Electrical Measurements (142)

Objectives

- To study simple series and parallel DC circuits.
- To apply Ohm's law.
- To use digital multimeters.
- To study voltage-current characteristics of linear and nonlinear devices.
- To build a variable voltage divider potentiometer.

Introduction

While originally used to describe metallic wires, the relation known as **Ohm's law** has proven useful for describing the behavior of many materials. This principle was discovered in 1827 by Georg S. Ohm (1787 - 1854) and is the basis of many essential facts in practical electricity. It relates the current through a component in an electrical circuit (\(I\)) to the potential difference across that element (\(V\)) and to the resistance of the component (\(R\)) as

\[ V = IR. \quad (1) \]

Current is typically measured in amperes (A), potential difference is measured in volts (V) and resistance is measured in ohms (Ω).

There exists a large class of materials where the value of \(R\) is found experimentally to be independent of \(V\) and \(I\). In such a case, Eq. (1) is a very simple linear relation between the current through and the voltage across the element. Such elements are ordinarily called **resistors**, symbolized as shown in Fig. 1. They are said to be linear or ohmic devices.

![Figure 1: Symbol for a resistor](image)

Nowadays, there are many components or chips that rely on semiconducting materials, which cannot be assigned a static value for resistance. Furthermore, some substances may have resistances that depend on other physical properties, such as their temperature, illumination, or strain.

Experimental procedure

Getting started

Circuit diagrams
Throughout the quarter, you will be presented with a number of circuit diagrams. These diagrams differ from many other illustrations used in physics because they do not depict the physical state of the circuit. Instead, they are a blueprint for how to electrically connect components.

**Connecting circuits**

To prevent blowing fuses in power supplies and meters, please use the following steps when connecting circuits:

- Turn off the power supply.
- Connect the circuit. For clarity, connect series loops first, then add sections in parallel (e.g., voltmeters). Follow wiring diagrams point by point as you connect the circuit.
- Select the meter function (current, voltage, resistance, etc.).
- Select the least sensitive range in that function (the largest numbers). If you are using an *auto-ranging* meter, there will be only one setting and the meter will adjust the range automatically.
- Turn on the power supply and increase the voltage slowly.
- Increase the meter sensitivity (if not using an auto-ranging meter) only enough to get a reading (not overload).

**Resistor values**

Many resistors are marked with colored bands which indicate their resistance values and tolerance. The bands are to be read starting closest to the end of the resistor as shown in Fig. 2.

![Resistor color code](image)

The digit values represented by each color are shown in Table 1. The tolerance values represented by each color are shown in Table 2.

<table>
<thead>
<tr>
<th>Digit</th>
<th>Color</th>
<th>Tolerance</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Black</td>
<td>2%</td>
<td>Red</td>
</tr>
<tr>
<td>1</td>
<td>Brown</td>
<td>5%</td>
<td>Gold</td>
</tr>
<tr>
<td>2</td>
<td>Red</td>
<td>10%</td>
<td>Silver</td>
</tr>
<tr>
<td>3</td>
<td>Orange</td>
<td>20%</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Green</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Blue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Violet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Gray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>White</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For example, if the colors are red, orange, yellow and silver, then the resistance is $R = 23 \times 10^4 \Omega \pm 10\%$ or 230 k$\Omega$

If there were three bands that were brown, black, and brown, then the resistance would be $R = 10 \times 10^4 \Omega \pm 20\%$ or 100 $\Omega$

**Group lab report**
Choose a group member to be the **record keeper**. (This person should be a different person from the record keeper last week.) After creating the lab report from the template below, make sure to click the "Share" button in the upper right corner and add all group member email addresses.

**Lab Template**

**Using Jupyter notebook**

In order to do data processing and analysis, we will use Jupyter notebooks (which run on the Python programming language). Download the following notebook file:

**Click here to download the Jupyter Notebook**

**Practice with multimeters**

**Using the multimeter**

Making electrical measurements is a bit different than most of the other types of measurements we've done. Using a ruler to measure a length won't change something's length, nor will weighing an object with a scale change its mass. But, using a multimeter can change how a circuit behaves if we're not careful. Thus, if you're seeing something on a meter that you don't expect, double check that the correct terminals are attached to the circuit.

Take a look at the generic multimeter shown in Fig. 3. One wire should always be connected to the common (COM) terminal, and the other will be attached to one of the following:

- "V/Ω" for measuring any voltage or current;
- "200 mA" for measuring a small current; or
- "10 A" for measuring a large current.

For measuring voltages, you'll connect the meter to either side of a component (i.e. in parallel).

For measuring currents, you'll connect the meter in-line with the component (i.e. in series).

Finally, you'll need to set the dial to what you want to measure. The tilde ~ indicates an AC value (not used today), whereas the straight & dashed line combination indicate DC values.
The specifics of how a modern multimeter works are beyond what we can teach in an introductory physics course. However, we can make a first order model for how we expect it to behave, as follows:

Note that the small resistance for current measuring mode are crucial since we want to change our circuit as little as possible when we attach our meter. To measure current the meter must be in series with other elements, and thus a small resistances make the most sense.

Likewise when measuring voltages we attach the meter in parallel with a component or branch, and by having a large resistance between the leads we ensure that this doesn't impact the behavior of the rest of the circuit much.

**Measuring direct current (DC)**

Using a resistor value between 1 kΩ and 10 kΩ, set up the circuit in Fig. 4.
Plug the black test lead into the “COM” jack on the multimeter and the red test lead into the “mA” jack. Set the function of the digital multimeter to be an ammeter.

For the resistor you have chosen and the maximum voltage available from the power supply (50 volts in this case), calculate the maximum current possible in your circuit. Set the range switch on the meter to a DC mA setting larger than which is your calculated value.

- Set the large current limit knob on the power supply to 0.2 A and set the smaller current limit knob fully clockwise.
- Set the current range to “Low” and set the knob fully clockwise.

Turn on the power supply and observe the meter. If the reading is negative, you may have connected the circuit differently from the diagram. Check it.

You may switch to a more sensitive range if the voltage you measure is small enough.

Adjust the power supply and observe and record the range of currents. Turn off the power supply.

There are a few reasons you might not be seeing a current in your circuit.

To start, make sure that your meter is on the current setting (i.e. the dial is turned to mA) and that the leads are in the correct socket. If this is the case and you’re still seeing nothing, the fuse in your meter may be blown. Here’s how to check:

Connect one meter in resistance mode to the other in current mode, as shown below. If the meter being tested reads 0.1 to 0.2 mA and the other reads a couple of ohms, then the fuse is fine.

If, as shown below, the meter being tested reads 0 mA and the other reads overload (O.L) then the fuse is probably blown. Fortunately, replacing them is easy.
There should be a plastic container with several screwdrivers and spare fuses in your lab room, ask your TA where it is if you can't find it.

First, turn over your meter and remove the screws that hold it closed with a Phillips (+ shaped) screwdriver. Don't worry if there's only one screw, many of our meters are left like that to make changing the fuse easier.

Next find the 500 mA fuse, which should be labeled both on the board and on the fuse itself. Some fuses have solid white bodies, whereas others have glass bodies with a thin wire inside. Either way, they work the same way.
Pop out the old fuse and replace it with a new one. A flathead screwdriver can be useful here. If you want to be extra certain that the new fuse is good (and that the old one is bad) use a different meter to test its resistance. It should read a couple of ohms, any more and the fuse is no good.

Close your meter back up and test it to make sure it works. The dead fuse can be thrown away, there's nothing hazardous about them. Don't worry about the cost, in bulk these fuses cost all of about $0.10.

Simultaneously measuring DC voltage
Using the same circuit as above with the power off, add a voltmeter across $R$ as in Fig. 5.

Since the maximum voltage possible from the power supply is 50 V, set this second meter to read DC volts on an appropriate sensitivity range.

Plug the black test lead into the “COM” jack and the red test lead into the “V” jack.

Turn on the power supply. If the reading is negative, check the circuit.

Adjust the power supply and observe the range of voltage available.

Keep this circuit set up; you’ll be using it for the next part.

Testing conductive materials

Now that you have a bit of practice with the meters, you’ll use them to test the behavior of a few different conductive elements. For each element, you will vary the power supply voltage and then the voltage across the element along with the current through it. If a material is Ohmic, then a plot of the voltage versus current ($V$ vs $I$) should be linear; if it is not Ohmic, then the curve will have a different shape. You should also swap the connections on your element at some point so that you can test if the directionality matters at all.

Produce voltage versus current plots for the following elements:

A resistor

A light bulb
Practice: Connecting circuit elements

Next, you'll practice connecting multiple elements together in different configurations.

Resistors in series

- Choose two resistors, measure their resistances individually, and then connect them in series as in Fig. 6.
- Using the resistance values for each resistor measured earlier, calculate the expected total series resistance.
- For one setting of the power supply, measure $V$ and $I$ and determine the total resistance.

Resistors in parallel

- Connect your resistors and the meters in the circuit shown in Fig. 7.
- For one setting of the power supply, measure $V$ and $I$ and determine the total resistance.
Resistor A can't be in parallel with B or C (it only shares 1 common connection with them). Nor can it be in series with just resistor B or C; the current through A is split between B and C. More advanced techniques are used to analyze the behavior of such networks.

Voltage division

Now we’ll do something that is ubiquitous in electronics: dividing voltage. In some cases, this is done so that different things can be powered by a single battery. In other instances, voltage dividers form the basis of sensors that connect physical properties (like position) into electrical properties (like voltage).

Here we'll introduce the notation of a voltage input $V_{in}$ and a voltage output $V_{out}$. For the purposes of this class, $V_{in}$ will usually denote a voltage from a power supply, and $V_{out}$ will denote where to measure a voltage to determine the effect of the circuitry.

Not necessarily. If there's no meter or other circuit attached to the $V_{out}$ connections, then having a current there would imply that electrons were flying off or on to the wires. Voltages can exist without currents. For example, a battery on a shelf has a fixed voltage across the terminals even though no electrons are moving.

Fixed voltage divider

Connect the circuit shown in Fig. 8. Be sure that both meters are on the DC voltage setting. This circuit is useful when a fixed fraction of some input voltage is needed.

From Ohm’s law and how resistors add in series, it can be shown that

$$V_{out} = f_{resistance}R_2R_1 + R_2V_{in}. \quad (2)$$

For one power supply setting, measure the input and output voltages to test the above relation for your circuit.

Replacing $R_2$ with an element whose resistance depends on some physical quantity (e.g. temperature, pressure, light) is a way of making a basic sensor.

Slide-wire potentiometer

A variable voltage divider can be made by replacing the fixed resistors with a length of resistance wire and a sliding contact as shown in Fig. 9.
For this setup, you’ll test the effect changing the sliding contact has on the output voltage ($V_{out}$). If the wire is uniformly made, then the resistance across a portion of it is proportional to length. Using this with eq. 2, we can find the relation:

$$V_{out} = f_{resonance} L_2 L_1 + L_2 V_{in} \quad (3)$$

Keeping $V_{in}$ constant, test this relationship and record your results (along with a plot) in your report.

Keep $V_{in}$ from the supply around 10V or 20V or so, unless you enjoy the smell of burning wood.

**Report submission**

Take a look over your report and make sure it’s complete. Download your report as a PDF and upload it to the form below. **Make sure to log out of your Google account when you are done!**