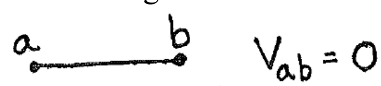
DIRECT-CURRENT CIRCUITS

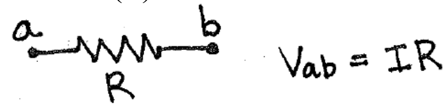
INTRODUCTION

Until now we have studied phenomena arising from static distribution of charges. We now take the next logical step, and allow the charges to move in steady currents in conducting materials. In this experiment we will construct several simple direct current (DC) electrical circuits. In doing so we will verify the following properties of circuit elements:

1. The potential difference, V_{ab}, between any two points ***a*** and ***b*** of an *ideal* wire is zero, independent of the current through the wire.



2. **Ohm's Law:** The potential difference between two ends of an *ideal* resistor is proportional to the current, *I*, flowing through the resistor. The proportionality constant is called the *resistance* (*R*).



3. A **voltmeter** is a device used to measure the potential difference (voltage) between two points. Its symbol is given in Figure 12:

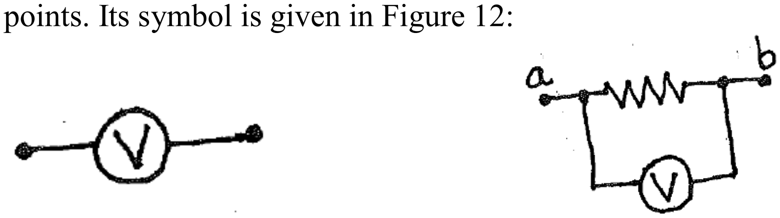


Figure 12. Symbol for a voltmeter and its correct usage for measuring V_{ab}.

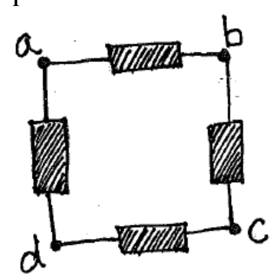
An *ideal* voltmeter behaves as if it were a resistor with infinite resistance: no current will flow through the voltmeter. Measuring the voltage thus *does not disturb the circuit*. You can think of current as "preferring" to go through the path of least resistance – if it is faced with two paths, one with a small resistance and one with a very large resistance, most of the current will flow through the former path. The voltmeter shown in Figure 12 is measuring the voltage V_{ab} across the resistor; it is connected in *parallel* with the resistor.

4. An **ammeter** is a device used to measure the current *I* at any point in a circuit. Its symbol is given in Figure 13.

Figure 13. The symbol for an ammeter and its correct usage for measuring the current *I*.

An *ideal* ammeter behaves as if it were an ideal piece of wire. Its resistance is 0, and all of the current will flow through it (the current doesn't have much of a choice, the ammeter is blocking its path!). Measuring the current *can disturb the* *circuit* if it is not properly connected. If you were to connect an ammeter across the resistor as you would a voltmeter, ALL of the current would flow through the ammeter (instead of the resistor) because it has such a tiny resistance – this can result in the poor ammeter blowing a fuse! Instead, you should always connect the ammeter as shown in Figure 13, in *series* with the circuit.

5. **Kirchhoff's loop rule for voltages:** The algebraic sum of the voltages around a loop is equal to zero.

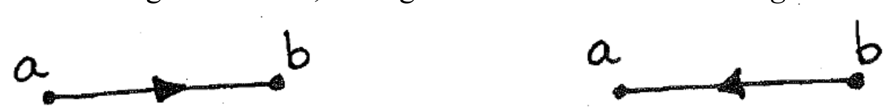


$$V_{ab} + V_{bc} + V_{cd} + V_{da} = 0$$

Figure 14. Example circuit with black boxes representing circuit elements (batteries, resistors, capacitors, etc). The voltages from points *a* to *b, b* to *c, c* to *d,* and *d* to *a* will all add up to zero.

As can be seen, the sum of the voltages across each one of the circuit elements shown in Figure 14 will add to zero. Notice that at least one voltage must be positive and at least one voltage must be negative.

6. **Kirchhoff's junction rule for currents**: In order to apply Kirchhoff's junction rule, we must *always* establish a sign convention for the direction of the current in a conductor. In Figure 15(a), we show a wire connecting the points *a* and *b*, with an arrow pointing from *a* to *b*. If positive charges are flowing from *a* to *b*, we say that the algebraic value of current is *positive*.[11] On the other hand, if positive charges are flowing from *b* to *a*, the algebraic value of current is *negative*.



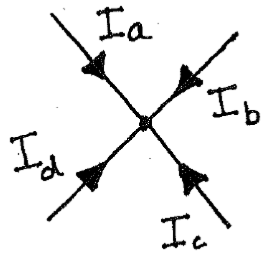
(a) (b)

Figure 15. Two possible conventions for the current in a wire.

Notice that the arrow does not indicate which direction the physical current is flowing; it merely establishes a sign convention. We could just as well have drawn the arrow pointing from *b* to *a*, as shown in Figure 15(b). In this case, if positive charges happen to be flowing from *a* to *b*, the algebraic value of the current is *negative*, and so forth.

Kirchhoff's junction rule is usually stated as follows: *The algebraic sum of all of the currents flowing into a junction is exactly zero.* Physically, this simply means

[11] An algebraic number is a signed number, that can be positive, negative, or zero.



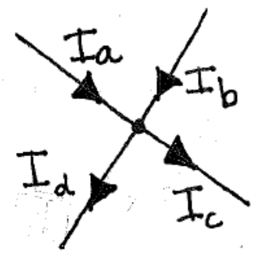


Figure 16. Two possible depictions of Kirchhoff's junction rule.

that charge cannot accumulate at a point. The picture associated with this rule is usually depicted as in Figure 16(a), with all arrows pointing toward the junction. The mathematical statement of Kirchhoff's law is $I_a + I_b + I_c + I_d = 0$. Notice that the algebraic value of at least one current must be negative, and the algebraic value of at least one current must be positive.

We could just as well have defined our current conventions as shown in Figure 16(b). In this case, it is still true that the algebraic sum of all the currents flowing into the junction is zero. However, the currents flowing *into* the junction are I_a, I_b, $-I_c$, and $-I_d$. Therefore, the mathematical statement of Kirchhoff's law, applied to this figure, is $I_a + I_b - I_c - I_d = 0$. Notice that this could just as well be written $I_a + I_b = I_c + I_d$. An intuitive way of stating this is that the total current flowing into a junction must equal the total current flowing out of the junction. Remember, though, that the algebraic value of each current may be positive, negative, or even zero.

PRELIMINARY MEASUREMENTS

For these measurements you do not need the PASCO power supply. Please make sure it is not connected to your circuit and set it aside. This is important!

The three resistors supplied have the following nominal resistances:

Green-blue-brown-gold	560 Ω ±5%
Blue-gray-brown-gold	680 Ω ±5%
Gray-red-brown-gold	820 Ω ±5%

Almost all hand-held multimeters, including the ones used in this lab, have a built-in capability for measuring electrical resistance. You will first use the multimeter to find the exact resistance of the resistors. See the Appendix at the end of the manual on multimeters for more information.

Experiment 1

Measure the resistance of each of the three commercial resistors provided (three measurements). Compare with the nominal values given above. Are your resistors within the expected range? Be sure to use your measured resistance values for the remainder of the lab.

COMBINATIONS OF RESISTORS

For these measurements you do not need the PASCO power supply. Please make sure it is not connected to your circuit and set it aside. This is important!

Resistors in series: When two resistors are placed one right after the other in a circuit, we say they are connected in *series.* In this configuration, the current going through one resistor must also go through the other – there is only one path for the current to follow.

Figure 17. Resistors in series.

The total resistance for resistors in series is simply the sum of the individual resistances:

$$R_{total} = R_1 + R_2 \tag{14}$$

Resistors in parallel: When two resistors are placed in such a way that the current can go through both resistors at once, we say they are connected in *parallel.*

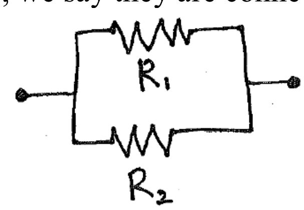


Figure 18. Resistors in parallel.

The total resistance for resistors in parallel is written as:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} \tag{15}$$

In this experiment, you will verify these laws for resistors in series and parallel, and see how the laws still apply for more complicated configurations (*e.g.* one resistor in series with two resistors in parallel).

Experiment 2

1. Connect two of the three commercial resistors in series and measure the resulting resistance. Compare with the value predicted by the series resistance law.
2. Connect two of the three commercial resistors in parallel and measure the resulting resistance. Compare with the value predicted by the parallel resistance law.
3. Measure the resistance of a network that has one resistor in series with a pair of resistors connected in parallel. Does it agree with the predicted value using the laws of parallel and series resistors?

THE SIMPLEST POSSIBLE CIRCUIT

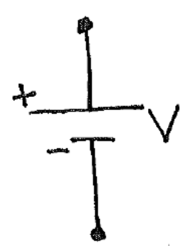
In this experiment we will verify Ohm's law for the simplest conceivable circuit. In doing so, we will verify the six basic properties stated in the introduction. Before we do so it is very important to define our sign conventions.

A typical electrical circuit consists of elements like resistors, capacitors, batteries, and other elements connected by conducting metallic wires. As you have already seen, we can assign letters to junctions of these elements, like ***a, b, c, d,*** etc. We can also measure the electrostatic potential between any pair of points; *e.g.* V_d-V_b. Only the *difference* in potential is physically observable, because we can always add a constant to every potential without changing the physical effects.

Our convention for potential difference is as follows: The difference in potential between point ***a*** and point ***b***, namely, $V_a - V_b$, will be given the symbol V_{ab}:

$$\begin{aligned} V_a - V_b &\equiv V_{ab} \\ V_b - V_a &\equiv V_{ba} \\ V_{ab} &= -V_{ba} \end{aligned} \tag{16}$$

In a circuit diagram, a voltage *source* (such as a battery or a power supply) is denoted as a long line over a short line, as in Figure 19:



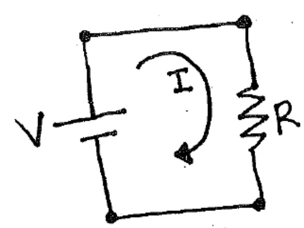


Figure 19. A voltage source with voltage V by itself, and a voltage source in a circuit.

The long line is the positive terminal (associated with the color red), and the short line is the negative terminal (associated with the color black). In this circuit, the current will always flow out of the positive terminal, through the rest of the circuit, and back in to the negative terminal.

Potential differences are measured with instruments known as *voltmeters* (in our case, this is simply a multimeter in voltage-measuring mode). Typically, there are two connections, usually labeled "**VΩ**" (for volts or ohms) and "**COM**" (for common). It is customary to connect a red probe to the VΩ terminal, and a black probe to the COM terminal. If the red probe touches point ***a*** and the black probe touches point ***b***, then the meter will read $V_a - V_b$ (so V_{ab}), and *vice versa*.

Preliminary setup

For this set of experiments we will be using a PASCO power supply. To read the voltage on the output terminals you need to set the switch at the top to VOLTS; or to monitor the output current you need to set the switch to AMPS.

There are two knobs on the front panel: VOLTAGE ADJUST and CURRENT LIMIT. The voltage adjust is designed to never allow the voltage to exceed the setting of the VOLTAGE ADJUST knob, which can be varied from 0 V to 15 V. The current limit is designed to never allow the current to exceed the setting of the CURRENT LIMIT knob, which can be varied from 0 mA to 200 mA.

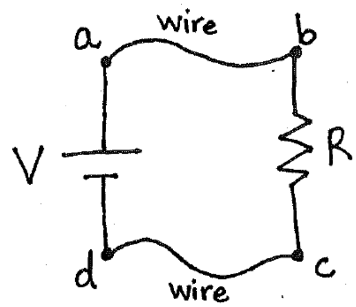


Figure 20. One resistor connected to a voltage source V. The wavy lines are jumper wires (banana cords in our case) connecting points *a* to *b* and *c* to *d*.

Now set up the above circuit with four terminals, ***a***, ***b***, ***c***, and ***d***, exactly as shown in Figure 20. Here, V represents the voltage of the power supply – set this to anywhere between 5 and 10 Volts.

Experiment 3a – Voltage

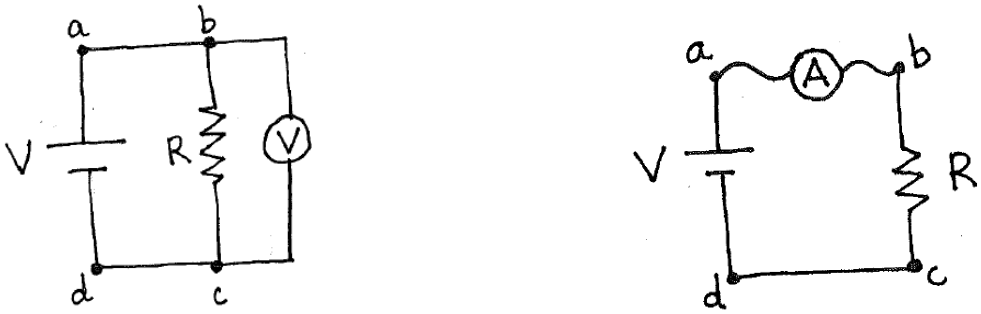
Note that you will not have to modify the circuit in any way to measure voltages, you simply have to stick the voltage probes into the correct points!

1. Using the multimeter in voltage mode, place the red probe into point ***a*** (the back of the banana cord hooked up to the power supply) and the black probe into point ***b*** (the other end of the same banana cord hooked up to the resistor). The readout will be V_a-V_b (V_{ab}). Does this correspond with what you would expect for a wire?
2. Now, measure V_{bc} across the resistor (see Figure 21(a)). Is this voltage positive or negative? Note what happens to the sign if you swap the black probe and the red probe (this is the value of V_{cb}).
3. Measure and record the potential difference between every consecutive pair of terminals; *i.e.* V_{ab}, V_{bc}, V_{cd}, and V_{da}.[12] Be sure to keep track of the signs! *Note that*

[12] The voltage across an element is sometimes called the *voltage drop*.

the voltage on the power supply display is positive (V_{ad}) – for the purpose of the loop rule, however, we want V_{da}.

4. Verify that the algebraic sum of these voltages is zero.



(a) (b)

Figure 21. (a) A voltmeter measuring V_{bc} or V_{cb}, and (b) an ammeter measuring I_{ab}.

Experiment 3b – Current

*Note that you **will** have to modify the circuit to measure the current – the ammeter must be placed such that all of the current you want to measure flows through it!*

1) Make sure that the power source is off.
2) Make sure your multimeter is set to current mode. It should display the current in units of milliamps.
3) Set up the complete circuit but *without* the multimeter (if you haven't changed it since Experiment 3a, then this is done already).
4) To measure the current between points ***a*** and ***b*** (I_{ab}) – as seen in Figure 21(b):
   a) Disconnect the jumper wire that connects point ***a*** to point ***b***.
   b) Connect point ***a*** to the 300 mA terminal on the Fluke multimeter and point ***b*** to the COM terminal on the multimeter.
   c) Turn on the power source.
5) Using the same technique, measure the current flowing from point ***c*** to point ***d***. Compare the result with the current flowing from ***a*** to ***b***. Are the currents the same or different? Are the signs different? Is this what you expect?

Since you now know the current passing through your resistor and the value of the resistor, calculate the expected voltage across the resistor using Ohm's law. Does it correspond with the voltage you measured in Experiment 3a?

TWO RESISTORS IN SERIES

Set up the following 6- terminal circuit exactly as in Figure 22:

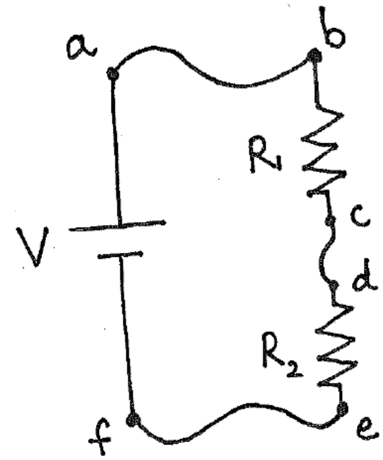


Figure 22. Two resistors in series.

Experiment 4a - Voltage

1) Measure the potential difference between these pairs of points as you go around the circuit: V_{bc}, V_{de}, and V_{fa}.
2) What *should* the voltages across V_{ab}, V_{cd}, and V_{ef} be? If you aren't sure, check them.
3) Verify that the algebraic sum of the above six voltages is zero.
4) Now, measure the voltage drop across both resistors, V_{be}. Verify that it corresponds almost exactly to the voltage drop from the power supply, V_{fa} (apart from a sign change).

Experiment 4b – Current

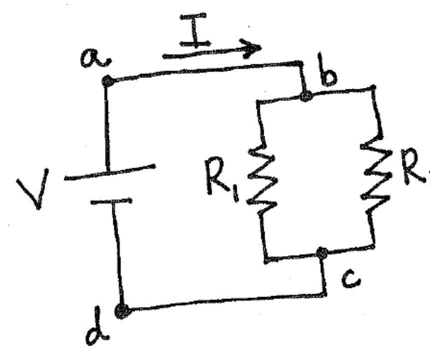
1) By replacing the wire jumpers (one at a time) with the ammeter, measure, in turn, the currents I_{ab}, I_{cd}, I_{ef}. (Be sure to follow closely the process outlined in Experiment 3b!)
2) What do you conclude about the current at every point in this circuit?

Now that you know the voltage across each resistor, and the current going through each resistor, use Ohm's law to calculate the theoretical values of each resistor. How closely do these values match with the actual resistor values you measured in the first experiment?

Finally, use the total current flowing through the resistors, I_{ab}, and the total voltage across the resistors, V_{be}, to determine the *effective* resistance (R_{total}) of the two resistors taken together. Compare this 'effective resistance' with the result using the equation for resistors in series.

PRE-LABORATORY

1. Draw a two terminal diagram showing a resistor, R_1, in series with two other resistors in series, R_2 and R_3. Give an equation for the total resistance of this configuration.
2. Draw a two terminal diagram showing a resistor, R_1, in series with two other resistors in parallel, R_2 and R_3. Give an equation for the total resistance of this configuration.
3. Say the resistors are connected in the following circuit, with $R_1 = 100\ \Omega$, $R_2 = 200\ \Omega$, and $V = 14$ Volts:



What is the current, I, going from point **a** to point **b**?