UNIT 3

Electricity and Magnetism

Chapter 9

Circuits

Introduction to Chapter 9

In our homes, you can have many electrical devices on at any one time. How is this possible? What do circuits in our homes look like? In this chapter, you will learn about the two kinds of circuits, called *series circuits* and *parallel circuits*. In series circuits, all the current flows through one path. In parallel circuits, current can flow through two or more paths.

Investigations for Chapter 9

9.1	**More Electric Circuits**	*What kinds of electric circuits can you build?*

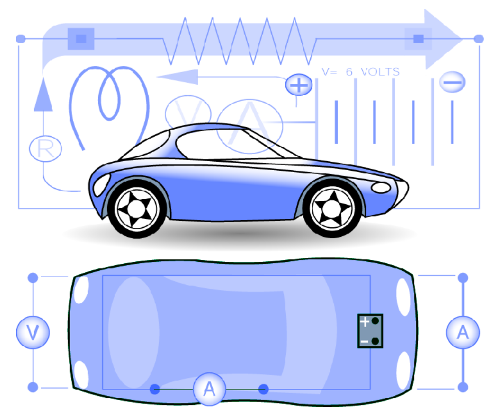
In this Investigation, you will compare how two kinds of circuits work by building and observing series and parallel circuits. You will explore an application of these circuits by wiring two switches in series and in parallel.

9.2	**Series Circuits**	*How do you use Ohm's law in series circuits?*

In this Investigation, you will find out how to add resistance in a series circuit. You will also build a light bulb circuit with a dimmer switch and use this circuit to graph the resistance of a light bulb at different levels of current.

9.3	**Parallel Circuits**	*How do parallel circuits work?*

In this Investigation, you will analyze how a parallel circuit works by measuring voltage and current in different parts of the circuit. You will use your understanding of parallel circuits to design a battery voltage tester circuit.



Learning Goals

In this chapter, you will:

- ✔ Identify a series circuit.
- ✔ Identify a parallel circuit.
- ✔ Describe how our houses are wired.
- ✔ Build series and parallel circuits.
- ✔ Calculate total resistance in series circuits.
- ✔ Build circuits with fixed and variable resistors.
- ✔ Analyze series circuits using Ohm's law.
- ✔ Use Kirchhoff's voltage law to find the voltage drop across a circuit component.
- ✔ Compare current in series and parallel circuits.
- ✔ Compare voltage in series and parallel circuits.
- ✔ Use Kirchhoff's current law to find an unknown current in a parallel circuit.
- ✔ Identify a short circuit.
- ✔ Explain why a short circuit is dangerous.

Vocabulary

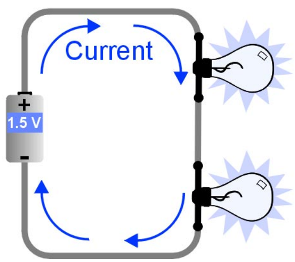
Kirchhoff's current law	parallel circuit	short circuit
Kirchhoff's voltage law	series circuit	

9.1 More Electric Circuits

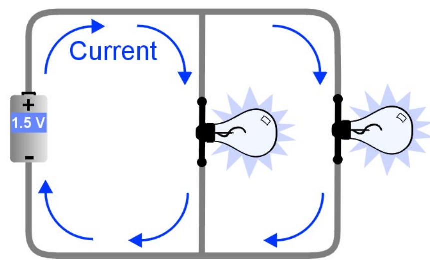
We use electric circuits for thousands of different things from cars to computers. In this section you will learn about two basic ways to put circuits together. These two types of circuits are called *series* and *parallel*. Series circuits have only one path; the flow of charge has only one place to go. Parallel circuits have branching points and multiple paths for current to flow.

Series circuits

Two bulbs in a series circuit



Two bulbs in a parallel circuit



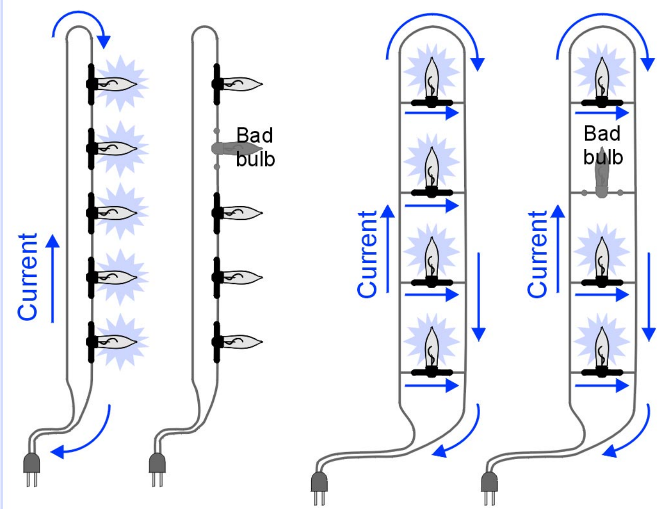
What is a series circuit? In a **series circuit** the current can only take one path. All the current flows through every part of the circuit. All the circuits you have studied so far have been series circuits. For example, if you have a battery, a light bulb, and one switch, everything is connected in series because there is only one path through the circuit.

What is a parallel circuit? In a **parallel circuit** the current can take more than one path. Parallel circuits have at least one branch where the current can split up.

Combinations It is possible to create circuits with both series and parallel wiring. You need at least three light bulbs. Can you think of a way to wire three bulbs using both series and parallel connections?

Holiday lights

Series circuit **Parallel circuit**



Many people use strings of lights to decorate their houses, especially at holiday time. Inexpensive versions of lights are wired in series, while better ones are wired in parallel.

In the series circuit, if one bulb goes bad the whole circuit is broken and no bulbs light. It is very difficult to find the bad bulb to replace it because all the lights are out.

In the parallel circuit, each bulb has its own path for current, independent of the others. If one bulb fails, the others will still light. The bad bulb is easy to spot and replace.

Household wiring

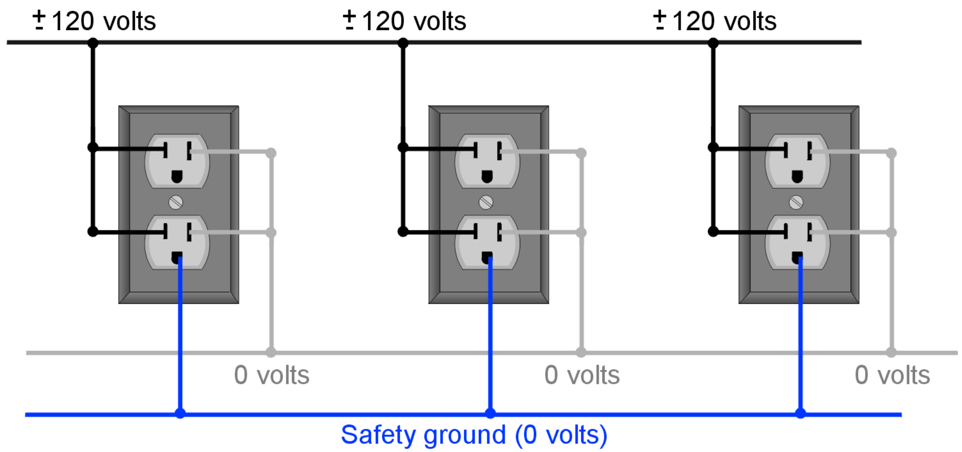
Parallel circuits for homes and buildings

The electrical circuits in homes and buildings are parallel circuits. There are two great advantages of parallel circuits that make them a better choice than series circuits.

1 Each outlet has its own current path. This means one outlet can have something connected and turned on (with current flowing), while another outlet has nothing connected or something turned off (no current flowing).

2 Every outlet sees the same voltage because one side of each outlet is connected to the same wire.

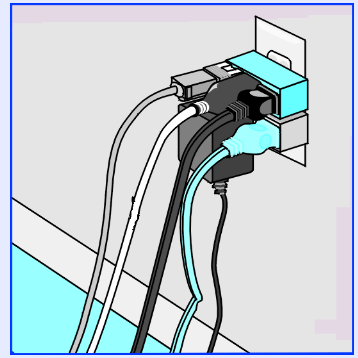
Parallel wiring of electrical outlets



Why series circuits would not work

Parallel circuits mean that a light in your home can be on at the same time that the TV is off. If our homes were wired in series, turning off *anything* electrical in the house would break the whole circuit. This is not practical; we would have to keep everything on all the time just to keep the refrigerator running! Also, in a series circuit, everything you plugged in would use some energy and would lower the voltage available to the next outlet.

What happens if you plug in too many things?



In a parallel circuit, each connection uses as much current as it needs. If you plug in a coffeemaker that uses 10 amps and a toaster oven that uses 10 amps, a total of 20 amps needs to come through the wire.

If you plug too many appliances into the same outlet, you will eventually use more current than the wires can carry without overheating. Your circuit breaker will click open and stop the current. You should unplug things to reduce the current in the circuit before resetting the circuit breaker.

9.2 Series Circuits

Ohm's law is a powerful tool for analyzing circuits. You have studied Ohm's law in a series circuit with one resistor. In this section you will learn how to analyze more complex series circuits with more than one resistance.

Current and voltage in a series circuit

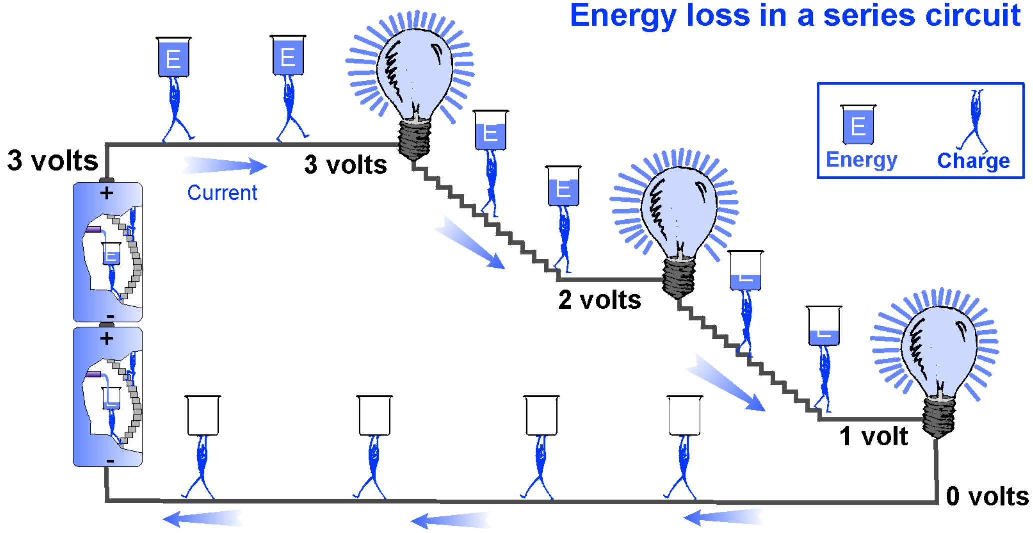
In a series circuit, current is the same at all points

In a series circuit, all current flows through a single path. What goes into one end of the wire must come out the other end of the wire. The value of current is the same at all points in the circuit. The amount of current is determined by the voltage and resistance in the circuit, using Ohm's law.

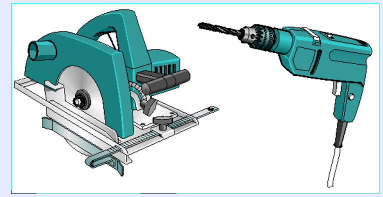
Voltage is reduced by each resistance

The law of conservation of energy helps us to understand what happens to energy in a series circuit. Consider a circuit with three bulbs. Using two batteries, every charge starts at 3 volts. As each charge moves through the circuit, some energy is transformed into light by each bulb. That means that after every bulb, the energy must be lower. We see the lower energy as a drop in voltage from 3 volts, to 2 volts, to 1 volt and finally down to zero volts after the last bulb.

Energy loss in a series circuit



Drills, saws, and extension cords



If you know people who work with power tools, you may have noticed that they use a heavy extension cord when the regular cord can't reach. One reason to use a heavy cord is that it can safely carry the amps used by power tools.

There is a second reason as well. If a thin extension cord is used, the motor in a power tool can overheat and burn out. This happens because the voltage available for the motor is lower than it should be.

The motor gets lower voltage when energy is lost along the cord. This energy loss is called a voltage drop, and is related to resistance. Heavy extension cords have lower resistance and use less energy than thin cords of the same length.

How to find the current in a series circuit

Start with resistance and voltage

You need to know how much resistance the circuit has to find the current. In many cases you know the voltage, such as from a battery. If you know the resistance, Ohm's law can be used to find the current.

Each resistance in a series circuit adds to the total. You can think of it like adding pinches to a hose (figure 9.1). Each pinch adds some resistance. The total resistance is the sum of the resistances from each pinch.

Two ways to find the current

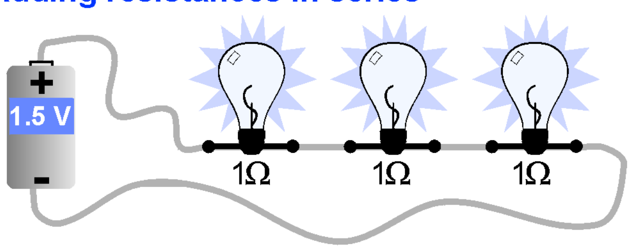
How would you find the exact amount of total resistance in a series circuit? You could use several methods:

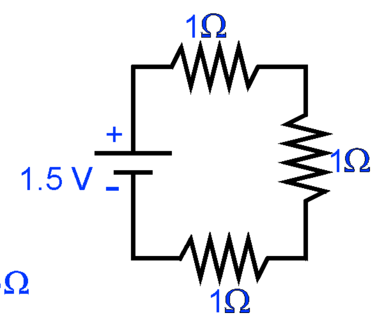
- You could measure total voltage and current through the circuit, and use Ohm's law to calculate the total resistance of the circuit (R = V/I).
- You could add together the resistance of each component in the circuit.

Add up resistances to get the total

If you know the resistance of each component, you can simply add them up to get the total for the circuit. Once you know the total resistance, use Ohm's law to calculate the current.

Adding resistances in series





Total resistance = $1\Omega + 1\Omega + 1\Omega = 3\Omega$

Ignore resistance of wires and batteries

Every part in a circuit has some resistance, even the wires and batteries. However, light bulbs, resistors, motors and heaters usually have much greater resistance than wires and batteries. Therefore, when adding resistances up, we can almost always leave out the resistance of wires and batteries.

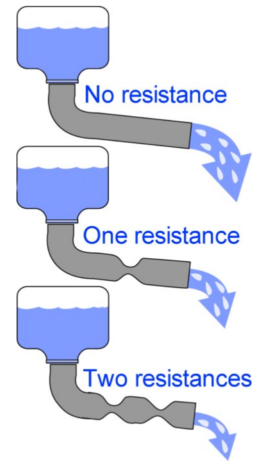


Figure 9.1: *Each time a hose is pinched, the flow of water slows more.*

Example

How much current is in a circuit with a 1.5 volt battery and three 1 ohm resistances (bulbs) in series?

Solution

Add the resistance of each component:

1 ohm + 1 ohm + 1 ohm = 3 ohms

Use Ohm's law to calculate the current from the voltage and the total resistance.

I = V/R = 1.5 volts ÷ 3 ohms
= 0.5 amps

Answer: 0.5 amps

Voltage in a series circuit

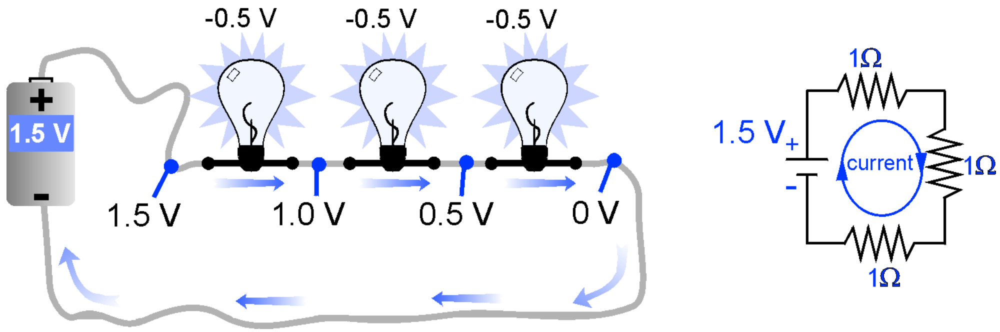
Each resistance drops the voltage

You have learned that energy is not created or destroyed. This rule is known as the law of conservation of energy. However, energy is constantly being transformed from one form to another. As current flows along a series circuit, each resistance uses up some of the energy. As a result, the voltage gets lower after each resistance.

The voltage drop

We often say each separate resistor creates a *voltage drop*. If you know the current and resistance, Ohm's law can be used to calculate the voltage drop across each resistor. For example, in the three-bulb series circuit, the voltage drop across each bulb is 0.5 volts (figure 9.2).

Each resistance drops the voltage



Kirchhoff's law

Over the entire circuit, the energy taken out must equal the energy supplied by the battery. This means the total of all the voltage drops must add up to the total voltage supplied by the battery (energy in). This rule is known as Kirchhoff's voltage law, after German physicist Gustav Robert Kirchhoff (1824-87):

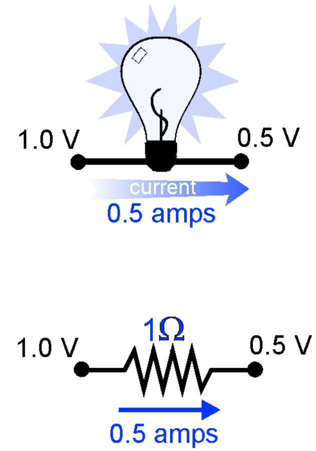
Kirchhoff's voltage law

Around any closed circuit, all the voltage changes must add up to zero.

Batteries raise voltage, resistances lower voltage.
For the example circuit above, the total of all voltage changes is:

$$\text{Voltage changes} = \underbrace{+1.5\text{ V}}_{\text{Battery}} - \underbrace{0.5\text{ V}}_{\text{Bulb}} - \underbrace{0.5\text{ V}}_{\text{Bulb}} - \underbrace{0.5\text{ V}}_{\text{Bulb}} = 0$$

Voltage drop across a resistor (bulb)



Calculating the voltage drop
Ohm's law

$V = IR$
$= (0.5 \text{ amps}) \times (1 \text{ ohm})$
$= 0.5 \text{ volts}$

Figure 9.2: *When current flows through any resistance the voltage drops because some of the energy is used up. The amount of the voltage drop is given by Ohm's law.*

9.3 Parallel Circuits

In the last section, you learned how to analyze series circuits. In this section, you will take a closer look at parallel circuits. You previously learned that parallel circuits are used for almost all electrical wiring in houses and buildings.

Current in a parallel circuit

Separate paths are parallel branches

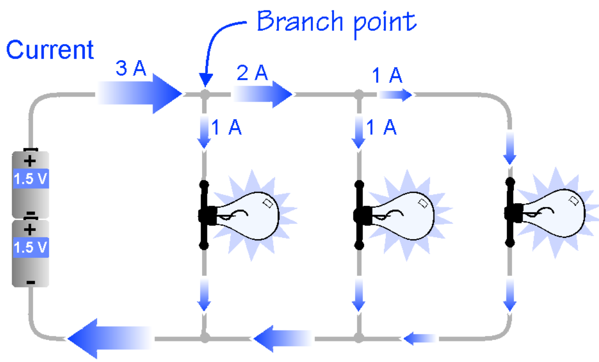
A parallel circuit has at least one point where the circuit divides, creating more than one path for current to flow. Each path in the circuit is sometimes called a *branch*. The current through a branch is also called the *branch current*.

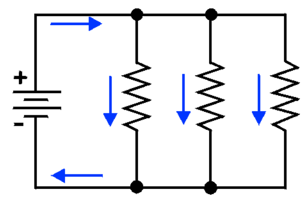
Kirchhoff's current law

When analyzing a parallel circuit, remember that the current always has to go somewhere. If current flows into a branching point in a circuit, the same total current must flow out again. This rule is known as Kirchhoff's current law.

Example, three bulbs in parallel

For example, suppose you have three light bulbs connected in parallel, and each has a current of 1 amp. The battery must supply 3 amps since each bulb draws 1 amp and there are 3 bulbs. At the first branch, 3 amps flow in, 1 amp flows down to the first bulb, and 2 amps flow on to the remaining 2 bulbs.

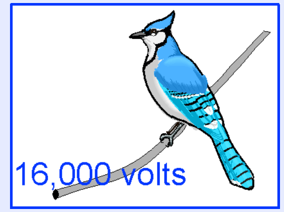




Kirchhoff's current law

All the current flowing into a branch point in a circuit has to flow out again.

Why aren't birds electrocuted?



If high-voltage wires are so dangerous, how do birds sit on them without being instantly electrocuted? First, the bird's body has a higher resistance than the electrical wire. The current tends to stay in the wire because the wire is an easier path.

The most important reason, however, is that the bird has both feet on the same wire. That means the voltage is the same on both feet and no current flows through the bird.

If a bird had one foot on the wire and the other foot touching the electric pole, then there would be a voltage difference. A lot of electricity would pass through the bird.

Voltage and resistance in a parallel circuit

Each branch sees the same voltage

In a parallel circuit the voltage is the same across each branch because all the branch points are on the same wire. One way to think of a parallel circuit is to imagine several series circuits connected to the same battery. Each branch has a path back to the battery without any other resistance in the way.

Branches don't always have the same current

The amount of current in each branch in a parallel circuit depends on how much resistance is in the branch. When you plug a desk lamp and a power saw into an outlet, they each use very different amounts of current (figure 9.3).

Lower resistance means more current flows

You can calculate current through the lamp and saw with Ohm's law (figure 9.4). The 100-watt bulb has a resistance of 145 ohms. Since the outlet has 120 volts across it, the bulb draws about 0.8 amps. A power saw has a much lower resistance, 12 ohms. Consequently, the power saw draws a much higher current of 10 amps when connected to the 120-volt outlet.

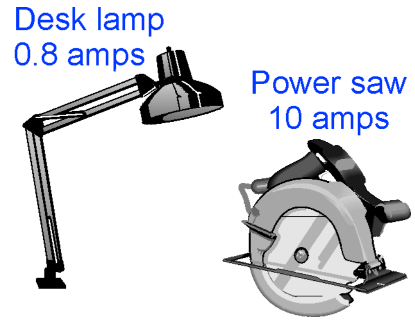
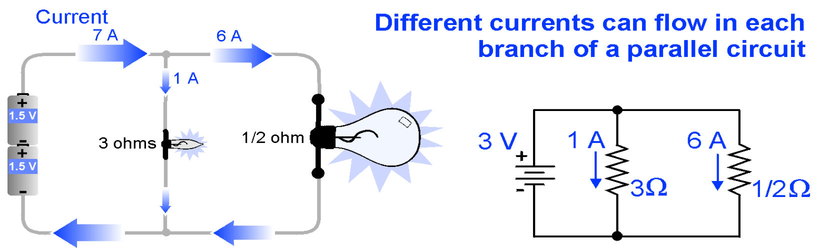


Figure 9.3: *Different appliances use different amounts of currrent.*

Example: Calculating currents in a parallel circuit

For the circuit and its diagram shown below, a student was able to calculate the currents from the information given about the circuit. Can you duplicate her work?



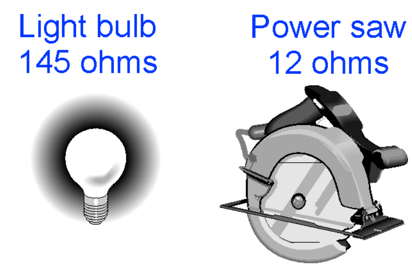
Step 1: Calculate current through each part of the circuit.

Step 2: You are given total voltage and the resistance of each bulb.

Step 3: Useful equations are: Ohm's law, $V = IR$, and Kirchhoff's current law, $I_t = I_1 + I_2$

Step 4: Branch 1 current: $I_1 = V/R_1$ Branch 2 current: $I_2 = V/R_2$ Total current: $I_t = I_1 + I_2$

Step 5: $I_1 = 3\ V / 3\ \Omega = 1$ $I_2 = 3\ V / 0.5\ \Omega = 6\ A$ $I_t = 1\ A + 6\ A = 7\ A$



$$I = \frac{V}{R} = \frac{120\ V}{145\ \Omega} = 0.83 \text{ amps}$$

$$I = \frac{V}{R} = \frac{120\ V}{12\ \Omega} = 10 \text{ amps}$$

Figure 9.4: *Calculating the current from the resistance and voltage. Household electric circuits are wired in parallel at 120 volts.*

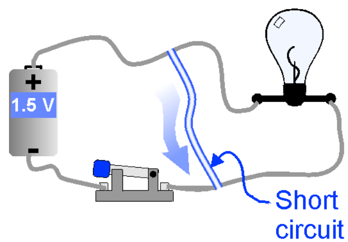
Open circuits and short circuits

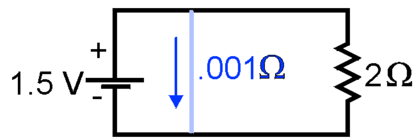
What is a short circuit?

A **short circuit** is a circuit path with zero or very low resistance. You can create a short circuit by connecting a wire directly between two ends of a battery. Often, short circuits are accidentally caused by connecting a wire between two other wires at different voltages. This creates a parallel path with very low resistance. In a parallel circuit, the branch with the lowest resistance draws the most current (figure 9.5).

Why short circuits are dangerous

Short circuits are dangerous because they can cause huge amounts of current. For example, suppose you connect a length of wire across a circuit creating a second current path as shown below. The resistance of the wire could be as low as 0.001 ohms. That means the current through your wire could be as high as 1,500 amps! This much current would melt the wire in an instant and probably burn you as well. Short circuits should always be a concern when working around electricity. Fuses or circuit breakers are protection from the high current of a short circuit.





$$I = \frac{V}{R} = \frac{(1.5\ V)}{(0.001\ \Omega)} = 1{,}500\ \text{amps}$$

Open and closed circuits

Open and closed circuits are not the same as short circuits. An open circuit means the current path has been broken, possibly by a switch (figure 9.5). Current cannot flow in an open circuit. A closed circuit is a circuit that is complete and allows current to flow.

Protecting against short circuits

Every electrical outlet in your house or apartment is connected to a circuit breaker that allows a maximum of 15 or 20 amps to flow. If something electrical breaks and causes a short circuit, the breaker will open before the current has time to cause a fire. If a circuit breaker always trips when you plug in an appliance, that appliance probably has a short circuit.

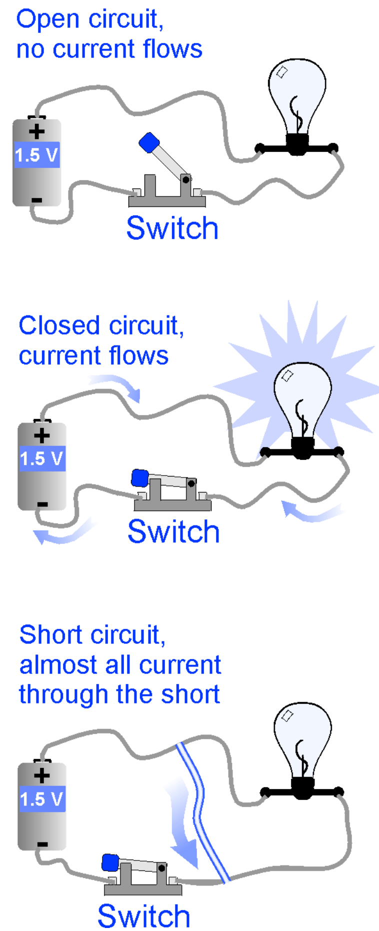


Figure 9.5: *A short circuit is a very low resistance path that can draw huge amounts of current. An open circuit is a break in the circuit that shuts off the flow of current. Switches are used to open and close circuits.*

Chapter 9 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

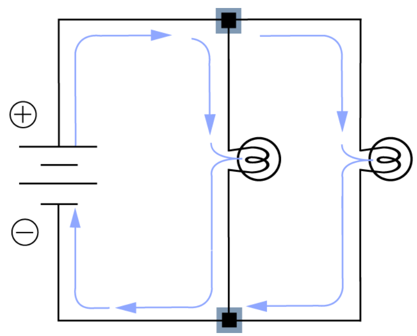
Set One	
1. series circuit	a. In a circuit, all the voltage drops must add up to the total voltage supplied by the battery
2. parallel circuit	b. A circuit that has only one path for the flow of charge
3. Kirchhoff's voltage law	c. A circuit that has more than one path for the flow of charge
4. Kirchhoff's current law	d. Two switches wired in parallel
5. short circuit	e. A circuit path with very low resistance
	f. If current flows into a branch in the circuit, the same amount of current must flow out again

Concept review

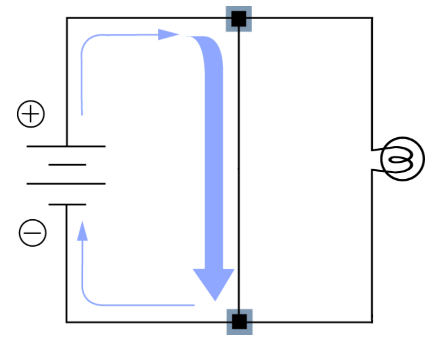
1. Explain the advantage of using a parallel circuit if you have more than one device in the circuit.
2. Imagine that an electrician wired the kitchen in your house so that all the outlets were connected in a single series circuit. Describe what you would have to do to keep the refrigerator running constantly.
3. If you have a light, and one switch that controls it, the light and the switch are wired in ________.
4. Is the current at every point in a series circuit the same?
5. What happens to the total resistance of a series circuit as you add more resistance? Does total resistance of the circuit decrease, increase, or stay the same?
6. Explain why Kirchhoff's voltage law is an application of the law of conservation of energy.
7. Describe what happens to the potential energy of charges in a circuit as they move through a bulb.
8. What happens to the total current of a parallel circuit as you add more branches with current through them? Does total current of the circuit decrease, increase, or stay the same?

9. The voltage across each branch of a parallel circuit is equal to the ________.
10. If a parallel circuit has two branches with equal resistance, what is the total resistance of the circuit?
11. For each diagram below, label the circuit *series*, *parallel*, or *short circuit*. The arrows indicate the flow of current.

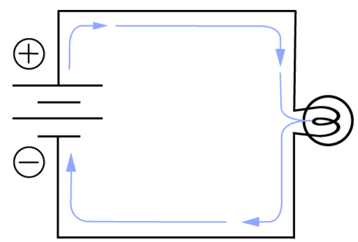
 a.



 b.

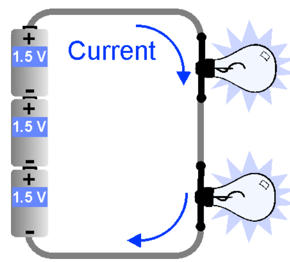


 c.



Problems

1. Answer the following:
   a. A circuit with three 1.5-volt batteries has two matching light bulbs. What is the voltage drop across each light bulb?
   b. Explain how you figured out your answer.



2. A student builds a circuit using three 1-ohm resistors in series. The current in the circuit is 1.5 amps. Use Ohm's law to determine the voltage of the circuit. (Hint: Draw the circuit described in the question.)
3. A student sets up a series circuit with four 1.5-volt batteries, a 5-ohm resistor, and two 1-ohm resistors. (Hint: Draw the circuit described in the question.)
   a. What is the total resistance in her circuit?
   b. Use Ohm's law to determine the value of current for the circuit.
4. A lab group was given a kit containing four 1.5-volt batteries, eight wires, and a resistor set containing three 1-ohm resistors and two 5-ohm resistors. They use all the batteries to build a series circuit. They use a meter to find that the current is 0.857 amps. What resistors did they use and what was the total resistance in the circuit?

5. A lab group was asked to create two circuits with two 1.5-volt batteries. They are given three 1-ohm resistors and two 5-ohm resistors.

   a. The first circuit should have the highest possible current without creating a short circuit. Which resistor(s) should they use and what will the current in the circuit be?

   b. The second circuit should have a current of exactly 1 amp. Which resistor(s) should they use?

6. A circuit breaker in your house is set for 15 amps. You have plugged in a coffeemaker that uses 10 amps. You want to plug in four more things. Which of the four items will cause the circuit breaker to trip because the current is too high?

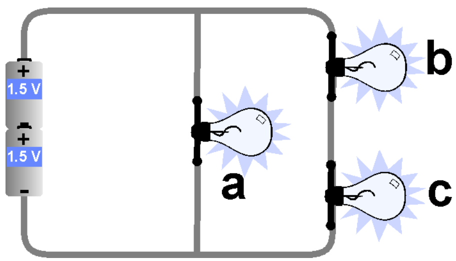
   a. A light that uses 1 amp.

   b. A can opener that uses 2 amps.

   c. A mixer that uses 6 amps.

   d. An electric knife that uses 1.5 amps.

7. Which of the following statements are **true** about the circuit drawn?



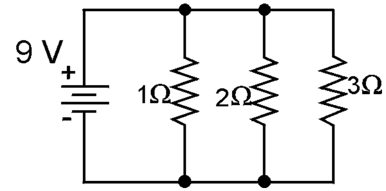
   a. Bulb **a** is brighter than bulb **b** or bulb **c**.

   b. Bulb **a** is dimmer than bulb **b** or bulb **c**.

   c. Bulb **b** is the same brightness as bulb **c**.

   d. Bulb **c** is brighter than bulb **b**.

8. Shown below is a parallel circuit with three branches. Branch 1 contains a 1-ohm resistor, branch 2 contains a 2-ohm resistor, and branch 3 contains a 3-ohm resistor. The circuit is powered by one 9-volt battery.



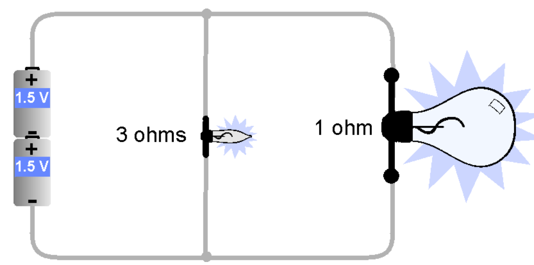
   a. Use Ohm's law to calculate the current in each branch of the circuit.

   b. Use Kirchhoff's current law to calculate the total current in the circuit.

   c. It is possible to replace all three resistors with a single resistor and have the total current in the circuit be the same. Use Ohm's law to calculate what the value of the single resistor should be to keep the total current the same.

   d. If someone were to add a fourth branch (containing a 4-ohm resistor) to the circuit, would the total current of the circuit decrease, increase, or stay the same?

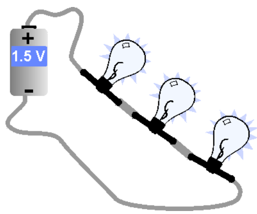
9. Two 1.5-volt batteries are used to connect the circuit below.



   a. What is the total current in the circuit?

   b. Which bulb uses more current?

10. If one bulb is removed from the circuit below, the other bulbs will:



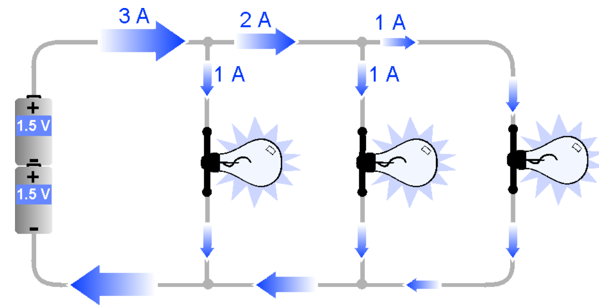
a. get brighter.

b. go out.

c. get dimmer.

d. stay at the same brightness.

11. The resistance of each of the three bulbs in the circuit below is:



a. 1 ohm.

b. 2 ohms.

c. 6 ohms.

d. 3 ohms.

Applying your knowledge

1. In an automobile, the warning bell turns on if you open the door while the key is in the ignition. The bell also turns on if you open the door while the headlights are on. A single circuit with three switches and a bell can be built to ring in both cases. One switch is attached to the door, one switch is attached to the ignition, and one switch is attached to the headlights. Figure out what circuit would make the bell ring at the right times and build or draw your circuit.

2. A burglar alarm system has switches in each door and window. If the door or window is opened, the switch opens a circuit. Draw a circuit that uses one battery and one light bulb to check five doors and windows. The bulb should go out if any of the five doors or windows is opened.