Lab 1: DC Elements and Measurements

Reference Reading: Chapter 1, Sections 1.1 - 1.6.
Time: One lab period will be devoted to this lab.
(Based on Lab 1 from "Basic Electronics: Carnegie Mellon Lab Manual," C. Meyer)

Goals:

1. Become familiar with basic DC ("direct current": zero frequency or constant bias) elements, measurements, and responses.
2. Become familiar with *I-V* curves for several (linear and non-linear) elements we will use throughout the semester.
3. Become familiar with power dissipation computation and the power limitations of real devices.
4. Be able to replace a circuit element with a "Thèvenin equivalent" circuit which has the same *I-V* curve.
5. Test the basic circuit theory of linear devices developed in class and the textbook, most importantly, the voltage-divider equation and Thèvenin's theorem.

Expectations:

1. In each section, you are expected to provide a neat table of the data that you measured where you clearly label what each data set is and include units for all measured quantities. You are expected to clearly record the measured values of any components that you use.
2. Your final plots of data should be made using Excel, OpenOffice, Google Sheets, or python code. You may choose the format that is most comfortable for you. Make sure that your data points appear clearly on the plots, that all axes are clearly labeled and have units. These plots should be neatly inserted into your electronic lab book. They should always be associated with text discussing the source of the data in the plot as well as its analysis.
3. If it is possible to compare your measurements with an expectation or a prediction, you are expected to do so. As an example, does the slope of the *I–V* curve of a resistor agree with the measured resistance?
4. You are expected to answer the questions encountered in this manual in your lab write up. You do not need to include answers to the "additional problems" at the end of the lab, however, those questions may be used in lab quizzes during the semester.

1.1 Introduction

The electrical current, I, through a circuit element is almost always related to electric fields resulting from the application of a voltage, V, across the circuit element. The potential energy difference across a circuit element is also proportional to the voltage, V. Increasing V across a device corresponds to increasing the average electric field inside the device. The actual electric field inside the device may be highly non-uniform and depend on the arrangement and properties of the materials within the object. However, the behavior of a circuit element within a circuit is generally deter- mined by the relationship between *I* and *V* without detailed knowledge of the actual electric field. In this lab, you will study the relationship between *I* and *V* for a variety of devices.

1.1.1 The I-V curve.

The "*I-V* curve" of a circuit element or device may be obtained in the following manner. First, the element is connected to an external power source such as a variable-voltage power supply. Next, the current through the device, *I*, and the voltage across the device, *V*, are measured. The external power supply is then varied so *I* and *V* are changed and the new values are measured. This procedure is repeated and the points are plotted on a graph of *I* vs. *V*. The curve which connects these points is called the *I-V* curve for the device being tested.

"Linear" devices have *I-V* curves that are straight lines. For many devices, the "response" or current through the device is proportional to the "input" or voltage across the device over a broad range and their *I-V* curves obey Ohm's law:

$$V = IR. \tag{1}$$

Devices which obey Ohm's law are called "resistive" elements. Other elements may have non-linear *I-V* curves or responses. In some cases, the response is not even symmetric about zero voltage (the response depends on the polarity of the applied voltage).

For direct current, power dissipation can always be written as

$$P = IV. \tag{2}$$

This is just the potential energy change per charge (*V*) times the amount of charge per second (*I*) passing through. For resistive elements, this reduces, using Ohm's law, to

$$P = IV = I^2R = \frac{V^2}{R} \tag{3}$$

Any of these forms can be used for resistors – choose the most convenient for your purposes. For non-linear devices, you must use Equation (2).

1.1.2 Diodes and light-emitting diodes

Most of the components whose *I-V* curves we measure will be symmetric for positive and negative voltage. However, both the Zener diode and the light-emitting diodes are exceptions to this behavior. They have a very definite polarity. Figure 1 shows the two diodes as well as how they should be connected in your circuit. The figures shows that the two legs of a diode have different names. They are known as the anode and the cathode. A diode is said to be forward biased if the voltage at the anode is more positive than the voltage at the cathode. The diode is said to be reverse biased if the opposite is true. Most diodes only allow current to flow in one direction (from anode to cathode). Zener diodes will allow current to flow from the cathode to the anode if the reverse bias voltage is large enough.

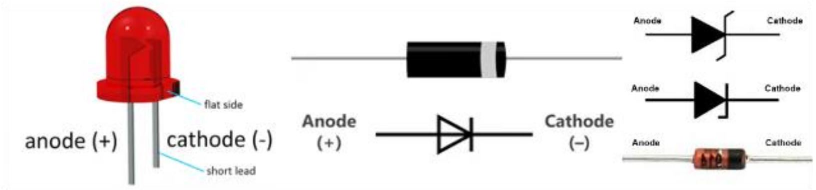


Figure 1 This figure shows, a light emitting diode (LED), a standard diode, and a Zener diode. The anode and cathode are labeled for each diode. The Zener diode shows the symbol used by both IEEE (top) and IEC (middle).

1.1.3 The Potentiometer

In Figure 2 we show a drawing and the schematic diagram for a potentiometer. These circuit elements have three electrical connections labeled as a, b and c in the figure. If the potentiometer is rated as 1 kΩ, then the resistance between terminals a and c is always R_{ac} = 1 kΩ. The resistances between the outer legs and the center leg, R_{ab} and ˆ, satisfy the relation

$$R_{ac} = R_{ab} + R_{bc} \tag{4}$$

but the actual values of these latter two resistances depend on the orientation of the dial. If the dial is all the way to one end of its range, then we have R_{ab} = 1 kΩ and R_{bc} = 0 Ω, while at the other end of its range we have R_{ab} = 0 Ω and R_{bc} = 1 kΩ. If the dial is in the center of its range, the R_{ab} = R_{bc} = 500 Ω. For what we do in this lab, we will want to connect one outside leg (a or c) and the center leg (b) into our circuits.

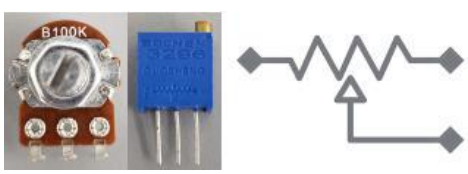


Figure 2 Pictures of potentiometers available in lab and the schematic symbol of the potentiometer that we will use in this lab.

1.2 Preliminary Lab Questions

(These are in a separate Jupyter Notebook. You already have them available.)

The work in this section must be completed and signed off by an instructor before you start working on the lab. Do this work in your lab book.

1. Carefully plot the $I - V$ curve of an ideal resistor of $R = 100\ \Omega$ for voltage values between 0 and 15 V. Be sure to label both axes and put the correct numerical values on them.
2. Two resistors, R_1 and R_2, are placed in series, what is the equivalent resistance of the two?
3. Three resistors, R_1, R_2, and R_3, are placed in parallel. Sketch the circuit represented by this. What is the equivalent resistance of the three? Sketch the equivalent circuit.
4. You have a perfect current source of $I = 1$A and connect it to a load, R_L. Draw the $I - V$ curve of this device for voltages between 1 mV and 10 V.

1.3 Equipment and Parts

In this lab we will utilize the following equipment. This equipment is located at your lab station.

1. The Jameco DC Power supply.

2. The Amprobe 37XR-A digital meter.

3. The Jameco proto-board.

You will also need the following components in order to carry out this lab. It makes more sense to get them as you need them, rather than all at once before the start of the lab.

1. One each of the following resistors: 10 Ω, 47 Ω, 100 Ω and 10 kΩ.

2. Two 1 kΩ resistors.

3. Four precision 10 kΩ resistors.

4. Five precision 20 kΩ resistors.

5. A 1 kΩ potentiometer.

6. A 10 kΩ potentiometer.

7. A low-current light-emitting diode (red, green or yellow).

8. A very bright light-emitting diode (blue or violet).

9. A 5.1 V Zener diode.

10. A light bulb.

11. A double-A (AA) 1.5 V battery.

12. Assorted wires for connections.

1.4 Procedure

1.4.1 *I-V* (current-voltage) curves of passive circuit elements

A passive element is a two-contact device that contains no source of power or energy; an element that has a power source is called an "active" element. In the first part of the laboratory, you are to measure and plot the current vs. voltage curve for various passive circuit elements. You are also to plot the power dissipation in each element vs. voltage drop across the device.

You need to decide which of the circuit elements are resistive and which are not resistive. For those elements which are resistive, determine the resistance, *R*. To do these measurements, you will connect the device under test to a variable voltage power supply and measure I and V as you vary the voltage control of the power supply. Use the circuit shown in Figure 3.

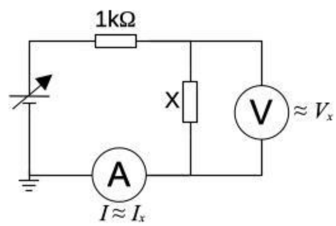


Figure 3 The setup for measuring the I-V curve for a passive element, X. The objects labeled A and V are an ammeter (ampere-meters) and a voltmeter, respectively. The voltage supply is a variable one with a range from 0 to 15 V. To understand why the current and voltage are only approximately I_X *and* V_X*, see Section 1.3.3 of your textbook.*

1. In this first lab, your first challenge is to correctly wire the circuit in Figure 3 Figure 3on the protoboard at your lab station.
2. If you have not wired-up circuits before, have the instructor check your wiring before switching on the power supply.
3. Use your circuit from Figure 3 to measure the *I-V* curves and the power dissipation of the following elements.
    - A 1k Ω resistor.
    - A 47 Ω resistor.
    - A 5.1 V "Zener diode".
    - A "low-current LED" (red, green or yellow).
    - A "very-bright LED" (blue or violet).
    - light bulb (replace the 1kΩ resistor in Figure 1.2 with 100 Ω). Don't go above about 10 V in this case.

The electronic symbols of these elements are shown in Figure 4, where we also include the symbol for a DC voltage supply. When making these measurements, record the applied voltage from the supply, the voltage across the device from the voltmeter, and the current through the device. These component symbols are all contained in IEEE Standard 315-1975 (Reaffirmed 1993). They are all available in the add-on package loaded into the Libre Office Draw program.

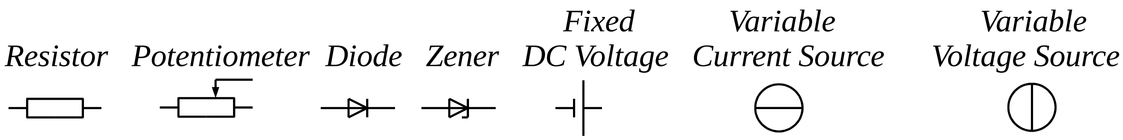


Figure 4 The electronic symbols for the components used in this lab. For the diodes, the end with the vertical line is the cathode and the other end is the anode. You can ignore the values shown in the figure. Those will change depending on the specifics

4. Make a table of all your data points and plot them as you go along. Reverse the polarity of the applied voltage by reversing the leads on the power supply; this allows you to do measurements from −15 to +15 volts on the supply.
5. When measuring the Zener diode and the LEDs, be sure to have positive voltages correspond to forward biasing the diode and negative voltages corresponding to reverse biasing the diode (see Section 1.1.2).

Data Collection:

In this section of the lab, we want to collect data to allow us to measure the *I-V* curve of the passive element, X in Figure 3. In order to do this, we need to record the voltage, V_X, across the element X and the current I_X through the element X. It would also be advisable to record the supply voltage, V_S, which we are varying from -15V to +15 V. As you collect this data, it is advisable to build your *I-V* curve as you collect data. If you are recording the data in a spread sheet, you can identify the cells that are used by a plot before you start taking the data. As you enter the data, your plot will automatically fill in the new points. The purpose of this is to let you know if you have collected enough data. If the curve is a simple straight line, then fewer points are necessary than the case where the curve is changing rapidly.

You will need to include data driven plots in your lab reports. You can accomplish this using a spreadsheet or by entering the points into an array in python and then plotting them. Keep in mind that data points are just that. You should (in general) not connect them with lines. There is uncertainty in each measurement. The trend of the relationship between your data points is what we are interested in. Fit curves should be represented by solid lines, data points should be, well, points. If you use a spreadsheet for data analysis, you will need to save the graphs as images (jpg or bmp files) so that you can include them in you jupyter notebook.

In collecting your data, the following should guide you in developing your lab book. First, record the expected and measured values of all components. For example, for the 1 kΩ resistor in the circuit, write:

The 1 kΩ resistor has a measured value of *xxxx* Ω.

Similarly, for the components, X, record the measured values when appropriate. Finally, your data should be collected in a table that looks something like Table 1.1. Note that each of the columns has a label to indicate what quantity is in that column as well as the unit associated with the quantity.

Data for the component X.		
Source Voltage V_S (Volts)	Component Voltage V_X (Volts)	Component Current I_X (Amperes)

Table 1 A sample data table for measuring the I-V curve of a passive element X.

You can build tables in Jupyter Notebooks. See the example provided.

1.4.2 *I-V* (current-voltage) curves of *active* circuit elements

The *I-V* (load) curves of active circuit elements, such as batteries and power supplies, can be obtained by connecting the elements to an external circuit consisting of a single variable resistor. A circuit for measuring the *I-V* curve of active elements is shown in Figure 5. A circuit connected to a power source is often called the "load" on the power source and in this case the single resistor, R_L, is called the load resistor. As you will see, a big load (that is, a small resistance) tends to load down the source.

Question 1.1 *Think about this language: what's "big" about connecting a small resistor?*

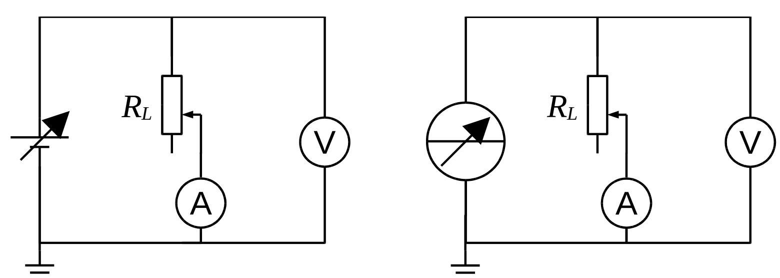


Figure 5 The setup for measuring the load curve of a power source. The objects labeled A and V are an ammeter (ampere-meters) and a voltmeter, respectively. The load is a potentiometer. The figure shows both a voltage source (left) and a current source (right).

The *I-V* curve is obtained by varying the load resistor R_L to obtain a set of (V,I) points to plot on a graph. You must find a suitable range of values for R_L so that you get a range of values for I and V. If all your values of $\underline{R_L}$ are too large, V will vary only a tiny amount; if R_L is too small, the total power V^2/R_L could exceed the power limitations of the resistor.

Any circuit with two output terminals can be considered as a source. It can be a battery, a power supply, or two terminals on the outside of a black box. It does not matter. What does matter is that there is an *I-V* curve for the source, and there are probably many circuits that give the same or equivalent *I-V* curves.

Use the circuit shown in Figure 5 to measure the *I-V* curves and power output of the devices listed below. For parts 1 and 2, use a 1 kΩ potentiometer for R_L. In part 3, us a 10 kΩ potentiometer for R_L.

1. a 1.5 V battery
2. a “50 mA current source” circuit: set up your power supply as follows
    a. with an open circuit at the output terminals, set the voltage knob to 10 V,
    b. turn the “current limit” knob to zero,
    c. attach a 10 Ω resistor across the output terminals, and then
    d. set the “current limit” knob to 50 mA (0.05 on the power-supply meter). Note that some of the supplies may be too sensitive to set the current at 50mA. For these, you may need to set it to 0.06 or 0.07. Be sure to note in your lab book what value you set this to.
    e. Remove the 10 Ω resistor and use the output terminal as the “source” in Figure 5.
3. the voltage-divider network shown in Figure 6, using $R_1 = R_2 = 1$ kΩ and the power supply set to V=10V.

When measuring the battery, you should expect most of the voltages to be near 1.5 V. If they are not, then your battery may need to be replaced. For the 50 mA current source, you want to take measurements for voltages in the range of 0 V up to about 10 V. If all of your measurements are very near 10 V, you have not done this correctly. For the voltage divider, you should make a careful comparison of your measurements with what you expect from the divider that you built.

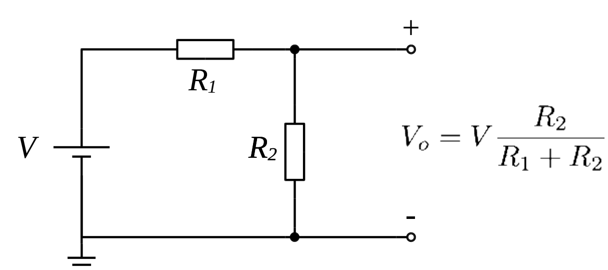


Figure 6 The voltage-divider circuit for use in part 3.

We will find it useful to be able to mimic the behavior of source circuit elements with an *equivalent circuit* consisting of either 1) an ideal voltage source in series with a resistor (Thévenin equivalent circuit), or 2) an ideal current source in parallel with a resistor (Norton equivalent circuit).

Question 1.2 *What are the Thévenin voltage and resistance, and the Norton current and resistance of each of the active devices you investigated above?*

1.4.3 The R-2R ladder or current divider

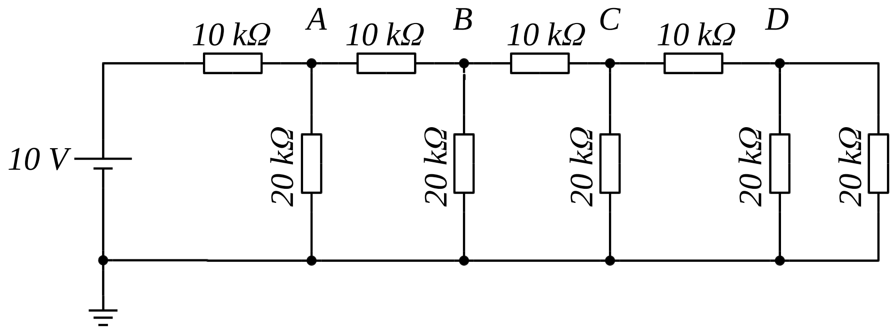


Figure 7 An R–2R resistor ladder. In this, and subsequent diagrams in this section, 10 stands for 10kΩ and 20 for 20kΩ.

The type of circuit shown in Figure 7 is used in digital-to-analog conversion (DAC), as you will see next semester. For the present, it is an interesting example of a resistor network which can be analyzed in terms of voltage and current division and, from various points of view, in terms of Thévenin equivalents.

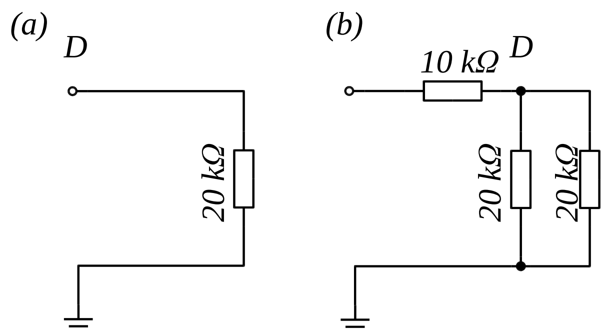


Figure 8 (a) shows the circuit to measure the resistance R from D to ground. (b) shows the circuit to measure the resistance R from C to ground.

We are going to study the properties of this network as we build it. It will be useful to collect all the parts that you need to construct this network using 1% metal-film resistors, but **do not** build it until you have read through the remainder of this section. **If you are so foolish as to ignore this warning, you will find that you need to dismantle the network to make your measurements!**

1. Start by simply putting a 20 kΩ on the board, as shown in Figure 8a. Measure the resistance from the point D to ground using your multimeter as an ohmmeter. We refer to this as looking to the right into the load.
2. Now add the two resistors, as shown in Figure 8b, and measure the resistance looking to the right into the load (C to ground).

3. Continue to add pairs of resistors and measure the resistance looking into the load, (B or A to ground).
4. Add the final pair of resistors and measure the resistance between the terminals to which the voltage source will be connected.

You should now have the resistance network (without the voltage source) on your proto-board using 1% metal-film resistors. These resistors should all be within 1% of their nominal values (that is, the stated tolerance is the maximum deviation, not a standard deviation); the better the precision, the better the network that can be constructed. Show by calculation in your notebook that the results of the resistances from above are as expected.

Question 1.3 *Calculate what you expect for the above measurements and compare them with what you have observed. Find and draw the equivalent resistance that the voltage source will see once it is connected to the resistor network that you built.*

5. Now connect the power supply set to 10 V to the circuit and measure the voltage to ground from points A, B, C and D.

Question 1.4 *Show that these voltages are in accord with expectations. Compute the current and power drawn from the power supply.*

Question 1.5 *Let's think about extending the network to an infinite number of resistors in the chain. If we were to do this, what would the equivalent resistance of this network be?*

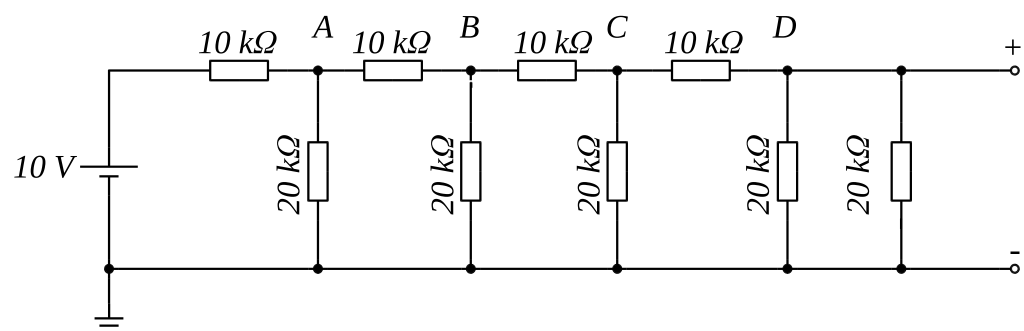


Figure 9 An R–2R resistor ladder.

Let us now consider the network shown in Figure 9, where we connect two outputs at the end of the circuit. A measurement of the voltage between these terminals will yield the "open-circuit voltage" of our ladder. If we look back into these new output terminals, we can talk of the circuit in terms of its Thévenin equivalent.

Question1.6 *Sketch the Thévenin equivalent circuit for this circuit in your lab book and determine the theoretical values for the Thévenin voltage and resistance.*

6. We can now determine V_{th} and R_{th} of the Thévenin equivalent circuit. You can measure the open-circuit voltage by measuring the voltage between the + and − terminals. The equivalent resistance can then be determined by measuring the short-

circuit current, for example, by putting an ammeter between the + and − terminals. However, although it is safe in this case, this is generally considered to be a dangerous procedure.

Question 1.7 *Why is this procedure considered dangerous?*

7. To illustrate a common practical way to determine the Thévenin equivalent resistance of a circuit, place a known resistance, with a value of the same order of magnitude as the expected Thévenin equivalent resistance, between the + and − terminals. Measure the voltage across this known resistor and use this voltage to determine the current flowing through the known resistor. Using the open circuit voltage and the above measurement as two points on an *I–V* curve, the value of the Thévenin equivalent resistance, $\underline{R_{th}}$, can be determined.

Question 1.8 *Draw the relevant Thévenin equivalent circuit for this measurement in your notebook and determine R_{th}. How does the predicted short-circuit current compare to what you found by connecting an ammeter between the + and − terminals? Why is it safe to measure the short-circuit current with this circuit?*

A conclusion you should assimilate from this part of the lab is that a complicated circuit (for example, the *R*–2*R* ladder) can be thought of from many points of view – many terminal pairs. For each pair of terminals, there is a Thévenin equivalent circuit that would mimic the behavior of those terminals. There is no equivalent circuit for the entire circuit, but only for specific pairs of terminals. Knowing the Thévenin equivalent circuit for a pair of terminals makes it easy to think about what will happen to something you want to connect to those terminals. We will use this concept throughout the course!

1.5 Additional Problems

After completing this lab, you should be able to answer the following questions.

1. You build the circuit shown in Figure 10 below in lab. You supply an input voltage V_0 to the circuit and look at the output voltage and current between the terminals *A* and *B*. In building your circuit, you have carefully chosen your resistors such that R_1, R_2 and R_4 all have the same resistance, *R*, while R_3 has twice this resistance (2*R*). (a) In terms of input voltage, V_0, and the characteristic resistance, *R*, what is the output voltage of our circuit, V_{AB}? (b) If you connect an ammeter in series with resistor R_4, what does the ammeter read (value and units)? (c) If you connect an ammeter in parallel with resistor R_4, what does the ammeter read? (d) Sketch the Thévenin equivalent circuit as seen looking into *A*-*B* for your circuit. In terms of V_0 and *R*, what are V_{th} and R_{th}?

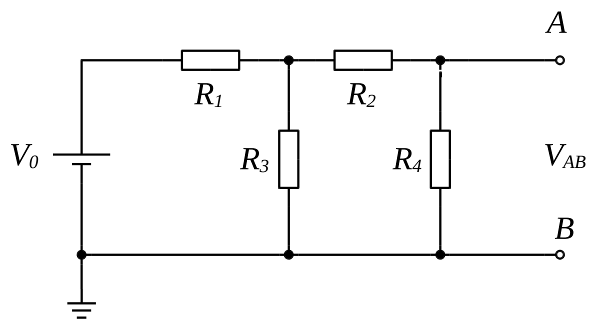
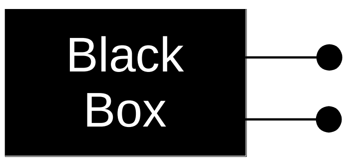


Figure 10 The circuit diagram for problem 1.

2. You measure the data in the table in Figure 11 for the *I*–*V* curve between the two output terminals of the black-box circuit shown in Figure 11. (a) Make an accurate sketch of the *I*–*V* curve for your data. (b) What is the open-circuit voltage between the two terminals? (c) What load resistance was used to measure the 10 V data point?



Voltage (V)	Current (mA)
1.0	10.0
6.0	5.0
10.0	1.0

Figure 11 The black-box circuit and data for problem 2.