WPI | Department of Physics

# Ohm's law and Resistance

**1120 Lab 2**

Last Edited April 2, 2024

Written by Dana

## Lab Objectives

Construct an electric circuit, and investigate

1. Current (I) - Voltage (V) relations in a circuit, and
2. Effect of electric resistance in the circuit.

After completion of this experiment (in a virtual environment), the students will be able to

1. Construct an electric circuit using various circuit components.
2. Explain the current-voltage relations in a simple circuit.
3. Explain how resistance affects the flow of current in an electric circuit.

## Simulations and websites used in this lab

- PhET Circuit Construction Kit.
- WPI's Jupyter Hub's Python.
- WPI Teaching Physics Labs Github.

## Deliverable Summary

1. Construct a simple circuit with the following components: connecting wires, a resistor, a bulb, a battery, a switch, an ammeter, a voltmeter, such as in figure 2 (Although this one is missing the switch). Take a snapshot of the circuit you constructed and paste it into your worksheet. Label the various components of the circuit.

2. In the circuit you constructed in Question 1 measure the voltage across the resistor using a 'voltmeter' and the current in the circuit using an 'ammeter'.

   Repeat your observations by increasing the voltage (adding batteries or changing the voltage value in the slide bar that appears when you select the battery) in the circuit. Record your observations in the following table: [1]

3. Transfer the data in Question 2 to a Jupyter Notebook and plot a graph, taking current (I) on the x - axis and voltage (V) on the y - axis. [2]

   (a) Draw a curve of the best-fit on the graph, showing the equation of fit.
   (b) What is the slope if the best fit line is linear.
   (c) What physical quantity is this?
   (d) Also copy the graph from Python and paste below.

   In your caption please explain how the current in the circuit varies with the applied voltage – linearly or non- linearly? What physical quantity does the ratio of voltage (V) to current (I) give? What is the SI unit of this quantity? (2 sentences)

4. Measure the voltage across the resistor in the circuit using a 'voltmeter' and the current in the system using an 'ammeter'. Record your observations like in a table below.

   Then increase the number of resistors in series in the circuit and record your observations, similar to Fig. 7. Remember, your voltmeter must always be around all resistors that you are measuring.

[1] Current's symbol is I, but it is measured in Amps so the A refers to the units of your values in that table column.

[2] If you do not wish to use Python you can use any other programming language (R, Matlab, C++, etc) you wish. You are not, however, allowed to use Excel or Google Sheets. If you need help with Python please either see #pythonhelp on our Slack channel, or our Github repository.

5. Transfer the data in Question 4 to a Jupyter Notebook and plot a graph, taking current (I) on the x - axis and voltage (V) on the y - axis. [3]
   (a) Draw a curve of the best-fit on the graph, showing the equation of fit.
   (b) What is the slope on the line, if the best fit line is linear.
   (c) Also copy the graph from Python and paste below.

   How do the voltage and current change when you go on adding more and more resistors in series?

6. Repeat Question 4 and 5 BUT NOW, add resistors in parallel. Record your observations in a table, like the one as follows:

7. Repeat Question 4 and 5 BUT NOW, add change the lightbulb to a 'real lightbulb'. Record 5 voltages from 1 V to 40 V. Record your observations in a table, like the one as follows:

8. **Conclusion**

   Please write a conclusion section based on the results you have collected today. For reference on what it should look like please consult the Generic Deliverables at this link. For guidance on what questions should be addressed please see below.

   (a) What physical quantity will you get from the ratio of V to I? What is the SI unit?
   (b) Based on the observation from the PART-B of this experiment, what do you conclude on the equivalent resistance of several resistors when they are connected in (i) series, and (ii) parallel?
   (c) Is your lightbulb data linear? If so which parts are linear, if not which parts are not linear and why might that be?
   (d) Summarize what you learned about electric current, potential difference, and resistances from these Lab activities in a virtual environment. You should reference the introduction to complete this. (3-4 sentences)

## Theory

### Electric Circuit

An electric circuit is a path for the flow of electric charge carriers (electrons and ions). A simple electric circuit consists of a source of potential difference (p.d.) like a battery or a power supply, connecting wires, a resistor, and a switch. A circuit in which a current is flowing is called a closed circuit and a circuit with an open switch or circuit-breaker is called an open circuit. When a p.d. is maintained in a closed circuit, the charges flow and the flow constitutes a current. Thus, we define an electric current as the rate of flow of charge. Mathematically,

$$I = \frac{dQ}{dt} \tag{1}$$

where dQ is the amount of charge that passes through the cross-section of a wire in time interval dT. In a metallic conductor, the current is formed by the flow of electrons ($charge = -1e = -1.610^{-19}C$). The electrons flow from the negative terminal of a battery to its positive terminal through the external circuit.

Conventionally, the direction of current is considered in the direction opposite to the direction of motion of electrons, and this is called the conventional current. The SI unit of current is Ampere (A). If 1 Coulomb of charge flows through a cross-section of a conductor in 1 second, the current is 1 Ampere:

$$1A = \frac{1C}{1s} = 1Cs^{-1}. \tag{2}$$

Since 1A is a fairly large amount of current, the commonly used submultiples of ampere are milliampere ($1mA = 10^{-3}A$) and microampere ($1\mu A = 10^{-6}A$).

To maintain a current in an electric circuit, we need to apply a potential difference (p.d.) or voltage across the circuit. It can be done by using the sources of electric energy like a battery or a power supply connected to an alternating current source.

[3] If you do not wish to use Python you can use any other programming language (R, Matlab, C++, etc) you wish. You are not, however, allowed to use Excel or Google Sheets. If you need help with Python please either see #pythonhelp on our Slack channel, or our Github repository.

**Ohm's Law**

When a potential difference is applied across a resistor, it causes a flow of current through it. Ohm's law states that the current flowing through the resistor is directly proportional to the potential difference applied, provided that the temperature of the resistor remains constant. Mathematically,

$$I \propto V \tag{3}$$

If I is the current (in amperes) flowing through the resistor and V is the potential difference (in volts), then, Ohm's law can be written as above. This means that if the voltage (V) across a resistor is increased, the current (I) increases linearly.

We can write Eq. 3 as

$$V = RI \tag{4}$$

where R is the proportionality factor, and it is called the resistance of the resistor. The SI unit of resistance is Ohm ($\Omega$). For metallic wires at constant temperature, the resistance of a given resistor is constant. Note that p.d. (or voltage) is measured by a voltmeter which is connected in parallel to the resistor across which the p.d. is to be measured and current is measured by an ammeter which is connected in series in the circuit.

**Resistance**

Electrical resistance is the property of materials which opposes the flow of charges through them. The resistance is usually denoted by R and the SI unit is Ohm ($\Omega$).

The ratio of the voltage applied across a resistor to the current flowing through it gives the resistance of the resistor.

$$\frac{V}{I} = R. \tag{5}$$

For a simple metallic resistor at normal temperatures, R is constant. The resistors which demonstrate this behavior are called Ohmic conductors. Semiconductor diode, ionized gases, and the glowing filament in a bulb the ratio $\frac{V}{I}$ is not constant. They are, therefore, are called Non- Ohmic conductors. The resistance of a wire given by

$$R = \rho \frac{L}{A}. \tag{6}$$

where L is the length of the wire, A is its area of cross-section, and $\rho$ is called the resistivity of the material of the wire.

The following figure shows a simple electric circuit with a battery which has an internal resistance r = 2 $\Omega$. The battery has an emf $\eta$ = 12 V. An external resistance R = 4 $\Omega$ is connected in the circuit.

## Electo Magnetic Force

The Electro Magnetic Force, or EMF, of a battery is equal to the potential difference in voltage when no current flows. It's unit is commonly $\eta$, and is measured in Volts. It is the amount of energy of the battery provided to each coulomb of charge that passes through. An ideal battery, such as the ones in our Phet's, have no internal resistance and the terminal voltage is equal to the emf of the battery.

In real batteries this is not the case, however for these remote labs you can measure the emf as the voltage you measure across the battery.

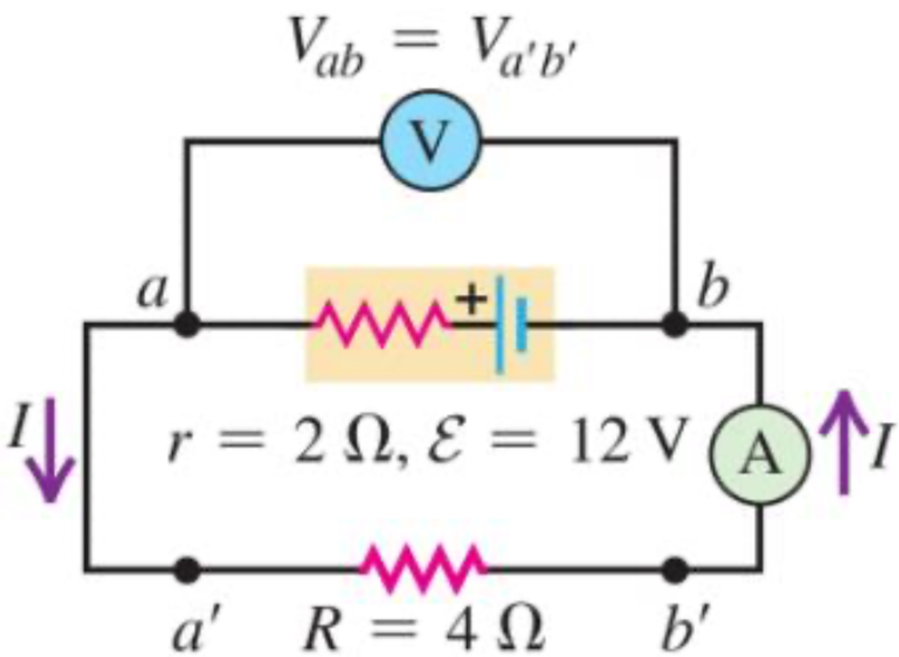



Figure 1: Simple circuit with a battery.

In the above circuit, I is the conventional current, A is the ammeter, and V is the voltmeter. You will be constructing a simple electric circuit like the one shown in the following figure:

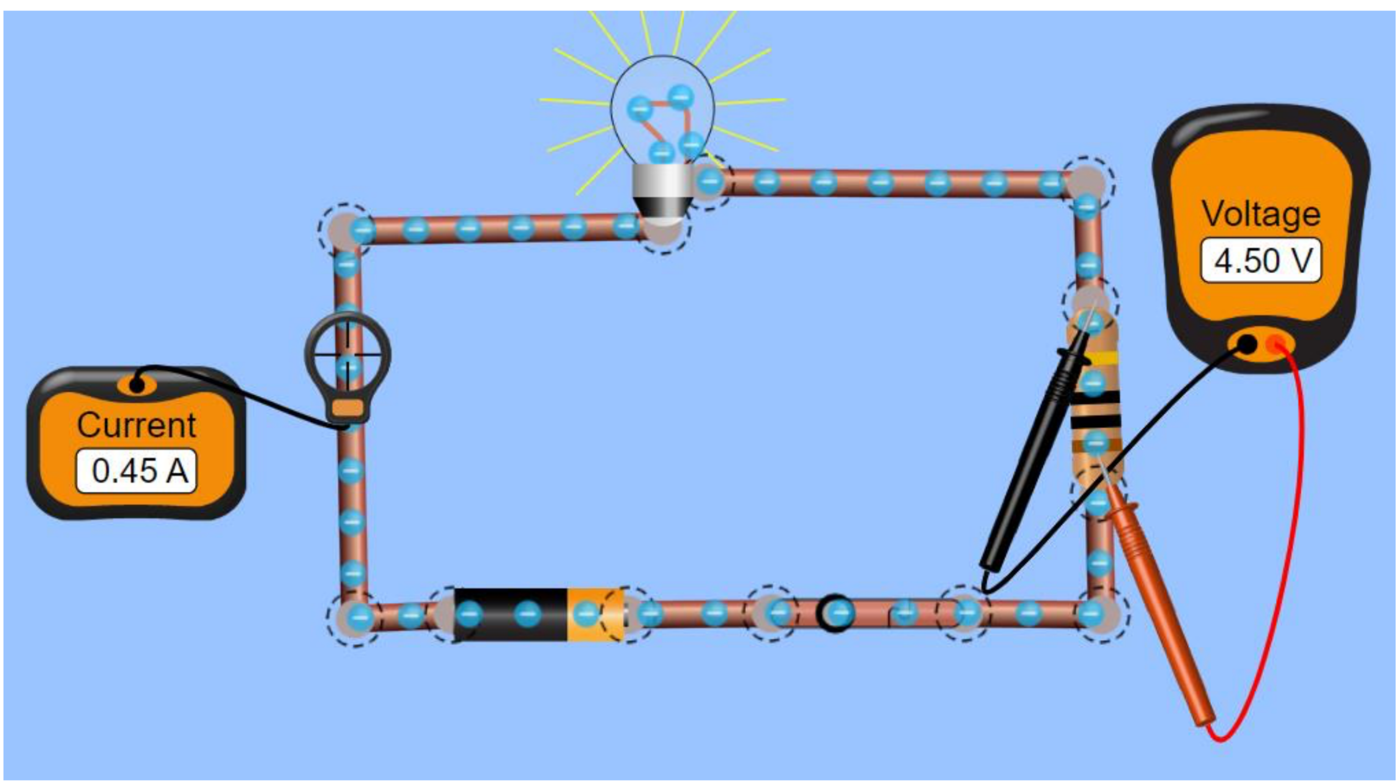



Figure 2: Example circuit in the PhET.

The following figure shows the electric circuit in Figure 2, drawn using electric circuit symbols. The 'arrows' represent the direction of the conventional current.

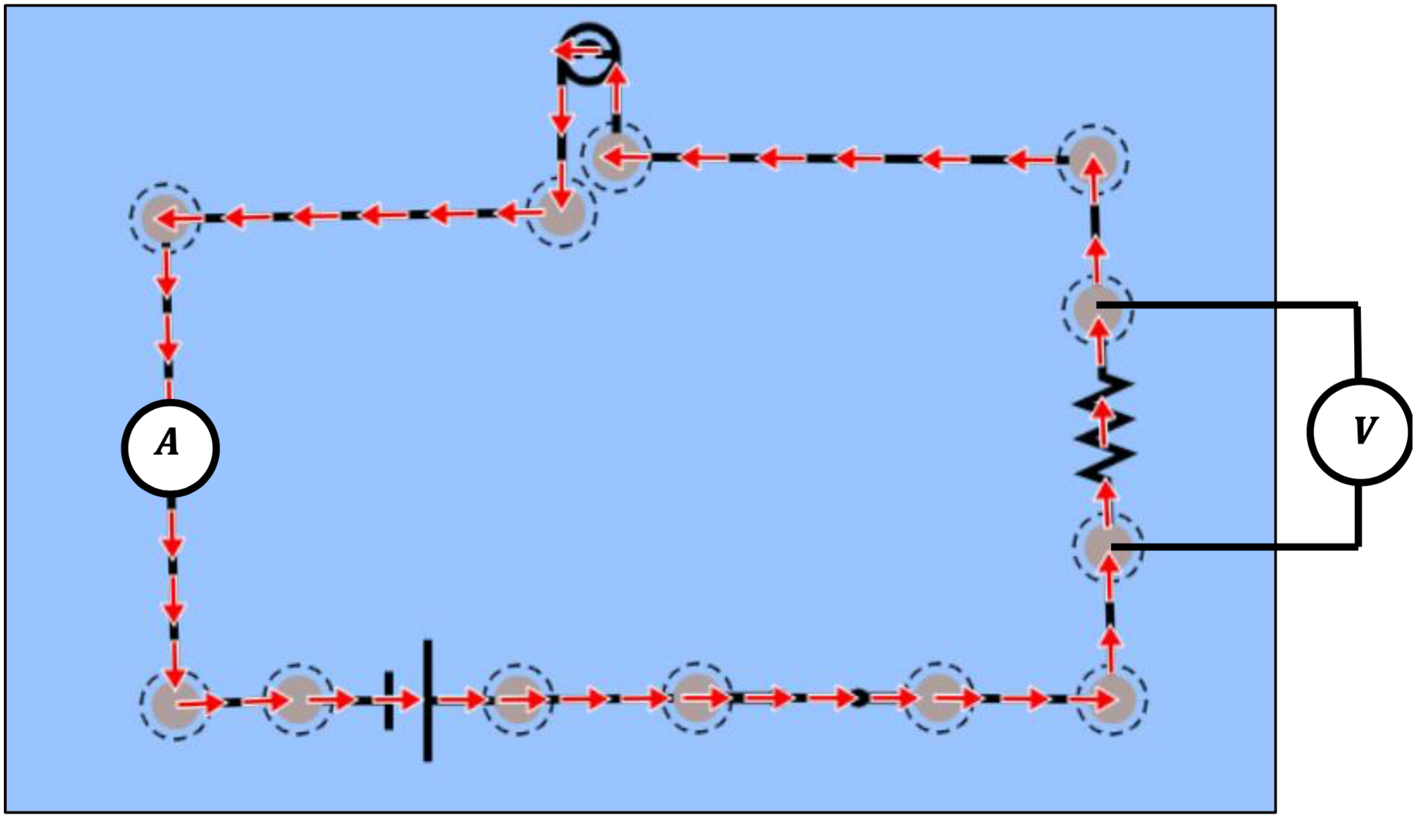



Figure 3: Example circuit with the resistor, lightbulb, battery, current meter, and voltage meter replaced by their symbols.

**Equivalent resistance in a circuit**

If multiple resistors are connected in a circuit, the total resistance in the circuit can increase or decrease depending on how the resistors are connected. If several resistors are connected in series, their equivalent resistance is given by the sum of the resistance of the individual resistor. For example, Fig. 4 shows that the three resistors with resistances $R_1, R_2$ and $R_3$ are connected between the points a and b in series. Their equivalent resistance,

$$R_{eq} = R_1 + R_2 + R_3 \tag{7}$$

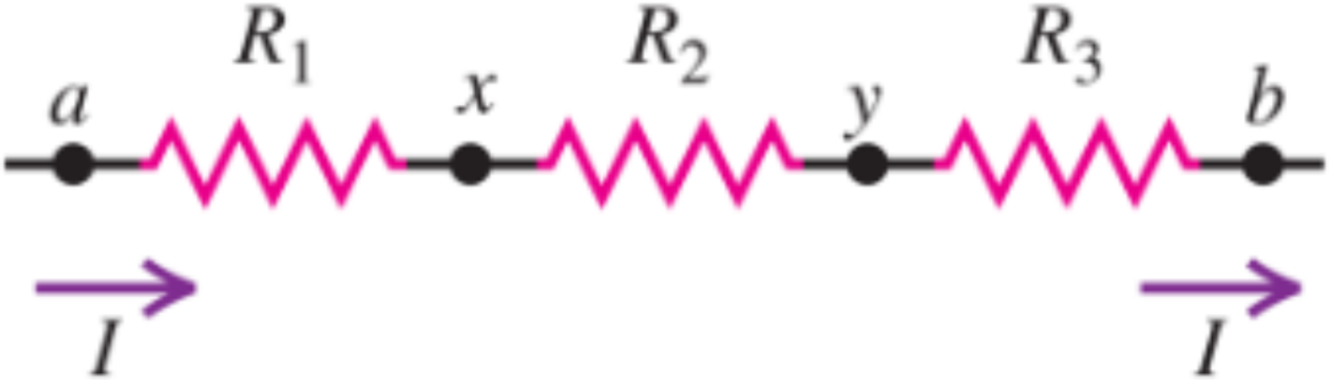



Figure 4: Resistors connected in series.

If several resistors are connected in parallel, the reciprocal of their equivalent resistance is given by the sum of the reciprocal of the resistance of the individual resistor. For example, Fig. 5 shows that the three resistors with resistances $R_1, R_2$ and $R_3$ are connected between the points a and b in parallel. Their equivalent resistance,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \tag{8}$$

The resistors can also be combined in a mixed combination as shown in Fig. 6. How do you calculate the equivalent resistance between the points a and b in such combination?

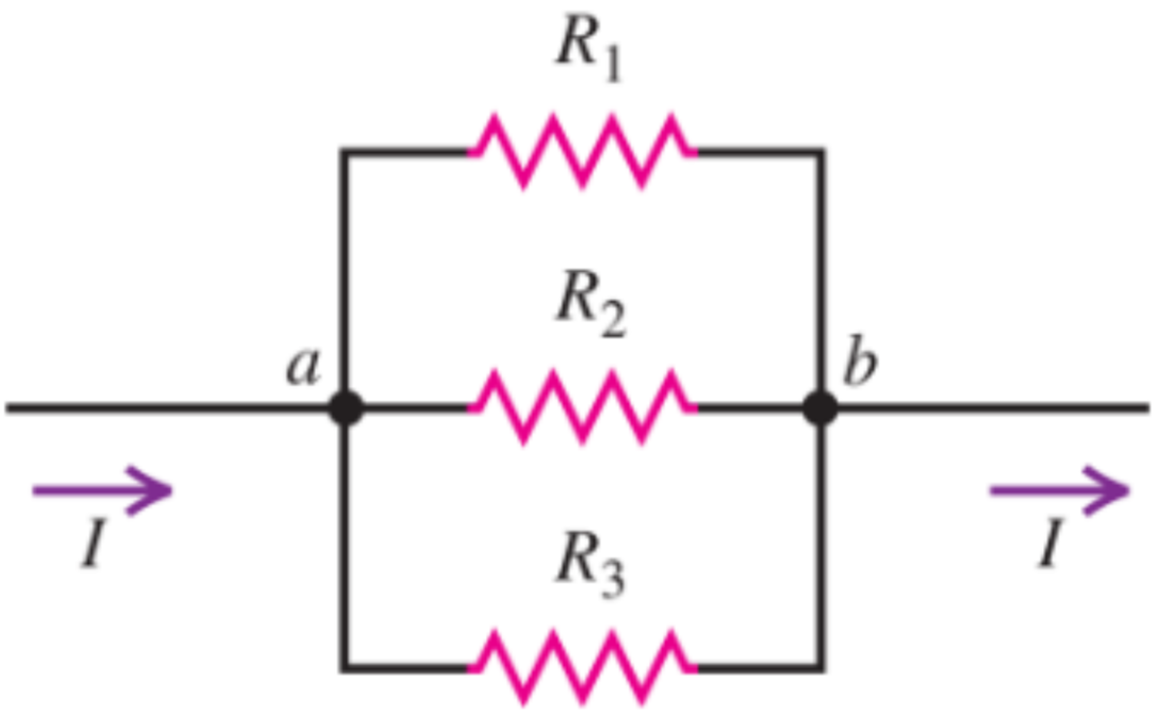



Figure 5: Resistors connected in parallel

## Procedure

### Part A

Before you proceed, click on the following link and watch a short video for the circuit- construction in a 'real' lab: Circuit in a real lab

Click on the following link or copy and paste it in a web browser in your computer: **PhET Circuit Construction Kit.**

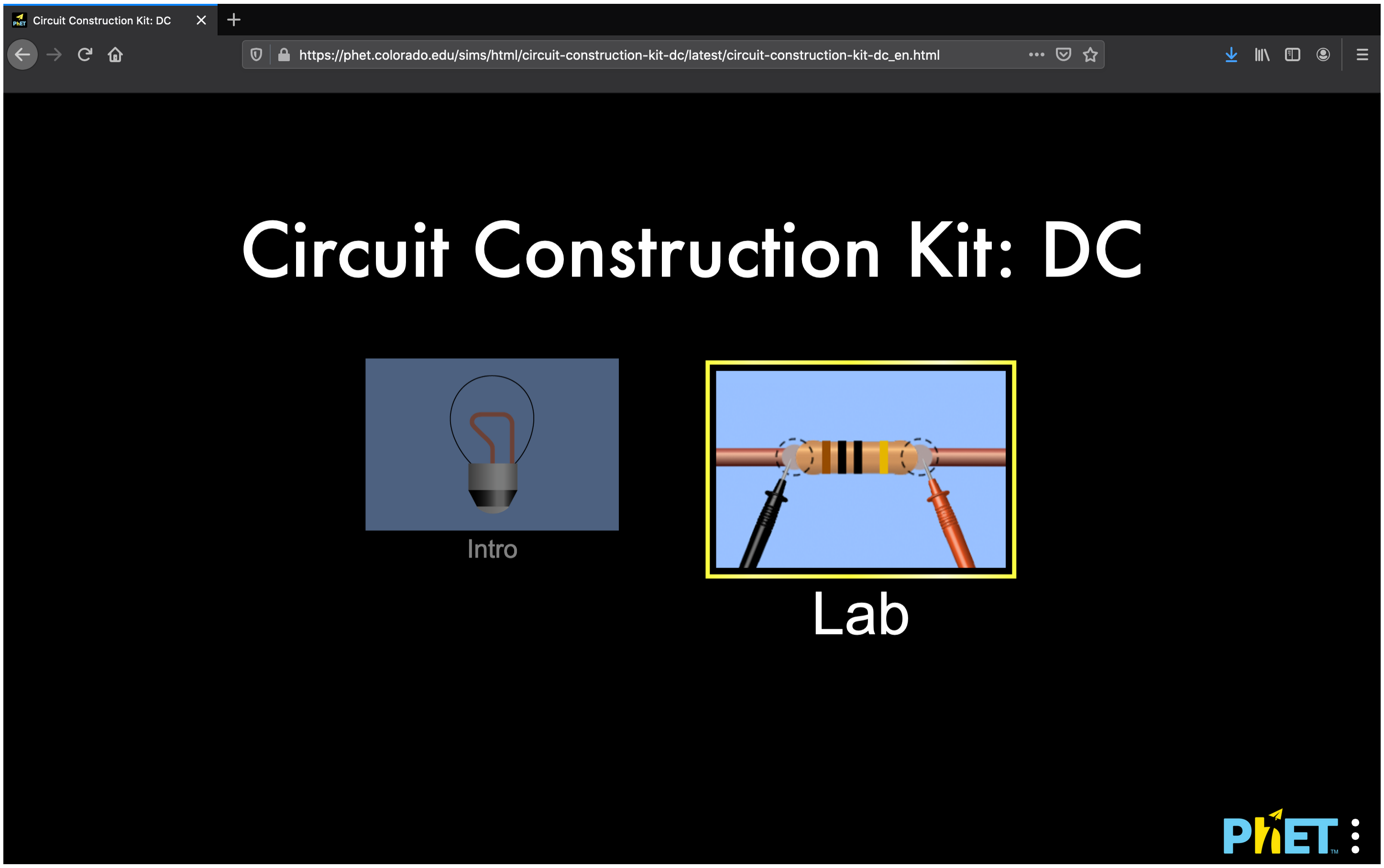



Figure 6: Select the lab option.

**Question 1** *Construct a simple circuit with the following components: connecting wires, a resistor, a bulb, a battery, a switch, an ammeter, a voltmeter, such as in figure 2 (Although this one is missing the switch). Take a snapshot of the circuit you constructed and paste it into your worksheet. Label the various components of the circuit.*

**Question 2** *In the circuit you constructed in Question 1 measure the voltage across the resistor using a 'voltmeter' and the current in the circuit using an 'ammeter'.*

*Repeat your observations by increasing the voltage (adding batteries or changing the voltage value in the slide bar that appears when you select the battery) in the circuit. Record your observations in the following table:* [a]

[a] Current's symbol is I, but it is measured in Amps so the A refers to the units of your values in that table column.

| Table for question 2 | | | |
|---|---|---|---|
| Obs. No. | Voltage (V) | Current (A) | Ratio of V to I ($\frac{V}{I}$) |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |

**Question 3** *Transfer the data in Question 2 to a Jupyter Notebook and plot a graph, taking current (I) on the x - axis and voltage (V) on the y - axis.* [a]

1. *Draw a curve of the best-fit on the graph, showing the equation of fit.*
2. *What is the slope if the best fit line is linear.*
3. *What physical quantity is this?*
4. *Also copy the graph from Python and paste below.*

*In your caption please explain how the current in the circuit varies with the applied voltage – linearly or non- linearly? What physical quantity does the ratio of voltage (V) to current (I) give? What is the SI unit of this quantity? (2 sentences)*

[a] If you do not wish to use Python you can use any other programming language (R, Matlab, C++, etc) you wish. You are not, however, allowed to use Excel or Google Sheets. If you need help with Python please either see #pythonhelp on our Slack channel, or our Github repository.

**Part B**

In this part, you will investigate the effect of resistance in an electrical circuit. Please continue with the same PhET, PhET Circuit construction kit DC.

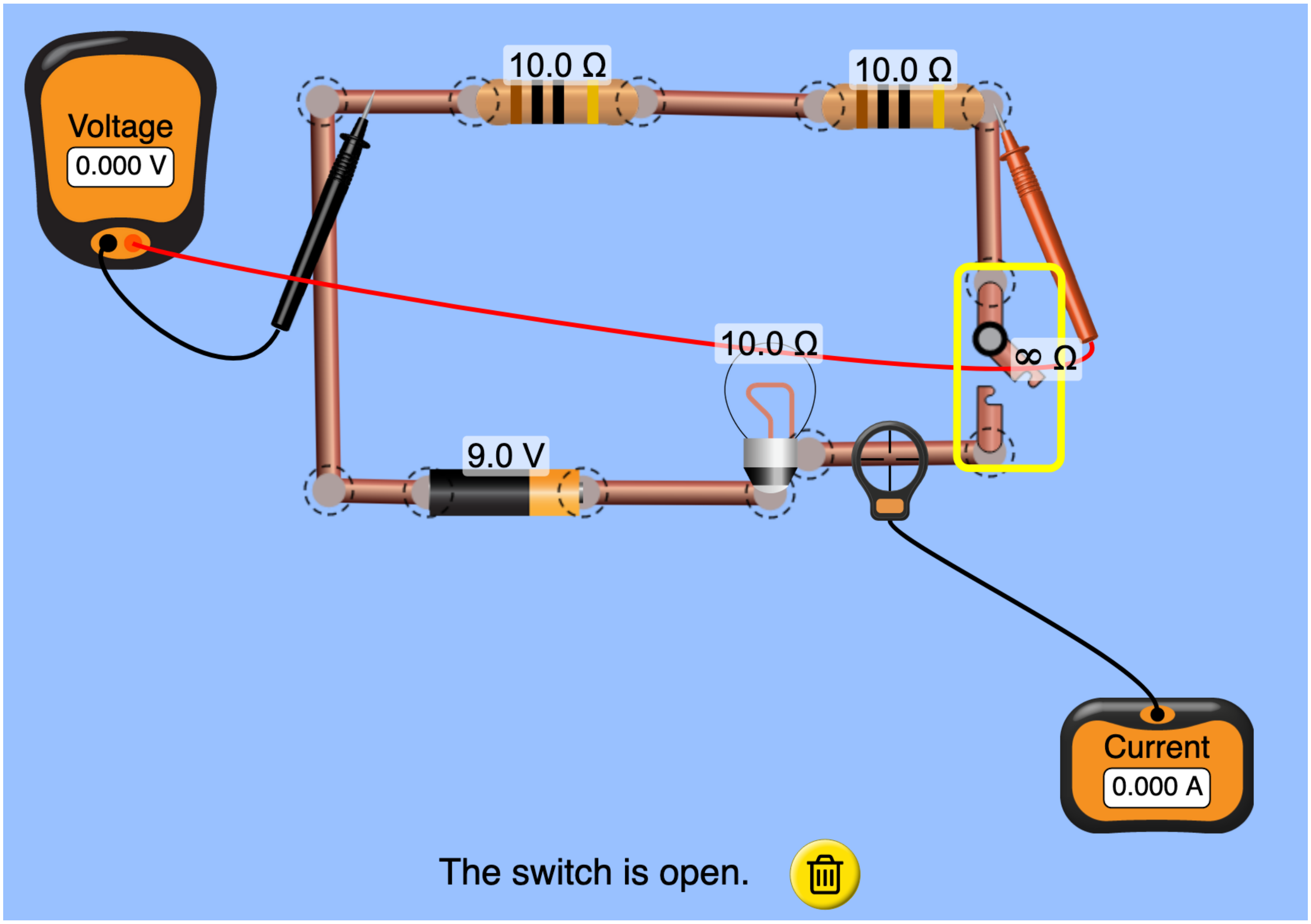



Figure 7: Here you can see an example of the Phet with two resistors in series. The switch is open so there are no voltage or current readings. When you take your measurements please close the switch.

**Question 4** *Measure the voltage across the resistor in the circuit using a 'voltmeter' and the current in the system using an 'ammeter'. Record your observations like in a table below.*

*Then increase the number of resistors in series in the circuit and record your observations, similar to Fig. 7. Remember, your voltmeter must always be around all resistors that you are measuring.*

| Table for question 4 | | | |
|---|---|---|---|
| No. of resistors in series | Voltage (V) | Current (A) | Ratio of V to I ($\frac{V}{I}$) |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |

**Question 5** *Transfer the data in Question 4 to a Jupyter Notebook and plot a graph, taking current (I) on the x - axis and voltage (V) on the y - axis.* [a]

1. *Draw a curve of the best-fit on the graph, showing the equation of fit.*
2. *What is the slope on the line, if the best fit line is linear.*
3. *Also copy the graph from Python and paste below.*

*How do the voltage and current change when you go on adding more and more resistors in series?*

[a] If you do not wish to use Python you can use any other programming language (R, Matlab, C++, etc) you wish. You are not, however, allowed to use Excel or Google Sheets. If you need help with Python please either see #pythonhelp on our Slack channel, or our Github repository.

**Question 6** *Repeat Question 4 and 5 BUT NOW, add resistors in parallel. Record your observations in a table, like the one as follows:*

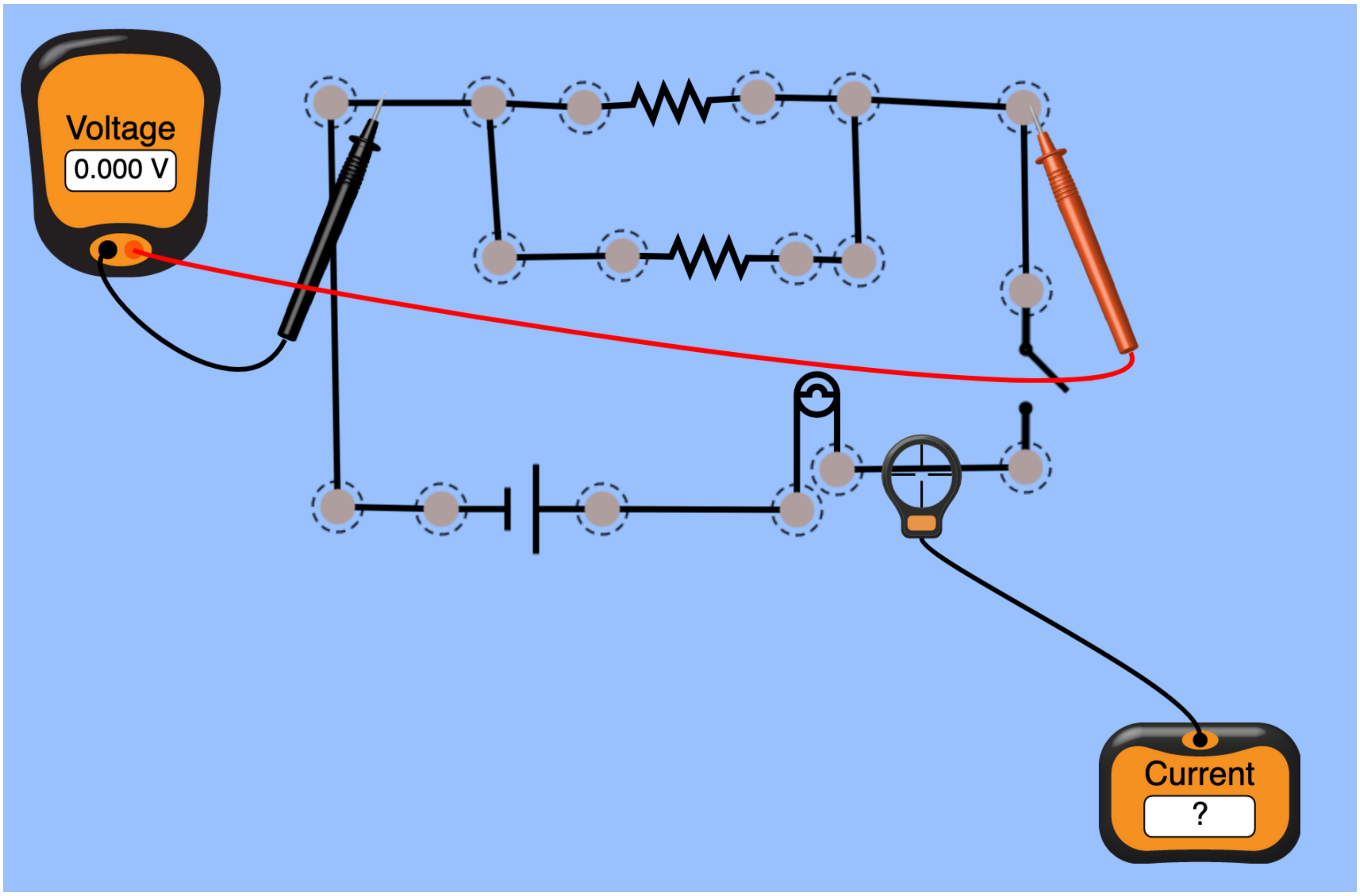
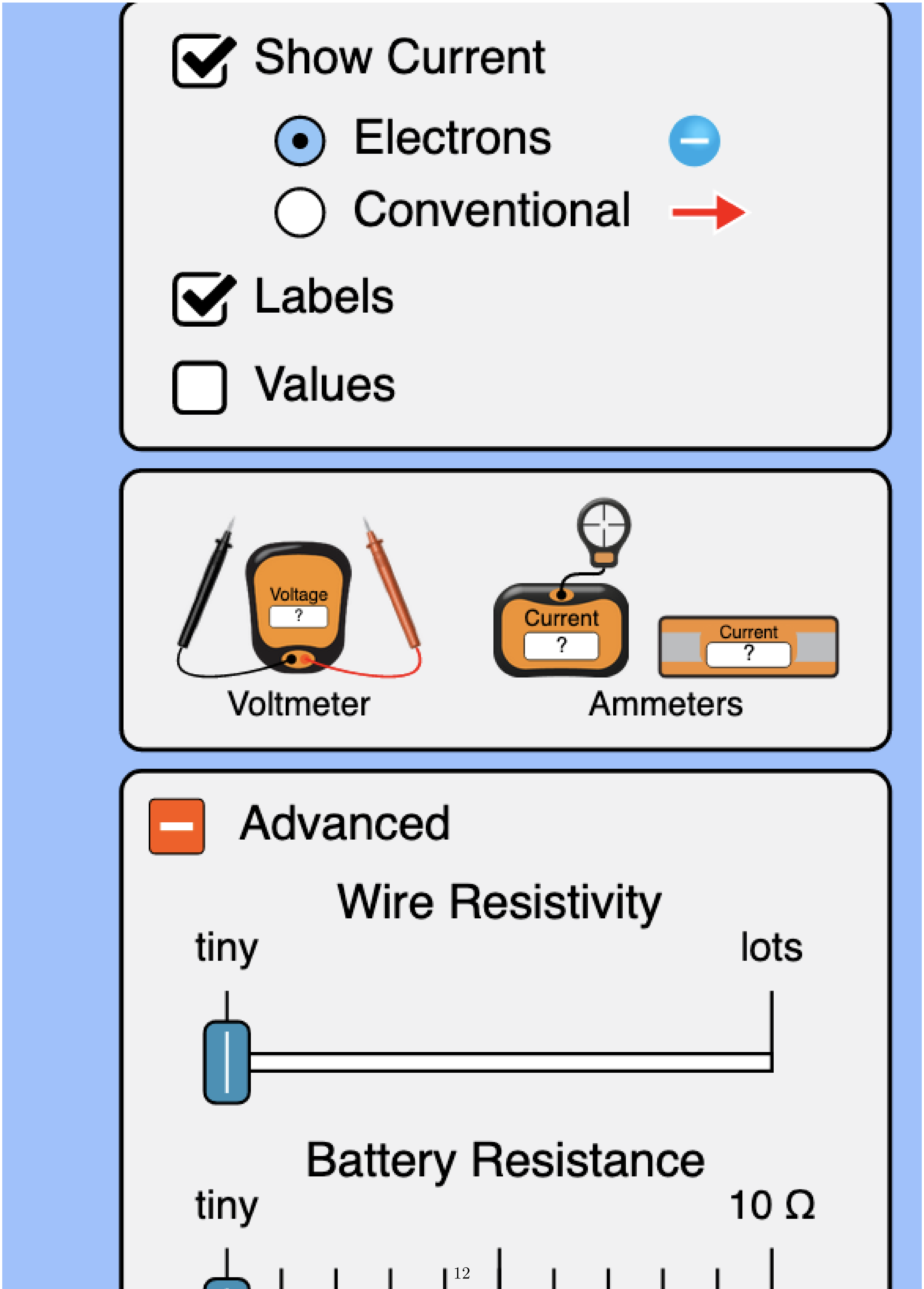



Figure 8: Here you can see an example of the Phet with two resistors in parallel. The switch is open so there are no voltage or current readings. When you take your measurements please close the switch. The circuit has been drawn using typical American circuit symbols, which have a brief explanation in the Appendix.

| Table for question 6 | | | |
|---|---|---|---|
| No. of resistors in parallel | Voltage (V) | Current (A) | Ratio of V to I ($\frac{V}{I}$) |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |


Show Current
Electrons
Conventional
Labels
Values
Voltage
?
Current
?
Current
?
Voltmeter
Ammeters
Advanced
Wire Resistivity
tiny
lots
Battery Resistance
tiny
10 Ω

**Question 7** *Repeat Question 4 and 5 BUT NOW, add change the lightbulb to a 'real lightbulb'. Record 5 voltages from 1 V to 40 V. Record your observations in a table, like the one as follows:*

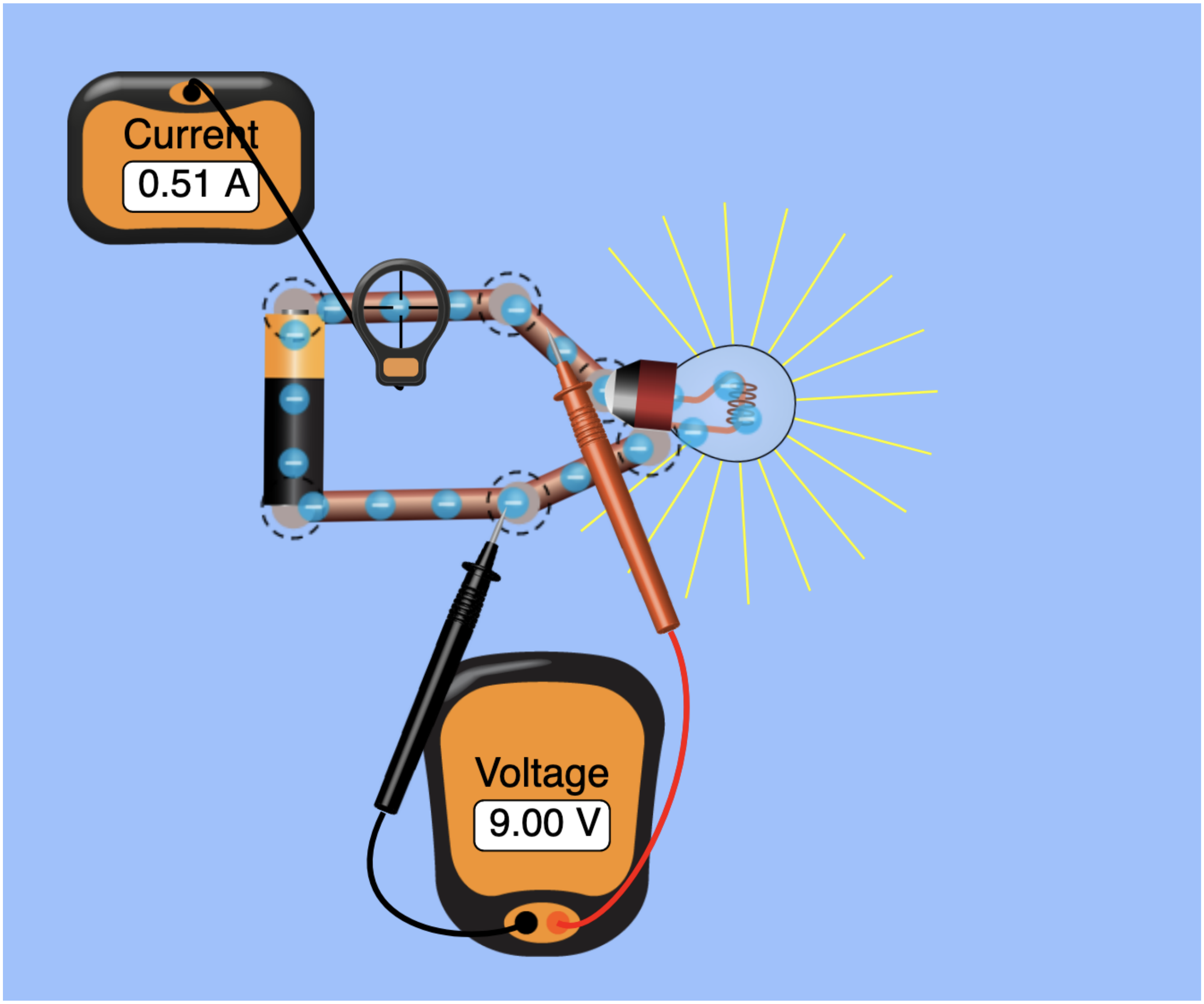



Figure 10: Here you can see an example of the Phet circuit using the 'real lightbulb'. As you can see this one has a red band, and is labeled 'Real Bulb' in the sidebar. We also have excluded a resistor from this circuit.

| Table for question 7 | | | |
|---|---|---|---|
| Trial Number | Voltage (V) | Current (A) | Ratio of V to I ($\frac{V}{I}$) |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |

**Question 8 Conclusion**

*Please write a conclusion section based on the results you have collected today. For reference on what it should look like please consult the Generic Deliverables at this link. For guidance on what questions should be addressed please see below.*

1. *What physical quantity will you get from the ratio of V to I? What is the SI unit?*
2. *Based on the observation from the PART-B of this experiment, what do you conclude on the equivalent resistance of several resistors when they are connected in (i) series, and (ii) parallel?*
3. *Is your lightbulb data linear? If so which parts are linear, if not which parts are not linear and why might that be?*
4. *Summarize what you learned about electric current, potential difference, and resistances from these Lab activities in a virtual environment. You should reference the introduction to complete this. (3-4 sentences)*

When you have completed all the questions please save your answers as a PDF, and upload them to the Canvas assignment associated with this lab. If you have trouble converting to a PDF please ask your Lab Instructor(s) for help. You should have four graphs, and four tables as well as answering all the questions in the grey boxes.

## Appendix

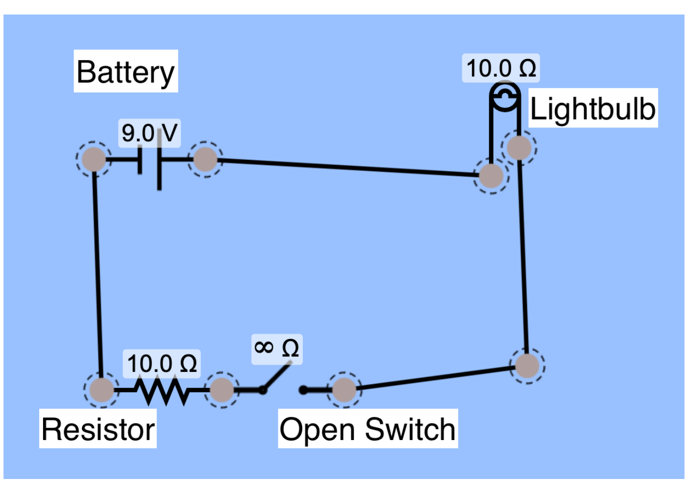



Figure 11: Here you can see what the Phet symbols means in this labeled example circuit.

### The Figures and Caption Rules

There are a few very important aspects to creating a proper figure and caption. If you follow these rules, not only will you get points on your physics lab grades, you will impress your instructors and peers in the future.

#### The Caption

- The caption should start with a label so you can reference the figure from other places in your paper/report. For this course you should use "Figure 1", "Figure 2", etc.

- The caption should allow the figure to be standalone, that is to say, by reading the caption and looking at the figure, it should be clear what the figure is about and why it was included without reading the whole paper.
- The caption should contain complete sentences and be as brief as possible while still conveying your information clearly (this is not always easy).
- Please add captions to your tables as well, otherwise we will not know what we are looking at.

### The Figure

- **Make sure that the resolution is high enough to not be pixelated at its final size.**
- Check that any text is readable at the final size (Using a smaller graph in Logger Pro will cause the text to be larger in relation to the graph when inserted into another program).
- For graphs, ensure that the axes are labeled (including units) and that there is a legend if you have multiple data sets on the same graphs.

### Tables

- The first row of the table should be a header, where each item is labeled with what is contained in that row. If it is a physical measurement it should have the correct units.
- For tables include a short caption of what is contained in the table, or what was examined.
- The caption should start with a label so you can reference the figure from other places in your paper/report. For this course you should use "Table 1", "Table 2", etc. For an example of a good table caption please see Figure 12.

**Table 1. Baseline characteristics of study participants**

| Variables | Intervention group (n=14) | Control group (n=15) |
|---|---|---|
| Women (no [%]) | 7 (50) | 5 (33) |
| Median age (range) | 22.0 (19 – 58) | 21.0 (18 – 70) |
| First winter in icy conditions (no [%]) | — | 1 (7) |
| Previous falls on ice (no [%]) | 8 (57) | 11 (73) |
| ≥ 1 fall this winter (no [%]) | 4 (29) | 7 (50) |
| Injury from fall this winter (no [%]) | 1 (7) | — |
| Time been walking this route (no [%]): | | |
| <6 months | 3 (21) | 2 (13) |
| 6–12 months | 9 (64) | 9 (60) |
| >12 months | 2 (14) | 4 (26) |

Figure 12: An example table from the paper Lianne Parkin, Sheila M Williams, and Patricia Priest, "Preventing Winter Falls: A Randomised Controlled Trial of a Novel Intervention" 122, no. 1298 (2009): 9.

## Python

According to IEEE Spectrum, Python is the most popular programming languages. Python is a free, general purpose, cross discipline programming language that has moved to the forefront of many disciplines.

If you decide to use Python your TA's will help you troubleshoot your code. While they might be able to help you troubleshoot when you use a different program or code, be aware of the fact that they are not familiar with all programming codes. There are many languages (R, Matlab, Opal, Julia, etc.) out there that are just as useful as Python, but we have chosen to use Python here. You may use any programming language you wish, but not Excel or Google Sheets.

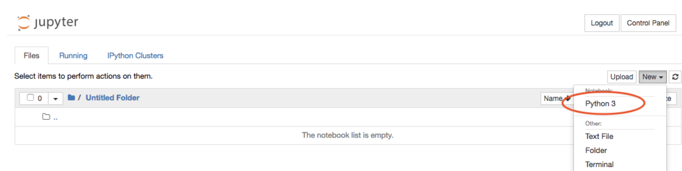



Figure 13: Navigate to `jupyterhub.wpi.edu/hub/login` and sign in with your WPI email address and password, choose an instance to spawn (either is fine) and create a new Python 3 file as shown here

We have set up a Jupyter notebook you may use. The website is https://jupyterhub.wpi.edu/hub/login.[4] There are many ways to learn Python, including reading a book, asking a friend, working through examples, or googling furiously when problems arise. We encourage you to discover which approach works best for you. Going forward this class will provide basic Python examples, but feel free to iterate upon the template we provide. What we provide is a stripped down version, and elaboration is encouraged. See this Github repository for our examples. We hope at the end of this term you will be able to add to your resume "Proficient in Python".

Jupyter uses a cell based system and evaluated variables carry over to the next cell. There are a few different types of cells, Figure 14 shows 2 kinds, the code cell, which we will be using most of the time, and the markdown cell, which you can use to add nicely formatted notes to you file.

[4] If you cannot log in please email WPI's IT department, and they will be happy to help polite students. The first thing they will tell you, however, is to check to make sure you don't have to change your password and try a VPN if you are off campus.

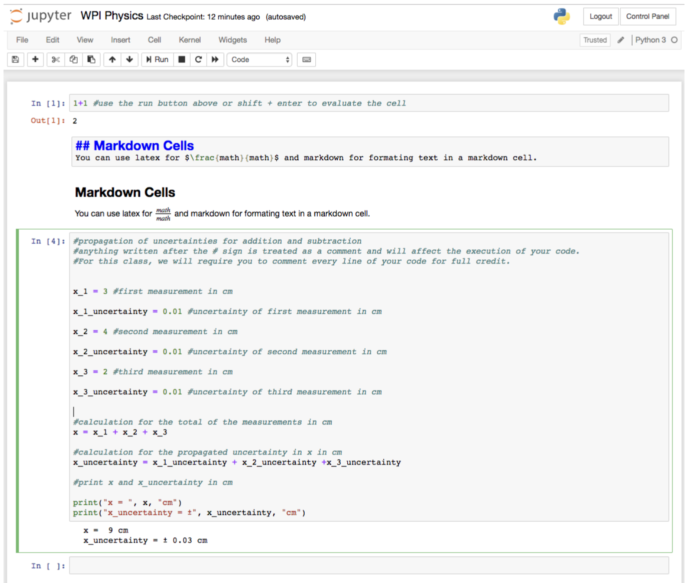



Figure 14: Above is the code that you could use use to propagate uncertainty for values that are added or subtracted. Always remember to comment your code.

If you prefer to work through a book or examples we recommend Mark Newman's book, which is available for free on his website [1]. Chapter Two is a basic introduction to the syntax for Python. Chapter Three covers graphs and visualizations, and we hope you will look into it if you learn best from a book. If you wish to get a head start in this class we recommend reading this book.

If you wish for a more advanced textbook there is a compilation of free online computational physics books here.

## Acknowledgement

This lab was first developed by Dr. Rudra Kafle to replace the on-site labs for D term, 2020 due to the COVID-19 Emergency. They have been iterated upon by Dana, who takes full credit for any mistakes therein.

## References

[1] Mark Newman. *Computational Physics with Python*. CreateSpace Independent Publishing Platform, 2012.