowness of the bandwidth) of the radio is not very high, i.e., the drop-off of $V_R(\omega)$ around $\omega = \omega_o$ is not very steep (the bandwidth is relatively wide).

MATERIALS and EQUIPMENT

1	Digital Multimeter (DMM)
1	Oscilloscope (scope)
1	Philips 6303 RCL Meter
1	Function Generator (FG)
1	3.0 kΩ, 1/4 W, 5% resistor
1	33 mH inductor
1	0.1 μF capacitor
1	proto-board
-	various cables and test leads (banana plug-alligator clip cables, scope probe, FG coaxial lead)
-	various jumper wires

PROCEDURE

Part I: Frequency Response

1. Measure the resistances of the resistor R and of the inductor R_L. Record in **Table 11-1**. Justify if R_L can be neglected (or not) with respect to R; assume R_L does not change with frequency.

2. Measure the inductance and the capacitance of the inductor and capacitor, respectively. Record in **Table 11-1**.

3. *Calculate* the expected **angular resonant frequency ω_o** and the expected **circular resonant frequency f_o** of the basic RLC series circuit in **Figure 11.1** using the measured component values. Record in **Table 11-1**.

4. *Calculate* the two frequencies of the RLC series circuit when $V_R = \dfrac{V_S}{\sqrt{2}}$, f_1 and f_2 (ω_1 and ω_2). Record in **Table 11-1**. These are the **half-power frequencies** (power is proportional to voltage squared).

5. Build the circuit shown in **Figure 11.1**.

6. Set the function generator to 8.0 V_{p-p} (4.0 V_p) sine wave at 100 Hz, <u>as measured on the oscilloscope</u>. Make sure that the DC Offset of the FG is zero. Record the measured voltage in the title of **Table 11-2**. Record the measured frequency f in the first row of **Table 11-2**.

Note: Frequency can be measured on the scope or with the DMM.

Note 2: Voltage measurements in **Table 11-2** will be made on the DMM using r.m.s. values (it is easier than using the scope). Recall that $V_{rms} = 0.707V_p$, where V_p is the peak voltage of a pure sinusoid.

7. Using the DMM, measure the r.m.s. voltage V_{rms} across the FG. Record in the title of **Table 11-2**. *Do the scope and DMM voltage measurements correlate? Does $0.707V_p = V_{rms}$?*

8. Measure the r.m.s. voltage across the resistor $V_{R,rms}$ and record it in **Table 11-2**.

9. Measure the r.m.s. voltages across the inductor and capacitor, $V_{L,rms}$ and $V_{C,rms}$, and record in **Table 11-2**.

10. Repeat the measurements for f, $V_{R,rms}$, $V_{L,rms}$ and $V_{C,rms}$ by varying the input frequency using:

    f = 200, 300, 500, 1.0k, 2.0k, 3.0k, 5.0k, 10k , 20k, 30k, and 50k Hz.

    Complete **Table 11-2**. Make sure the amplitude of the voltage source remains constant.

11. From the data in **Table 11-2**, estimate the value of f that gives the maximum voltage across the resistor. *Is this value in reasonable agreement with that calculated in* **Step 3**?

12. Take five additional data points: one at the calculated resonance frequency f_o, and four near and around the resonance frequency (two on either side). Record in **Table 11-2**.

Part II: Half-Power Frequency

13. Set the FG frequency to those calculated in **Step 4**, first f_1 and then f_2. Measure $V_{R,rms}$ for each value, and record in **Table 11-3**. Convert the $V_{R,rms}$ values into the amplitude values $V_R = \sqrt{2}\, V_{R,rms}$. Do the amplitudes of V_R equal $0.707 V_s$?

> **CAUTION**: Note that $V_{R,rms} = 0.707 V_R$, and $V_{R,half\text{-}power} = 0.707 V_{R,max}$, where V_R is the amplitude of the sinusoid, and $V_{R,max}$ is the maximum value V_R can be. While the equations look similar, the reasons behind $V_{R,rms}$ and $V_{R,half\text{-}power}$ are not. The first converts the sinusoid amplitude into an effective DC voltage, and the second compares the power of two AC signals. As noted above, $V_{R,rms}$ measurements were used as DMM measurements of voltage drops are easier than scope measurements.

The quantity $|\omega_2 - \omega_1|$ is called the *bandwidth*.

Part III: Phasor Diagram

14. Set the FG to provide an 8.0 $V_{p\text{-}p}$ sine wave at 2000 Hz. Record the measured voltage and frequency values in the title of **Table 11-4**. Assume the FG has zero phase, i.e., $\mathbf{V_S} = V_S \angle 0°$.

15. Calculate the peak voltage across the resistor for $f = 2000$ Hz, and record in the title of **Table 11-4**.

16. Using two channels on the oscilloscope, measure the peak voltage $V_{R,p}$ and the phase shift ϕ_R of $\mathbf{V_R}$ with respect to the input voltage $\mathbf{V_S}$, and record in **Table 11-4.** *Does* $\mathbf{V_R}$ *lead* or *lag* the input?

17. Switch the positions of the resistor and inductor so that the inductor is connected to ground. Measure the peak voltage $V_{L,p}$ and the phase shift ϕ_L of $\mathbf{V_L}$ with respect to the input, and record in **Table 11-4.** *Does* $\mathbf{V_L}$ *lead* or *lag* the input?

18. Switch the positions of the inductor and capacitor so that the capacitor is connected to ground. Measure the peak voltage $V_{C,p}$ and the phase shift ϕ_C of $\mathbf{V_C}$ with respect to the input voltage, and record in **Table 11-4.** *Does* $\mathbf{V_C}$ *lead* or *lag* the input?

19. Clean up.

WHAT TO TURN IN

In order: (1) ***Data Sheets*** , (2) ***Plots*** in response to the Post-lab Questions (one graph per page), and (3) any calculation sheets. Other than the Excel plots, no typed response is needed.

POST LAB QUESTIONS

1. In Excel, plot amplitude (peak-voltage) versus frequency, V_p **vs.** ω (rad/sec) on a semi-log plot for each passive element using the data of ***Table 11-2***.

   Plot the three curves – $V_R(\omega)$, $V_L(\omega)$ and $V_C(\omega)$ – on one graph. Do not forget to convert the r.m.s. data into amplitudes: $V_p = \sqrt{2}\, V_{R,rms}$.

   The *x*-axis (ω) should be a **log-scale** axis.

   Use an ***x-y scatter plot***, with a smooth line through the data points.

   Do not use a curve-fit (trendline).

   Indicate on the graph the resonant frequency ω_b, in radians/sec, and the two half-power frequencies, ω_1 and ω_2.

2. On ***engineering paper***, using a complex set of axes, draw the phasors found from the ***measurements*** in ***Table 11-4*** (the measured V_p and the measured phase angles ϕ). All of the phasors should start from the origin of the axes. Recall that the source voltage has zero phase shift ($\mathbf{V_S} = V_S \angle 0°$).

   Draw the phasor lengths and angles to scale, using a ruler and protractor**.** Use a reasonable amount of space on the paper.

   Also, show *graphically* that $\mathbf{V_S} = \mathbf{V_L} + \mathbf{V_C} + \mathbf{V_R}$, i.e., construct a phasor ("vector") quadrilateral with ruler and protractor.

DATA SHEET, pg. 1/3	Name
Expt. #11 Resonance	Lab Partner

Table 11-1 Resistor, Capacitor and Inductor Values;
            Predicted Resonant and Half-Power Frequencies. *Include units.*

Element	Measured Value	
3.0 kΩ resistor	$R =$	
33 mH Inductor	$R_L =$	
	$L =$	
0.1 µF Capacitor	$C =$	
Resonant frequency, calculated	$\omega_o =$	$f_o =$
Frequency at $V_R = V_S / \sqrt{2}$	$\omega_1 =$	$f_1 =$
	$\omega_2 =$	$f_2 =$

DATA SHEET, pg. 2/3	Name
Expt. #11 Resonance	Lab Partner

Table 11-2 Frequency and Voltage Measurements: RLC Circuit, **8.0 V$_{p-p}$ sine wave**.

Measured source signal: V_{pp} = _____ V ; V_{rms} = _____ V

f	f	$V_{R,rms}$	$V_{L,rms}$	$V_{C,rms}$
nominal	measured	measured	measured	measured
Units: **Hz**	**Hz**	**V**	**V**	**V**
100				
200				
300				
500				
1.0k				
2.0k				
3.0k				
5.0k				
10k				
20k				
30k				
50k*				
f_o =				

* A frequency of 50kHz may be pushing the limits of the oscilloscope, so readings at this level
  may not be valid.

Note: DMM measurements are V_{rms} values, not amplitudes V_p.

DATA SHEET, pg. 3/3	Name
Expt. #11 Resonance	Lab Partner

Table 11-3 Half-Power Measurements: RLC Circuit, **8.0 V$_{p-p}$ sine wave**

Nominal source signal amplitude V_S = 4.0 V.

Predicted amplitude of resistor voltage at half-power frequency (Step 4):

$V_{R,half-power}$ = 0.707$V_{R,max}$ = 0.707V_S = _____ V

	f	$V_{R,rms,half-power}$ (r.m.s.)	$V_{R,half-power}$ (amplitude)	*% Difference of V_R* w.r.t. predicted
Units	Hz	V	V	%
f_1				
f_2				

Note: DMM measurements are V_{rms} values, not amplitudes V_p.
Convert measured r.m.s. values into amplitude values $\left(V_R = \sqrt{2}\, V_{R,rms}\right)$

Table 11-4 Measured Peak Voltages and Phases: RC Circuit, **8.0 V$_{p-p}$, 2000 Hz sine wave.**
Assume voltage source has zero phase: $\mathbf{V_S} = V_S\angle 0°$.

Measured peak-to-peak source signal: V_{pp} = _____ V, f = _____ Hz.

Predicted peak resistor voltage for given frequency: $V_{R,p}$ = _____ V.

Component	Peak Voltage V_p (V)	Phase Angle ϕ (degrees)	Does the Component Lead or Lag the Source?
Source		0.0°	
Resistor			
Inductor			
Capacitor			

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Appendix A: RESISTOR COLOR CODES

Rev.: 7/29/14 DJD

The standard method of labeling resistors is shown in *Figure A.1*. There are four colored bands: the three that are often grouped together give the resistance value; the fourth gives the *tolerance*. In *Figure A.1*, from left to right:

- the **first two bands** represent the *1st* and *2nd digit* of the **nominal** ("in name only") *value* of the resistor.

- the **third band** is the *multiplier band*, which gives the number of zeros that follow the first two digits (or the exponent on the 10 in scientific notation).

- the **fourth band**, often offset from the others, is the *tolerance band*. The manufacturer states that the resistor's actual value is within a certain percentage of its nominal value.

The values that correspond to the color bands are given in *Table A-1*. The color code (0, 1, 2…; Black, Brown, Red...) can be remembered with a mnemonic. Many mnemonics can be found with an internet search. I came up with a modification of the rainbow mnemonic:

"BB ROY G BiV without the i, GW."

"a BB shot out Roy G. BiV's eye. Gee Whiz!"

A way to remember that Black is 0 and White is 9: black is the absence of light so it is "nothing" or zero; white is all colors of light, so it is the largest number, 9.

Reading the Code

What is the value and tolerance of a resistor with color bands: Yellow / Violet / Red / Silver ?

First, find the *tolerance band*, which is generally gold or silver. **Place the tolerance band on the right**.

From the left, the first band is **Yellow: 4**; the second is **Violet: 7**. The first two digits of the resistance are: **47**. The third band gives the multiplier (number of zeroes after the first two digits). Here, **Red: 2**. The resistance is:

$$47 \times 10^2 \ \Omega = 4700 \ \Omega = 4.7 \ k\Omega$$

Silver indicates a tolerance of 10%. Thus, the resistor has a value of:

$$\boxed{4700 \ \Omega \pm 10\%}$$

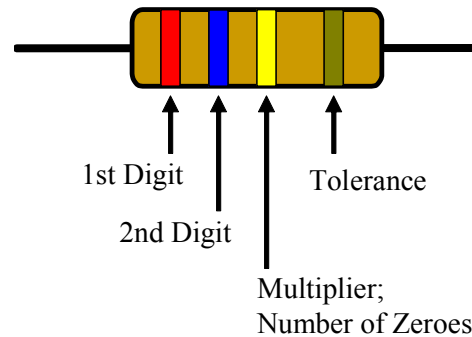With a 10% tolerance, the actual value may range between 4230 and 5170 Ω.

Figure A.1 Four-band Resistor Color Code. With the tolerance band on the right, the first three bands are read from left to right to give the value of the resistance.

Table A-1 Four-Band Resistor Color Code.

Color of Band	Value of first two digits (1st, 2nd band)	Multiplier (3rd band)		Tolerance (4th band)
		Multiply first two digits by	Zeroes after first two digits	
Black	0	$10^0 = 1$	0	-
Brown	1	$10^1 = 10$	1	1%
Red	2	$10^2 = 100$	2	2%
Orange	3	1000	3	3%
Yellow	4	10^4	4	-
Green	5	10^5	5	-
Blue	6	10^6	6	-
Violet	7	10^7	7	-
Gray	8	10^8	8	-
White	9	10^9	9	-
Gold*	-	$10^{-1} = 0.1$	-	5%
Silver	-	0.01	-	10%
None	-	-	-	20%

*Note: Most resistors in the ENGR 171 lab have a tolerance of 5% (gold).

I expect every ENGR 171 student to know the standard 4-band resistor code from memory.

Power Rating

Resistors have a ***power rating*** P_{max} (for DC current and voltage, the power dissipated by a resistor is: $P = i^2R = V^2/R$). If a resistor must dissipate more power than its *power rating* for some time, it will overheat, burn and smoke. Common resistors typically have power ratings of ¼ W or ½ W.

The power rating is related to the surface area of the resistor. A resistor removes energy from a circuit via heat. The more surface area, the greater the resistor's ability to dissipate heat. A ½ W resistor is therefore larger (has more surface area) than a ¼ W resister. If the resistor cannot dissipate heat to the surroundings fast enough, it will fail.

Circuits are usually designed so that at maximum power, a resistor only needs to dissipate half of its power rating (a *Factor of Safety* of 2).

The resistors generally used in ENGR 171 are rated at ¼ W.

Advanced Resistor Codes – More Bands

Some resistors have more than four bands. These resistors have better properties than standard resistors (and cost more). The additional bands include:

Third Digit Band (a **five-band resistor**)

A resistor with 1% tolerance has four bands grouped together to specify its magnitude: three to specify the first three digits, and the fourth to specify the multiplier. These resistors have special thermal properties to provide the tight 1% tolerance.

Quality Band

If there is a band beyond (to the right of) the *tolerance band*, it is the *quality band*. The quality band represents the "percent failure rate per 1000 hours." This rating is for the maximum wattage being continuously applied to the resistor.

Quality band colors are Brown (1%); Red (0.1%); Orange (0.01%) and Yellow (0.001%).

Standard Values for Resistors

Standard resistance values come in seemingly odd values. The ***standard values*** for the **first two digits** of 20%, 10% and 5% resistors are as follows:

20% tolerance:

10,   15,   22,   33,   47,   68,   100

10% tolerance:

10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, 100

5% tolerance:

10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 27, 30, 33, 36, 39, 43, 47, 51, 56, 62, 68, 75, 82, 91, 100

Consider the nominal 4700 Ω, 10% tolerance resistor; it can vary in actual value from 4230 to 5170 Ω. The next standard resistor down from 4700 is 3900 Ω (3510 to 4290 Ω), and the next standard resistor up is 5600 Ω (5040 to 6160 Ω). The range of the 4700 Ω resistor overlaps with the ranges of its two "nearest neighbors." This overlap effect allows for the seemingly strange intervals of standard resistances. An overlap occurs for most, but not all, nearest neighbor resistors.

When a designer specifies a resistor in a system that is to be massed-produced, he or she must take into account that actual resistors will only be within tolerance of their nominal values; resistor values will not be exact.

If you want a particular nominal resistance not listed in the standard values, use a combination of standard resistors. If you need an exact resistance in lab, use a potentiometer as a variable resistor. ∎

Sources:

Electrical Engineering Faculty, Cal Poly SLO, *Electric Circuit I Laboratory* manual, El Corral Publications, Winter 2001.

Tsividis, Yannis, *A First Lab in Circuits and Electronics*, Appendix A: Component Value Codes, John Wiley and Sons, 2002, pp. 122-3.

"Resistor Color Codes," http://wiki.xtronics.com/index.php/Resistor_ Codes, accessed June 25, 2010.

Appendix B: CAPACITOR CODES

The various methods for labeling capacitor values can be difficult to understand. **When in doubt, measure**. Use the Philips PM 6303 RCL Meter in lab.

Large capacitors ("caps") have their *values* and *units* printed on them. For example, "10 μF" (10×10^{-6}F) on the lower cap in *Figure B.1*.

Most small capacitors have two or three numbers printed on them, and possibly a letter. Examples include "47", "0.05K", "103M", "101", "104K" (*Figure B.2*), etc. The digits give the capacitance in *picofarads* **pF** (1 pF = 10^{-12} F) or in *microfarads* μF (10^{-6} F), but we are not explicitly told which. In general, the unit is pF (sometimes called "puff"). For "0.05", experience teaches that 0.05 pF is too small for practical capacitors, so the value is 0.05 μF (50,000 pF).

The letter indicates the *tolerance* (*Table B-2*).

Three-Digit Codes

For *three-digit codes* such as "103", the first two digits are the first two digits of the capacitor value in *picofarads*. The third digit is the number of zeroes after the first two digits, or the *multiplier*. This is the same system used with four-band resistors (without the colors).

Thus, "103" represents 10 followed by 3 zeros ($10 \times 10^3 = 10{,}000$). So "103" is 10,000 pF = 10 nF = 0.01 μF.

The third-digit multiplier code is given in *Table B-1*.

Examples of 3-digit Codes:

"224" is 22×10^4 pF = 220,000 pF = 0.22 μF
"685" is 68×10^5 pF = 6.8 μF

The 3-digit code is the most common capacitor code you will see in ENGR171.

Two-Digit Codes

Capacitors with two-digit integers are read as picofarads; e.g., "47" printed on a small disk is 47 pF. It is a basically a 3-digit code with "0" for the third number.

Decimal Codes

Decimal numbers such as "0.1" and "0.05" are usually the value in microfarads: 0.1 μF and 0.05 μF.

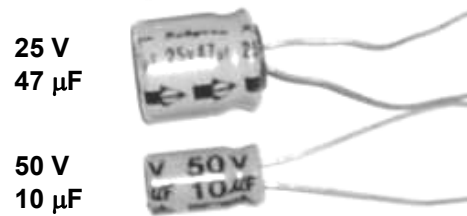**25 V**
47 μF

50 V
10 μF

Figure B.1 Electrolytic capacitors tend to be relatively large and cylindrical. Large caps have their value printed on them (here, 47 μF and 10 μF). The polarity of electrolytic caps is indicated on them: the arrows visible on the upper cap point to the negative side. A negative sign is also often printed on the negative side. Additionally, the negative lead (wire) is manufactured shorter than the positive lead.
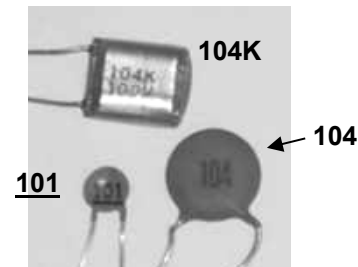

104K

104

101

Figure B.2 Caps with 3-digit codes.

Table B-1 *Multiplier*. The third digit in the 3-digit capacitor code indicates the number of zeroes that follow the first two digits. Capacitance in picofarads (pF).

Third Digit	Multiplier
0	$10^0 = 1$
1	$10^1 = 10$
2	$10^2 = 100$
3	$10^3 = 1000$
4	$10^4 = 10{,}000$
5	$10^5 = 100{,}000$
6	Not used
7	Not used
8	$10^{-2} = 0.01$
9	$10^{-1} = 0.1$

Polarity

The polarity of an ***electrolytic capacitor*** is indicated on the capacitor, usually by arrows pointing to the negative side, and/or a negative sign "−" as shown in ***Figure B.1***. An electrolytic capacitor must be connected in a circuit with the correct polarity (proper orientation), otherwise it will not work correctly, and may explode in service.

Another way of identifying the polarity of an electrolytic capacitor is to look at the two leads (wires) of the capacitor. The negative side is manufactured with a shorter lead.

Tolerance

Tolerances are given as letters; a list of a few tolerance codes is given in ***Table B-2***. For "104 K", the capacitance is $0.1\,\mu F \pm 10\%$; the capacitance can vary from 0.09 to 0.11 μF.

In general, the capacitors used in lab have less tolerance than the resistors; capacitor tolerances are more difficult to control.

Maximum Allowable Voltage

The maximum allowable voltage – the ***voltage rating*** of a capacitor – may be printed on the capacitor packaging, as seen in the lower capacitor of ***Figure B.1*** (50 V). For others, the *specification sheet* must be referenced. If the capacitor is subjected to an excessive voltage, it may explode or break down. In design, the voltage rating of a capacitor is usually twice the maximum voltage it is expected to be subjected to in service (a typical engineering *Factor of Safety* of 2).

Capacitor Type

Sometimes the type of capacitor is printed on its casing, but usually not. There are many types of capacitors, each having different strengths and weaknesses. They generally have a ***dielectric*** between their electrodes (the capacitor plates). A dielectric material increases the capacitance of the capacitor (instead of just having air between the electrodes).

Brief descriptions of the types of capacitors can be found at:

http://www.sentex.net/~mec1995/gadgets/caps/caps.html

Very brief descriptions of a few caps that you may come across are given below.

Table B-2 Capacitor Tolerance.

Letter	Tolerance
D	± 0.5%
F	± 1%
G	± 2%
H	± 3%
J	± 5%
K	± 10%
M	± 20%

Electrolytic capacitors (***Figure B.1***) are cylindrical (the parallel plates, separated by a non-conducting paper, are rolled around each other like a cinnamon roll), and are made with an electrolyte (essentially salt in a solvent), with aluminum electrodes. Electrolytic capacitors are one of the most widely-used types of capacitors (look inside a tower computer … but do not break it).

Ceramic disk capacitors are shaped like a disk (***Figure B.2***). They tend to be very small in size and can have very small capacitances. They are also one of the most widely-used types of capacitors.

Polyester film capacitors use a polyester film as a *dielectric*. They tend to be rectangular in shape.

Epoxy capacitors use a polymeric epoxy as a protective coating. They also are rectangular in shape, and often resemble Chiclet gum (DO NOT put them in your mouth!). ∎

Sources:

Tsividis, Yannis, *A First Lab in Circuits and Electronics*, Appendix A: Component Value Codes, John Wiley and Sons, 2002, pg.123.

"Capacitor Codes," http://wiki.xtronics.com/index.php/Capacitor_ Codes, accessed June 25, 2010.

van Roon, Tony, "Capacitors," http://www.sentex.net/~mec1995/gadgets/ caps/caps.html, accessed June 25, 2010.

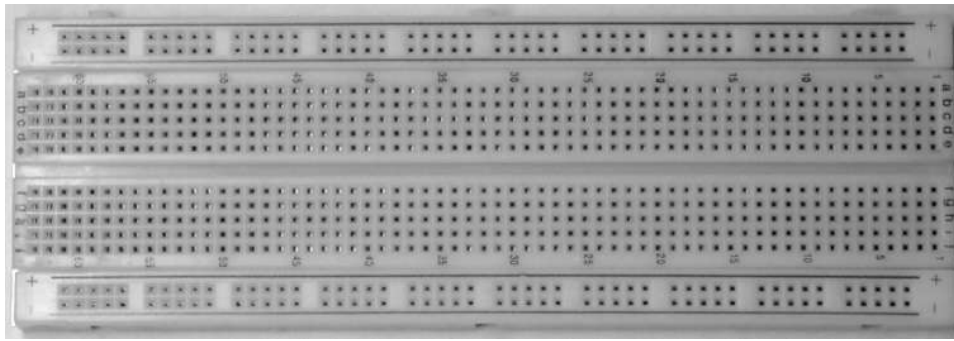# Appendix C: PROTO-BOARD (Bread Board)   Rev.: 7/29/14 DJD

Figure C.1 Proto-board used in ENGR 171.

A *Proto-Board*, or *Bread Board*, is used to building temporary circuits (e.g., prototypes). A typical board is shown in *Figure C.1*. The square *holes*, or *sockets*, are 0.1 inches apart, and provide locations to insert the leads (wires) of resistors, capacitors, inductors, op-amps, etc.

The sockets are connected beneath the board surface as shown in the pictorial in *Figure C.2*. Each socket is represented by a square, and the thin lines between sockets illustrate how they are connected. Sockets that are connected to each other are at the same *node* (and thus at the same voltage).

The board in *Figure C.1* (the one you probably have in ENGR 171) has red "+" and blue "–" lines printed along each long side. The sockets next to a red "+" line are all connected to each other (*Figure C.2*); those next to a blue "–" line are all connected to each other. These four separate "+" and "–" lines provide convenient interfaces (*buses*) to connect several components or devices to the same voltage. It is suggested to use the topmost "+" bus line for positive input, the very bottom "–" bus line for negative input, and one of the inner bus lines for *ground*.

Some boards have a printed black line along one side that is broken in the middle; in this case, the *bus line* (socket connection) is broken in the middle. Some boards have no printed lines, so it is a good idea to check socket continuity along the sides of the board with an ohmmeter (if two holes are connected, the resistance will be very small (e.g., <10 Ω); if not connected, the ohmmeter will display "OL").

In the central part of the board, the sockets are numbered along the sides (1, 2, 3... 62, 63) and they are lettered along the ends (a, b, c... i, j) allowing a specific hole to be identified (e.g., 53b).

Sockets are connected in groups (sets) of 5. In each numbered row, sockets a, b, c, d, e are connected to each other. Likewise, sockets f, g, h, i, j are connected to each other. Socket set a–e and set f–i are separated by a *trough*; set a–e is <u>not</u> connected to set f–i (*Figure C.2*).

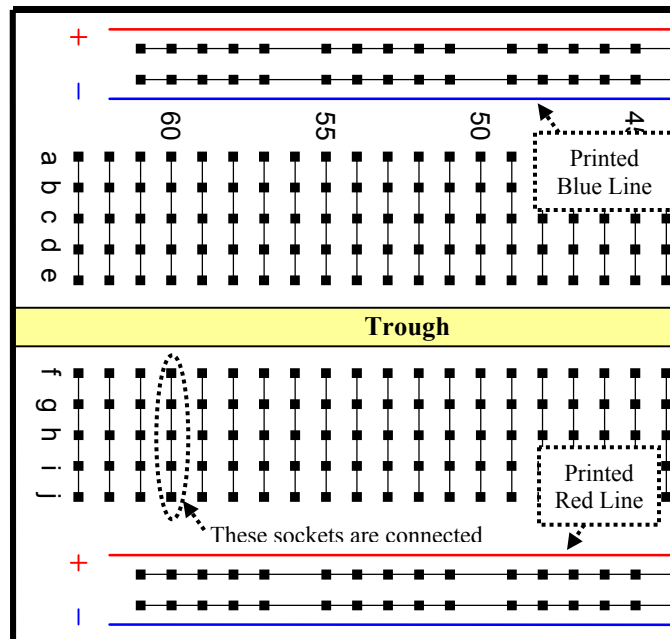The numbered rows are <u>not</u> connected to each other (*Figure C.2*).

Figure C.2 Pictorial of part of the proto-board of *Figure C.1*. Sub-surface connections between sockets (squares) are indicated by thin lines connecting them. For example, sockets 60f-60j (circled) are connected.

Circuits can be built as shown in *Figure C.3*. **Try to build a neat circuit** so that you (and your lab partner and instructor) can actually figure out what is going on. **You and your lab partner should check the circuit to ensure it is set up correctly before applying power**. Also check the circuit if you suspect it is not acting as it should.

A sloppy circuit can have errors that are difficult to see (*Figure C.4*). Resistors can be connected in the wrong order. Or, the resistor leads (wires) may touch causing a short-circuit, be placed in the wrong socket, or be pulled out accidentally.

Use **jumper wires** (pre-cut short wires) to connect holes as necessary. They can be used to help separate (spread out) components or blocks of components. In other cases, jumpers may not be required and cause clutter (*Figure C.4*).

Operational amplifiers have 8 terminals (leads). Op amps must be connected **across the trough** so that each lead is connected to a different 5-hole set (*Figure C.5*). If the op-amp is plugged into holes that are all on one side of the trough, the terminals will be short-circuited. ■
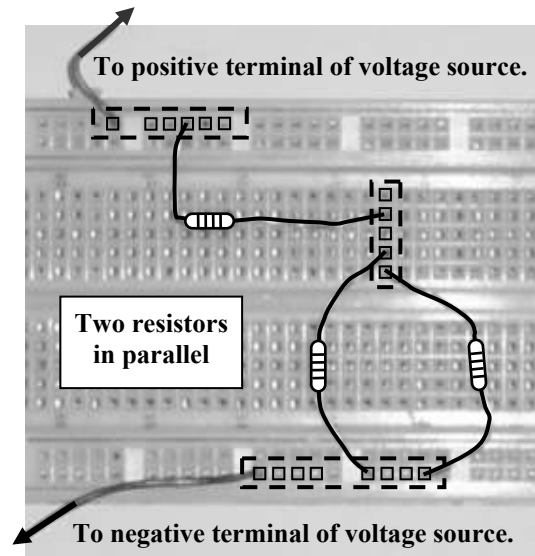
Figure C.3 Try to build neat circuits. Here, resistors are well-spaced, and lay flat on the board. In this figure, squares represent different sockets or holes. Dashed rectangles emphasize the *nodes* – sets of holes that are connected to each other (and thus at the same voltage).
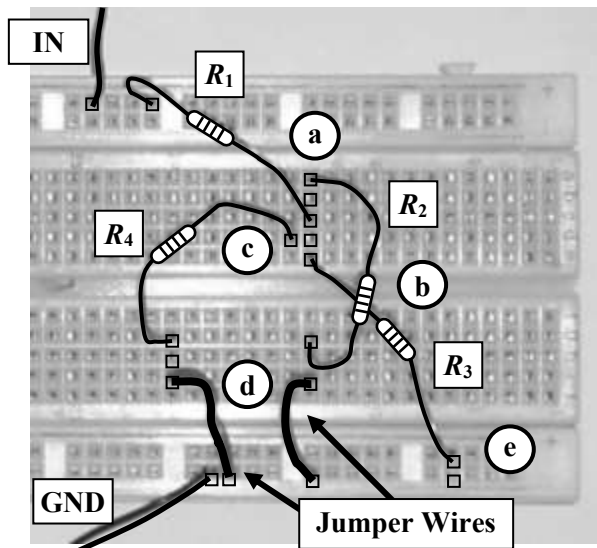

Figure C.4 A few common sources of error and suggestions for neater circuits. In this circuit, resistors R_2, R_3 and R_4 are supposed to be in parallel with each other. **(a)** For a neater circuit, the lead of resistor R_1 might switch sockets (holes) with the lead of R_2. **(b)** Resistors R_2 and R_3 cross; if wires touch, the system may become short-circuited. **(c)** The right lead of resistor R_4 is not connected to another wire/component; it is in the wrong 5-hole set. **(d)** Unnecessary jumper wires; take resistor R_2 and R_4 direct to ground if possible. **(e)** Resistor R_3 is not connected to the correct bus line.
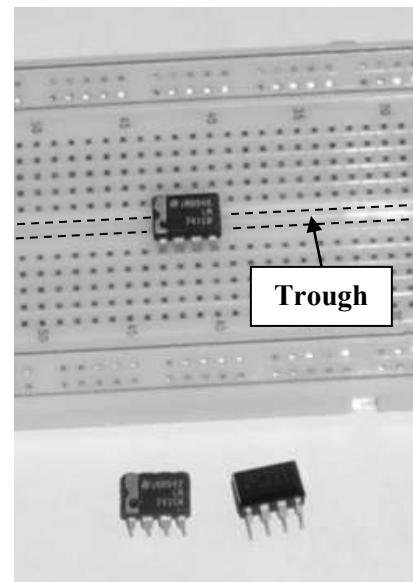

Figure C.5 An op-amp must be placed across the proto-board *trough* (shown dashed) so that each of the op-amp's 8 terminals is connected to a different 5-hole set.

Appendix D: GROUND CONNECTIONS

Rev.: 7/4/11 DJD

from: Tsividis, Yannis, *A First Lab in Circuits and Electronics*, New York: John Wiley & Sons, 2002, pp. 11-13.

Slight reformatting of text and [added comments], and recreation of figures: by D.J. Dal Bello, 2004-05.

Introduction

The issue of ground connections is one that will concern you again and again, in this and other labs. Read this chapter carefully, and try to understand it as much as possible. Not everything in it may make perfect sense in the beginning; some of this material will become clearer as you gain laboratory experience. Nevertheless, it pays to have a preliminary understanding at this point. As you attempt to connect various instruments in future experiments, you may need to return to this chapter for advice.

Producing Positive or Negative Supply Voltages with Respect to Ground

Lab instruments have terminals so that you can connect them to the circuits you are working with. For example, a "*floating*" power supply has plus (+) and minus (–) terminals. The voltage between them is a well-defined quantity, which you can set at will. However, the voltage between one of these terminals and a third point, such as the instrument's metal case (if it has one) or the case of another instrument, may not be well defined and may depend, in fact, on instrument construction and parasitic effects that are not under your control. Parasitic voltages can interfere with proper operation of the circuits you are working with, or can even damage them. Worse, in some cases they can cause an electric shock.

To avoid such situations, instruments have an additional terminal called **the ground**, often labeled **GND** or indicated by one of the symbols shown in **Figure D.1**; … . The ground terminal may be connected to the internal chassis of the instrument (it is sometimes referred to as the **chassis ground**); to the instrument's metal case; and if the power cord of the instrument has three wires, to the ground [third] lead of the cord's plug. When you plug in the instrument, this lead comes in contact with the ground terminal of the power outlet on your bench, which is connected to the **earth potential** [earth ground, $V = 0$] for safety and other reasons. In fact, other instruments on your bench [such as the oscilloscope], or other benches, or even elsewhere in the building may have their
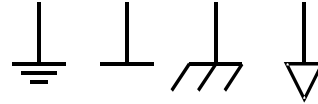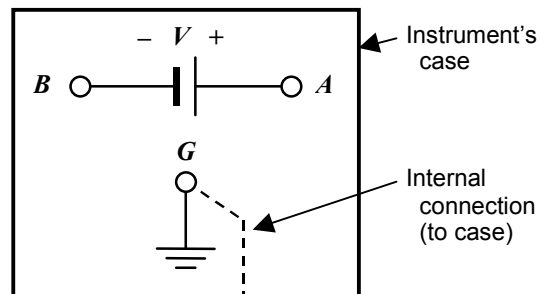

Figure D.1 [Rightmost figure added by DJD].

Figure D.2 [*Floating* terminals *A* and *B*, *Ground* terminal *G*].

grounds connected to that same point, through the third wire of their power cords.

When you use a power supply with the **output floating** (i.e., with neither of the output terminals connected to ground), you get the situation shown in **Figure D.2**. The circles (*A*, *B*, *G*) indicate terminals for making connections to the instrument's output or ground. In the following discussion V_{XY} will denote the voltage [difference] from a point *X* to a point *Y*. In **Figure D.2**, V_{AB} [$= V_A – V_B$] is the power supply's output voltage V, and it is well defined. However, V_{AG} and V_{BG} are *not* well defined and can cause the problems already mentioned.

To avoid this, you should strap [connect] one of the two output terminals to the ground terminal [G], as shown, for example, in **Figure D.3(a)**. Now *all* voltages are well defined: $V_{AB} = V$, $V_{BG} = 0$, and $V_{AG} = V_{AB} + V_{BG} = V + 0 = V$. If we assume that V is a positive quantity, the connection in **Figure D.3(a)** develops a positive voltage at terminal *A* with respect to ground. If you … need a negative voltage with respect to ground instead, you would use the connection in **Figure D.3(b)**. Here, terminal *B* has a potential of $–V$ with respect to ground [$V_{BG} = V_{AG} – V_{AB} = 0 – V$]. In some power supplies, ground connects as shown in **Figure D.3** are permanent, and you do

not have access to them. In other power supplies, it is up to you to make such connections.

Connecting One Grounded Instrument to Another

When more than one instrument or circuit with ground connections is used, one should think carefully. Consider … *Figure D.4*, where it is attempted to connect the output of one instrument to the input of another. For example, Instrument 1 can be a function generator [providing varying voltages]... Instrument 2 can represent an oscilloscope, or an oscilloscope probe [measuring varying voltages]. At first sight, the connections shown seem to be correct. However, there is a *big* problem. Although not apparent from *Figure D.4*, the ground terminals are connected not only to the instrument cases but also to the common ground of the power outlet on the bench (through the ground pin on the power plug, as explained earlier). Making these connections explicit, we have the situation shown in *Figure D.5*. It is now clear that the second instrument's ground connections short the first instrument's output across *CD* (i.e., they place a short circuit across it; you can trace this short circuit along the path *CIHGED*). [Thus output V_{DC} is forced to $V_{DC} = 0$.] Not only will this prevent a voltage from being developed at that output, but also it can damage the instrument. The problem is solved if the connection between the two instruments is modified, so that **the instrument ground is connected to instrument ground**, as shown in *Figure D.6*.

... one may wonder [why] the connection marked *x* is needed in *Figure D.6*, given that the two ground terminals are connected together anyway through the power cables, as shown by the heavy lines. The answer is that there may not always be a ground [third] terminal on the power plug, and even if there is one, it may not be reliable; although ideally all ground terminals on power receptacles should be at the same potential, they sometimes are not. In addition, the long ground wires (*IH* and *GH* in *Figure D.6*) may act as antennas, picking up interference. To be safe, then, use a short connection such as *x* between the ground terminals of the two instruments.

A final word of caution: Since an instrument's case is in contact with ground connections, you need to be sure that cables and devices do not accidentally come into contact with it. If this happens, malfunction or damage can occur.
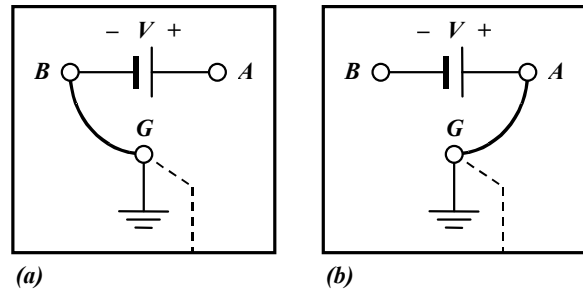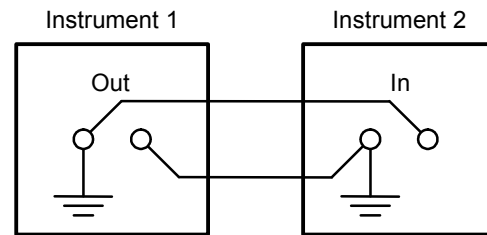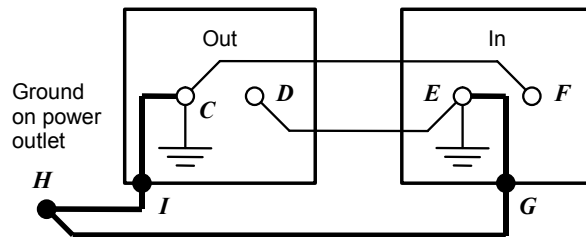

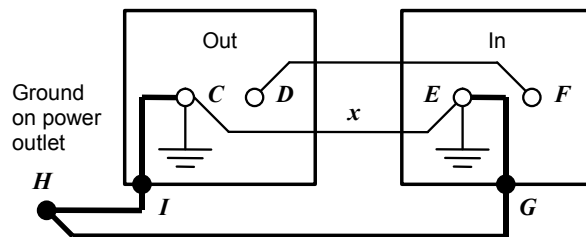*Figure D.3*

Figure D.4

Figure D.5

Figure D.6

These guidelines will be sufficient for the purposes of this lab. Grounding is actually a complicated issue, and you should not expect the simple practice discussed above to be adequate in all situations. As you gain experience, you will obtain a better feel for grounding practices. ■

Appendix E: FLUKE 45 DIGITAL MULTIMETER (DMM)
Revised: 7/29/14 DJD

You will make frequent use of the **FLUKE 45 Digital Multimeter**, or DMM (*Figure E.1*). It is called a *multi*meter since it can measure several quantities: DC voltage, DC current, AC voltage, AC current, resistance, frequency, and forward voltage drop across a diode. It is a *voltmeter* (measures voltage), an *ammeter* (current) and an *ohmmeter* (resistance), although not all at the same time.

The following pages provide some details on the Fluke 45 DMM to help you. Some advanced applications are given in the *Fluke 45 Quick Reference Guide* pamphlet in the top drawer of the lab benches, or in the *Reference Manual* in the reference manual drawer in M-433.
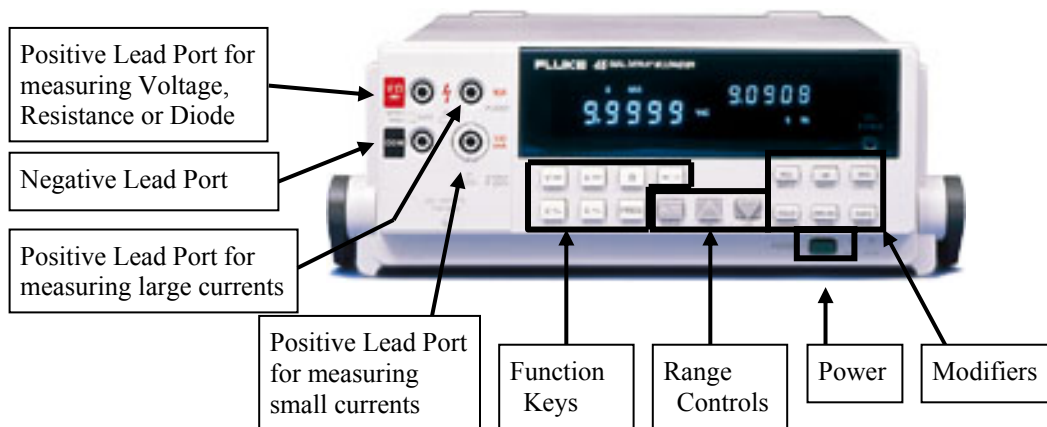

Figure E.1 Fluke 45 Digital Multimeter. On the Function Keys, DC is indicated by two parallel lines (solid and dashed) and AC by a sinusoidal icon. Lead ports are for banana-ended test leads.

Function Keys

Press the appropriate *Function Key* to measure a particular quantity; e.g., the DC voltage key to measure DC voltages. An AC measurement gives the *root-mean-square* value (r.m.s.), which is the subject of one of the ENGR 171 experiments.

Range

A *range*, or *scale*, is the region of values in which the DMM is trying to take measurements. On the Fluke 45 DMM, the "300 mV range" gives readings up to 300 mV (0.00001 to 0.29999 V). The "3 V range" gives values up to 3 V (0.0001 to 2.9999 V).

Likewise, for resistance, the "300 Ω range" goes from 0.01 to 299.99 Ω, while the "3 kΩ range" goes from 0.1 to 2999.9 Ω.

The Fluke 45 DMM is what is called a 4-1/2 digit, 30,000 count DMM. The term "4-1/2 digit" refers to a meter that gives measurements with four full digits ranging from 0 to 9, plus the leading "half digit" which is a zero, 1 or 2. Thus all numbers from 0 to 29,999 are represented. The "count" refers to the size of each *range*. Here, there are 30,000 "tick marks" or *counts* in each range.

The range values can be found in the "Fluke 45 Quick Reference Guide" in the top drawer of the lab benches, and in *Table E-1* at the end of this article.

When taking measurements, **record as many digits as the display reads**. **Do not round off** unless the last digit drifts with time.

Range Controls

- The **up arrow** ▲ increases the range (scale). For example, from the 300 mV range to the 3 V range.

- The **down arrow** ▼ decreases the range.

- The AUTO key lets the Fluke *autorange*, or automatically select the best range; the display window will read "AUTO." To turn autorange off, press the AUTO key again.

The range is adjusted to get measurements of better *resolution*. For the best resolution, use the smallest range larger than the value you are measuring; e.g., if measuring a 150 Ω resistor, use the 300 Ω range. The 3 kΩ and 3 MΩ scales will give readings, but not to the same number of meaningful digits. For example, a 150 Ω resistor was measured on the Fluke 45 DMM at three different ranges:

300 Ω range:	147.16 Ω
3 kΩ range:	0.1472 kΩ
3MΩ range:	0.0002 MΩ.

The 300 Ω range gave the best *resolution* for the 150 Ω resistor.

Always start at the highest scale (range) first. Trying to measure a value larger than the range setting may damage the DMM's internal circuitry.

Making Measurements

Always use appropriate meter leads. For the Fluke, one end of each lead is a banana plug, and the other can be an alligator clip, a mini-grabber, or a straight probe. Alligator clips can be connected to short *jumper wires* that can easily be inserted into proto-board sockets; mini-grabbers can be clamped directly to component wires.

The positive (red) test lead plugs into one of the positive (red) ports: [V,Ω,→], [10 A] or [100 mA] port. The negative (black) test lead plugs into the negative or common [COM] (black) port.

Again, always start at the highest scale (range) first. Trying to measure a value larger than the range setting may damage the DMM's internal circuitry.

If you try to measure a resistance larger than the current range, the DMM will read "OL" meaning "overload" (some call it "over limit" or "open line").

In analog (dial) meters, trying to measure a resistor larger than the DMM's range setting results in *pegging*. As the dial tries to turn to a value beyond its maximum for the selected range, the dial slams into the peg intended to limit its motion. This mechanically damages the DMM.
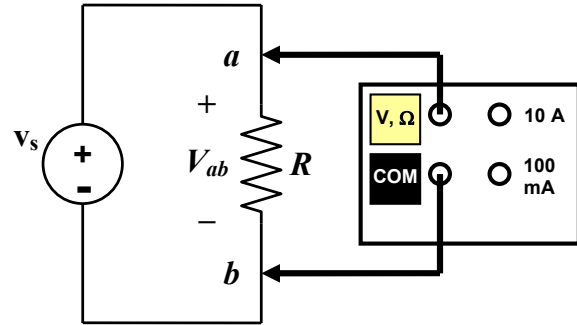

Figure E.2 Connection for using the DMM as a **voltmeter**, measuring voltage drop V_{ab} from *Node a* to *Node b* ($V_{ab} = V_a - V_b$).

Voltage Measurements

Voltage measurements are made _in parallel_ with the component(s) whose voltage is being measured (e.g., the resistor in *Figure E.2*). **In parallel, the component and the DMM have the same *voltage drop*.** As a *voltmeter*, the DMM presents a **high resistance** so that the current through the component being measured is practically unaltered (see *current dividers* in the textbook).

The voltmeter is connected across (in parallel with) the component. The assumed positive (higher voltage) terminal of the component (*Node a* in *Figure E.2*) is connected to the positive port [V,Ω,→] of the DMM. The assumed negative terminal (*Node b*) is connected to the negative port [COM].

Voltage has polarity. If the measured voltage drop from *Node a* to *Node b* is **positive**, then the higher voltage is indeed at the component terminal connected to the [V,Ω,→] port; i.e., $V_a > V_b$ ($V_{ab} = V_a - V_b > 0$).

If the measured voltage drop from *a* to *b* is **negative**, then the higher voltage is actually at the component terminal connected to the [COM] port; i.e., $V_b > V_a$ ($V_{ab} = V_a - V_b < 0$).

DC and AC Voltage Measurements

DC (constant) measurements are made by pressing the Function Key for DC voltage $\boxed{V =}$. If the voltage across the element varies periodically, the DC measurement gives the *average value* of the signal. If the signal is a pure sine wave, e.g., $v(t) = V_m \sin \omega t$, then the DMM displays the average value (i.e., zero, 0). However,

if the sine wave is offset, e.g., $v(t) = V_o + V_m\sin\omega t$, then the average value V_o is displayed.

AC (time-varying) measurements are made by pressing the Function Key for AC voltage $\boxed{V \sim}$. This measures the ***root-mean-square*** (***r.m.s.***) value of **only the time-varying part of the signal**. For a sine wave, $v(t) = V_o + V_m\sin\omega t$, the value displayed is $0.707V_m$, regardless of V_o.

To measure the ***total root-mean-square*** (***r.m.s.***) value of a time-varying signal **due to both its constant and time-varying parts, press both** $\boxed{V =}$ and $\boxed{V \sim}$ **at the same time**. The r.m.s. value of the total signal is displayed.

Current Measurements

Current measurements are made *in series* with the component whose current is being measured (***Figure E.3***). **In *series*, the component and DMM have the same current.** As an ***ammeter***, the DMM presents a **very small resistance** – it acts as a short – so that the current through the component is practically unaltered by the measuring device (see *voltage dividers* in the textbook).

The ammeter is inserted into the circuit by "breaking" the circuit, and inserting the ammeter into the "break". In other words, "**Break and Replace**". When the circuit is broken at a node, two new nodes are created – the ammeter is inserted between these two nodes.

In ***Figure E.3***, ***Nodes c*** and ***d*** were originally the same node; the circuit is broken at ***c-d***, and the ammeter placed between ***c*** and ***d***. Alternatively, imagine a *short* circuit (wire) between ***Nodes c*** and ***d***; then replace the *short* with the ammeter.

Current I is taken to enter the Fluke at the [10 A] or [100 mA] port (depending on if the current is large or small), and leaves through the [COM] port. Currents in ENGR 171 are less than 100 mA, so the lower current input port is used.

In ***Figure E.3***, current is assumed to flow from ***Node c*** to ***Node d***, from the [100 mA] port to the [COM] port.

If the measured current is **positive**, then the current physically flows from the [100 mA] port to the [COM] port (from ***c*** to ***d*** in ***Figure E.3***).

If the measured current is **negative**, then current physically flows in the opposite direction assumed (from ***d*** to ***c***).
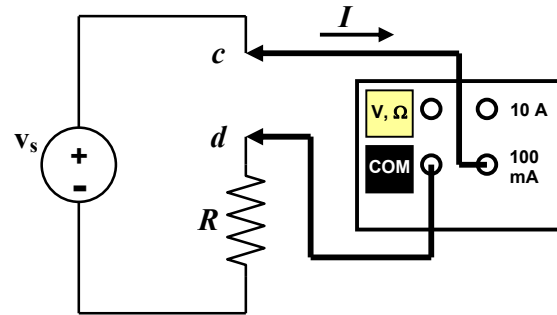

Figure E.3 Connection for using the DMM as an **ammeter**, measuring current *I* through the circuit branch between *Nodes c* and *d*. Use the 100 mA port for currents less than 100 mA.

Measuring current is more difficult than measuring voltage because the circuit must be "broken" and the ammeter correctly inserted into the circuit without change the circuit architecture.

The water analogy of electric circuits might be helpful. To measure water flow through a pipe, a meter must be inserted into the pipe. The pipe is cut; water that would flow out of the pipe must be directed into the meter, and then out of the meter back into the downstream pipe. To measure electric current, the wire ("pipe") must be broken; the current that would "flow out" of the wire must be directed into the meter, and then out of the meter back into the wire.

Three important points to remember:

1. **The current to be measured must be forced to go through the ammeter.**

2. **Do not change the circuit**. The components must be connected the same way as they were without the ammeter; the currents through each component must remain the same. Recall that the ammeter acts as a short.

3. **Do not connect the ammeter in parallel**.
   - this provides an alternate (new) path for the current to flow through, thus changing the circuit.
   - since the ammeter acts as a short, the current in this new path can be large – exceeding 100 mA – and blowing the fuse in the DMM (the fuse protects the DMM circuitry from being overloaded).

Resistance Measurements

Resistance measurements **are made** <u>*in parallel*</u> with the resistor being measured (***Figure E.4***). One lead of the resistor is connected to the [V, Ω, →] port, while the other is connected to the [COM] port. ***Resistors are not polarity sensitive***, so the resistor can be connected in either direction.

The DMM applies a calibrated voltage, and measures the current caused by the voltage. The ratio of the voltage to current is the resistance.

Two important points to remember when measuring resistances:

1. **Do not supply power to the circuit when measuring resistances**.

   - the external power may damage the calibrated voltage source in the DMM.

   - the external voltage will affect the current measured by the DMM, giving faulty readings.

2. **Isolate the resistor** (**remove it**) from the circuit to ensure that you are not measuring a parallel combination of some other resistances, as illustrated in ***Figure E.5***. (Note: the resistor does not need to be removed from the proto-board, but must be removed from the circuit).
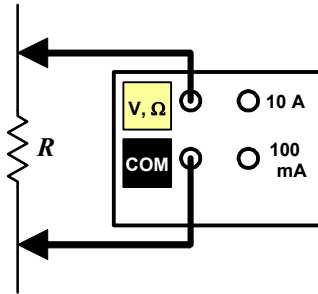
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Figure E.4 Connection for using the DMM as an **ohmmeter**, measuring the resistance of resistor *R*.
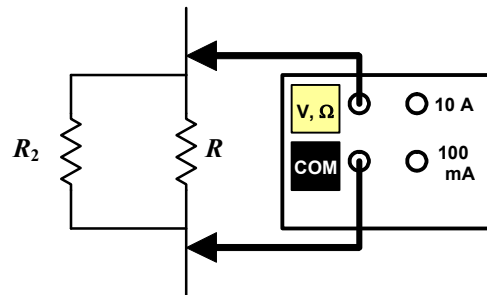

Figure E.5 Measuring the resistance of the parallel combination of *R* and R_2. To measure *R* alone, remove it from the circuit (here, disconnected from R_2.

Measure Voltage *in Parallel*.
Measure Current *in Series*.

For measuring current, you may have heard: "Break and Replace".

Voltage, *Current* and *Diode* measurements are *polarity sensitive*. It matters which component terminal is connected to which DMM port.

Table E-1 Typical Fluke 45 Ranges and Full-Scale Values, partial list (adapted from Tables 3-2 through 3-4, *Fluke 45 Dual Display Users Manual*).

Voltage Range (full scale)	Current Range (full scale)	Resistance Range (full scale)
300 mV (300.00 mV)*	30 mA (30.000 mA)	300 Ω (300.00 Ω)
3 V (3.0000 V)	100 mA (100.00 mA)	3 kΩ (3.0000 kΩ)
30 V (30.000 V)	10 A (10.000 A)	30 kΩ (30.000 kΩ)
300 V (300.00 V)	-	300 kΩ (300.00 kΩ)
1000 V (1000.0 V)	-	3 MΩ (3.0000 MΩ)
-	-	30 MΩ (30.000 MΩ)
-	-	300 MΩ (300.00 MΩ)

* Voltages are measured from 0 mV to 299.99 mV.

Reference:

The Fluke Corporation, *Fluke 45 User's Manual*, 1999.

Appendix E1: DIGITAL MULTIMETERS (DMMs): *Accuracy* and *Resolution*

Taken directly from the Cal Poly EE241 circuits lab manual, 2001.

Emphasis, [notes, clarifications, additions in square brackets], footnotes, and other minor editing
by D. J. Dal Bello, 2004-05, 2010-11, 2014.

Note: the text was originally written assuming a 3-1/2 digit, 2000-count DMM (i.e., a range from 0 to 2000 Ω).
AHC's Fluke 45 DMM is a 4-1/2 digit, 30,000-count DMM (e.g., 0 to 30,000 Ω). The ideas are the same.

A digital multimeter (DMM) is one of the most versatile instruments in an electronics laboratory. It is relatively inexpensive, accurate, and easy to use. DMMs usually measure DC and AC voltages, AC and DC currents, resistance, forward voltage drops in diodes, and sometimes conductance.

There are pitfalls in the use of DMMs. Students often believe that the numbers shown on a display are precisely accurate. This is never true, and often the relative error can be quite big when measuring small values on the selected range.

It is extremely important to distinguish between *accuracy* and *resolution*. [*Accuracy* is how close you are to the actual value. *Resolution*, or *precision*, is how well you can distinguish two different, but nearby, signals or values; e.g., the distance between marks on a ruler].

A 3-1/2 digit[1] meter can count up to 2000 in displaying the measured parameter, whether it be voltage, current, or resistance. The **resolution** for such a meter is one count or ±1 part in 2000[2]. So, for example, if you are measuring DC voltage on the 2 V **range**, the meter will measure from 0.001 V to 1.999 V. The **resolution** is then "one count" or 0.001 V [±0.0005 V].

The ***accuracy*** of a DMM, however, is another matter. It is always worse than the resolution. Accuracy is specified as **a percentage of the reading plus or minus 1 or 2 counts of the least significant digit**.[3] In an analog meter [a meter with a dial or needle] the accuracy is specified as a percentage of the full scale value of the range of the meter setting. Therefore, **digital instruments** have an additional advantage: their accuracy is mostly independent of the meter range. The accuracy is not completely independent of the range because of the 1 or 2 count uncertainty in the least significant digit.

As an example, suppose you measure 1.324 V on the 2 V DC range of a [3 1/2 digit] meter with a DC accuracy of 0.25% ± 1 count[4]. The error would then be:

$$(0.0025)(1.324 \text{ V}) + 0.001 \text{ V} = 4 \text{ mV}$$

As a percentage error, this would be:

$$\frac{0.0043}{1.324}(100\%) = 0.33\%$$

A more extreme example. Suppose on the 2 V DC range you measure 0.032 V. The error would be [to one significant figure]:

$$(0.0025)(0.032 \text{ V}) + 0.001 \text{ V} = 1 \text{ mV}$$

The *percentage error* would then be:

$$\frac{0.001}{0.032}(100\%) = 3.4\%$$

This is worse than a good quality analog meter, and much worse than the stated accuracy of the digital meter. [This problem is caused by trying to measure a quantity that is near the bottom of the range].

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[1] "3-1/2 digit" refers to a meter that gives 3 full digits ranging from 0 to 9, plus the leading "half digit" that is either a blank or a one (1)… thus all numbers from 0 to 1999.

 AHC's Fluke 45 reads to 2999.9; it is a "4-1/2 digit, 30,000 count" DMM – 4 full digits, plus the leading "half digit": blank, 1 or 2.

[2] The last digit has an uncertainty of ±0.0005 V, which is 0.5 parts in 1000, or 1 part in 2000.

 AHC's Fluke has a resolution of 1 part in 30,000; assume ±0.5 of the last digit.

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[3] It would seem that the *accuracy* should be ±(0.25% + 1 count), not (0.25% ± 1 count).

[4] Nominally, AHC's Fluke has a DC voltage accuracy of 0.025% + 2 counts; its resistance accuracy is 0.05% + 2 counts.

A **remedy for this problem would be to switch to the next lowest scale**, [from the 2-V range (±0.001 V for the 3-1/2 digit meter), to the] 200-mV [range (±0.0001 V)]. The reading error would still be 0.25%, but the least significant digit of uncertainty is now 0.1 mV = 0.0001 V. You would then measure something like: 0.0320 V. The error would then be:

$$(0.0025)(0.0320 \text{ V}) + 0.0001 \text{ V} = 0.2 \text{ mV}$$

and the percent error is:

$$\frac{0.0002}{0.0320}(100\%) = 0.6\%$$

To obtain the most accurate reading, choose the lowest range possible.

[Note: If it exists, the next lowest scale, 20 mV, would be unable to measure the 32 mV, since 32 is greater than 20 mV. The DMM will display "OL" for "overload".]

Other hidden sources of error in DMMs are noise, variations with temperature, and errors due to lack of calibration. The most accurate measurements that can be made on a DMM are DC voltages. All other measurements are less accurate, with AC current being the least accurate. When a single accuracy figure [rating] is given for a meter, it is always for DC voltage. Always read the complete specifications if measurements other than DC voltage are to be made.

AC Signals

Another thing to keep in mind is that most DMMs measure the average value of AC signals. This value is converted to the equivalent r.m.s. [root-mean-square] value **as if the signal were a sine wave**. Therefore, for non-sinusoidal waveforms, the readings will be very inaccurate. Analog meters measure AC signals the same way.

Some higher quality DMMs have a true r.m.s. capability which allows for the computation of the actual r.m.s. value [no matter what the waveform; AHC's Fluke can measure true r.m.s.]. There are limitations to this technique. The crest factor usually cannot be greater than about 5 to obtain accurate readings. The bandwidth of AC measurements is also quite limited. Most DMMs can measure AC voltages with their highest accuracy in the approximate range of 40 Hz to 5 kHz. Above 10 kHz, most DMMs are unusable.

[You will generally use the **oscilloscope** to measure AC voltages].

Analog Meters

Are analog [needle or dial] meters obsolete? Almost. Their only advantage is that they can show trends. It is easier to see a needle move than it is to keep track of numbers changing on a display. To accommodate this feature, some digital instruments have an analog display in addition to the digital display. Analog meters find use in specialized measurement situations, such as high voltage, low current, or high resistance.

The severest limitation of analog meters is their accuracy, which is never better than 2%. Digital meters can have more than 5-1/2 digits, giving a resolution of 5 parts per million[5]. ∎

References:

Electrical Engineering Department Faculty, Cal Poly, SLO. *Electric Circuit I Laboratory Manual*, Winter 2001.

The Fluke Corporation, *Fluke 45 User's Manual*, 1999.

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[5] A 5-1/2 digit, 20,000 count DMM has 6 total digits; the leading half digit, plus 5 full digits. The last digit has an uncertainty of 0.5 the last digit, i.e.,: 100,000±0.5, which is 5 parts in 1,000,000, or 1 part in 200,000.