General Physics Lab 4

Kirchhoff's Laws

Objectives:

- To study currents entering and exiting a node
- To observe voltages around a closed loop

Equipment:

- Multimeter with Probes
- Breadboard
- Jumper Wire Kit
- Two 9V Batteries
- 3 kΩ Resistor (orange, black, red, gold)
- 4.3 kΩ Resistor (yellow, orange, red, gold)
- 5.1 kΩ Resistor (green, brown, red, gold)

Physical Principles:

Kirchhoff's Current Law

The principle of conservation of electric charge implies that:

At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to 0.

Thus, in the case of Fig. 1, Kirchhoff's Current Law (also called Kirchhoff's Junction Law) yields the following.

$$I_1 + I_2 - I_3 + I_4 - I_5 = 0 \qquad (1)$$

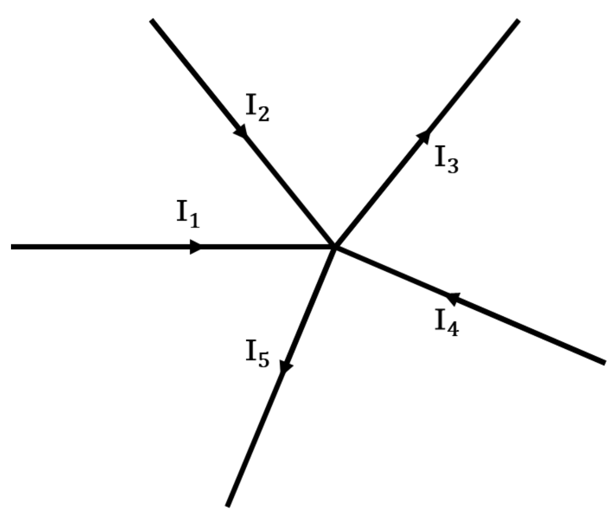


Fig. 1: Currents I_1, I_2, and I_4 are entering the node. Currents I_3 and I_5 are exiting the node.

Kirchhoff's Voltage Law

Conservation of energy requires that the sum of all the voltage drops around any closed loop in a circuit always equals zero.

Thus, in the case of Fig. 2, Kirchhoff's Voltage Law (also called Kirchhoff's Loop Law) yields the following.

$$V_s + V_1 + V_2 + V_3 = 20V - 2V - 12V - 6V = 0 \quad . \qquad (2)$$

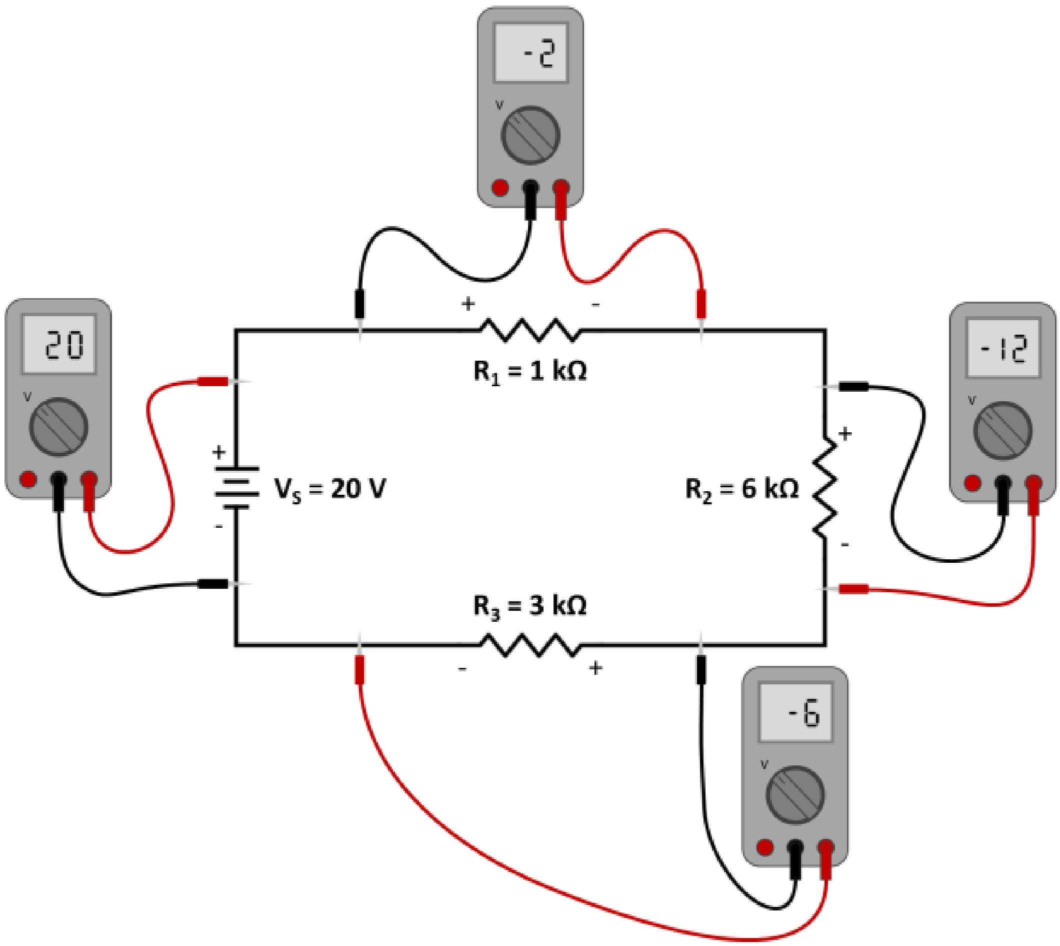


Fig. 2: The sum of all voltages around a closed loop will always be zero.
In this case, the source voltage is 20V and the voltage drops across the three resistors (R_1, R_2, R_3) are 2V, 12V, and 6V respectively.

Procedure:

Measure Resistance

1. Locate the 3 kΩ, 4.3 kΩ, and 5.1 kΩ resistors from your lab kit.

   You can tell the resistor's nominal value from the 4 or 5-band color code printed on the resistor. To interpret this code, look up a resistor color code table or use an online calculator such as this one: https://resistorcolorcodecalc.com/.

2. Turn the multimeter dial to measure ohms (Ω) and set it to the lowest range that will give a value. This will most likely be the 2000 Ω range or the 20k range.
3. Insert the black probe into the common (COM) port and the red probe into the port for resistance (Ω).
4. One at a time, carefully (it is easy to bend the resistor leads and hard to re-straighten them) place the resistors in the breadboard and measure the individual resistances in kΩ (see Fig. 3).

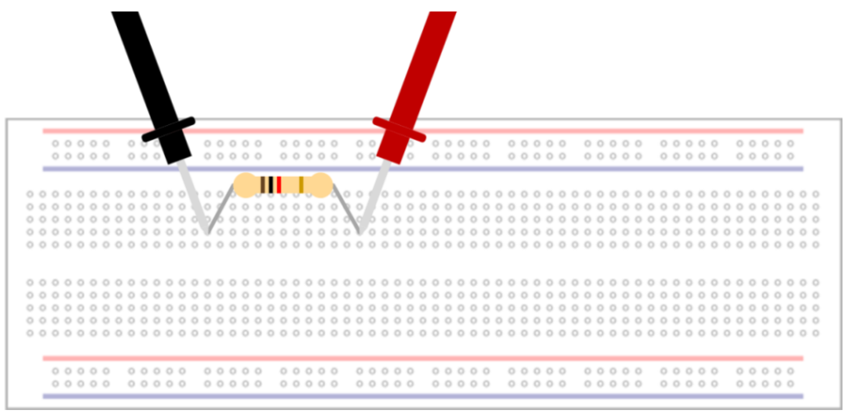


Fig. 3: Carefully place each resistor in the breadboard as shown and measure the individual resistance of each.

Check Battery Voltages

1. Turn the multimeter dial to measure DC voltage (V ⎓) and set it to the 20V range.
2. Insert the black probe into the common (COM) port and the red probe into the port for Voltage (V).
3. Measure the voltages (V_{S1} and V_{S2}) of two 9V batteries by touching one probe to each pole of the battery (see Fig. 4). Record the values, and if the two voltages are different, keep track of which battery is which.

   Nominally the batteries should be 9V, but when new they are often a little higher than this. If the voltage of either battery has dropped below 8.5V, replace it with a different battery.

WARNING: Never attempt to measure across the poles of a battery or other power source while the multimeter is in current mode (A). Doing so will blow the internal fuse or even destroy the multimeter.

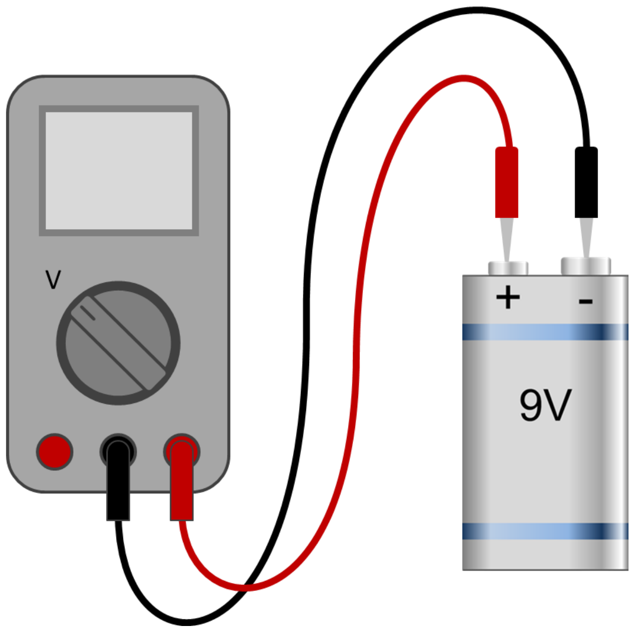


Fig. 4: Set multimeter dial to measure voltage (20V range), black probe in COM port, red probe in V port. Touch red probe to positive battery pole and black probe to negative battery pole.

Build the Circuit

1. Build the circuit in Fig. 5. Note that the blue line of holes on the breadboard (Fig. 5b) are all connected underneath, replacing the bottom wire in the circuit diagram (Fig. 5a) and completing the circuit.
2. Make sure that any wires/leads that are supposed to be connected are placed in the same row of 5 holes.
3. Also, pay attention to the battery polarity (- + vs. + -) when building the circuit.

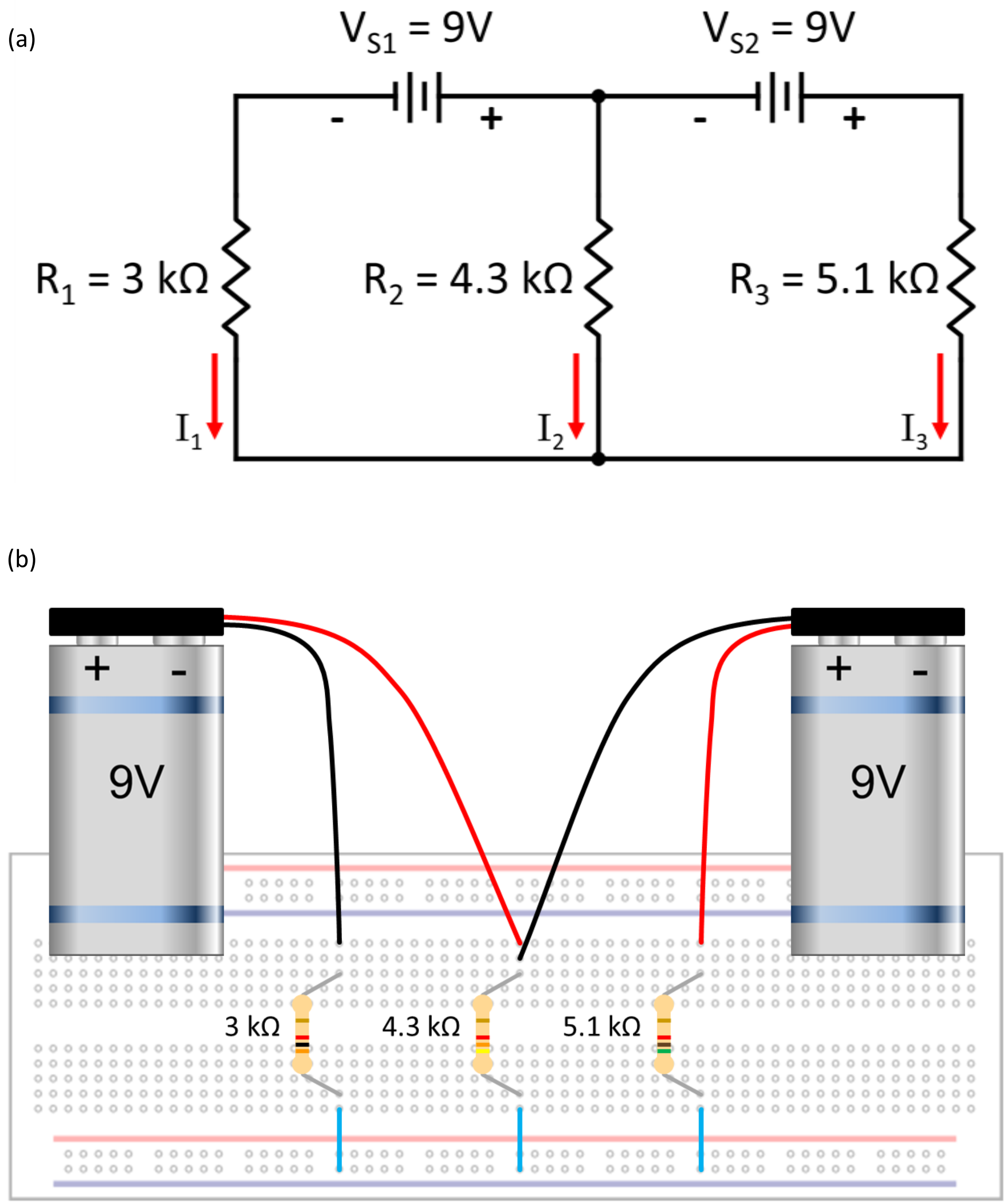


Fig. 5: Complex circuit to study Kirchhoff's Laws: (a) Circuit diagram with nominal voltages, resistances, and currents labeled, (b) Breadboard wiring diagram with two 9V batteries, three resistors, and jumper wires. Make sure any wires/leads that should be connected are placed in the same row of 5 holes. The jumper wires (blue) connect the resistors to the blue line of breadboard holes at the bottom. This blue line is connected underneath, completing the circuit. The jumper wires will be useful later when measuring the currents.

Measure Voltages

The complex circuit for this experiment contains three closed loops as shown in blue (see Fig. 6). When measured, the sum of the voltages around any of these loops should be zero.

1. Set the meter to measure voltage (20V range) and connect the probes as before (black in COM, red in V).
2. Measure and record the individual voltage differences around <u>each</u> of the three loops (see Fig. 7).
3. Verify that the sum of the voltages around each loop is zero.
4. Voltage measurements around a loop can be confusing, so make sure to measure the polarity as shown in Fig. 7 and pay attention to whether the measured value is positive or negative.

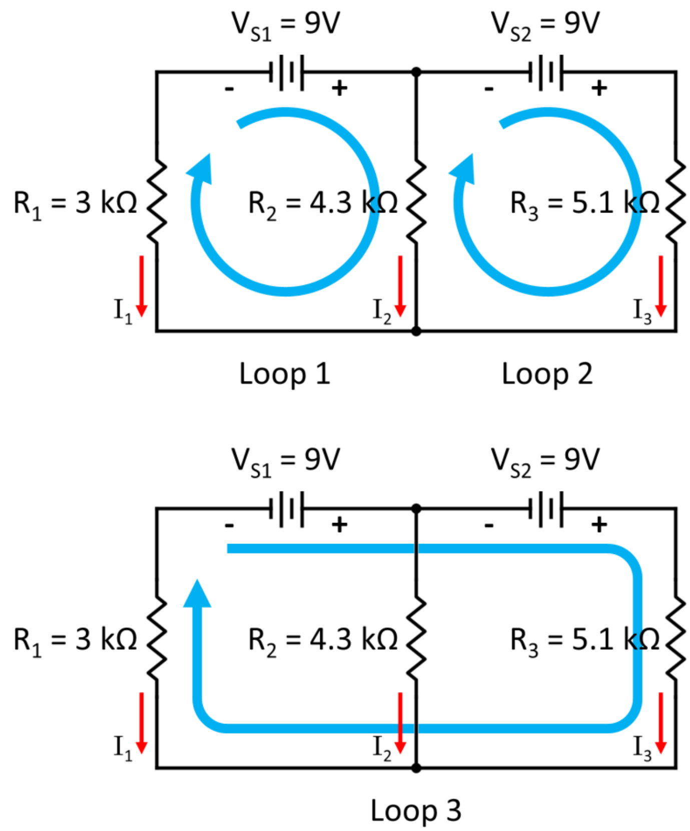
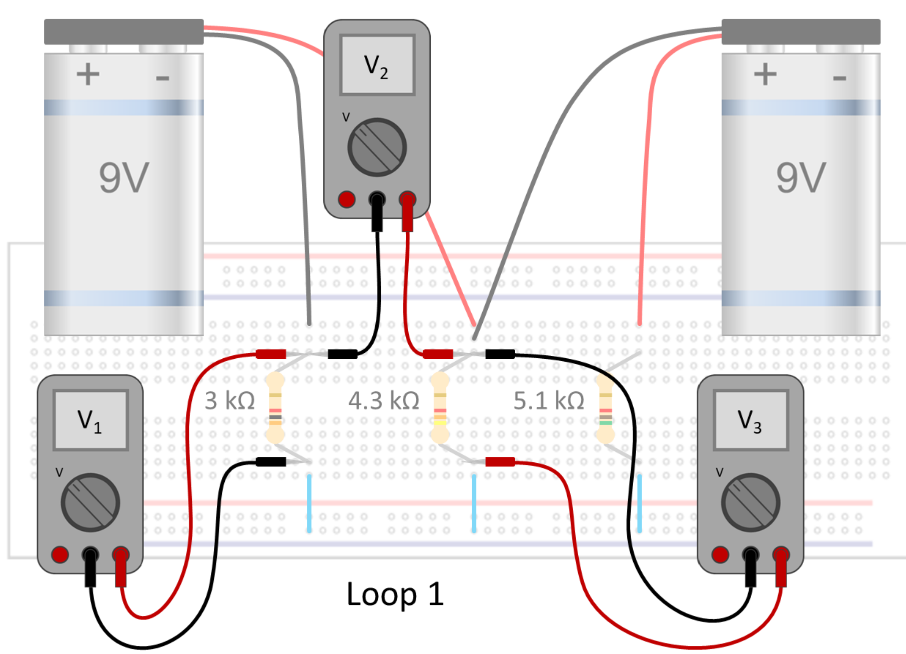
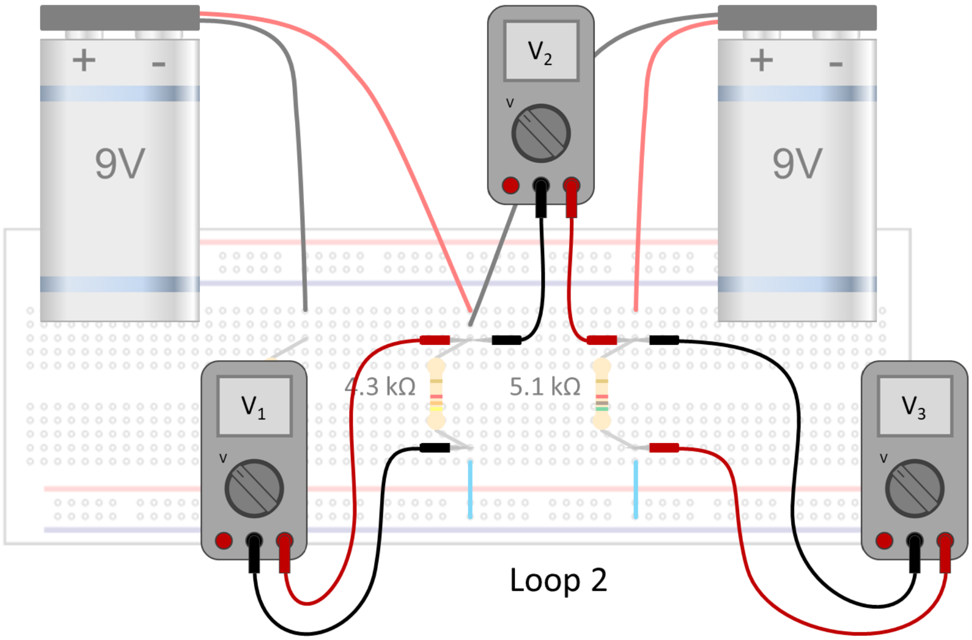


Fig. 6: Three loops in a complex circuit. The sum of the voltages around each closed loop should be zero.

(a)



(b)



(c)

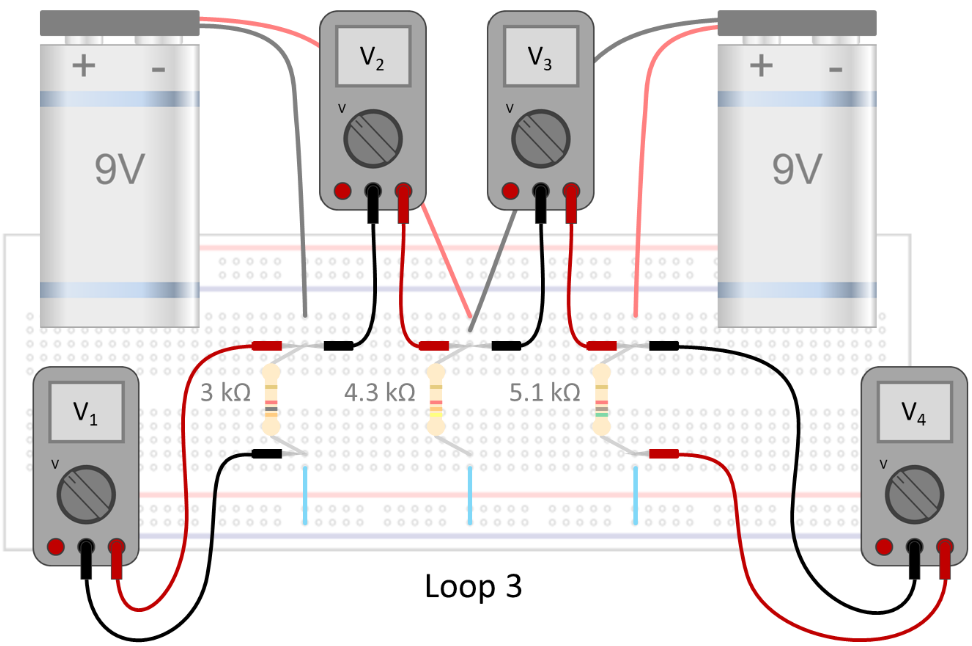


Fig. 7: Use a voltmeter to measure the voltage differences around each closed loop. Measure each voltage (V_1, V_2, V_3, V_4) one at a time as you go around the loop. Pay attention to the polarity of the voltmeter probes (black-red vs. red-black). In order to avoid confusion, follow the polarity shown in these diagrams and record the values as displayed, including whether the value is positive or negative.

Measure Currents

1. Remove the multimeter from the circuit, turn the dial to measure current (amps). To be careful, start on the 200 mA range and if the measurements are less than 20 mA, switch to the 20 mA range.
2. The black probe should still be in the COM port. If the red probe is not already in the mA port, move it to that port.
3. Measure the current (I_1) in the first branch of the circuit.
    a. This is best accomplished by removing the jumper wire connecting R_1 to the blue line of holes and replacing it with the multimeter acting as an ammeter as shown in Fig. 8a.
    b. If you see that the current is less than 20 mA, turn the dial down to the 20 mA range and record the current, I_1.
    c. To avoid confusion, pay attention to the polarity of the multimeter probes (black-red vs. red-black) and follow the same arrangement as in Fig. 8a.
    d. Be sure to record the sign (+/-) of the current as displayed on the multimeter. In Fig. 8a, the ammeter is oriented to measure positive current as drawn downward in Fig. 5a. If you measure a negative current, it just means that the current is flowing in the opposite direction of the arrow in Fig. 5a.
    e. Consistency is important in these measurements and calculations so you need to keep the sign of the current, even if it ends up negative.
4. After recording the current, I_1, remove the multimeter from the circuit and replace the original jumper wire.
5. Repeat this process with the other two branches to measure I_2 and I_3. Each time, pay attention to the polarity and the placement of the multimeter probes.
6. Verify that the sum of the currents entering the node is zero
(i.e. currents entering the node equals currents exiting the node).

IMPORTANT: When you finish the experiment, turn off the multimeter to save the battery. The simpler inexpensive multimeters often do not shut off automatically. Also, be sure to disconnect the batteries from the circuit.

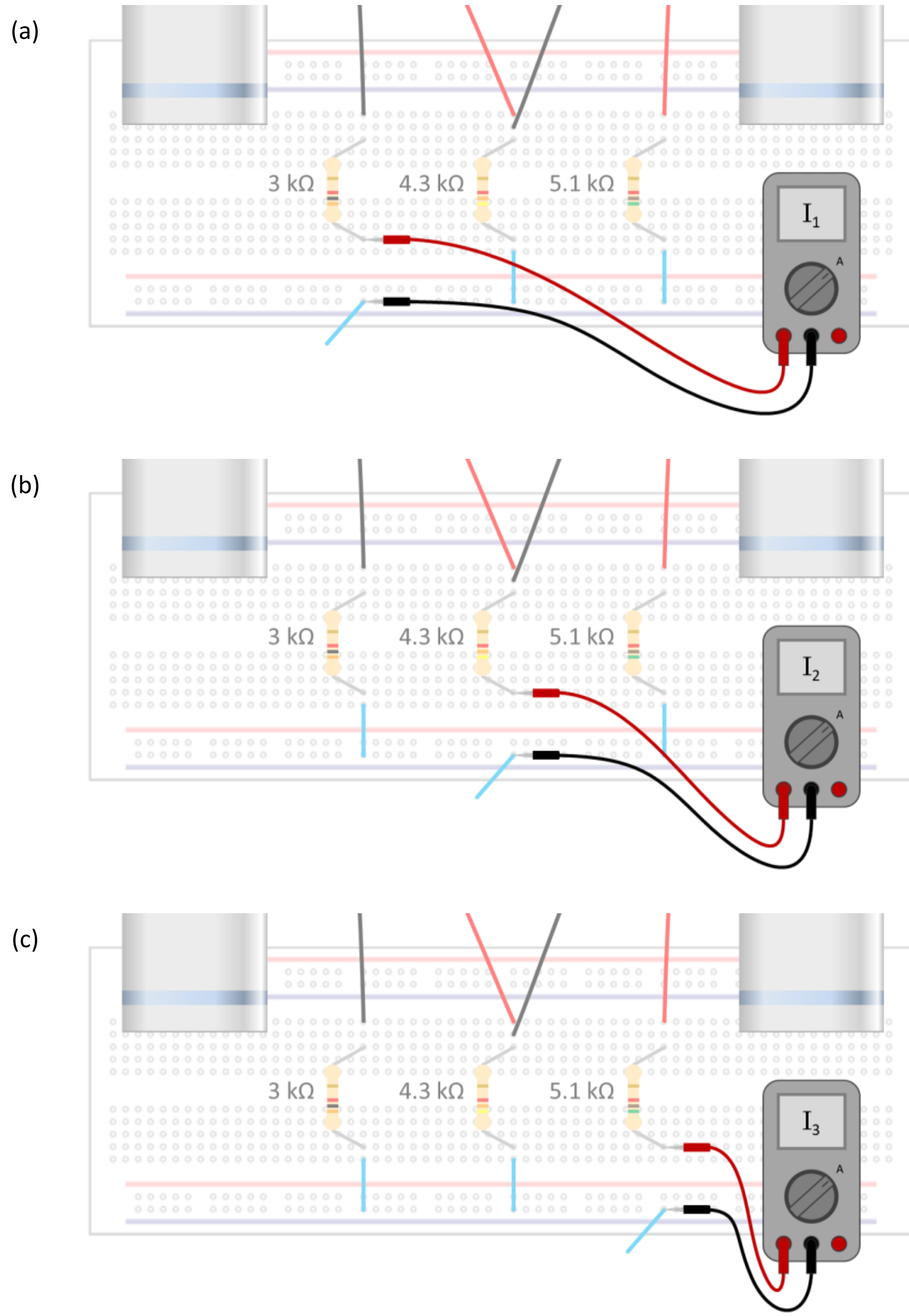


Fig. 8: Use an ammeter to measure the three currents in the complex circuit.
(a) Measure I_1 by removing the jumper wire below R_1 and replacing it with the ammeter.
(b) Measure I_2 by removing the jumper wire below R_2 and replacing it with the ammeter.
(b) Measure I_3 by removing the jumper wire below R_3 and replacing it with the ammeter.

Analysis:

The three currents (I_1, I_2, I_3) can be determined theoretically using Kirchhoff's Laws as follows.

Kirchhoff's Current Law applied to this circuit yields the following equation.

$$I_1 + I_2 + I_3 = 0 \qquad (3)$$

Kirchhoff's Voltage Law applied to each of the three loops yields the following three equations.

$$R_1 I_1 - R_2 I_2 + 0 I_3 = -V_{S1} \qquad \text{(Loop 1)} \qquad (4a)$$

$$0 I_1 + R_2 I_2 - R_3 I_3 = -V_{S2} \qquad \text{(Loop 2)} \qquad (4b)$$

$$R_1 I_1 + 0 I_2 - R_3 I_3 = -(V_{S1} + V_{S2}) \qquad \text{(Loop 3)} \qquad (4c)$$

In order to solve for the three unknowns (I_1, I_2, I_3), we need three independent equations. The three voltage law equations are not independent, so we cannot solve for the currents with them alone. Instead, we must choose the one current law equation (Eq. 3) and any two of the voltage law equations (Eq. 4a, 4b, 4c).

In each of these equations, the currents (I_1, I_2, I_3) are the variables. In the current law equation, the coefficients are 1 and the constant is zero. In the voltage law equation, the resistors (R_1, R_2, R_3) are the coefficients, and the battery voltages (V_{S1}, V_{S2}) are constants.

Using the measured resistances and battery voltages (make sure not to swap the battery voltages), enter the coefficients and constants for your three selected equations into the provided Kirchhoff's Laws Solver (or an equation solver of your choosing) to calculate the predicted currents. Pay attention to the signs (+/-) of the coefficients.

Hint: If you enter the resistances in kΩ, the calculated currents will be in mA.
If you enter resistances in Ω, the calculated currents will be in A.

Take a screenshot of the equation solver with your numbers and the solutions.

If a predicted current comes out negative – no big deal – it just means that the current was drawn backward in Fig. 5 (a).

Compare the theoretical currents to the measured currents using a percent difference for each.

$$\%Diff = \frac{|I_{measured} - I_{theory}|}{I_{measured}} \times 100\%$$