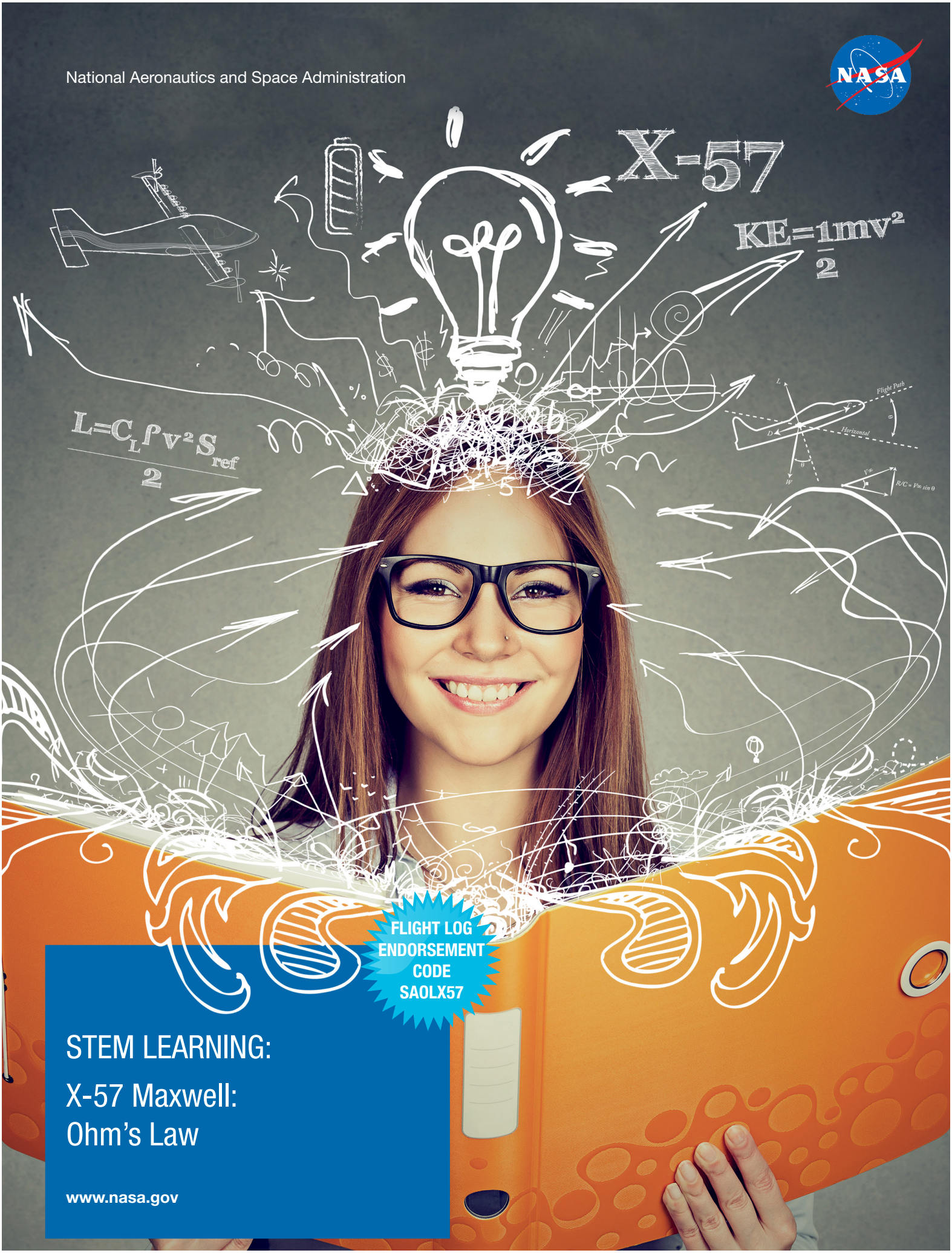
National Aeronautics and Space Administration



STEM LEARNING:

X-57 Maxwell: Ohm's Law

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BACKGROUND INFORMATION

What is the X-57?

NASA's X-57 Maxwell is a small, experimental aircraft powered completely by batteries. It is NASA's first all-electric experimental aircraft, or X-plane. Compared to standard fuel-powered airplanes, the X-57 is designed to have increased high-speed cruise efficiency, zero in-flight carbon emissions, and flight that is much quieter for the community on the ground.

One of the primary goals of the X-57 project is to develop all-electric technology that will make flying cleaner, quieter, and more sustainable. The technologies and verification and testing processes created for the X-57 will be an important part of future projects that work towards more sustainable aviation.

The X-57 requires banks of batteries to produce enough electricity to power its fourteen wing-mounted engines. There is an extensive electrical distribution system that carries the electricity to the motors.

Figure 1. This artist's rendering shows the X-57 in flight. Credit: NASA

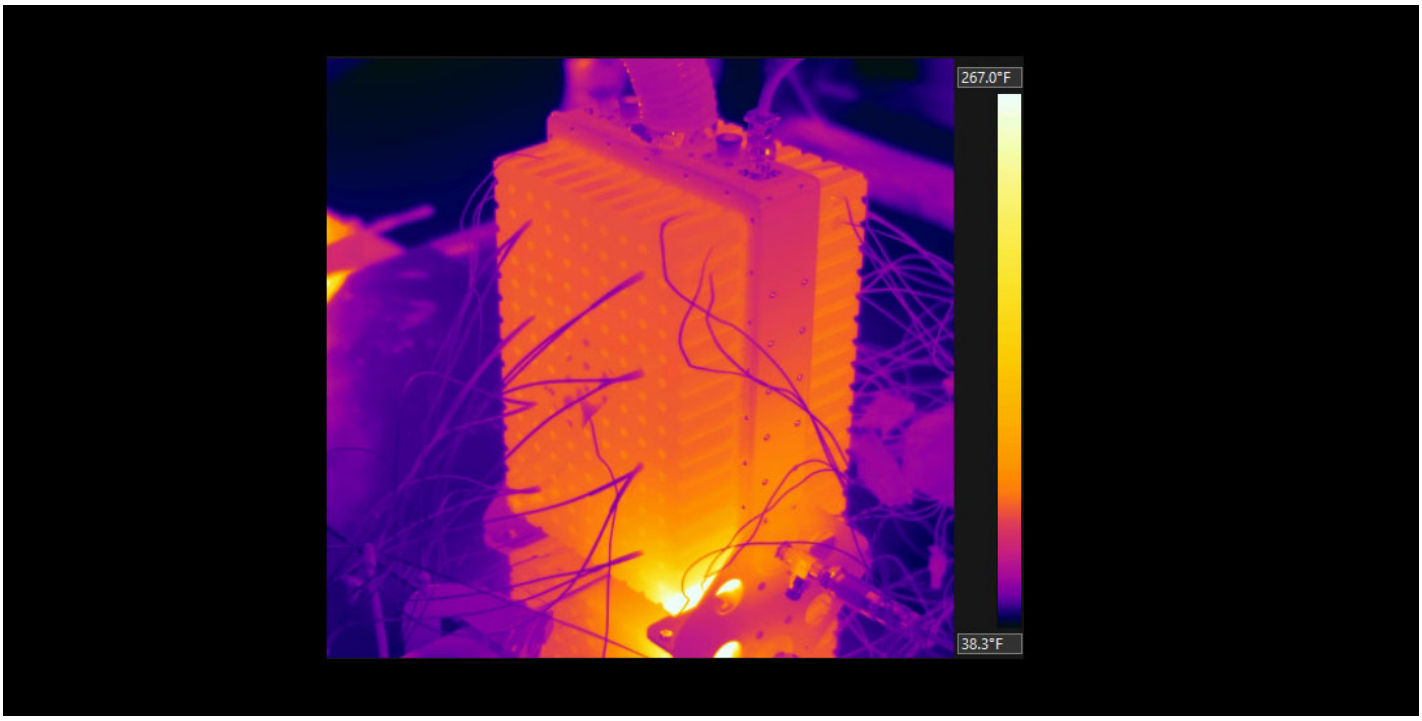
VOLTAGE, CURRENT, AND RESISTANCE

Since the X-57 is powered by electricity provided by the batteries, it is very important for engineers to understand how electricity flows through the plane's circuits. Electricity is the movement of electrons through a circuit. To understand the flow of electricity, you also need to understand the concepts of voltage, current, and resistance.

Voltage is the electrical force that causes electrons to flow and is measured in Volts (V). It is the difference in charge between any two points in a circuit. If, for example, a circuit is powered by a 3-volt battery, the 3 volts represent the difference in charge between where the electrons leave the battery and where they flow back into the battery.

Current is a measure of how quickly electrons move through a circuit and is measured in Amperes (A), or Amps for short. The higher the charge or amps are, the more quickly electrons are flowing.

Resistance is a measure of how easily electricity can pass through a conductor and is measured in Ohms (Ω). If something has a high resistance, only a small amount of electricity can pass through it, but if it has a low resistance, more electricity can flow through. If you only need a specific amount of current to flow through a circuit, a resistor(s) can be added to the circuit to limit current.



In this thermal runaway and propagation test, conducted in cooperation with Electric Power Systems and Empirical Systems Aerospace, an intentional thermal event was induced on a trigger battery cell to allow researchers to observe its impact on neighboring battery cells. The test showed that the battery system design successfully isolated the thermal runaway event to the trigger battery cell, preventing it from spreading to other cells. The design will allow NASA's all-electric X-57 Maxwell to continue to operate and land safely in the event of a thermal runaway. Credit: NASA

OHM'S LAW

Ohm's law is a scientific law which states that the amount of current flowing through a conductor is directly proportional to the voltage applied to it. Whenever a voltage is applied to a conductor, electrical current flows through it. According to Ohm's law, if the voltage is higher, more current flows through and if the voltage is lower, less current flows through.

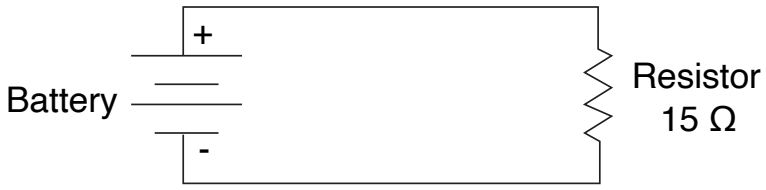
Mathematically, Ohm's law is written as:

$$\text{Voltage} = \text{Current} \times \text{Resistance} \quad \text{-or-} \quad V = IR$$

If the voltage and resistance are known, this formula can also be used to solve for the current. To do this, divide both sides by the resistance to get:

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}} \quad \text{-or-} \quad I = \frac{V}{R}$$

The following examples demonstrate how to use Ohm's law to solve for current or voltage in a circuit.



Solving for voltage:

In the circuit shown above, 0.6 A of current flows through the resistor. What is the voltage of the battery?

$$V = IR = (0.6\ \text{A})(15\ \Omega) = \mathbf{9\ V}$$

Solving for current:

In the circuit shown above, a 1.5 V battery is connected to a 15 Ω resistor. How much current flows through the resistor?

$$I = \frac{V}{R} = \frac{1.5\ \text{V}}{15\ \Omega} = 0.1\ \text{A}$$

STUDENT ACTIVITY

In this activity, you will be creating several simple paper circuits and using a voltmeter to measure current.

Each student or group needs:

- Circuit Template Worksheet
- Voltmeter
- CR2032 battery
- Small binder clip
- Approximately 54" double-sided conductive copper foil tape (1/4" width)
  Note: you can also use single-sided conductive copper foil tape but will need to fold over the turns if using this kind of tape and will need a slightly longer piece. Double-sided copper foil tape is conductive on both sides. Some copper tape does not have conductive adhesive, so it is only conductive on one side. An internet search will show tutorials about how to do this.
- (5) Resistors – Any resistance will work, but 15-100 Ω resistors are recommended.
  You can use 2 resistors per student or group instead of 5, but you will have to move them from circuit to another.
- Scissors for cutting conductive tape

Each group will:

Prior to completing the circuit activity, complete the following problems to ensure you can solve problems using Ohm's law:

Solve for the value indicated:

$$V = IR \qquad I = \frac{V}{R}$$

When a battery is connected to a 50 Ω resistor, 0.4 A of current flows through the circuit. What is the voltage of the battery	0.2 A of current flow through a 15 Ω resistor when it is connected to a battery. What is the voltage of the battery?	A light bulb with a resistance of 90 Ω has 0.05 A flowing through it. What voltage was applied to the light bulb?
A 5 V battery is used to power a light bulb with a resistance of 10 Ω. What current flows through the light bulb?	A 12 V power source is attached to a 60 Ω resistor. How much current flows through the resistor?	A motor that has a resistance of 18 Ω is attached to a 60 V power source. What current will flow through the motor?

SIMPLE CIRCUIT

1. Each circuit template can be cut out individually or left together on one page.
2. Cut pieces of conductive tape and cover each of the grey lines on the "Simple Circuit" template.
3. Place the resistor across the gap where it shows the resistor ( ).
4. Cut 2 small pieces of conductive tape, each approximately 0.25 inches long.
5. Use the 2 small pieces of tape to attach each end of the resistor to the circuit, ensuring that the resistor is touching the circuit on both sides of the gap.
6. Fold over the corner of the paper, folding along the dashed line.
7. Place the battery inside the fold with the positive side of the battery touching the circle marked with the +.
8. Use the binder clip to hold the battery in place.
9. Turn the dial on the voltmeter so it measures voltage.
10. Touch the positive (red) lead of the voltmeter to the conductive tape next to circle labeled "1" and the negative (black) lead to the conductive tape next to the circle labeled "2."
11. Read the voltage off the voltmeter and record it here: _____ V
12. Use this voltage and the resistance of your resistor to calculate the current flowing through the resistor:

13. Turn the dial on the voltmeter so that it measures current.
14. Touch the positive (red) lead of the voltmeter to the conductive tape next to circle labeled "1" and the negative (black) lead to the conductive tape next to the circle labeled "2."
15. Read the current off the voltmeter and record it here: _____ A
16. Compare the current you calculated with the current you measured. How similar were they?

SERIES CIRCUIT (OPTIONAL)

1. Cut pieces of conductive tape and cover each of the grey lines on the "Series Circuit" template.
2. Place resistors across the gaps where it shows the resistors ( ).
3. Cut 4 small pieces of conductive tape, each approximately 0.25 inches long.
4. Use the small pieces of tape to attach each end of the resistors to the circuit, ensuring that the ends of the resistors are touching the circuit on both sides of the gap.
5. Fold over the corner of the paper, folding along the dashed line.
6. Place the battery inside the fold with the positive side of the battery touching the circle marked with the +.
7. Use the binder clip to hold the battery in place.
8. Turn the dial on the voltmeter so it measures voltage.
9. Touch the positive (red) lead of the voltmeter to the conductive tape next to circle labeled "1" and the negative (black) lead to the conductive tape next to the circle labeled "3."
10. Read the voltage off the voltmeter and record it here: _____ V
11. When multiple resistors are connected in a series circuit, the total resistance is the sum of each of the resistors. Calculate the resistance for this circuit by adding together the resistances of the 2 resistors. What is your total resistance? _____ Ω
12. Use this voltage and the total resistance to calculate the current flowing through the circuit:
13. Turn the dial on the voltmeter so that it measures current.
14. Touch the positive (red) lead of the voltmeter to the conductive tape next to circle labeled "1" and the negative (black) lead to the conductive tape next to the circle labeled "3."
15. Read the current off the voltmeter and record it here: _____ A
16. Compare the current you calculated with the current you measured. How similar were they?
17. (Optional) You can experiment with measuring the current flowing through each resistor and/or the voltage drop across each resistor by connecting the leads of the voltmeter to spot "1" and "2" or between spots "2" and "3."

PARALLEL CIRCUIT (OPTIONAL)

1. Cut pieces of conductive tape and cover each of the grey lines on the "Parallel Circuit" template. **Do not place conductive tape over gaps between the grey lines.**

2. Place resistors across the gaps marked with the resistor —/\/\/\— symbol.

3. Cut 4 small pieces of conductive tape, each approximately 0.25 inches long.

4. Use the small pieces of conductive tape to attach each end of the resistors to the circuit, ensuring that the ends of the resistors are touching the circuit on both sides of the gap.

5. Fold over the corner of the paper along the dashed line.

6. Place the battery inside the fold with the positive side of the battery touching the circle marked with the +.

7. Use the binder clip to hold the battery in place.

8. Measure your circuit's voltage. To do this:
   a. Turn the dial on the voltmeter so it measures voltage.

   b. Touch the positive (red) lead of the voltmeter to the conductive tape next to circle labeled "1" and the negative (black) lead to the conductive tape next to the circle labeled "2."

   c. Read the voltage off the voltmeter and record it here: _____ V

9. When two resistors are connected in a parallel circuit, the total resistance is calculated using the following formula:

$$\frac{1}{\text{Total Resistance}} = \frac{1}{R1} + \frac{1}{R2}$$

   where R1 and R2 are the resistance of each of the 2 resistors. Use this formula to calculate the total resistance in this circuit.

   What is your total resistance? _____ Ω

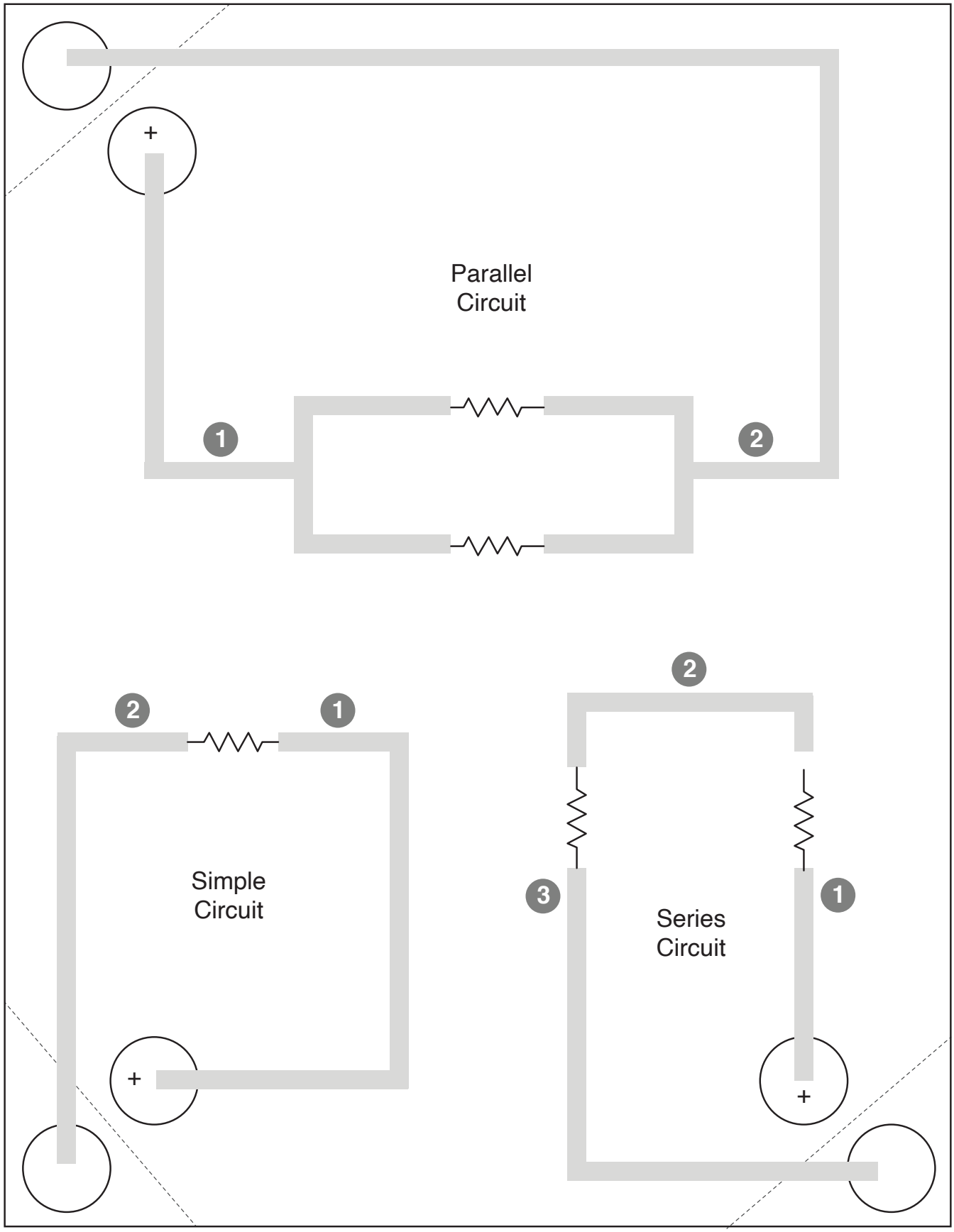
10. Use this voltage and the total resistance to calculate the current flowing through the circuit:

11. Next, measure the circuit's current. To do this:
   a. Turn the dial on the voltmeter so that it measures current (Amps).

   b. Touch the positive (red) lead of the voltmeter to the conductive tape next to circle labeled "1" and the negative (black) lead to the conductive tape next to the circle labeled "2."

   c. Read the current off the voltmeter and record it here: _____ A

12. Compare the current you calculated with the current you measured. How similar were they? If they were different, why do you think that might have happened?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