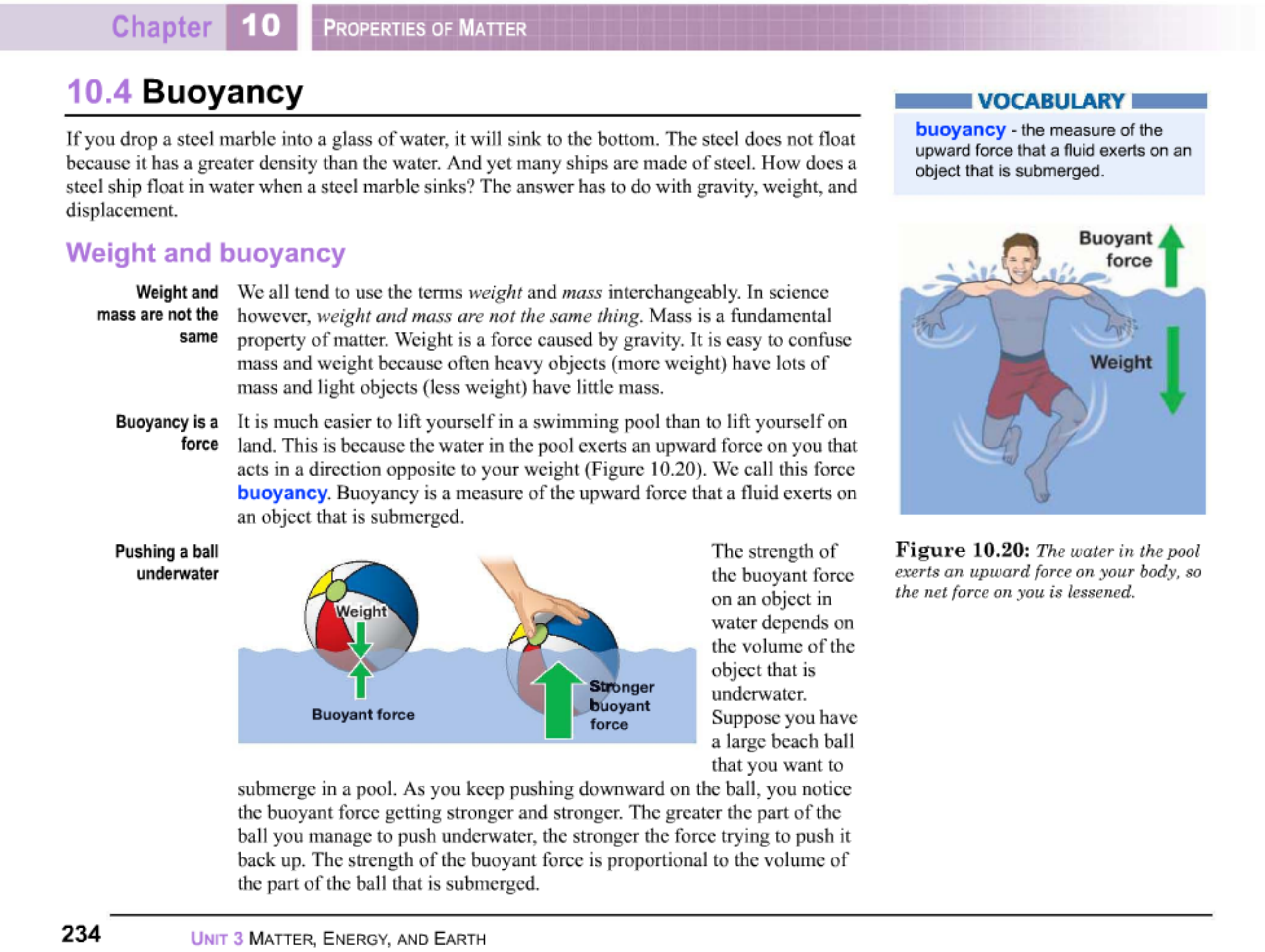


10.4 Buoyancy

If you drop a steel marble into a glass of water, it will sink to the bottom. The steel does not float because it has a greater density than the water. And yet many ships are made of steel. How does a steel ship float in water when a steel marble sinks? The answer has to do with gravity, weight, and displacement.

VOCABULARY

buoyancy - the measure of the upward force that a fluid exerts on an object that is submerged.

Weight and buoyancy

Weight and mass are not the same

We all tend to use the terms *weight* and *mass* interchangeably. In science however, *weight and mass are not the same thing*. Mass is a fundamental property of matter. Weight is a force caused by gravity. It is easy to confuse mass and weight because often heavy objects (more weight) have lots of mass and light objects (less weight) have little mass.

Buoyancy is a force

It is much easier to lift yourself in a swimming pool than to lift yourself on land. This is because the water in the pool exerts an upward force on you that acts in a direction opposite to your weight (Figure 10.20). We call this force **buoyancy**. Buoyancy is a measure of the upward force that a fluid exerts on an object that is submerged.

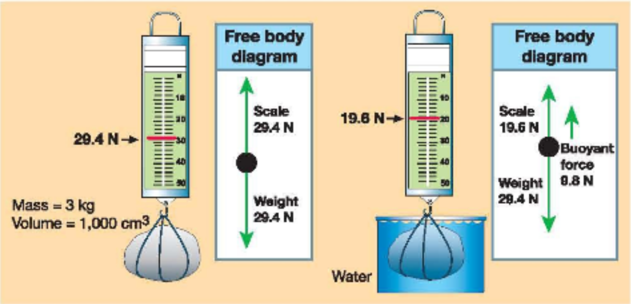
Figure 10.20: *The water in the pool exerts an upward force on your body, so the net force on you is lessened.*

Pushing a ball underwater

The strength of the buoyant force on an object in water depends on the volume of the object that is underwater. Suppose you have a large beach ball that you want to submerge in a pool. As you keep pushing downward on the ball, you notice the buoyant force getting stronger and stronger. The greater the part of the ball you manage to push underwater, the stronger the force trying to push it back up. The strength of the buoyant force is proportional to the volume of the part of the ball that is submerged.

Archimedes' principle

What is Archimedes' principle? In the third century BCE, a Greek mathematician named Archimedes realized that buoyant force is equal to the weight of the fluid displaced by an object. We call this relationship **Archimedes' principle**. For example, suppose a rock with a volume of 1,000 cubic centimeters is dropped into water (Figure 10.21). The rock displaces 1,000 cm^3 of water, which has a mass of 1 kilogram. The buoyant force on the rock is the weight of 1 kilogram of water or 9.8 newtons.



A simple buoyancy experiment Look at the illustration above. A simple experiment can be done to measure the buoyant force on a rock (or other small object) using a spring scale. Suppose you have a rock with a volume of 1,000 cubic centimeters and a mass of 3 kilograms. In air, the scale shows the rock's weight as 29.4 newtons. The rock is then gradually immersed in a container of water, but not allowed to touch the bottom or sides of the container. As the rock enters the water, the reading on the scale decreases. When the rock is completely submerged, the scale reads 19.6 newtons.

Calculating the buoyant force Subtracting the two scale readings, 29.4 newtons and 19.6 newtons, results in a difference of 9.8 newtons. This is the buoyant force exerted on the rock, and it is the same as the weight of the 1,000 cubic centimeters of water the rock displaced.

VOCABULARY

Archimedes' principle - states that the buoyant force is equal to the weight of the fluid displaced by an object.

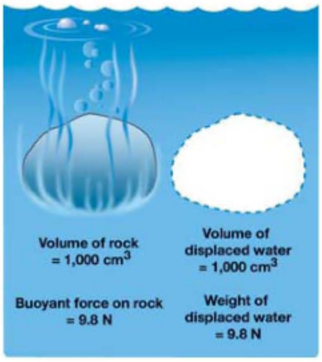
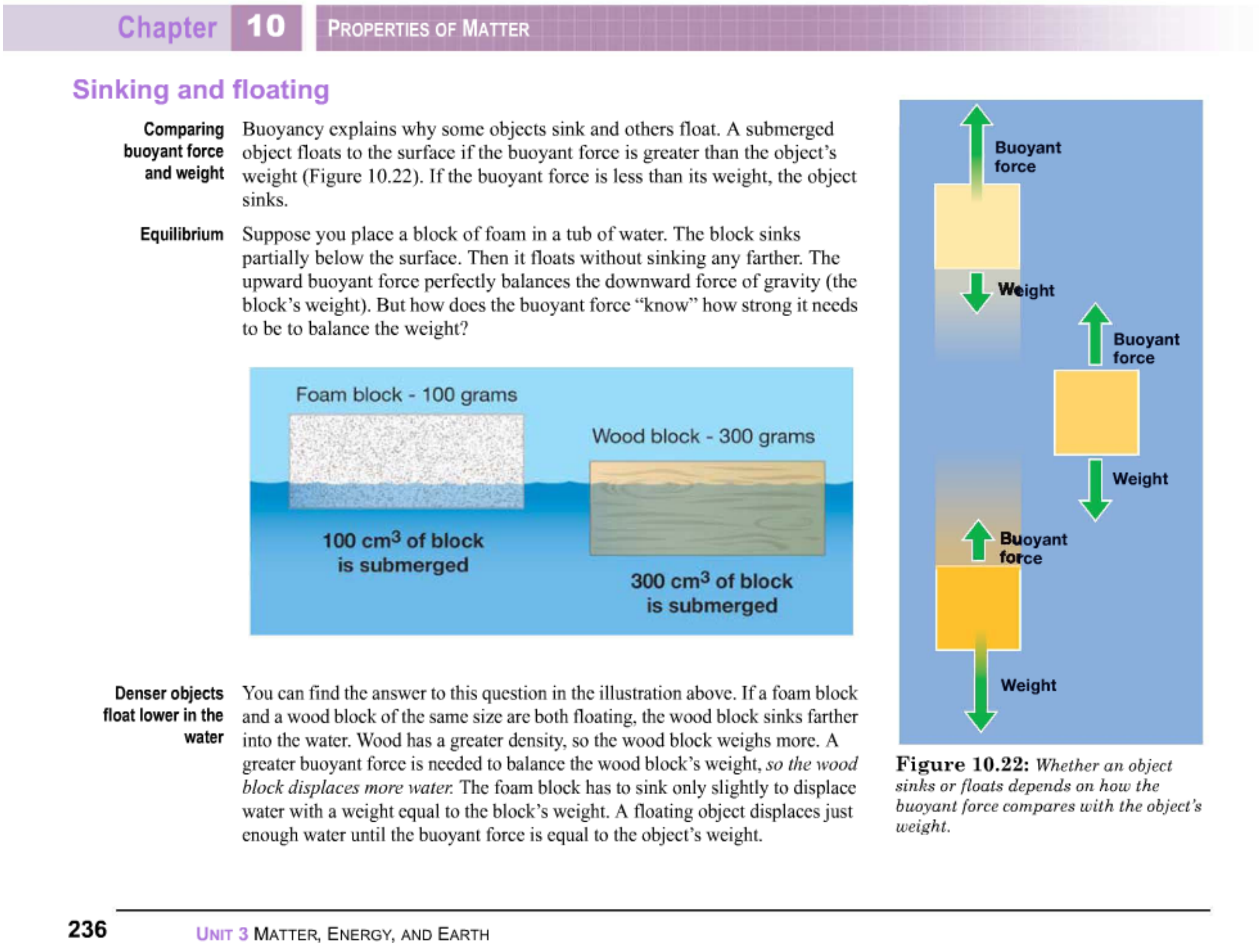


Figure 10.21: *A rock with a volume of 1,000 cm^3 experiences a buoyant force of 9.8 newtons.*



Sinking and floating

Comparing buoyant force and weight Buoyancy explains why some objects sink and others float. A submerged object floats to the surface if the buoyant force is greater than the object's weight (Figure 10.22). If the buoyant force is less than its weight, the object sinks.

Equilibrium Suppose you place a block of foam in a tub of water. The block sinks partially below the surface. Then it floats without sinking any farther. The upward buoyant force perfectly balances the downward force of gravity (the block's weight). But how does the buoyant force "know" how strong it needs to be to balance the weight?

Denser objects float lower in the water You can find the answer to this question in the illustration above. If a foam block and a wood block of the same size are both floating, the wood block sinks farther into the water. Wood has a greater density, so the wood block weighs more. A greater buoyant force is needed to balance the wood block's weight, *so the wood block displaces more water.* The foam block has to sink only slightly to displace water with a weight equal to the block's weight. A floating object displaces just enough water until the buoyant force is equal to the object's weight.

Figure 10.22: *Whether an object sinks or floats depends on how the buoyant force compares with the object's weight.*

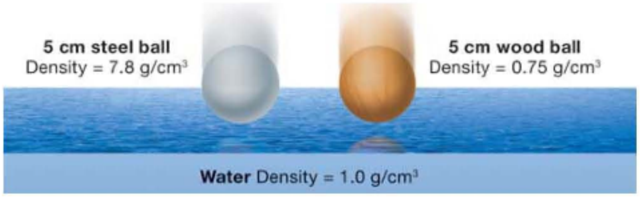
Density and buoyancy

Comparing densities

If you know an object's density, you can immediately predict whether it will sink or float—without measuring its weight. An object sinks if its density is greater than that of the liquid it is submerged into. It floats if its density is less than that of the surrounding fluid.

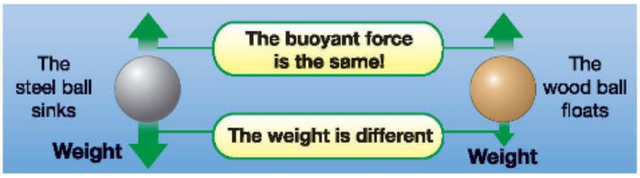
Two balls with the same volume but different densities

To see why, imagine dropping a steel ball and a wood ball into a pool of water. The balls have the same size and volume but have different densities. The steel ball has a density of 7.8 g/cm^3, which is greater than the density of water (1.0 g/cm^3). The wood ball has a density of 0.75 g/cm^3, which is less than the density of water.



Why one sinks and the other floats

When they are completely underwater, both balls have the same buoyant force because they displace the same volume of water. However, the steel ball has more weight since it has a higher density. The steel ball sinks because steel's higher density makes the ball heavier than the same volume of water. The wood ball floats because wood's lower density makes the wood ball lighter than the same volume of displaced water.



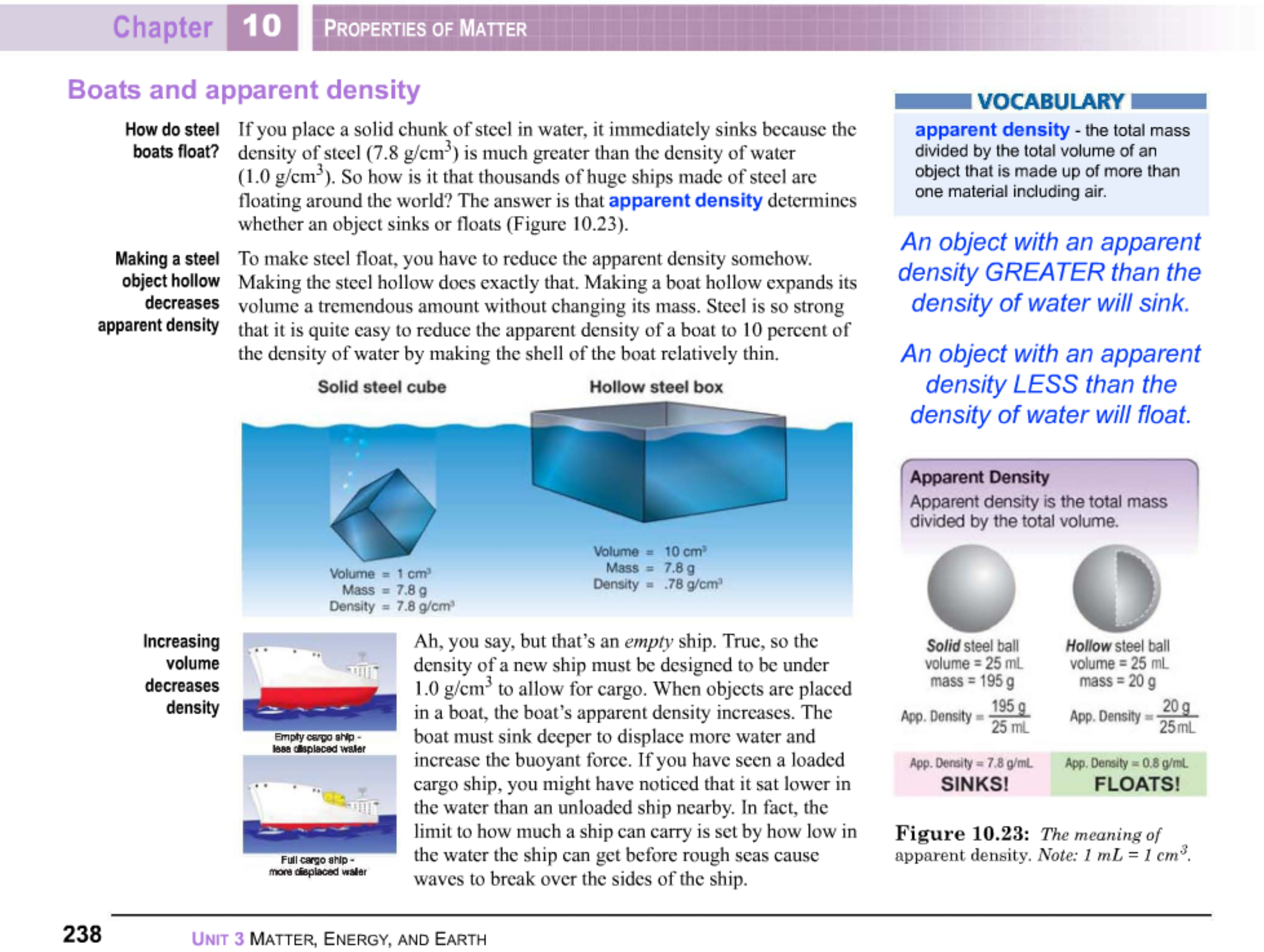
TECHNOLOGY

Buoyancy and Submarines

Deep beneath the ocean surface are undersea mountains and volcanoes and many clues to past and present conditions of our planet. Exploring the deep ocean requires sophisticated engineering. The U.S. Navy's submarine *Alvin* is a research vessel that can dive to 4,500 meters below the ocean surface. Scientists aboard *Alvin* have discovered strange life forms near deep hot spots where there is no light, and pressures are 400 times greater than at Earth's surface!

Alvin's depth is controlled by changing its average density. There is a chamber aboard the submarine that can be filled with air or water. To dive, water is pumped into the tank and air is released. The tank's average density becomes greater than the density of water and the submarine sinks.

When *Alvin* reaches the proper depth, the amount of air and water is adjusted with pumps until the average density of the whole vessel is the same as the density of water. This is called neutral buoyancy. When it is time for *Alvin* to head back to the surface, water is pumped out of the tank and replaced with air. *Alvin*'s average density decreases and the submarine rises.



Boats and apparent density

How do steel boats float? If you place a solid chunk of steel in water, it immediately sinks because the density of steel (7.8 g/cm^3) is much greater than the density of water (1.0 g/cm^3). So how is it that thousands of huge ships made of steel are floating around the world? The answer is that **apparent density** determines whether an object sinks or floats (Figure 10.23).

Making a steel object hollow decreases apparent density To make steel float, you have to reduce the apparent density somehow. Making the steel hollow does exactly that. Making a boat hollow expands its volume a tremendous amount without changing its mass. Steel is so strong that it is quite easy to reduce the apparent density of a boat to 10 percent of the density of water by making the shell of the boat relatively thin.

Increasing volume decreases density Ah, you say, but that's an *empty* ship. True, so the density of a new ship must be designed to be under 1.0 g/cm^3 to allow for cargo. When objects are placed in a boat, the boat's apparent density increases. The boat must sink deeper to displace more water and increase the buoyant force. If you have seen a loaded cargo ship, you might have noticed that it sat lower in the water than an unloaded ship nearby. In fact, the limit to how much a ship can carry is set by how low in the water the ship can get before rough seas cause waves to break over the sides of the ship.

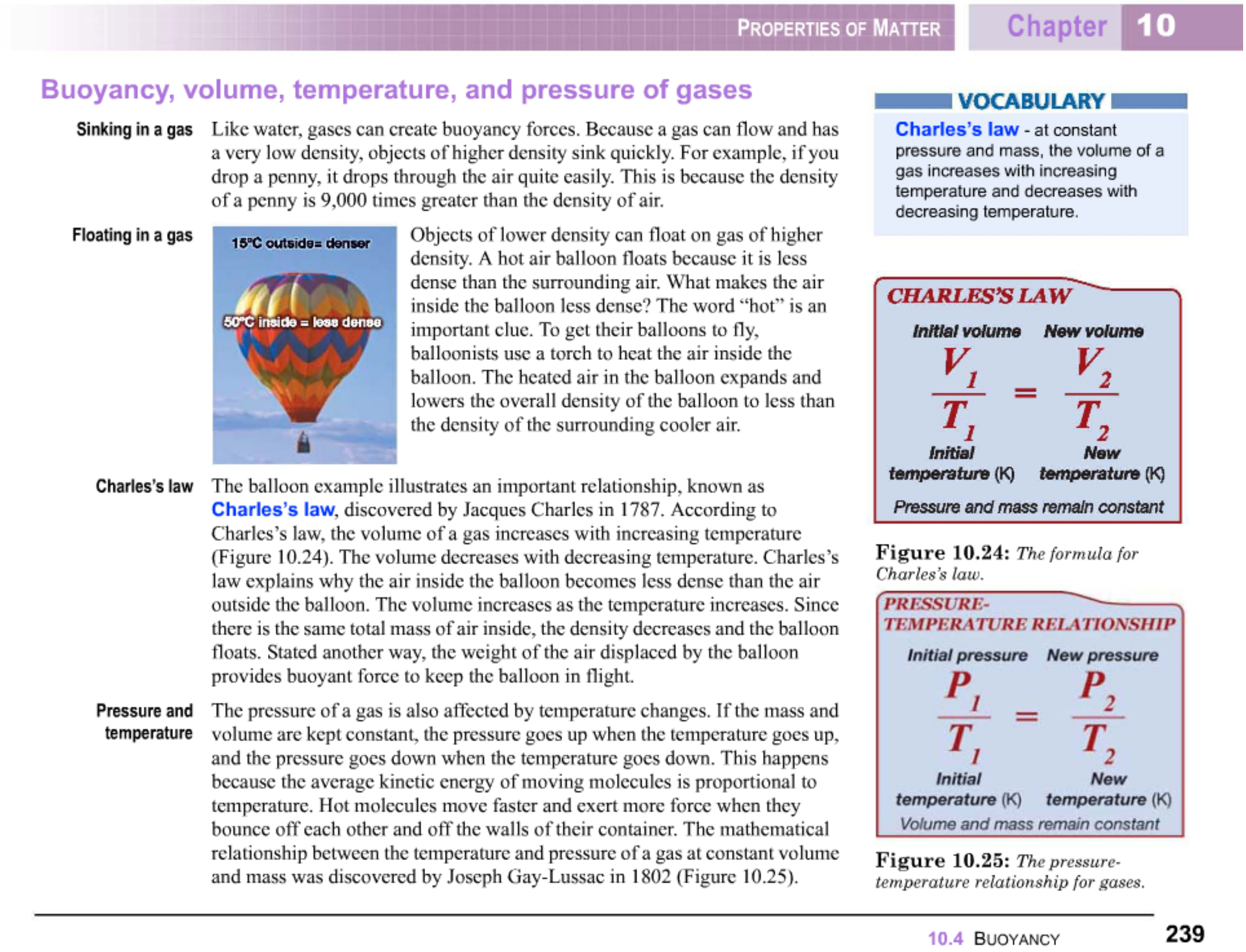
VOCABULARY

apparent density - the total mass divided by the total volume of an object that is made up of more than one material including air.

An object with an apparent density GREATER than the density of water will sink.

An object with an apparent density LESS than the density of water will float.

Figure 10.23: *The meaning of* apparent density. *Note: 1 mL = 1 cm^3.*



Buoyancy, volume, temperature, and pressure of gases

Sinking in a gas Like water, gases can create buoyancy forces. Because a gas can flow and has a very low density, objects of higher density sink quickly. For example, if you drop a penny, it drops through the air quite easily. This is because the density of a penny is 9,000 times greater than the density of air.

Floating in a gas Objects of lower density can float on gas of higher density. A hot air balloon floats because it is less dense than the surrounding air. What makes the air inside the balloon less dense? The word "hot" is an important clue. To get their balloons to fly, balloonists use a torch to heat the air inside the balloon. The heated air in the balloon expands and lowers the overall density of the balloon to less than the density of the surrounding cooler air.

Charles's law The balloon example illustrates an important relationship, known as **Charles's law**, discovered by Jacques Charles in 1787. According to Charles's law, the volume of a gas increases with increasing temperature (Figure 10.24). The volume decreases with decreasing temperature. Charles's law explains why the air inside the balloon becomes less dense than the air outside the balloon. The volume increases as the temperature increases. Since there is the same total mass of air inside, the density decreases and the balloon floats. Stated another way, the weight of the air displaced by the balloon provides buoyant force to keep the balloon in flight.

Pressure and temperature The pressure of a gas is also affected by temperature changes. If the mass and volume are kept constant, the pressure goes up when the temperature goes up, and the pressure goes down when the temperature goes down. This happens because the average kinetic energy of moving molecules is proportional to temperature. Hot molecules move faster and exert more force when they bounce off each other and off the walls of their container. The mathematical relationship between the temperature and pressure of a gas at constant volume and mass was discovered by Joseph Gay-Lussac in 1802 (Figure 10.25).

VOCABULARY

Charles's law - at constant pressure and mass, the volume of a gas increases with increasing temperature and decreases with decreasing temperature.

CHARLES'S LAW

Initial volume, New volume

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Initial temperature (K), New temperature (K)

Pressure and mass remain constant

Figure 10.24: *The formula for Charles's law.*

PRESSURE-TEMPERATURE RELATIONSHIP

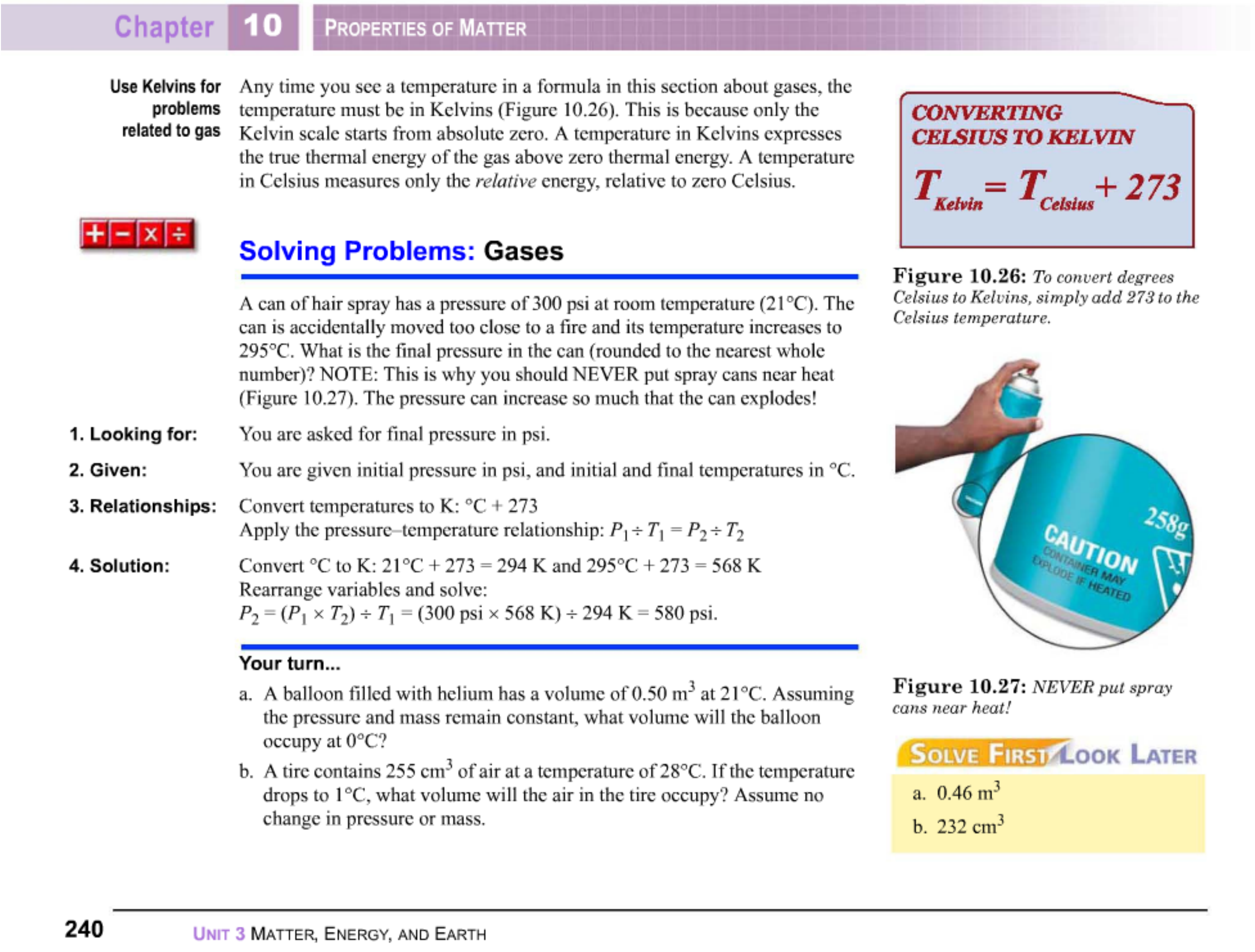
Initial pressure, New pressure

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Initial temperature (K), New temperature (K)

Volume and mass remain constant

Figure 10.25: *The pressure-temperature relationship for gases.*



Use Kelvins for problems related to gas

Any time you see a temperature in a formula in this section about gases, the temperature must be in Kelvins (Figure 10.26). This is because only the Kelvin scale starts from absolute zero. A temperature in Kelvins expresses the true thermal energy of the gas above zero thermal energy. A temperature in Celsius measures only the *relative* energy, relative to zero Celsius.

CONVERTING CELSIUS TO KELVIN

$$T_{Kelvin} = T_{Celsius} + 273$$

Figure 10.26: *To convert degrees Celsius to Kelvins, simply add 273 to the Celsius temperature.*

Solving Problems: Gases

A can of hair spray has a pressure of 300 psi at room temperature (21°C). The can is accidentally moved too close to a fire and its temperature increases to 295°C. What is the final pressure in the can (rounded to the nearest whole number)? NOTE: This is why you should NEVER put spray cans near heat (Figure 10.27). The pressure can increase so much that the can explodes!

1. Looking for: You are asked for final pressure in psi.

2. Given: You are given initial pressure in psi, and initial and final temperatures in °C.

3. Relationships: Convert temperatures to K: °C + 273

Apply the pressure–temperature relationship: $P_1 \div T_1 = P_2 \div T_2$

4. Solution: Convert °C to K: 21°C + 273 = 294 K and 295°C + 273 = 568 K

Rearrange variables and solve:

$P_2 = (P_1 \times T_2) \div T_1 = (300 \text{ psi} \times 568 \text{ K}) \div 294 \text{ K} = 580 \text{ psi}.$

Your turn...

a. A balloon filled with helium has a volume of 0.50 m^3 at 21°C. Assuming the pressure and mass remain constant, what volume will the balloon occupy at 0°C?

b. A tire contains 255 cm^3 of air at a temperature of 28°C. If the temperature drops to 1°C, what volume will the air in the tire occupy? Assume no change in pressure or mass.

Figure 10.27: *NEVER put spray cans near heat!*

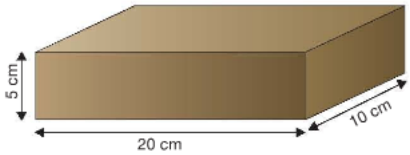
SOLVE FIRST LOOK LATER

a. 0.46 m^3

b. 232 cm^3

Section 10.4 Review

1. The buoyant force on an object depends on the _____ of the object that is underwater.
2. What happens to the buoyant force on an object as it is lowered into water? Why?
3. The buoyant force on an object is equal to the weight of the water it _____.
4. When the buoyant force on an object is greater than its weight, the object _____.



5. A rectangular object is 10 centimeters long, 5 centimeters high, and 20 centimeters wide. Its mass is 800 grams.
   a. Calculate the object's volume in cubic centimeters.
   b. Calculate the object's density in g/cm^3.
   c. Will the object float or sink in water? Explain.
6. Solid iron has a density of 7.9 g/cm^3. Liquid mercury has a density of 13.5 g/cm^3. Will iron float or sink in mercury? Explain.
7. Why is it incorrect to say that heavy objects sink in water?
8. Steel is denser than water, yet steel ships float. Explain.
9. If mass and pressure are constant, what is the relationship between temperature and volume?
10. A helium balloon has a pressure of 40.0 psi at 20°C. What will the pressure be at 40°C? Assume constant volume and mass.

CHALLENGE

Legend has it that Archimedes added to his fame by using the concepts of volume and density to figure out whether a goldsmith had cheated Hiero II, the king of Syracuse. The goldsmith had been given a piece of gold of a known weight to make a crown. Hiero suspected the goldsmith had kept some of the gold for himself and replaced it with an equal weight of another metal. Explain the steps you could follow to determine whether or not the crown was pure gold.