



**Duke University  
Department of Electrical and Computer Engineering**

**EE-61L  
Electric Circuits Laboratory**

**Introduction to Wireless Control  
and  
Virtual Instrumentation using Agilent VEE**

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Version 1.1: Spring 1995  
Version 1.2: Fall 1995  
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**With assistance from Christopher E. Cramer, Ph.D., and  
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## Introduction

Welcome to the new EE61 laboratory. Over the past 6 years several grants have been awarded to the EE61 program for its leadership as a national role model for introductory circuits. The primary contributors have been Agilent Technologies, the National Science Foundation, the Lord Foundation and National Instruments. The funds provided by these grants have been used to purchase Hewlett-Packard (now Agilent Technologies) state-of-the-art digital test equipment, personal computers and LabVIEW full-development systems including GPIB interface cards.

It is a general practice in introductory circuits courses to require students to build a simple circuit, make some measurements to verify the theory, and finally to disassemble the circuit. We believe that it would be a much richer learning experience if the circuits built at each lab meeting were sub-circuits of a pertinent, real-world system. Rather than disassembling circuits at the end of each lab meeting, the sub-circuits could be mounted on a circuit board and interconnected as the semester progresses. This is what we are trying to implement in the new EE-61 lab.

### 1. Laboratory Make-Up Policy

Every student is required to perform all laboratory exercises. In order to make-up a lab you will need to provide a memorandum from the Dean's office certifying that your absence from the lab meeting is excused. Students who miss a lab and are unable to provide documentation excusing them run the risk of failing EE61L and must see their course instructor **immediately**.

### 2. General Laboratory Operating Procedures

Listed below are the operating procedures that you are expected to follow in the laboratory.

1. Please treat the instruments with care, as they are very expensive. For example, the scope probes alone cost \$200.
2. Read the laboratory documentation prior to each lab meeting.
3. Read the question section before leaving the lab because some of the questions may require observations of the lab equipment.
4. Return the components to the **correct** bins when you are finished with them.
5. Before leaving the lab, place the stools under the lab bench.
6. Before leaving the lab, turn off the power to all instruments including the printer.
7. Before leaving the lab, turn off the main power switch to the lab bench.

### 3. Laboratory Journals

You are required to obtain a spiral bound notebook into which data and notes are to be entered during each lab exercise. At the end of each lab exercise you, your lab partner, and the lab TA must **sign and date** your journal. These journals will be examined periodically by your lab TA and evaluated as part of your laboratory grade.



#### 4. Laboratory Reports

1. Laboratory reports will be due at the **beginning** of each lab meeting. Work that was performed the previous lab meeting is to be documented and turned in the following week at the beginning of the lab period.
2. Late reports will have points deducted at a rate of 10% per weekday. A report will be considered one day late if it is handed in after the lab has started. **No lab reports may be handed in more than one week late.**
3. **All lab exercises must be performed, and all lab reports must be turned in to pass the course.**
4. Laboratory exercises and the writing of laboratory reports are performed in pairs. **The lab report turned in by each student pair must be entirely their own work.** In addition, each student pair is required to write the statement, "We have neither received nor provided any help on the writing of this lab report," and sign their names beneath on the title page of their lab reports.

While content is clearly the primary objective, neatness and organization will be weighted significantly in the grading of your lab reports. It is **required** that you type your lab reports using LATEX. A LATEX tutorial is provided in the EE61 Coursepak and is available on the EE61 webpage which is accessible directly from the Duke EE Homepage (<http://www.ee.duke.edu/>) under Course Homepages (Local Access Only).

Circuit diagrams may be hand-drawn, but wires should be drawn using a straight edge. It is recommended that you learn to use xfig to draw your circuit diagrams and merge the diagrams as postscript files into your LATEX documents. Tutorials describing how to use xfig and how to merge the diagrams as postscript files into LATEX documents are provided in the EE61 Coursepak as well as on the EE61 webpage. A good laboratory report is concise while providing enough detail such that another person could reproduce the results. Another person should be able to read your lab reports and know what you did and how you did it. A detailed description of the format you are to use for your laboratory reports along with an example lab report is presented at the end of this introduction.

Your lab reports should not contain the degree of detail as present in the lab manual. Try to keep your reports as concise as possible without deleting essential information. Provide minimum *procedure* statements (eg. "We obtained four 22 nF capacitors.") You may assume that the reader has knowledge and proficiency in the use of the lab instruments. Writing of lab reports is not intended to be "busy work" in which you simply rephrase what is stated in the lab manual. You should provide data, as well as comments and observations to indicate your understanding.

#### 5. PSpice Results Presentation

Most of the laboratory experiments and homework assignments will require you to perform PSpice simulations. There is a PSpice tutorial included in the EE-61 coursepak. In general, you must include the following items in order to receive full credit for this portion of laboratory reports and homework assignments:

1. **Circuit diagram** with the nodes labeled as used in the PSpice code, element values and problem statement
2. **Analysis** (calculations)
3. **Simulation results:** the output that PSpice produces including the source code, DC values, and any graphs.



4. **Justification** that the PSpice results are correct. In the case of DC analysis, a direct comparison of the calculated value with the value produced by PSpice including percent error is sufficient. However, in the more general case, the output voltage or current will be time-varying and a more detailed explanation is required. You can verify that the graphs produced by probe are correct by calculating a few theoretical values and comparing them with the corresponding coordinates on the graphs produced by PSpice. A more sophisticated verification might include calculation of min/max values and the times at which they occur. For AC circuit simulations, you must show that the amplitude, frequency and phase of the output voltage (current) produced by PSpice (using probe) is the same as the theoretical value(s). The source code and DC values are always produced in the .out file and you should include this file in your PSpice Results Presentation. Be sure to edit the .out file to eliminate white space and any irrelevant information in order to save paper. Whether you are simulating a simple DC circuit or a complex circuit with time-varying sources, **you must always provide a written statement of justification.**

### Perspective and Writing Style

Over the past several years there has been an increasing number of journal articles written in the first person, plural. For example, "In this paper we present a new method for depositing thin films..." However, most journal papers are written in the *third person omniscient*. For example, "This paper presents a new method for depositing thin films..." Proponents of the use of the first person claim that its use promotes the use of the active voice as opposed to the passive voice, and that the use of the passive voice is to be avoided. For example, "We show that our method performs better..." in contrast with, "It is shown that the method proposed performs better..." Proponents of the use of the third person claim that the use of the first person is awkward and less professional than sentences crafted in the third person. It is up to you to decide which perspective to use in your writing style. You should examine the writing in the various *IEEE Transactions* and compare different authors' writing styles.

## 6. Acknowledgment

Six stations of Hewlett-Packard (now Agilent Technologies) digital test instruments, PCs and printers, LabVIEW software and GPIB cards were donated by the National Science Foundation. Eight stations of digital test instruments were donated by Hewlett-Packard (now Agilent). Five Hewlett-Packard PCs were donated by the Lord Foundation of North Carolina. Five HP Printers were purchased by the Department of Electrical Engineering. Five copies of LabVIEW software were donated by National Instruments. There are a number of undergraduates who have helped with lab exercise development: Vladi Ivanov, Niles Murthy, William Howell, William Lawson, Andre Starobin, Fay Chang, Pamir Gelenbe, Teresa Lam, Shahid Khan, Adeline Chew and Raymond Woo. Graduate assistance has been provided by Will Washington, Evrim Eicoz, Lisa Gresham, Stacy Tantum, Richard Anderson and Joseph Supple.

### Laboratory Report Format

Use the following guide for your laboratory report format.

1. **Title:** On a separate cover page provide the title of the lab exercise, your name, your partner's name, and the date the exercise was performed. On the bottom of the title page, write the phrase "I have neither received nor provided any assistance in the writing of this laboratory report," and sign your name beneath.
2. **Abstract:** Provide a brief statement (no more than a few sentences) of your results and conclusions obtained from the laboratory exercise.
3. **Introduction:** Describe the objective and summarize what you did in the laboratory exercise.



4. **Analysis:** In some of the laboratory exercises you will be required to perform theoretical calculations. In this section, you are to present equations and their solutions as appropriate. If you need to make use of experimental data, you may choose to present this section after the section entitled **Experimental Results**.
5. **Experimental Results:** In some of the laboratory exercises you will be required to make various measurements. In this section, you are to present your experimental set-up along with your measurements. State what equipment was used in your measurements and what was measured. Provide diagrams (eg. XFIG) as necessary to illustrate your experimental set-up. Data are usually presented in the form of either a table or a graphs. Provide tables, diagrams and figures as appropriate to present your experimental results.
6. **Simulation Results:** In some of the laboratory exercises you will be required to perform computer simulations using PSpice. In this section, you are to present your simulation results.

There is a PSpice tutorial available on the EE61 webpage (<http://www.ee.duke.edu/>) under Course Homepages (Local Access Only) that illustrates many of the features available in **probe**, the graphics post-processor in PSpice. For details regarding PSpice syntax and numerous examples of the use of PSpice commands you should refer to *SPICE for Circuits and Electronics using PSpice* by Rashid.

In general, you must include the following items in order to receive full credit for this portion of your laboratory reports:

- Circuit diagram with the nodes labeled as used in the PSpice code, element values and problem statement.
  - A listing of your PSpice code (or schematic if using psched).
  - PSpice and probe output as appropriate.
  - Additional tables and graphs as required to present/illustrate your simulation results.
7. **Discussion:** In this section (if appropriate) you are to compare theoretical, experimental, and simulation results. Most measurements will contain some error (difference between theoretical and measured values). Always calculate percent error and then describe possible or known sources of the error. An error percentage of 5% is not uncommon. If the percent error is less than 5%, consider the theory and measurements to coincide. If the error percentage is greater than 5%, it is very likely that something has not been accounted for in the theory or a measurement was not performed properly. Present theoretical values, measured values, simulated values and percent error in the form of a table.
  8. **Conclusion:** In this section you are to state whether the objectives of the lab were met. Were there any errors in measurements that you could not account for? What changes in the lab exercise would you suggest? Please explain and provide justification.

The following sample lab report (from EE61) illustrates the format you are to use for writing your laboratory reports. While the sample lab report is not perfect, it does provide a good model for the type of content that is appropriate for each section.



**Duke University**  
**Department of Electrical and Computer Engineering**  
**EE61 Laboratory**  
**Lab 2 - Operation of the Digital Instruments and Basic**  
**Measurements**

Laboratory performed on

December 11, 1999

Your Name

Partner: partner's name (if appropriate)

I have neither received nor provided any assistance in the writing of this lab report.

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**Abstract:**

The constant voltage (CV) and constant current (CC) controls on the DC power supply were investigated. By adjusting the CC control, the current available from the DC power supply is adjusted. A 1 k $\Omega$  1/4 Watt carbon resistor was examined in terms of its color code (nominal value and tolerance) and measured. Graphite resistors were created by drawing rectangles and filling them in with graphite using a pencil (#2 lead equivalent to HB). We obtained a relationship between the dimensions of the rectangles and the resistance of the graphite resistors. The resistances of our bodies were measured and found to be in the range of 90 - 100 k $\Omega$ . Measurements of current were made using the ammeter and voltage using the voltmeter. Differences between the ideal meters and physical meters were observed. Measurements of the amplitude and frequency of a sinusoidal voltage produced by the function generator were made using the oscilloscope. The voltage indicated on the front panel display of the function generator indicates the true value of the terminal voltage only if the load resistance is 50  $\Omega$ . In the process of making these measurements we gained familiarity with the test instruments.

**I Introduction:**

The objective of this laboratory exercise is to learn to use properly each test instrument at the lab bench. We used four Agilent digital instruments during this lab: the Agilent E3611A DC power supply, the Agilent 33120A function generator, the Agilent 34401A digital multimeter, and the Agilent 54600B digitizing oscilloscope. We learned the correct method of measuring physical quantities (voltage, current, resistance) with the digital multimeter, the correct method of measuring voltages with the oscilloscope, the correct method of producing desired waveforms with the function generator, and the correct method of obtaining desired DC voltages from the DC power supply.

**II. Experimental Results***A. DC Power Supply and Digital Voltmeter*

In this experiment, we examined the role of the CV and CC Set buttons on the front panel of the DC power supply. We set the DC power supply to provide 3 V (as indicated on its front panel display) and then used the multimeter to obtain the more accurate value of 3.076 V. We then connected the DC power supply to the oscilloscope and measured the voltage using two methods. First, the voltage was 3.069 V using the automatic measuring feature, and then it was measure to be 3.1 V manually (counting the divisions and multiplying by the number of volts per division). We set the voltage on the power supply to 0 V and using the CC Set button, set the current limit to 0.05 A. We connected a 50  $\Omega$  (nominal) resistor to the power supply and then connected the multimeter across the resistor and power supply. The multimeter was set to measure DC voltage. We slowly increased the voltage, and when we reached 2.62 V the power supply changed from CV to CC.

*B. Resistance Measurement*

In the first part of this experiment we compared the actual value of a 1 k $\Omega$  1/4 Watt carbon resistor and its nominal value as indicated by its color code. In the second part of this experiment we measured a set of carbon graphite resistors we created using a pencil and drew conclusions about the relationship between their physical dimensions and resistance.

We selected a nominal 1 k $\Omega$  resistor and measured its resistance to be 995.9  $\Omega$  with the multimeter.

We created graphite resistors of different dimensions by drawing rectangles of various sizes on paper and filling them in with pencil and then measured the resistance across the rectangles using the multimeter. Our findings are summarized in Table 1 below.



Table 1. Resistance and physical dimensions of carbon resistors

Length	Width	Resistance
0.25 in	0.125 in	10.3 kΩ
0.125 in	0.25 in	6.9 kΩ
1.0 in	0.125 in	53.2 kΩ
0.125 in	1.0 in	20.1 kΩ
2.0 in	0.125 in	67.7 kΩ
0.125 in	2.0 in	16.8 kΩ
0.5 in	0.25 in	20.4 kΩ
0.25 in	0.5 in	9.1 kΩ
0.25 in	0.25 in	17.3 kΩ
0.5 in	0.5 in	10.6 kΩ

We measured the resistance across our bodies between right and left hands using the multimeter. I had a resistance of 910 kΩ while my lab partner had a resistance of 955 kΩ.

C. Current and Ohm's Law

In this experiment we assembled the circuit shown in Figure 1 using the DC power supply ( $v_s$ ) set to 10 V and the same (nominal 1 kΩ) resistor R measured earlier to be 995.9 Ω. We measured the voltage across the power supply to be  $v_s = 10.07$  V using the multimeter. We measured the current flowing through the resistor to be  $i = 10.09$  mA and then switched the leads to find that the current in the opposite direction was -10.09 mA as expected (ie. that the current in one direction is the negative of the current in the other direction).

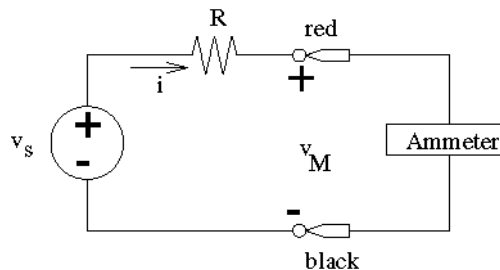


Figure 1: Circuit for measuring current.

D. Ideal vs. Practical Voltmeter

In this experiment we compared an ideal voltmeter with a practical voltmeter. An ideal voltmeter has an infinite resistance since it is an open circuit. Although it is impossible to make a physical voltmeter with infinite resistance, a well designed voltmeter exhibits a very large internal resistance. To determine the internal resistance of the digital voltmeter we set up the circuit shown in Figure 2.

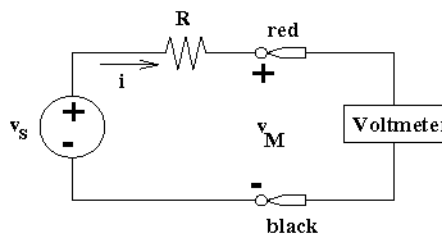


Figure 2: Circuit used to determine the internal resistance of the voltmeter.





We selected a resistor (nominal 1 M Ω) and measured its actual value,  $R = 1.001\text{ M}\Omega$ , and then set the DC power supply to deliver 10 V and measured its actual value to be  $v_s = 10.068\text{ V}$ . Next we assembled the circuit in Figure 2 and measured the voltage across the voltmeter to be  $V_M = 9.1554\text{ V}$ . As will be shown in the analysis section, these measured values may be used to determine the internal resistance of the voltmeter.

E. Ideal vs. Practical Ammeter

In this experiment we compared an ideal ammeter with a practical ammeter. An ideal ammeter has zero resistance since it is a short circuit. As with the voltmeter, it is impossible to make a physical ammeter ideal, so all ammeters exhibit a small internal resistance. To determine the internal resistance of the ammeter we set up the circuit shown in Figure 1. We selected a resistor  $R$  (nominal 100 Ω) and measured its actual value,  $R = 100.53\text{ }\Omega$ , and then set the DC power supply to deliver 10 V and measured its actual value,  $v_s = 9.97\text{ V}$  with the oscilloscope. Next we assembled the circuit in Figure 1 and measured the current,  $i = 97.05\text{ mA}$  using the ammeter. As will be shown in the analysis section, these measured values may be used to determine the internal resistance of the ammeter.

F. Measurement of Time-Varying Sources

In this experiment we used the function generator to provide a time-varying voltage which we measured with the oscilloscope. First, we set the function generator to produce a 10 kHz sine wave with  $6\text{ V}_{p-p}$  as displayed on the front panel of the function generator. We then connected the oscilloscope to the function generator as shown in the first circuit of Figure 3.

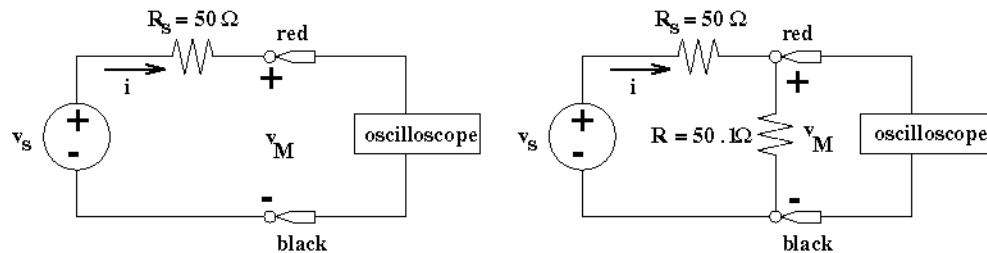


Figure 3: Circuits used to demonstrate the relationship between the voltage displayed on the front panel and load resistance.

Using the automatic voltage measurement feature of the oscilloscope as well as manual estimation (counting reticle squares on the scope screen), determined the peak-to-peak voltage, the frequency, and the period of the sinusoidal voltage. After having made these measurements, we connected the function generator and the oscilloscope across a nominal 50 Ω resistor (measured to be 50.1 Ω), leaving the settings on the function generator unchanged (See the second circuit in Figure 3). We used the automatic voltage measurement feature of the oscilloscope to find the peak-to-peak voltage and printed out a copy of the sine wave using the HP Deskjet printer (Figure 3). Our results are summarized in Table 2 below.

Table 2. Measurement of time varying sources

	displayed by the function generator	measured manually without the 50 Ω resistor	measured by the oscilloscope without the 50 Ω resistor	measured by the oscilloscope with the 50 Ω resistor
Peak-to-peak voltage	6 V	12.2 V	12.2 V	6.21 V
Frequency	10 kHz	10.0 kHz	10.0 kHz	10.0 kHz
Period		10 μs	100.0 μs	100.0 μs



### III. Analysis

#### A. DC Power Supply and Digital Voltmeter

With the current limiter on the DC power supply set to 50 mA, we calculated the voltage at which the DC power supply would transition from CV to CC using Ohm's Law. Using the measured value of R (51.66  $\Omega$ ), the transition should occur at the voltage  $v = Ri = (|51:66|)(|0:05|) = 2:583V$ .

#### B. Resistance Measurement

The measured value of the nominal 1 k $\Omega$  resistor was 995.9  $\Omega$ . The % deviation of the measured value from the nominal value is 0.41%.

#### C. Current and Ohm's Law

Assuming that the ammeter in Figure 1 has a negligibly small resistance compared to the resistance  $R = 995.9 \Omega$ , the theoretical value for the current is  $i = \frac{v}{R} = \frac{10.07}{995.9} = 10.111 \text{ mA}$ .

#### D. Ideal vs. Practical Voltmeter

The current shown in Figure 2 is given by the equation:

$$i = \frac{v_s - v_m}{R} \quad (1)$$

where  $v_s$  is the voltage provided by the source DC power supply and  $v_m$  is the voltage across the voltmeter. Using Ohm's Law, the internal resistance of the voltmeter ( $R_M$ ) may be expressed in terms of R,  $v_s$ , and  $v_M$  by the equation

$$R_M = \frac{v_M}{i} = \frac{v_M}{\frac{v_s - v_M}{R}} = \frac{Rv_M}{v_s - v_M} \quad (2)$$

Using the measured values  $R = 1.001 \text{ M}\Omega$ ,  $v_s = 10.068 \text{ V}$ , and  $v_M = 9.155 \text{ V}$ , we calculated the internal resistance of the voltmeter to be 10.04 M $\Omega$ .

#### E. Ideal vs. Practical Ammeter

According to Ohm's Law, the current the circuit of Figure 1 will be

$$i = \frac{v_s}{R + R_M} \quad (3)$$

The internal resistance of the ammeter ( $R_M$ ) can be found by algebraically manipulating this equation:

$$R_M = \frac{v_s}{i} - R \quad (4)$$

Using the measured values  $R = 100.53 \Omega$ ,  $v_s = 9.97 \text{ V}$ , and  $i = 97.05 \text{ mA}$ , we calculated the internal resistance of the ammeter to be 2.2  $\Omega$ .



### F. Measurement of Time-Varying Sources

The oscilloscope has a very large internal resistance ( $R_{osc} \gg 1 \text{ M}\Omega$ ). Therefore the voltage drop across the  $50 \Omega$  internal resistance of the function generator in the first circuit of Figure 3 is negligible. The voltage  $v_M$  measured in this case is the same as the voltage  $v_s$ , which was measured to be  $12.2 \text{ V}$ . In the second circuit of Figure 3, the voltage drop across the load

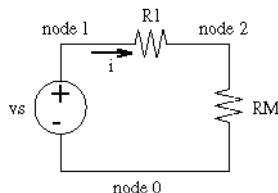
resistor will be  $v_M = \frac{v_s R_M}{R_M + R_s}$  by voltage division. Using  $R_s = 50 \Omega$  and  $R = 51.2 \Omega$ , the

theoretical value for  $v_M$  is  $6.172 \text{ V}$ . The measured value of  $v_M$  was  $6.21 \text{ V}$ . The percent error for this measurement is  $0.62\%$ .

## IV. Simulation Results

The circuit in Figure 1 used to measure the internal resistance of the ammeter was simulated using PSpice. The node designation used in PSpice is shown in Figure 4. The measured values  $v_s = 9.97 \text{ V}$ ,  $R_1 = 100.53 \Omega$ , and the value of  $R_M = 2.2 \Omega$  determined from analysis using the measured values  $v_s$ ,  $R_1 = R$ , and  $i$ , were used in the simulation.

The results produced by PSpice were obtained from the file lab1sim.out as follows.



**Figure 4: PSpice node designation for simulating the circuit used to measure the internal resistance of the digital ammeter.**



\*\*\*\* 08/19/95 13:49:35 \*\*\*\*\* PSpice 6.2 (April 1995) \*\*\*\*\* ID# 83013 \*\*\*\*

\*Lab1sim.CIR

\*\*\*\*CIRCUIT DESCRIPTION

\*\*\*\*\*

vs 1 0 9.97  
R1 1 2 100.53  
RM 2 0 2.2  
.tran 2.0 2.0  
.probe  
.end

\*\*\*\* INITIAL TRANSIENT SOLUTION                      TEMPERATURE = 27.000 DEG C

\*\*\*\*\*

NODE	VOLTAGE	NODE	VOLTAGE
(1)	9.9700	(2)	0.2135
VOLTAGE SOURCE NAME		CURRENT	
vs		-9.705E-02 V	

TOTAL POWER DISSIPATION                      9.68E-01 WATTS

JOB CONCLUDED                      TOTAL JOB TIME                      .66

The value of the current  $i$  in Figure 4 was measured to be 97.05 mA (Section II, Part E). The value of the current produced by the PSpice simulation is identical to the value measured, except for the sign. The current value shown (above) in the file Lab1sim.out corresponds to the current that flows in the direction of the voltage drop of the source  $v_s$ , which is in the opposite direction of  $i$ .

### V. Discussion

#### A. DC Power Supply and Digital Voltmeter

The DC power supply can operate in either of two modes: CV or CC. In the CV mode the power supply acts as a voltage source and the amount of current drawn depends on the resistance of the circuit as seen from the terminals of the DC power supply. The amount of current drawn from the power supply cannot exceed the value set by the current limiter. If the circuit attempts to draw more current than the value set by the current limiter, the power supply will enter the CC mode and the voltage produced at its terminals will drop as necessary to maintain the current set by the current limiter. In the CC mode, the DC power supply acts as a current source. With the power supply set to 3 V (on its display) driving a 50 Ω(nominal) resistor, we calculated the point of transition from CV to CC to be 2.583 V while the measured transition point was 2.62 V. The percent error is 1.43% indicating close agreement between the theoretical and measured points of transition from CV to CC.

#### B. Resistance Measurement

The nominal 1 kΩ resistor had a measured resistance of 995.9 Ω. The percent deviation from nominal is 0.41%, well within the 5% tolerance indicated by its gold tolerance band.

Based on the resistance measurements of the graphite resistors that we constructed, we determined that resistance increases with the length-to-width ratio of the carbon rectangle, but also depends on the intensity of the graphite. An increase in the length, while holding the wide



constant produces and increase in resistance. We also concluded that as the width is increased, the resistance is decreased.

I had a resistance of 90 k $\Omega$  between right and left hands while my lab partner had a resistance of 95 k $\Omega$ . Considering that a current of 100-200 mA through a person's heart will almost certainly kill them, we calculated, using Ohm's Law ( $v = iR$ ), that 9 kV-18 kV across my hands would be lethal for me and 9.5 kV-19 kV across my lab partner's hands would be lethal for her. Of course, a much lower voltage would be lethal since our bodies' resistance is significantly reduced when current is passed through our skin. It is well-known that the standard wall socket voltage (120V RMS) can be lethal in certain circumstances (eg. if a person's body is immersed in water).

### C. Current and Ohm's Law

The current in the circuit of Figure 1 was measured using the ammeter to be 10.09 mA. The theoretical value for this current, assuming that the ammeter has no internal resistance, was found to be 10.111 mA. The % error is calculated to be 0.208%. It was found later that the ammeter has an internal resistance of 2.2  $\Omega$ . Taking the internal resistance of the ammeter into account, the theoretical value for the current would be 10.09 mA, producing a 0.0% error.

### D. Ideal vs. Practical Voltmeter

The calculated value for the internal resistance of the voltmeter was based upon measurements of  $R$ ,  $v_s$ , and  $v_M$  in Figure 2 and found to be 10.04 M $\Omega$ . Ideally, the internal resistance of the voltmeter would be infinite. In applications in which it is desired to measure the voltage across a resistance whose value is much smaller than the internal resistance of the voltmeter, the voltage displayed by the voltmeter will be accurate. However, in certain applications, the voltage whose value is desired may be across a resistance that is not much smaller than the internal resistance of the voltmeter. In this case, the internal resistance of the meter must be taken into account in order to yield an accurate measurement.

### E. Ideal vs. Practical Ammeter

The calculated value for the internal resistance of the ammeter was based upon measurements of  $R$ ,  $v_s$ , and  $i$  in Figure 1 and found to be 2.2  $\Omega$ . Ideally, the internal resistance of the ammeter would be zero. In applications in which it is desired to measure the current through a resistance whose value is much larger than the internal resistance of the ammeter, the current displayed by the ammeter will be accurate. However, in certain applications, the current whose value is desired may be through a resistance that is not much larger than the internal resistance of the ammeter. In this case, the internal resistance of the meter must be taken into account in order to yield an accurate measurement.

### F. Measurement of Time-Varying Sources

We found that the terminal voltage of the function generator varies with load resistance. The peak-to-peak value shown on the front panel display of the function generator assumes that the load is 50  $\Omega$ . Therefore it is necessary to measure carefully the voltage at its terminals each time the function generator is used. We cannot simply assume that the front panel indicates the true value of the terminal voltage. However, the frequency displayed on the front panel is correct and not dependent on the load resistance. When the 51.2  $\Omega$  resistor was driven by the function generator (Figure 3), the load voltage was measured to be 6.21 V. Given that the internal resistance of the function generator is 50  $\Omega$ , we solved for the voltage

$v_s$  by  $v_s = \frac{(R + R_s)v_M}{R} = 12.27$  V, which agrees closely with the value on the front panel display (12.2V). Under open circuit conditions (Figure 3), the terminal voltage is twice the value shown on the front panel display.

### G. Questions from Laboratory Manual

Several questions were posed in the laboratory manual. My responses to them follows.



1. **Suppose you set the voltage of the DC power supply to 5V. You connect it to a circuit and the voltage provided by the power supply drops to 3V. What happened?**

If I set the voltage of the DC power supply to 5 V as indicated on its front panel, connected it to a circuit and then noticed that the voltage supplied by the power supply dropped to 3 V, I would assume that the circuit drew more current than the value set by the current limiter, causing the power supply to enter the constant current mode. The voltage dropped to 3 V because the load drew the maximum current at 3 V.

2. **What is the "resolution" of a digital display? Compare the resolution of the digital display on the front panel of the DC power supply to the display on the front panel of the multimeter. Why must you use the multimeter to set the DC supply to 0.75V?**

The "resolution" of a digital display is the smallest increment that can be represented. If the display has a floating point, then the resolution is directly related to the number of digits in the digital display. The resolution of the multimeter is 6 digits when acting as a voltmeter allowing it to measure mV. The resolution of the power supply is 3 digits. Hence, the resolution of the multimeter display is much greater than that of the DC power supply. It is necessary, in general, to measure the terminal voltage of the DC power supply using the multimeter in order to obtain the most accurate value.

3. **Suppose you set the function generator such that it produces a 1 kHz sinusoidal voltage with 5V peak-to-peak across a 25  $\Omega$  load. What will be the peak-to-peak voltage displayed on the front panel of the function generator?**

The function generator has an internal resistance of 50  $\Omega$ . The voltage displayed on the front panel is the voltage that would appear across its terminals if it were connected to a 50  $\Omega$  load. Since the voltage across the terminals of the function generator is twice as large as the value indicated on its front panel when it is under open circuit conditions, the voltage across the terminals of the function generator would be one and a half times as large as the value indicated on its front panel when it has a load resistance of 25  $\Omega$ . This conclusion was drawn

from the voltage division equation  $v_M = \frac{v_s R}{R + R_s}$ . With  $R = 25 \Omega$  and  $R_s = 50 \Omega$ ,  $v_M = \frac{v_s}{3}$ . Since

$v_s = 2v_{display}$ ,  $v_{display} = 1.5v_M$ . Therefore, if you set the function generator such that it produces a 1 kHz sinusoidal voltage with 5 V peak-to-peak across a 25  $\Omega$  load the peak-to-peak voltage displayed on the front panel of the function generator would be 7.5 V.

## VI. Conclusion

In this laboratory exercise we learned to use the instruments at the lab station. These instruments include: The function generator, the digitizing oscilloscope, the multimeter, and the DC power supply.

The most fundamental concept learned in this lab is that the values displayed on the front panel of the instruments may be misleading if not properly interpreted. For example, the peak-to-peak voltage as shown on the front panel of the function generator is accurate only if the load resistance is exactly 50  $\Omega$ . It is therefore necessary to use the voltmeter or the oscilloscope to measure the amplitude of voltages produced by the function generator each time a new circuit is assembled. We also learned the importance of measuring resistance values using the ohmmeter. The value determined by the color code is only the resistor's nominal ("In name only") value. Therefore, each time a new resistor is utilized, its value will be measured using the ohmmeter and recorded for subsequent analysis. We obtained measured values for the internal resistances of both the voltmeter and the ammeter and recognize the importance of including their effects in certain measurement conditions.

The concepts we learned and the skills we developed will enable us to successfully proceed to future lab exercises.