Section 5 Electric Power: Load Limit

What Do You See?

Learning Outcomes

In this section, you will

- **Define** power, insulator, and conductor.
- **Use** the equation for power, $P = IV$.
- **Calculate** the power limit of a 120-V household circuit.
- **Differentiate** between a fuse and a circuit breaker.
- **Identify** the need for circuit breakers and fuses in a home.

What Do You Think?

Everybody has at one time blown a fuse, or tripped a circuit breaker causing the lights to go off in a circuit in the house.

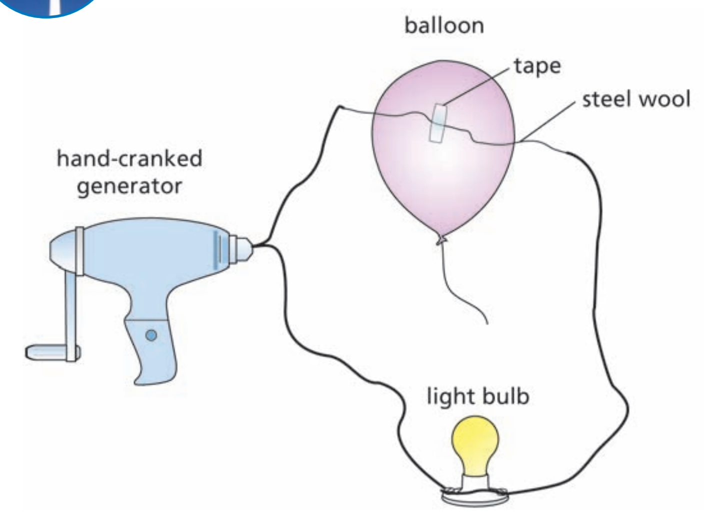
- **What is the function of a fuse or circuit breaker?**
- **Exactly what conditions do you think make a fuse blow or a circuit breaker trip?**

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

Investigate

1. Create your own *fuse* by taping a very thin strand of steel wool to an inflated balloon. Connect the hand generator to one end of the steel wool. Connect the other end of the steel wool to a light bulb. Complete the circuit by connecting the other end of the light bulb to the generator. (You can use additional wires.)

   Begin cranking the generator, slowly at first, and observe the steel wool. Gradually increase the speed of the generator and watch what happens to your fuse.



a) What happens to the light when your fuse blows?

2. Your teacher will do the next part of the *Investigate* as a demonstration for the entire class. You will intentionally exceed the load limit of the power strip that is specially fitted with an external fuse. Household circuits operate at dangerous voltage and current levels, so you should never experiment with those kinds of circuits. Your teacher will add light bulbs, heat lamps, hot plates, hair dryers, and other appliances to the circuit until the fuse blows. Observe the number of appliances needed to reach the load limit and the manufacturer's ratings of the appliances.

a) Why do you think that the fuse blew?

b) Why did the circuit require multiple appliances to blow the fuse?

c) Can you develop a model that explains why the fuse behaves the way it does?

3. In your log, create a table like the one shown.

Appliance	Voltage	Power (watts)	Current (amps)

4. Fill in the table in your log.

a) List each of the appliances needed to blow the fuse in the first column of the chart.

b) House circuits in the United States are all 120 V. Complete the second column of your chart by listing 120 V for each appliance.

Appliances have either power ratings or current ratings noted somewhere on the appliance.

- Power is the amount of energy used per unit time and is measured in watts. One watt (1 W) is equal to one joule per second (1 J/s).
- Current is the flow of electric charge and is measured in amperes (amps, for short). One amp (1 A) is equal to one coulomb per second (1 C/s).

c) Record either the current rating or the power rating of each appliance in the chart.

5. The product of voltage and current is power. $P = VI$

You could derive this equation by looking at the definitions of each quantity.

Quantity	Definition	Units
voltage (V)	energy/charge	J/C or V
current (I)	charge/second	C/s or A
power (P)	energy/second	J/s or W

a) Show that the units on both sides of the equation $P = VI$ are identical.

b) Complete the remainder of your appliance chart by calculating the current or power for each appliance using $P = VI$.

6. Based on the table in *Steps* 2 and 3, answer the following questions.

a) Find the total current and total power of the appliances that blew the fuse.

b) If the fuse had a current rating, did the total current of the appliances exceed that rating?

Physics Talk

ELECTRICAL POWER

What Is Power?

The brightness of a bulb is dependent on the **power**, or the rate at which energy is supplied to the bulb. What is power, and how it is different from energy?

Physics Words

power: the rate at which energy is transmitted, or the amount of energy used in a given unit of time.

Think back to your Electron Shuffle. Each student was a unit of charge and carried a certain amount of energy (a pretzel) through the circuit to the light bulb. Imagine repeating this investigation, only this time keep track of the amount of energy (number of pretzels) left with the light bulb in a certain amount of time, for example 30 s.

First, consider what will happen if the circuit is set up with a 1-V battery (each student carrying one pretzel) and turned on for 30 s. During this time, 30 pretzels leave the battery, and 30 pretzels are left at the light bulb.

Now suppose this is repeated using a 2-V battery, that is, the battery gives out two pretzels to each student unit of charge. Remember, that with twice as much voltage, the current will be twice as much, so students would walk faster with the 2-V battery than with the 1-V battery. In 30 s, 120 pretzels leave the battery, and 120 pretzels are left at the light bulb. If only the voltage had changed, it would have been 60 pretzels. If only the current had changed, it would have been 60 pretzels. With both the current and voltage changing, there are 120 pretzels.

The amount of energy delivered (number of pretzels) for the 2-V battery is four times the energy delivered with the 1-V battery.

If more electric charges were delivering their energy (voltage) at a higher rate of flow (current), it makes sense that you get more power as the current and/or the voltage increase. Increasing the voltage increases the current as well as the amount of energy delivered. This, in turn, increases the power to the light bulb. More power is more energy every second and that will make the bulb brighter.

Is There an Equation?

Power equals voltage multiplied by current.

Power (P) is the energy per time. The units are joules per second (J/s), or watts (W).

Voltage (V) is energy per charge. The units are joules per coulomb (J/C) or volts (V).

Current (I) is the flow of charge per unit time. The units are coulombs per second (C/s) or amps (A).

Think of this in terms of dimensional analysis. Voltage is the amount of energy per unit of charge, and current is the amount of charge per unit of time.

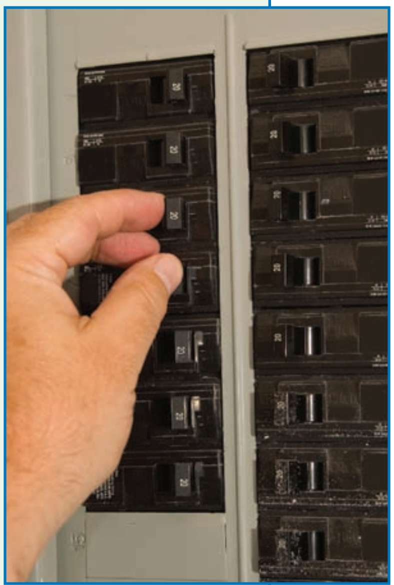
$$\begin{aligned}\text{Power} &= \text{voltage} \times \text{current}\\ &= (\text{energy per charge}) \times (\text{charge per second})\\ &= \frac{\text{energy}}{\text{charge}} \times \frac{\text{charge}}{\text{second}}\\ &= \text{energy/second}\end{aligned}$$

Using symbols:

$$\begin{aligned}P &= VI\\ &= \frac{\text{J}}{\cancel{\text{C}}} \times \frac{\cancel{\text{C}}}{\text{s}}\\ &= \text{J/s}\end{aligned}$$

Blowing a Fuse or Tripping a Circuit Breaker

A **fuse** and a **circuit breaker** are devices that are placed in an electrical circuit to protect it from damage due to too much current. A fuse is designed to melt when too much current flows through, thereby breaking the circuit. A circuit breaker operates like an automatic switch to open the circuit when there is too much current flowing. Unlike a fuse that must be replaced once it has been blown, a circuit breaker can be reset to close the circuit again and return to normal operation. When the wire in a fuse melts and the circuit is opened, the expression used is "blow a fuse." When a circuit breaker opens a circuit when too much charge is flowing through, the expression used is "trip a circuit breaker."



Physics Words

fuse (electrical): a device placed in an electrical circuit that melts when too much current flows through it, thereby breaking the circuit; it protects the other parts of the circuit from damage due to too much current.

circuit breaker: a device placed in an electrical circuit that operates like an automatic switch to open the circuit when too much current flows through.

Some materials are considered to be good **conductors** of electricity. In a conductor, electric charge can flow easily. Metals, such as copper, are good conductors of electricity. That is why copper is commonly used for electrical wires. In a conductor, the outer electrons of each atom are loosely bonded and can be easily shared among atoms. Therefore, the electrons can move freely through the material. Conductors have a very low resistance to electric current. (You will learn more about electrons and bonds when you study the atom.)

Insulators do not allow electric charge to flow easily. The outer electrons of the atoms of insulators are tightly bonded. The electrons cannot be easily shared between neighboring atoms. Examples of insulators include air, glass, plastic, rubber, and wood. Insulators are used to provide protection from potentially dangerous amounts of current flowing through a conductor. The rubber coating on electrical wires protects you from the current flowing through the wire. Insulators have a very high resistance to electrical current. You unfortunately do not!

Did you ever wonder why some appliances cause a fuse to blow or a circuit breaker to trip? Why might turning on a hair dryer blow a fuse but turning on a radio would not? Devices that generate lots of heat also use lots of energy. In the appliance package that you will be creating for the wind generator, there is a load limit of 2400 W. In your own home, you are not restricted to a load limit. If you have the money, the electric company will set up more circuits, allowing you to use more electricity. The company can then collect more money from you.

Many people have plugged in a hair dryer and blown a fuse. If you think back, it always seems to be that a blown fuse or a tripped circuit breaker is due to someone plugging in a hair dryer, a toaster oven, or a hot plate (all heat-generating devices). It never seems to happen when someone plugs in a radio or a clock. The table below shows the power ratings of some appliances.

Appliance	Power rating (W)
hair dryer	1200
toaster oven	1500
radio	70
clock	3

The appliances with high power ratings are responsible for blowing a fuse or tripping the circuit breaker.

In the *Investigate*, you were able to burn a wire and explode a balloon by increasing the current. During the demonstration, something similar happened. As you added appliances, you kept increasing the current until a small wire in the fuse burned (or a circuit breaker tripped) and an open, incomplete circuit resulted. For this reason, a fuse must always be connected in series, so that when it burns out, the circuit will be open and current flow will stop.

Physics Words

conductor: a material through which electric current can move easily; metals are good conductors.

insulator: a material through which electric current cannot move easily; air, glass, plastic, rubber, and wood are examples of insulators.

Why have a fuse? It seems like a nuisance. If the power company will supply the electricity, why do you need fuses to limit the current and power you use? The fuse is a safety device. The fuse or circuit breaker is there to limit the total current in a typical circuit to 15 A or 20 A, depending upon the wires. All electrical currents generate heat. This is because the movement of electric charge in the resistors of the circuit involves transforming energy into heat. Even wires that typically have very low resistance can get hot. Since the job of the wires is to deliver energy to the circuit loads, you do not want the wires to get too hot, or they might cause a fire. Electrical fires within the walls are exceedingly dangerous because they often go undetected while building up deadly fumes. Limits must be set on how much current a wire may carry safely. That is the job of a fuse or circuit breaker.

If the fuse is rated at 15 A, you can use as many appliances as you like in that circuit as long as the total current is less than 15 A. Once you exceed 15 A, the fuse will blow, opening the circuit and reminding you to unplug some appliances.

Thinking About Your Appliance Package

Home circuits in the United States provide 120 V. Knowing this, you can calculate the current of each appliance.

Appliance	Power rating (W)	Voltage (V)	Current (A)
hair dryer	1200	120	10
toaster oven	1500	120	12.5
radio	70	120	0.6
clock	3	120	0.03

Brightness of a bulb is related to the rate of light energy emitted, which is related to the energy per second or power used. If bulbs are manufactured the same way, a 100-W bulb will be brighter than a 60-W bulb.

However, there are now 20-W compact fluorescent bulbs that can produce the same amount of light as 100-W conventional bulbs. Much of the 100 W of power used in the conventional bulb generates heat and not light. Replacing a conventional bulb with a compact fluorescent bulb saves quite a lot of power. When you are limited to 2400 W of peak power from the wind generator, the compact fluorescent bulbs may be just what you want to recommend.

Since the appliances you will use are all designed to operate at 120 V, the voltage of the circuits in your home needs to be 120 V. If the fuse or circuit breaker can handle a maximum of 15 A, then the power limit is 120 V × 15 A or 1800 W. If a toaster is 1200 W and a hair dryer is 1000 W, they cannot both be operating simultaneously on any one line in your house since they total 2200 W, which is more than the 1800-W limit. If you want to run both appliances at the same time, you must use different circuits, each with its own 1800-W limit.

A second way of viewing the circuit is to look at the current requirements of each appliance. Since the appliances are in parallel, the total current will be the sum of all of the individual currents. In the example above, the current of the 1200-W toaster can be found using the power equation. The current is 1200 W ÷ 120 V or 10 A. Similarly, the hair dryer requires about 8 A. The total current is about 18 A. This is more than the 15-A fuse can tolerate.

Sample Problem 1

A 12-V starter battery in a car supplies 48 A of current to the starter. What is the power output of the battery?

Strategy: You are asked to find the power, so you use the power equation that is specific to electrical circuits.

Given:

$V = 12\text{ V}$

$I = 48\text{ A}$

Solution:

$$P = VI$$

$$= (12\text{ V})(48\text{ A})$$

$$= \left(12\,\frac{\text{J}}{\cancel{\text{C}}}\right)\left(48\,\frac{\cancel{\text{C}}}{\text{s}}\right)$$

$$= 576\text{ J/s or about 580 W}$$

Sample Problem 2

A 75-W study lamp is plugged into the 120-V household outlet in your room. What current does the outlet supply to the light bulb?

Strategy: Again, use the power equation but rearrange the equation to solve for current.

Given:

$P = 75\text{ W}$

$V = 120\text{ V}$

Solution:

$$I = \frac{P}{V}$$

$$= \frac{75\text{ W}}{120\text{ V}}$$

$$= \frac{75\text{ (J/s)}}{120\text{ (J/C)}}$$

$$\frac{75}{120}\left(\frac{\cancel{\text{J}}}{\text{s}}\right) \times \left(\frac{\text{C}}{\cancel{\text{J}}}\right)$$

$$= 0.63\text{ C/s or }0.63\text{ A}$$

Light bulbs do not draw a lot of current.

Sample Problem 3

A light bulb operating at 120 V draws 0.50 A. Determine the bulb's

a) resistance

b) power

Strategy: Ohm's law can be used to determine the resistance of the light bulb. The power can be determined using $P = VI$.

Given:

$V = 120\text{ V}$

$I = 0.50\text{ A}$

Solution:

a) $V = IR$

Solving for R,

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

$$= \frac{120\text{ V}}{0.50\text{ A}}$$

$$= 240\ \Omega$$

b) $P = VI$

$$= (120\text{ V})(0.50\text{ A})$$

$$= 120\frac{\text{J}}{\cancel{\text{C}}} \times 0.50\frac{\cancel{\text{C}}}{\text{s}}$$

$$= 60\text{ J/s or }60\text{ W}$$

Checking Up

1. What is the purpose of a fuse in a circuit?
2. How must a fuse be connected in a circuit to prevent current from flowing when the circuit becomes "overloaded"?
3. A household circuit that uses 120 V has a 15-A fuse in the circuit. How many total watts from different appliances can the circuit supply before the fuse is in danger of burning out?
4. A 60-W and a 100-W bulb are each plugged into a 120-V circuit. Which light bulb will have the larger current?

Active Physics Plus

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Combining the Power Equation and Ohm's Law

Algebraically combining the power equation and Ohm's law can provide you with some very helpful equations.

Since $P = VI$ and $V = IR$

Substitute IR for V in the power equation

Then $P = (IR)I$

$$P = I^2R$$

This form of the power equation is helpful when you know the values of current and resistance. You do not need to find the voltage across the resistor.

Since $P = VI$ and $V = IR$

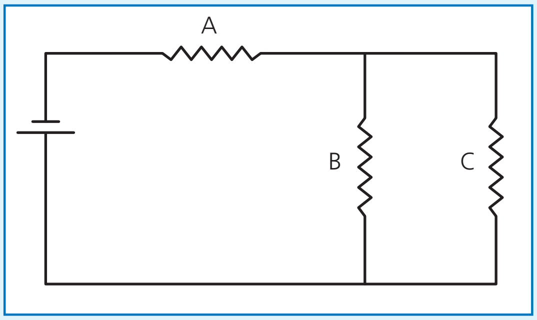
Subsitute $\frac{V}{R}$ for I in the power equation

Then $P = V\left(\frac{V}{R}\right)$

$$P = \frac{V^2}{R}$$

This form of the power equation is helpful when you know the values of voltage and resistance. It saves you from the need to find the current through the resistor.

1. In a series circuit, all resistors have identical currents.
   a) What is the relationship between the power and resistance of these resistors?
   b) In a parallel circuit, all resistors have identical voltages. What is the relationship between the power and resistance of these resistors?
2. Two identical resistors ($R = 6\ \Omega$) are connected in series to an 18-V battery.
   a) Calculate the current, voltage, and power of each resistor.
   b) These same identical resistors ($R = 6\ \Omega$) are now connected in parallel to an 18-V battery. Calculate the current, voltage, and power for each resistor.
3. A circuit consisting of three light bulbs is shown below. When light bulb B is removed, what happens to the brightness of the remaining two bulbs? (Use your model of the Electron Shuffle to guide you.)



What Do You Think Now?

At the beginning of this section, you were asked:

- **What is the function of a fuse or circuit breaker?**
- **Exactly what conditions do you think make a fuse blow or a circuit breaker trip?**

Now that you have completed this section, how would you now answer these questions? What else would you think you need to know to answer the questions more completely?

Physics Essential Questions

What does it mean?

What does it mean to blow a fuse or trip a circuit breaker?

How do you know?

In a typical household circuit, what evidence do you have that a 15-A fuse will blow when more than 1800 W are plugged in?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	* Models	Experimental evidence is consistent with models and theories

* Physicists use models to help understand and make sense of a wide variety of phenomena. How does the Electron-Shuffle model help you to understand the relationship among power, voltage, and current?

Why should you care?

The wind generator available for Homes For Everyone is limited to a maximum power of 2400 W at any one time. How will you use this information when you develop your appliance package? How can a fuse help to limit people's power consumption?

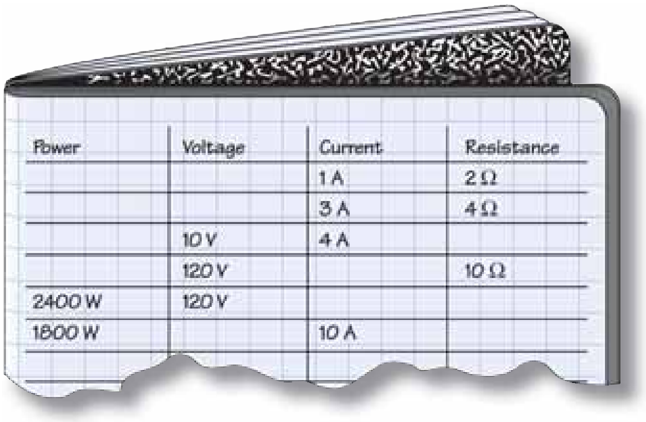
Reflecting on the Section and the Challenge

The total power capacity of the wind generator is 2400 W, so the load limit of the electrical system for the HFE dwelling is 2400 W, as outlined in the *Scenario* of the *Chapter Challenge*. Since most electrical appliances are designed around an industry standard of 120 V, the power plant of the wind generator will provide 120 V to circuits within the dwelling. In this *Investigate*, you learned what load limit means, and how to relate it to current and voltage. If the people in the dwelling try to run appliances that require more than 2400 W, the fuse will blow. If this were to happen in your own home, you could always choose a different line to run the extra appliances. With only one generator, this is not an option in the HFE dwelling. This will have direct application soon when you begin selecting appliances to be used in the dwelling.

Physics to Go

1. In your *Active Physics* log, complete the table below. The table provides two of the following four quantities in a circuit: voltage, current, power, and resistance. If you know two of these, you can find the others.

   Example: In the first row the resistance is 2 Ω and the current is 1 A. Using Ohm's law, $V = IR$, you can find the value of the voltage (V). The value of the voltage is 2 V. The power is given by $P = IV$. The power is 2 W.



Power	Voltage	Current	Resistance
		1 A	2 Ω
		3 A	4 Ω
	10 V	4 A	
	120 V		10 Ω
2400 W	120 V		
1800 W		10 A	

2. Explain in detail what load limit means, and include maximum current, in amperes, as part of your explanation.
3. An electric hair dryer has a power rating of 1200 W and is designed to be used on a 120-V household circuit. How much current flows in the hair dryer when it is in use?
4. A 120-V circuit for the kitchen of a home is protected by a 20-A circuit breaker. What combinations of the appliances listed below can be used on the circuit at the same time without the circuit breaker shutting off the circuit?
   - 1000-W toaster
   - 1200-W frying pan
   - 300-W blender
   - 600-W coffee maker
5. How many 60-W incandescent light bulbs can be operated at the same time on a 120-V, 15-A circuit in a home? How many energy-efficient 22-W bulbs can operate on a similar circuit?
6. Some electrical appliances are rated in horsepower (HP). 1 HP = 746 W. What amount of current flows in a 0.8 HP vacuum cleaner operating on a 120-V circuit?

7. Some electrical appliances are rated in amps. What is the power in watts of a 6-A appliance designed to operate on a 120-V circuit?

8. A 1500-W hair dryer is plugged into the outlet in your bathroom. How much current does this hair dryer draw?

9. When you turn on the toaster in the kitchen, it draws 8.0 A of current from the line.

   a) Find the power output of the toaster.

   b) You plug another toaster in the same outlet and the circuit breaker trips. What is the maximum current for the type of breaker you are using?

10. A 3-W clock operates at 120 V.

    a) How much current does the clock draw?

    b) Determine the clock's resistance.

    c) If the maximum current that can be drawn from the outlet is 15 A, how many clocks would it take to blow the fuse? (Assume all clocks could be plugged into the outlet.)

11. An iron has a resistance of 13.1 Ω. Could two identical clothing irons operate on the same fuse? (Assume $V = 120\text{ V}$ and $I_{max} = 15\text{ A}$.)

12. The load limit for a household circuit operating at 120 V is 2400 W. Exceeding that limit will result in a blown fuse. Which combination of the following devices would blow the fuse: mini-refrigerator (P = 300 W), microwave oven (R = 19 Ω), hair dryer (I = 12 A), coffee maker (R = 9.2 Ω).

13. How much current, in amps, must exist in the filament of

    a) A 60-W light bulb when it is operating in a 120-V household circuit?

    b) A 100-W light bulb?

    c) Fuses and circuit breakers are rated in amperes, usually 15 or 20 A for most household circuits. Use the equation $P = VI$ to show how you can calculate the load limit, in watts, of a 120-V household circuit protected by a 15-A circuit breaker.

14. ***Preparing for the Chapter Challenge***

    a) Find out about the power rating, in watts, of at least six electrical appliances. You can do this at home, at a store that sells appliances, by studying a catalog, or on the Internet. Some appliances have the watt rating stamped somewhere on the device itself, but for others you may have to check the instruction book for the appliance or find the power rating on the original package. Also, your local power company probably will provide a free list of appliances and their power ratings on request. If the appliance lists the current in amperes, you can assume a voltage of 120 V and calculate the power (in watts) by using the equation $P = VI$.

b) List three appliances you would include in the HFE appliance package that will be part of the *Chapter Challenge*. For each appliance, list the power demand. For each appliance, describe how it will contribute to the well-being of the people living in the dwelling.

Inquiring Further

Electrical system of a house

Find out about the electrical system of your home or the home of a friend or acquaintance. With the approval of the owner or manager, and with adult supervision, locate the load center, also called the main distribution panel, for the electrical system. Open the panel door and observe whether the system uses circuit breakers or fuses. How many are there, and what is the ampere rating shown on each fuse or circuit breaker?

You may find some larger fuses or breakers that control large, 240-V appliances such as a kitchen range (electric stove); if so, how many are there and what are their ampere ratings? If you can, determine what they control.

In some load centers there is a list of what rooms or electrical devices are controlled by each fuse or breaker, but often the list is missing or incomplete.

With the approval of the owner or manager, and with adult supervision, you can develop a list that indicates what each fuse or breaker controls. To do so, shut off one circuit and go through the entire house to find the lights and outlets that are "dead" (check outlets with a lamp that you can carry around easily). Those items that are "off" are controlled by that fuse or breaker. List them. Then turn that circuit back on and repeat the same process with another circuit.

Report your findings to your teacher in the form of a list or diagram of the house showing what is controlled by each fuse or circuit breaker.