Lab 3: Kirchhoff's Laws and Basic Instrumentation

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1. Purpose

The purpose of this exercise is to develop proficiency in the use of the digital multimeter in the context of verifying Kirchhoff's Voltage and Current Laws (KVL and KCL). In the process you will become familiar with the use of the breadboard.

1.1 Equipment

- Agilent E3631A DC Power Supply
- Agilent E34401A Digital Multimeter

2. Prototyping a Circuit

The solderless breadboard (sometimes called a protoboard) is the most common type of prototyping circuit board. Prototyping a circuit is the process of creating a model suitable for complete evaluation of its design and performance. This requires the circuit to be designed, built and tested in the laboratory. Theoretical calculations and computer simulation are part of the design process. Once the circuit configuration is determined, the circuit is built on a prototyping board. There are two main types of prototyping circuit boards:

1) Solderless Breadboards
2) Perfboard

Perfboard is a thin slab of either epoxy glass or phenolic with 1 mm diameter holes punched through it. As an example of epoxy glass perfboard, look on top of the instrument cabinet at your lab station. There should be a 4" x 8" section of epoxy glass perfboard with 3 types of diodes mounted on it. A circuit built on perfboard requires either soldering or wire wrapping the connections. A circuit built on a breadboard requires neither soldering nor wire wrapping the connections. Your laboratory instructor will assign to you and your partner a JE25 breadboard on which you will build your subcircuits throughout the semester. Be sure to observe the number shown on the breadboard (just below the JE25 identifier in the upper left corner) so that you can identify your board at each laboratory meeting. Located at each of the lab stations is a pair of prototyping boards permanently connected to the bench top. One of the boards is a breadboard and the other is a springboard (rarely seen anymore except in Radio Shack Electronics Projects Kits). You should use these boards on the bench top for making circuits that you intend to dismantle before leaving the lab at the end of the period. Any subcircuit that you intend to interconnect to others in later lab sessions should be built on your JE25 breadboard.

3. Using the Breadboard

Check out a Jameco JE25 breadboard from your lab TA. You will be using this board throughout the semester. Obtain a piece of masking tape and affix it to the top of your board. Write your name (and partner's name) on the tape. Write down the identification number of your board for reference. When you are finished with your board at the end of each lab, return your board to its sequential location in the cabinet. After you have checked out your breadboard, examine it closely with your partner. Your JE25 breadboard has two terminal strips, four bus strips, and three binding posts as shown in Figure 1. Each bus strip has two rows of contacts. Each of the two rows of contacts on the bus strips are a node. That is, every contact along a row on a bus strip is connected together, inside the breadboard. Bus strips are used primarily for power supply connections but are also used for any node requiring a large number of connections. Each terminal strip has 60 rows and 5 columns of contacts on each side of the center gap. Each row of 5 contacts is a node. You will build your circuits on the terminal strips by inserting the leads of circuit components into the contact receptacles and making connections with 22 AWG (American Wire Gauge) wire. There are wire cutter/strippers and a spool of wire in the lab. You will be using the red and black binding posts for power supply connections. Hence, it is a good idea to wire them to a bus strip.

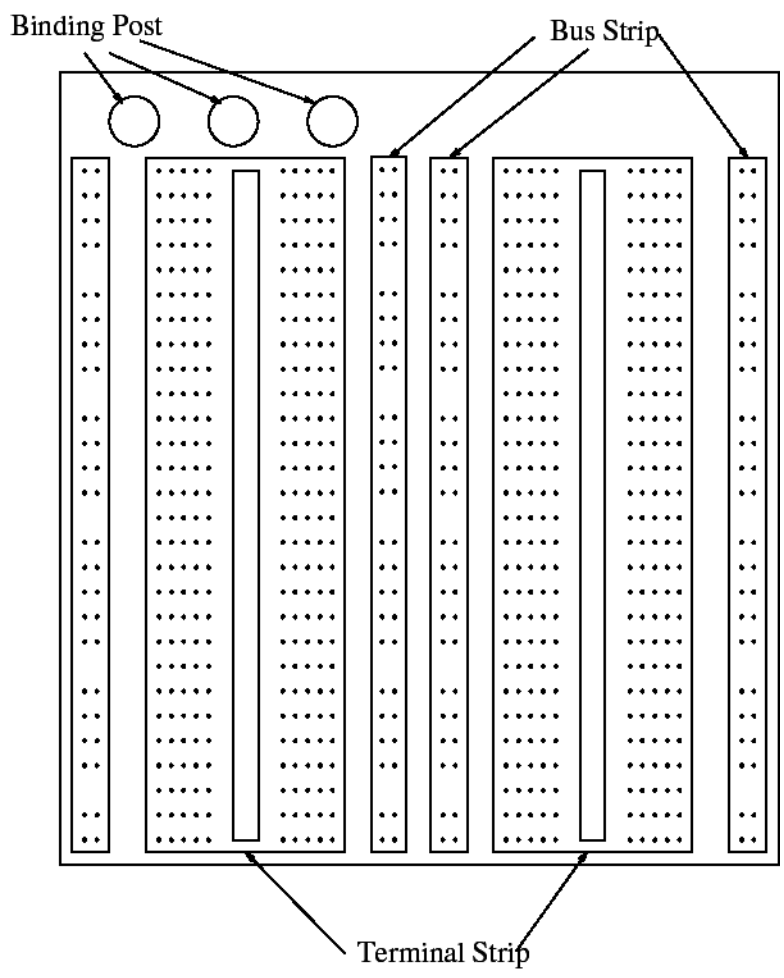

Figure 1: Jameco JE25 Solderless Breadboard

4. Using the Multimeter as a Voltmeter

A voltmeter is a device for measuring voltage. It measures the voltage **drop** from the red to the black probes. The voltmeter is placed in **parallel** with the circuit element whose voltage is to be measured. Recall that two elements are in parallel when they share the same pair of nodes and hence share the same voltage. Consider the voltage divider circuit shown in Figure 2 in which the voltage across R_2 is to be measured. If the presence of the voltmeter does not affect the voltage it is intending to measure, the meter must draw no current. That is, it must act as an open circuit. An open circuit may be thought of as an infinite resistance. Hence, an ideal voltmeter has an infinite resistance. You measured the internal resistance of the voltmeter in Experiment 2 and found the value to be on the order of MΩ which is large, but certainly not infinite.

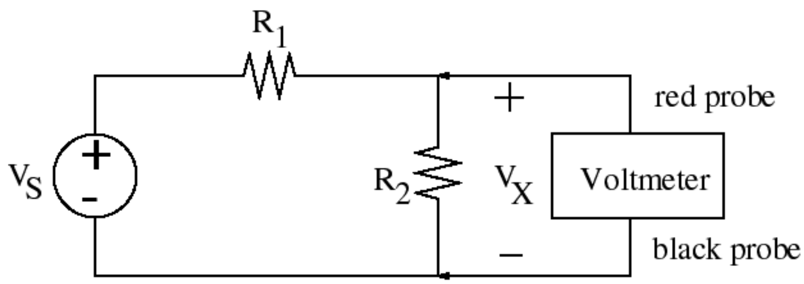

Figure 2: Voltage Divider Circuit

First consider the circuit with the voltmeter not present. In this case the voltage vx can be expressed in terms of the source voltage v_s and the resistors R_1 and R_2 by

$$V_x = V_s \frac{R_2}{R_1 + R_2} \quad (1)$$

With the voltmeter present, its resistance alters the voltage division equation which becomes

$$V_x = V_s \frac{R_2 R_M}{R_2 R_M + R_1 (R_2 + R_M)} \quad (2)$$

where R_M is the resistance of the voltmeter. You will not be able to see how this equation was obtained at first examination. Let the voltmeter in Figure 2 be represented by a resistance R_M. Use resistance reduction and voltage division to obtain an expression for v_x in terms of v_s. Then, clear the fractions in the numerator and denominator. Be sure to show your derivation in your lab report. Recall that an **ideal** voltmeter has infinite resistance. Letting the value of R_M in Equation 2 be infinite should result in Equation 1. Derive equation 1 from Equation 2 by taking the limit as $R_M \rightarrow \infty$. L'Hospital's Rule may be helpful.

You will now build the voltage divider circuit using the DC power supply as the voltage source v_s in Figure 2.

4.1 Voltage Divider with Moderate-Valued Resistors

1. Obtain two 1 kΩ resistors from the parts bin. Designate one of the resistors as R_1 and the other as R_2.

2. Measure the resistor values using the multimeter as an ohmmeter. Be sure to keep track of which resistor corresponds to which value measured!

3. Build the circuit in Figure 2 using the 1 kΩ resistors for R_1 and R_2.

4. Set the power supply to 5V. Use the voltmeter, not the front panel display of the power supply to ensure the proper setting. **Important Note:** You built the circuit before you set

the power supply voltage to 5V. If the current limiter is set to a value lower than than the current demanded by the circuit, the **constant current (cc)** indicator will light up and the voltage control knob will no longer adjust the output voltage. If this happens, simply increase the current limiter until you are able to achieve 5V in the **constant voltage (cv)** mode.

5. Using the voltmeter, measure the voltage across resistor R_1, and then across resistor R_2. Record these values, as always, and verify Kirchhoff's Voltage Law KVL.

6. Comment on the accuracy of measurements made considering the internal resistance of the voltmeter.

7. Create a table presenting theoretical and measured voltages along with percent error. Consider whether your theoretical values for the voltages across R_1 and R_2 should include the effect of R_M. **Important Note**: When you are calculating percent error, you should avoid cases in which the theoretical value is zero since the percent error is meaningless. To calculate percent error between theoretical and experimental verification of KVL, use the source voltage as the reference. For example, in the measurements made in this section, the theoretical value (and measured value!) for the voltage across the supply is 5V. The measured value is the same as the theoretical value because you used the voltmeter to set the power supply voltage to 5V. To obtain the KVL measured voltage, add the voltage across R_1 to the voltage across R_2. Compare with 5V.

4.2 Voltage Divider with Large-Valued Resistors

1. Obtain two 10 MΩ resistors from the parts bin. Designate one of the resistors as R_1 and the other as R_2.

2. Measure the resistor values using the multimeter as an ohmmeter. Be sure to keep track of which resistor corresponds to which value measured!

3. Build the circuit in Figure 2 using the 10 MΩ resistors for R_1 and R_2.

4. Set the power supply to 5V.

5. Using the voltmeter, measure the voltage across resistor R_1, and then across resistor R_2. Record these values, as always, and verify Kirchhoff's Voltage Law KVL.

6. Comment on the accuracy of the voltage measurements made (consider the internal resistance of the voltmeter).

7. Create a table presenting theoretical and measured voltages along with percent error. Consider whether your theoretical values for the voltages across R_1 and R_2 should include the effect of R_M.

5. Using the Multimeter as an Ammeter

An ammeter is a device for measuring current. It measures the current flowing from the red to the black probes **within the meter**. The ammeter is placed in series with the circuit element whose current is to be measured. Recall that two elements are in series when they share in the same branch and hence share the same current. Consider the current divider circuit shown in Figure 3.

The current through R_1 may be expressed as a fraction of is in terms of R_1 and R_2 using current division

$$i_1 = i_s \frac{\frac{1}{R_1}}{\frac{1}{R_1} + \frac{1}{R_2}} = i_s \frac{R_2}{R_1 + R_2} \quad (3)$$

You will now build the current divider circuit and make several measurements. Record all measured values and present percent error calculations and tables as appropriate.

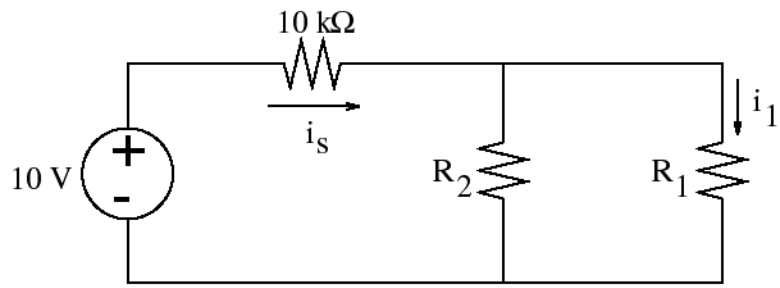

Figure 3: Current Divider Circuit

5.1 Current Divider with Moderate-Valued Resistors

1. Obtain two 100 Ω resistors from the parts bin. Designate one of the resistors as R_1 and the other as R_2.

2. Measure the resistor values using the multimeter as an ohmmeter. Be sure to keep track of which resistor corresponds to which value measured!

3. Build the circuit in Figure 3 using the 100 Ω resistors for R_1 and R_2.

4. Set the power supply to 10V. Don't forget to set the voltage using the voltmeter rather than depending on the front panel display of the power supply. **Important Note:** You built the circuit before you set the power supply voltage to 10V. If the current limiter is set to a value lower than than the current demanded by the circuit, the **constant current (cc)** indicator will light up and the voltage control knob will no longer adjust the output voltage. If this happens, simply increase the current limiter until you are able to achieve 10V in the **constant voltage (cv)** mode.

5. Using the voltmeter, measure the voltage across the 10 kΩ resistor followed by the parallel combination of resistors R_1 and R_2. Record these values, as always, and verify Kirchhoff's Voltage Law KVL.

6. Configure the multimeter to measure current. Remember that this requires two things: Remove the terminal of the red probe from the voltage/resistance measuring receptacle and insert it in the current measuring receptacle on the front panel of the multimeter. Then press the DC current button, also on the front panel of the multimeter.

7. Measure the current through the 10V source. Remember that you have to **break** the circuit and insert the ammeter in **series** with the 10V source to allow the current to flow through the ammeter.

8. Measure the current through R_1 and then the current through R_2.

9. Verify Kirchhoff's Current Law (KCL). Remember that a theoretical value of zero produces a meaningless percent error.

10. Comment on the accuracy of the voltage measurements made (consider the internal resistance of the voltmeter).

11. Comment on the accuracy of the current measurements made (consider the internal resistance of the ammeter).

5.2 Current Divider with Small-Valued Resistors

1. Obtain two 10 Ω resistors from the parts bin. Designate one of the resistors as R_1 and the other as R_2.

2. Measure the resistor values using the multimeter as an ohmmeter. Be sure to keep track of which resistor corresponds to which value measured!

3. Build the circuit in Figure 3 using the 10 Ω resistors for R_1 and R_2.

4. Set the power supply to 10V. Don't forget to set the voltage using the voltmeter rather than depending on the front panel display of the power supply.

5. Using the voltmeter, measure the voltage across the 10 kΩ resistor followed by the parallel combination of resistors R_1 and R_2. Record these values, as always, and verify Kirchhoff's Voltage Law KVL.

6. Configure the multimeter to measure current. Remember that this requires two things: Remove the terminal of the red probe from the voltage/resistance measuring receptacle and insert it in the current measuring receptacle on the front panel of the multimeter. Then press the DC current button, also on the front panel of the multimeter.

7. Measure the current through the 10V source. Remember that you have to **break** the circuit and insert the ammeter in **series** with the 10V source to allow the current to flow through the ammeter.

8. Measure the current through R_1 and then the current through R_2.

9. Verify Kirchhoff's Current Law (KCL). Remember that a theoretical value of zero produces a meaningless percent error.

10. Comment on the accuracy of the voltage measurements made (consider the internal resistance of the voltmeter).

11. Comment on the accuracy of the current measurements made (consider the internal resistance of the ammeter).

Return all parts to the **correct** drawer in the parts bin.

6. PSpice (to be done outside of lab)

In this laboratory experiment, you constructed a total of four circuits:

1. The voltage divider circuit in Figure 2 first with R_1 and R_2 each with a nominal value of 1 kΩ and then with a nominal value of 10 MΩ.

2. The current divider circuit in Figure 3 first with R_1 and R_2 each with a nominal value of 100 Ω and then with a nominal value of 10 Ω.

Using the values of the voltmeter and ammeter internal resistance that you measured in lab 2, use PSpice to simulate:

- the voltage divider circuit with the large-valued resistors. Note that there are two circuits to simulate. These two circuits correspond to the measurement of voltage across R_1 as well as the voltage across R_2.
- the current divider circuit with the small-valued resistors. Note that there are three circuits to simulate. These three circuits correspond to the measurement of current through the 10 kΩ resistor, the current through R_1, and the current through R_2.

7. Questions to be answered

1. The current division equation (Equation 3) does not include the resistance of the ammeter. Let the internal resistance of the ammeter be R_M. Write the expression for the current through R_1, i_1, including the resistance of the meter assuming that the ammeter is being used to measure the current i_1. Then take the limit of this expression as the ammeter internal resistance goes to zero, showing that the limit is given by Equation 3.
2. The voltage source and 10 kΩ resistor in Figure 3 form an approximate current source for small load resistances. If the voltage source and 10 kΩ resistor formed an **ideal** current source, then the current is would be constant, independent of the resistances of R_1 and R_2, which is certainly not the case. Consider the parallel combination of R_1 and R_2 as a single resistance R_L. If R_L is small compared to 10 kΩ, then the current is will be very nearly 1 mA (Recall that v_s = 10V) independent of R_L. Calculate the range of values of R_L such that the current is will deviate from 1 mA by no more than 5%.
3. Consider the circuit shown in Figure 4. Suppose you want to know the value of all voltages and currents in the circuit. Assume that you know nothing at all about the resistor values. You want the results to be as accurate as possible. You have a multimeter that you may use as either a voltmeter or an ammeter. Explain the sequence of measurements that you make. Comment on your level of confidence that your results are accurate. Don't forget that you have Ohm's Law and Kirchhoff's Laws that may be used.

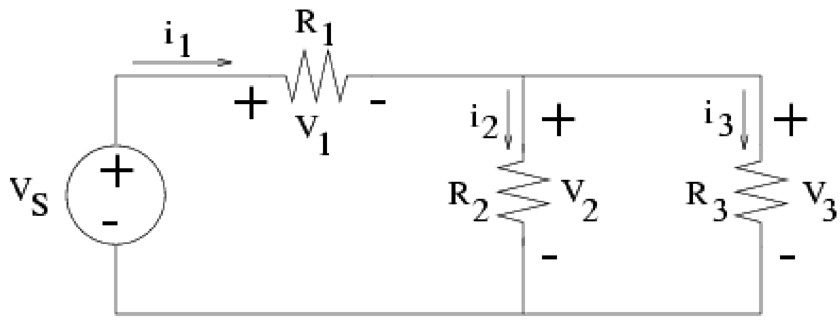

Figure 4: Resistive Network

8. PRE-LAB for Lab 4: Thevenin Equivalent Circuits

In Lab 4: Thevenin Equivalent Circuits, you will be investigating the concept of equivalent circuits as seen at a pair of terminals. Prior to entering the lab next week, you are to perform the theoretical calculations to obtain the Thevenin equivalent of the two circuits (Circuit 1 and Circuit 2) in terms of symbols. Before you calculate the Thevenin equivalent circuits, be sure to **REMOVE** R_4 from the circuit (both Circuit 1 and Circuit 2). Your lab TA will verify your analyses at the beginning of the lab meeting, and a portion of your lab grade will be based upon the correctness of your solutions.