**Simple Circuits**

**Equipment**

<table>
<thead>
<tr>
<th>Laptop with Logger-Pro Installed</th>
<th>LabQuest Mini</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protech Multimeter</td>
<td>Mastech Multimeter</td>
</tr>
<tr>
<td>Vernier Current Sensors</td>
<td>Vernier Differential Voltage Sensors</td>
</tr>
<tr>
<td>D Cell Batteries (2)</td>
<td>#14 light bulb</td>
</tr>
<tr>
<td>Resistors</td>
<td>Banana leads</td>
</tr>
<tr>
<td>Switch</td>
<td></td>
</tr>
</tbody>
</table>

**Introduction**

Studying simple circuits can be very useful to better understand the concepts of voltage, current and resistance. It also provides us the opportunity to learn about simple devices such as batteries and light bulbs. Knowing something about batteries can be particularly useful, so two of the goals of this lab are to learn why most batteries fail and how to test a battery. Next, in order to learn more about the physics associated with these devices, we will see how batteries and bulbs are connected in a "standard" flashlight. Finally, we will spend some time learning about series and parallel arrangements of resistors.

**Theory**

The most important equation for analyzing circuits, of course, is the fundamental relationship between voltage, $V$, current, $I$, and resistance, $R$.

$$R = \frac{\Delta V}{I}$$  \hspace{1cm} (1)

Another important equation is the one that describes power, $P$. Power is the rate at which energy is supplied to a resistor

$$P = I \Delta V = I^2 R = \frac{(\Delta V)^2}{R}$$  \hspace{1cm} (2)

This can also be interpreted as the rate at which electric potential energy is lost by the charges as they move through the resistor.

**I. Simple Circuit**

We begin the lab with a detailed study of the simple circuit that was introduced in the first laboratory.

**A. Current**

1. Open Logger Pro, connect two current probes to the LabQuest Mini and the LabQuest Mini to a USB port on your computer

2. When the program is ready, ensure nothing is connected to the current probes and **Zero** both probes.
3. Construct the circuit shown in the next diagram.

![Circuit Diagram]

4. Click on Collect to measure the two currents $I_1$ and $I_2$. Adjust the vertical scale on the graph so that noise is observable. Use the Statistics function in the Analyze menu to obtain a value for the currents. Record the values in the space provided then disconnect the battery.

R1: 

R2: 

(Note: The total uncertainty in the current is not just equal to the scatter in the data. The scatter only indicates the precision of the measurement. There is also uncertainty because of imperfect calibration of the ammeters. It has been determined that the uncertainty due to calibration is approximately 2%. For convenience, take the total uncertainty to be the sum of the uncertainty due to precision and the uncertainty due to calibration.)

R3: Depending on the instructions from your instructor, either Copy the graphs and Paste them into either your lab report or an Excel spreadsheet.

5. From the signs of the currents and the directions of the arrows on the current probes, determine the directions of $I_1$ and $I_2$.

R4: Refer to the previous diagram and indicate the direction of the current through the current probes, the battery, and resistor.

$I_1$ (right or left):
$I_2$ (right or left):
$I_{battery}$ (up or down):
$I_{resistor}$ (up or down):

The data should show that the current out of the battery (at the positive terminal) equals the current into the battery (at the negative terminal), to within experimental uncertainty. In other words, for this simple circuit $I_1$ and $I_2$ should be the same! It is a common misconception that charge flows out of a battery and somehow gets "used up" in a resistor.

R5: Discuss whether the data show that $I_1 = I_2$.

Because $I_1 = I_2$ is an important result, let’s do another experiment to confirm.

7. Interchange the positions of the ammeters in the circuit and reconnect the battery. The previous ammeter 1 becomes ammeter 2 with current $I_2'$, and vice versa. Collect data and record the results for $I_1'$ and $I_2'$. Don't forget that $I_2'$ will be graphically displayed where $I_1$ was displayed previously on LoggerPro!
R6: Depending on the instructions from your instructor, either **Copy** the graphs and **Paste** them into a your lab report or an Excel spreadsheet.

R7: Discuss whether the data confirm that $I_1' = I_2'$. (Note: We may find, for example, that $I_1 > I_2$. When we reverse the ammeters, if we find that $I_1' < I_2'$, this may indicate that the currents are not different but that the current probes are poorly calibrated. In simple terms, one meter may “read” higher than the other.)

R8: What is the **net charge** supplied by the battery in 1.0 s? Or stated another way, how much more charge flows out of the "+" terminal of the battery than flows into the "-" terminal of the battery? Discuss the reasons for your answer.

**B. Voltage**

1. Use the Protek multimeter (V/LOGIC scale) to measure the voltages indicated in R11 to R18. The letter codes associated with the circuit are given in the next diagram.

```
A1

b c
a d

1.5V +

d c
b a

A2

22Ω

g h

e f
```

It may be useful to review the *Introduction to Electrical Measurements* laboratory to remind yourself of the notation. Remember, when measuring $V_{xy}$, place the red “test” lead at point $x$ and the black “ground” or "COM" lead at point $y$. Record the voltages in the space provided and, to the right of the voltages, identify the circuit element across which the voltage is measured. (As an example, the first circuit element, "battery," is provided.)

R11 - R18

Note: All of the voltages should be negative or zero except for that across the battery.

R19: Give a physical explanation of the negative voltages. (Hint: See the lab *Introduction to Electrical Measurements.*)

2. **Kirchhoff's second** or loop rule is that the sum of the changes in potential (voltages) around any closed path of a circuit must be zero. Add the voltages listed in R11 to R18 and record the answer in the space provided.

R20:

R21: Discuss whether the data verify the **loop rule** to within the experimental uncertainty.

**C. Resistance of Wires and Ammeters**

1. Use the data and eq. (1) to calculate the resistance of a wire. Record the value in the space
What does the value of \( R_{\text{wire}} \) imply concerning the resistance of wires?

2. Use the data and eq. (1) to calculate the resistance of an ammeter. Record the value in the space provided.

What does the value of \( R_{\text{ammeter}} \) imply concerning the resistance of an ammeter?

II. Internal Resistance of a Battery

1. Disconnect the battery from the circuit. Refer to the next diagram and measure the voltage, \( V_{ij} \), across the battery while it is not connected to a circuit. We will take the value of \( V_{ij} \) to be equal to the emf of the battery (i.e., \( V_{ij} = \varepsilon \)). Record the value of \( V_{ij} \) as \( \varepsilon \) in the space provided.

The emf, \( \varepsilon \), should be larger than the value of \( V_{ah} \) (measured in R11), which was the voltage across the battery when the battery was creating current. (If your value of \( \varepsilon \) is not larger than \( V_{ah} \), consult your instructor.)

Since \( \varepsilon > V_{ah} \), we must conclude that, when charge is flowing through a battery, a negative voltage occurs somewhere inside the battery. This negative voltage occurs due to internal resistance, \( r \), inside the battery. In fact, all batteries can be represented as shown in the next diagram. Consequently, if there is a current, \( I \), upward (from bottom to top, or from point \( h \) to point \( a \)), then the voltage that appears across the terminals of the battery (the terminal voltage) is given by

\[
V_{ah} = \varepsilon - Ir
\]

2. Use eq. (3) with your previously collected data (R1, R2, R11 and R26) to calculate the internal resistance of your battery. Use the average value of the currents recorded in R1 and R2. Record your result in the space provided.

This is important because most batteries "go dead" because the internal resistance increases, not because the emf decreases. Consequently, in order to properly "test" a battery it must be
supplying a current. When there is current, one can either measure the voltage or the current. If either is low, the battery is "dead".

**III. Batteries in a Flashlight**

Next, we will study the operation of a standard flashlight. A standard flashlight requires 2 D-cell batteries. The batteries are placed in the flashlight "one after another" and thus we say that the batteries are in *series*. Let us study the consequence of placing batteries in series.

1. Connect the opposite end of two batteries together as shown in the next diagram.

![Diagram](image1.png)

2. Measure the voltages $V_{ba}$, $V_{cb}$ and $V_{ca}$ and record the values in the space provided.

R28 - R30:

3. Add the values $V_{cb}$ and $V_{ba}$ and record the sum in the space provided.

R31

R32: How does the sum compare with the value of $V_{ca}$? Give a physical explanation of why the total voltage is equal to the sum of the voltages for batteries in series. (Hint: Consider the electric potential energy of a charge that travels through both batteries from point a to point c).

**IV. Flashlight Bulbs**

A diagram of the cross section of a bulb is shown in the next diagram. The bulb should be a number 14 (#14). The number usually appears on the metal casing of the light bulb.

![Diagram](image2.png)

1. Study the diagram and the bulb (carefully unscrew the bulb from its socket) and decide where connections to the bulb must be made in order to make the bulb light. (Hint: The charge must flow through the filament, which is drawn as a resistor in the diagram.) These are also the positions where an ohmmeter must be connected to measure the resistance of the filament.

R33: Carefully describe where connections to the bulb must be made in order to make the bulb light (and to measure the resistance of the filament).

2. Use the Mastech multimeter to measure the resistance of the filament of the bulb. Record the value in the space provided. (Since the resistance is very low, on the order of 1 ohm, it is important for the leads to make good contact to the bulb.)
3. Connect the batteries in series to the light bulb as shown in the next diagram. This is the arrangement of the batteries and bulb in a typical flashlight that uses two D-cell batteries.

4. Use the computer to measure the current in the circuit and use the multimeter to measure the voltage across the light bulb. (Note that the multimeter and ammeter are very sensitive so that small changes in current or voltage are observable. However, if the current or voltage drifts more than you think that it should, consult your instructor.) Record the values in the space provided.

5. Use eq. (1) and the values of $V_{ca}$ and $I$ to calculate the resistance of the light bulb. Record the value in the space provided.

6. $R_{\text{bulb when glowing}}$ should be much larger than $R_{\text{bulb not glowing}}$. When the bulb is glowing the filament is very hot. The resistance of metals (such as the tungsten filament) increases as temperature increases. Resistance is caused by collisions between the electrons and the ions in the metal. Because the ions in the heated filament have more thermal energy, there are more collisions and thus the resistance is higher.

The data can be used to calculate the temperature of the bulb when it is glowing.

$$R = R_0 [1 + \alpha(T-T_0)]$$  \hspace{1cm} (4)

$R_0$ is the resistance at room temperature. For our experiment, $R_0$ is the resistance of the bulb measured by the multimeter (i.e., $R_0 = R_{\text{bulb not glowing}}$). $R$ is the resistance as a function of temperature. For our experiment, $R$ is the resistance when the filament is glowing (i.e., $R = R_{\text{bulb when glowing}}$). Next, $T_0$ is room temperature (20°C) and $T$ is the temperature of the filament while it is glowing. For a tungsten wire $\alpha = 0.0045 \, (^{\circ}\text{C}^{-1})$.

Use the data and eq. (4) to calculate the temperature of the lighted bulb filament, $T$. Record the value in the space provided.

Yes, the temperature should be very high. For comparison, the melting point of tungsten is (3410 ± 20)$^\circ$C. A high temperature is necessary for the filament to emit large amounts of visible light.

Because of the high temperatures involved, it takes several seconds for a light bulb to reach thermal equilibrium. This explains some of the drift in the voltage and current associated with lighting a bulb.

**V. Switches** To firm up our understanding of the voltage and current in a simple circuit, let us add a switch and make some measurements of the current as the switch is opened and closed.
1. Replace the current probe in CH1 on the LabQuest Mini with a voltage probe. You should now have a voltage probe in CH1 and a current probe in CH2.
2. Open the file VoltCurr.
3. With the voltage probe leads connected together (shorted) and the current probe disconnected from any circuit, Zero both probes.
4. Go to the Experiment drop-down menu, select Data Collection and ensure the sample rate is set to 100 samples/s (0.01 s/sample).
5. Construct the circuit shown in the next diagram.
6. Click on Collect and, while the computer is collecting data, open and close the switch at approximately one second intervals.

R39: Depending on the instructions from your instructor, either Copy the graphs and Paste them into your lab report or an Excel.
R40: On the graph, indicate when the switch is open and when the switch is closed.
R41: What is the voltage across the switch when the switch is open? Explain.
R42: What is the voltage across the switch when the switch is closed? Explain.

7. Replace the resistor in the circuit with a light bulb as shown in the next diagram.

8. Carry out the same experiment as above (i.e., while the computer is collecting data, open and close the switch at approximately one second intervals).
R43: Depending on the instructions from your instructor, either Copy the graphs and Paste them into your lab report or an Excel spreadsheet.

R44: Explain the difference in the shapes of the curves for the light bulb and the resistor. (Hint: Consider temperature and resistance.)

VI. Bulbs and Batteries Revisited As a prelude to the lab Kirchhoff’s Rules, we will study bulbs and batteries in series and parallel.

Warning: Please minimize the time that the bulbs glow in each of the remaining experiments.

A. Bulbs in Series and Batteries in Series
To understand the results you will observe in the following comparisons, it is important to realize that the brightness of a light bulb is related to the power supplied to it. Recall from eq. (2) that the power supplied to a light bulb is equal to the square of the voltage across the bulb divided by the resistance of the light bulb \( P = (\Delta V)^2 / R_{\text{bulb}} \). Since \( R_{\text{bulb}} \) is (nearly) the same in all our
comparisons, any differences observed in brightness can be correlated to different voltages across the bulbs.

1. Connect two bulbs in series with two batteries in series as shown in the next diagram.

![Diagram of bulbs in series](image)

**R45:** Compare the brightness of these bulbs with the brightness of a single bulb in the same circuit (as observed in the previous experiment). Give a reason for the behavior.

2. Remove one of the bulbs from its socket.

**R46:** What happens to the brightness of the other bulb? Give a reason for the behavior.

### B. Bulbs in Parallel and Batteries in Series

1. Connect two bulbs in parallel. Connect the parallel combination of bulbs to two batteries in series as shown in the next diagram.

![Diagram of bulbs in parallel](image)

**R47:** Compare the brightness of these bulbs with the brightness of the bulbs in part **VI.A.** Give a reason for the behavior.

2. Remove one of the bulbs from its socket.

**R48:** What happens to the brightness of the other bulb? Give a reason for the behavior.

### C. Batteries in Parallel and Bulbs in Parallel

1. Connect two batteries in parallel. Connect the parallel combination of batteries to a parallel combination of two bulbs as shown in the next diagram.
R49: Compare the brightness of these bulbs with the brightness of the bulbs in part VI.B. Give a reason for the behavior.

2. Remove one of the light bulbs from its socket.

R50: What happens to the brightness of the other bulb? Give a reason for the behavior.

3. Replace the light bulb then remove one battery.

R51: What happens to the brightness of the bulbs? Give a reason for the behavior described.

**End of Lab Checkout** Before leaving the laboratory, please dismantle any circuits or connections that you have made. Place the wires in one pile and return the meters to their boxes.