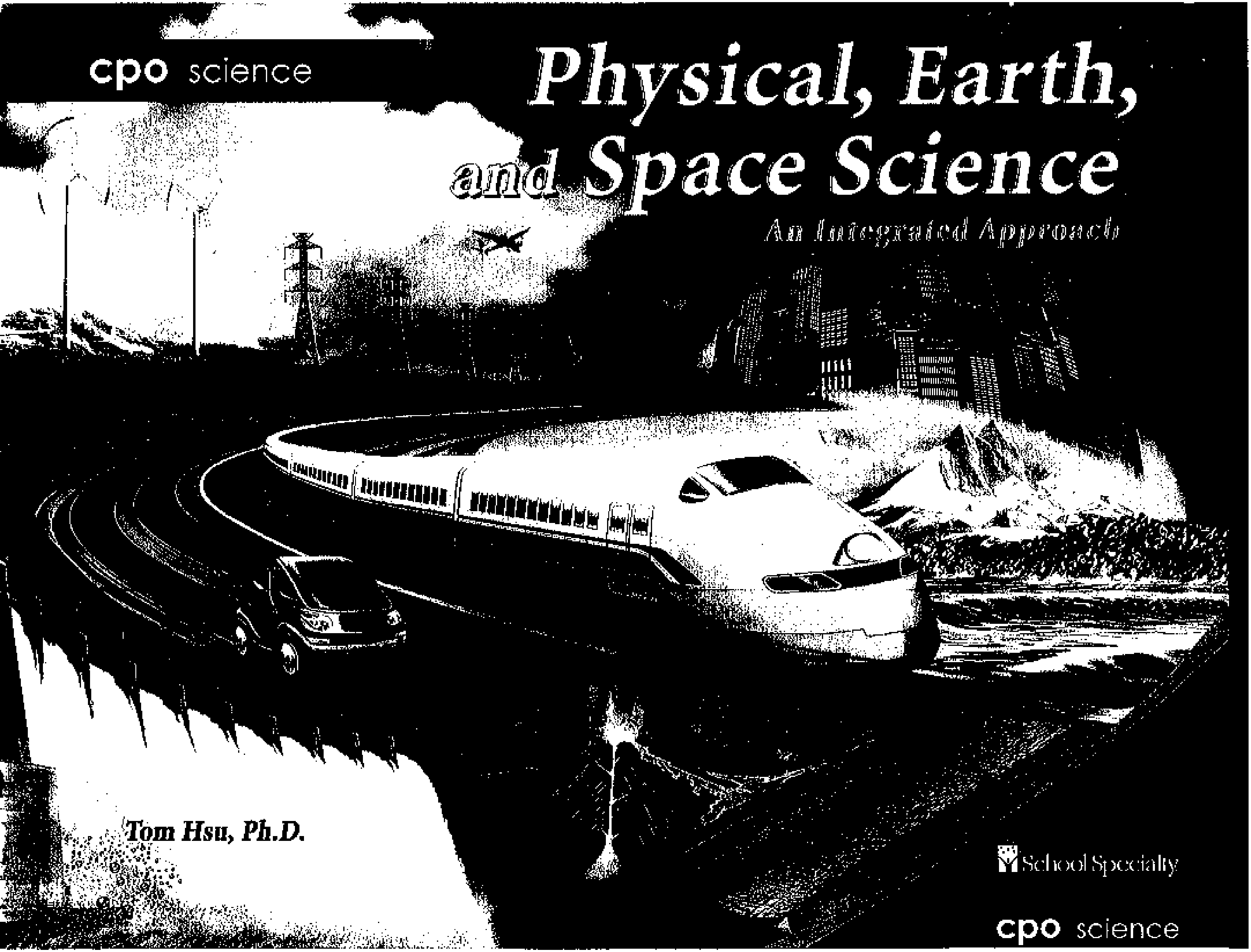
cpo science

Physical, Earth, and Space Science

An Integrated Approach



Tom Hsu, Ph.D.

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Chapter 10

Properties of Matter

Would you believe that someone has invented a solid material that has about the same density as air? It's so light, if someone put a chunk of it your hand you might not even notice. Silica aerogel is a foam that's like solidified smoke. Aerogel is mostly air and has remarkable thermal, optical, and acoustical properties.

Aerogels are fantastic insulators. You could hold a flame under a chunk of the material and touch the top without being burned. Aerogels have the potential to replace a variety of materials used in everyday life. If researchers could make a transparent version of an aerogel, it would almost certainly be used in double-pane windows to keep heat inside your house in the winter and outside in the summer. Opaque aerogels are already being used as insulators. Aerogels have been put to use by NASA in several projects, including the Mars Pathfinder, Soujourner and Stardust missions. Read this chapter to find out more about various types of matter and their properties.

Key Questions

✔ *What are some important properties of solids?*

✔ *What is a fluid and how are fluids different from solids?*

✔ *What is pressure?*

✔ *Why does a steel cube sink while a steel boat floats?*

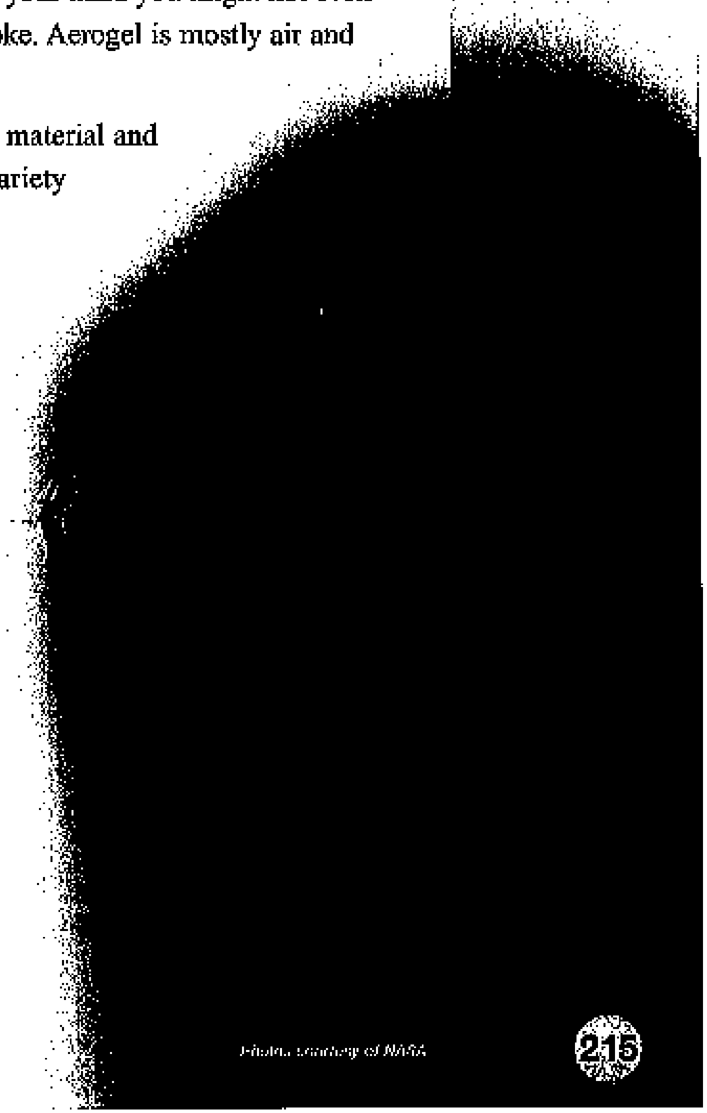


Photo courtesy of NASA

10.1 Density

Mass and volume are different properties of matter, but they are related. For instance, a solid block of wood and a solid block of steel can have the same volume, but they would *not* have the same mass. The steel block has a lot more mass than the wood block. Because of the mass difference, the wood block floats in water and the steel block sinks. Whether an object floats or sinks is related to the object's density. This section will explain density, a property of all matter.

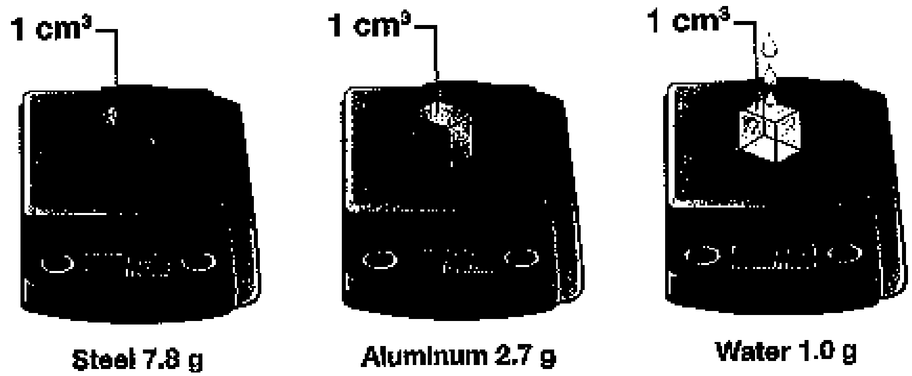
VOCABULARY

density - the mass per unit volu of a given material. Units for dens are often expressed as g/mL, g/c or kg/m^3.

Density is a property of matter

Density is mass per unit volume

Density describes how much mass is in a given volume of a material. Steel has high density; it contains 7.8 grams of mass per cubic centimeter ($7.8\ g/cm^3$). Aluminum, as you might predict, has a lower density; a 1-centimeter cube has a mass of only 2.7 grams ($2.7\ g/cm^3$).



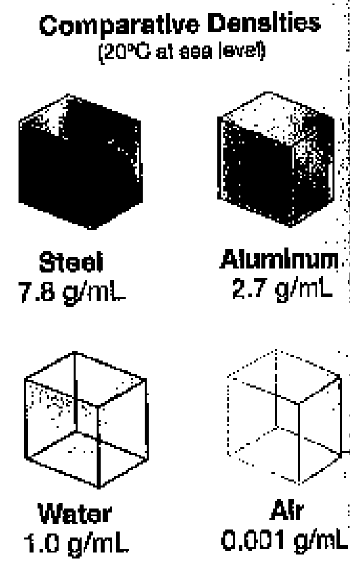


Figure 10.1: *The density of ste aluminum, water, and air express grams per milliliter (1 mL = 1 cm³*

The density of water and air

Liquids and gases are matter, therefore, they have density. The density of water is about 1 gram per cubic centimeter. The density of air is lower, of course—much lower. The air in your classroom has a density of about 0.001 grams per cubic centimeter ($0.001\ g/cm^3$). Density units can be expressed as g/cm^3, g/mL, or kg/m^3 (Figure 10.1).

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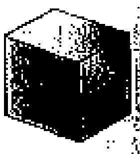
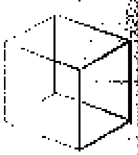


Aluminum
2.7 g/mL



Air
0.001 g/mL

ensity of stee
air expresse
mL = 1 cm³)

...s of density

...sity in units of g/mL

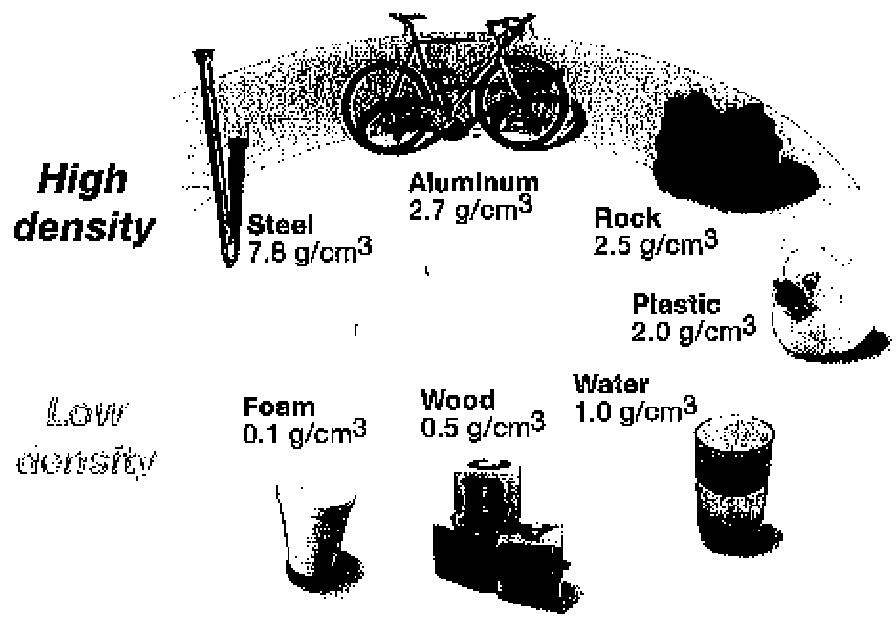
Your laboratory investigations will typically express density in units of grams per milliliter (g/mL). The density of water is one gram per milliliter. This means 1 milliliter of water has a mass of 1 gram.

...sity in units of g/cm^3 and kg/m^3

Some problems express density in units of grams per cubic centimeter (g/cm^3). Since 1 milliliter is exactly the same volume as 1 cubic centimeter, the units of g/cm^3 and g/mL are the same. For measuring large objects, it is easier to express density in units of kilograms per cubic meter (kg/m^3). Figure 10.2 gives the densities of some common materials in both units.

...erting units of density

To convert from one unit of density to the other, remember that 1 g/cm^3 is equal to 1,000 kg/m^3. To go from g/cm^3 to kg/m^3, you multiply by 1,000. For example, the density of ice is 0.92 g/cm^3. This is the same as 920 kg/m^3. To go from kg/m^3 to g/cm^3, you divide by 1,000. For example, the density of aluminum is 2,700 kg/m^3. Dividing by 1,000 gives a density of 2.7 g/cm^3.



Material	(kg/m^3)	(g/cm^3)
Platinum	21,500	21.5
Lead	11,300	11.3
Steel	7,800	7.8
Titanium	4,500	4.5
Aluminum	2,700	2.7
Glass	2,700	2.7
Granite	2,600	2.6
Concrete	2,300	2.3
Plastic	2,000	2.0
Rubber	1,200	1.2
Liquid water	1,000	1.0
Ice	920	0.92
Ash (wood)	670	0.67
Pine (wood)	440	0.44
Cork	120	0.12
Air (avg.)	0.9	0.0009

Figure 10.2: *Density of some common materials.*

SOLVE IT!

Ipe (pronounced ee-pay) is a Brazilian hardwood that can be used as a durable (but expensive!) construction material for decks, docks, and other outdoor projects. Every cubic foot of ipe weighs 69 pounds. Use dimensional analysis to convert the density of ipe to g/cm^3. How does the density of ipe compare to other woods and materials in the list above?

Density of solids and liquids

Density of a material does not change with quantity or shape

Density is a property of material that is independent of quantity or shape. For example, a steel nail and a steel cube have different amounts of matter and therefore different masses (Figure 10.3). They also have different volumes and shapes. But they have the same density. Dividing mass by volume gives the same density for the nail and the cube, because both are made of steel.

Density of a material is the same no matter what the size or shape of the material

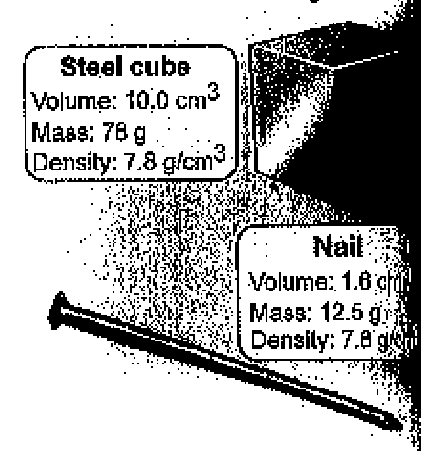
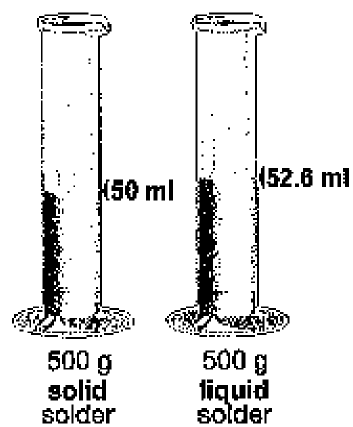


Figure 10.3: *The density of a s… nail is the same as the density of a… cube of steel.*

Liquids tend to be less dense than solids of the same material

The density of a liquid is usually a little *less* than the density of the same material in solid form. Take the example of solder (pronounced sod-der). Solder is a metal alloy used to join metal surfaces.



500 g of solid solder fills a volume of 50 mL. The density of solid solder is 10 g/mL. The same mass (500 g) of melted (liquid) solder has 52.6 mL of volume. Liquid solder has a lower density of 9.5 g/mL. The density of a liquid is lower because the atoms are not packed as tightly as they are in a solid. Imagine a brand-new box of toy blocks. When you open the box, the blocks are tightly packed, like the atoms in a solid. Now imagine dumping the blocks out of the box, and then pouring them back into the original box again. The same number of jumbled blocks take up more space, like the atoms in a liquid (Figure 10.4).

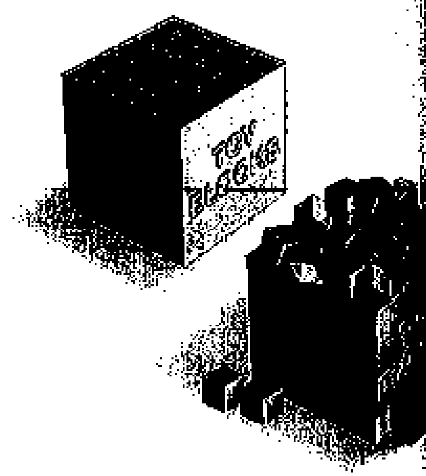


Figure 10.4: *The same number (… mass) of blocks arranged in a tight… repeating pattern take up less spac… than when they are jumbled up.*

Water is an exception

Water is an exception to this rule. The density of solid water, or ice, is *less* than the density of liquid water. When water molecules freeze into ice crystals, they form a pattern that has an unusually large amount of empty space. The water molecules in ice are actually farther apart than they are in liquid water. Because of this, ice floats in liquid water.

…rmining density

…ing density To find the density of a material, you need to know the mass and volume of a sample of the material. You can calculate density using the formula below.

DENSITY

$$D = \frac{m}{V}$$

Density (g/cm³ or g/mL); Mass (g); Volume (cm³ or mL)

Aluminum block
Mass = 10.8 grams
Volume = 4 cm³
Density = 2.7 g/cm³

Aluminum soda can
Mass = 10.8 grams
Volume = 400 cm³
Average density = 0.027 g/cm³

Figure 10.5: *The aluminum block and the soda can have the same mass but different volumes and densities. The density of the aluminum can is called its average density because it also includes the air inside the can as part of the volume.*

Density gives information …ut atoms and molecules Density gives us information about how tightly the atoms or molecules of a particular material are "packed." Diamond is made of carbon atoms and has a density of 3.5 g/cm^3. The carbon atoms in diamond are relatively tightly packed. Paraffin wax is also made mostly of carbon atoms, but the density is only 0.87 g/cm^3. The density of paraffin is low because the carbon atoms are mixed with hydrogen atoms in long molecules that take up a lot of space. The molecules in paraffin are not as tightly packed as the atoms in diamond.

The density of solid objects Suppose you have a piece of aluminum foil, a length of aluminum wire, and an aluminum brick. At the same temperature and pressure, the aluminum making each of these has the same density. It does not matter whether the aluminum is shaped into a brick, flat sheet, or long wire. The density is 2.7 g/cm^3 as long as the object is made of solid aluminum.

The average density of a hollow object If an object is hollow, its average density is less than the density of the material from which the object is made. Suppose a small block of aluminum with a mass of 10.8 grams is used to make a soda can (Figure 10.5). Both the solid block of aluminum and the soda can have a mass of 10.8 grams, but the hollow can has a much larger volume. The can has 100 times the volume of the block, so its density is 100 times less.

Solving Problems: Calculating Density

A solid wax candle has a volume of 1,700 mL. The candle has a mass of 1.5 kg (1,500 g). What is the density of the candle?

1. Looking for: You are asked for the density.

2. Given: You are given the mass and volume.

3. Relationships: Density is mass divided by volume.

4. Solution: Density = 1,500 g ÷ 1,700 mL = 0.88 g/mL

Your turn...

a. Look at Figure 10.7. A student measures the mass of five steel hex nuts to be 96.2 g. The hex nuts displace 13 mL of water. Calculate the density of the steel in the hex nuts.

b. The density of granite is about 2.60 g/cm^3. How much mass would a solid piece of granite have that measures 2.00 cm × 2.00 cm × 3.00 cm?

c. Ice has a density of about 0.920 g/cm^3. What is the volume of 100.0 g of ice?

To Find:	Use:
density	$D = \frac{m}{V}$
volume	$V = \frac{m}{D}$
mass	$m = D \times V$

Figure 10.6: *Using the density equation.*

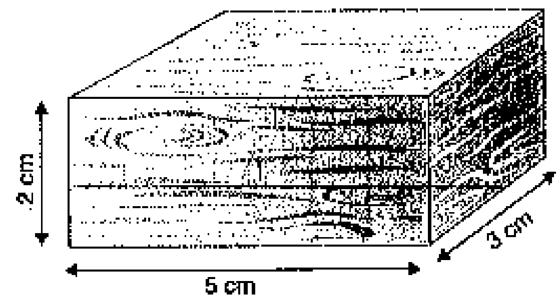
Figure 10.7: *A student measur volume and mass of five steel hex*

SOLVE FIRST LOOK LA

a. 7.4 g/mL; b. 31.2 g; c. 109

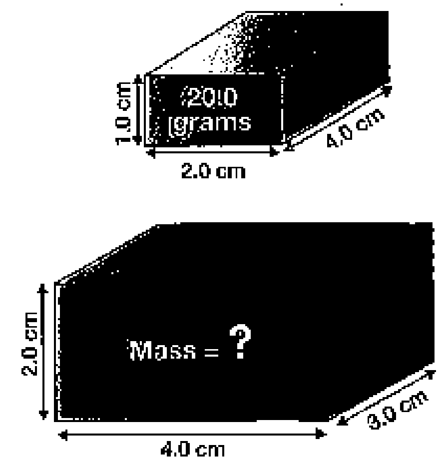
Section 10.1 Review

1. Define density, write the formula (from memory!), and give two different units used to measure density.
2. One cubic centimeter (cm^3) is the same volume as one ________.
3. A material's density is the same, no matter how large or small the sample is, or what its shape is, as long as it is a solid, uniform piece of the material. Explain how this is possible and give an example.
4. The density of balsa wood is about 170 kg/m^3. Convert to g/cm^3. Why do you think balsa wood, rather than oak or ash, is commonly used for building models? (Use evidence from Figure 10.2 on page 217.)
5. A certain material has a density of 0.2 g/cm^3. Is this material better for building a bridge or for making sofa cushions? Explain, using evidence from Figure 10.2 on page 217.



6. The piece of wood shown above has a mass of 20 grams. Calculate its volume and density. Then, use Figure 10.2 on page 217 to determine which type of wood it is. What are the two factors that determine a material's density?
7. The density of maple wood is about 755 kg/m^3. What is the mass of a solid piece of maple that has a volume 640 cm^3?

SOLVE IT!



Two toy blocks are made of the same type of material. One has a mass of 20.0 grams and its dimensions are 2.0 cm × 4.0 cm × 1.0 cm. The second block measures 4.0 cm × 3.0 cm × 2.0 cm. Calculate the mass of the second block.

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.

Weight and buoyancy

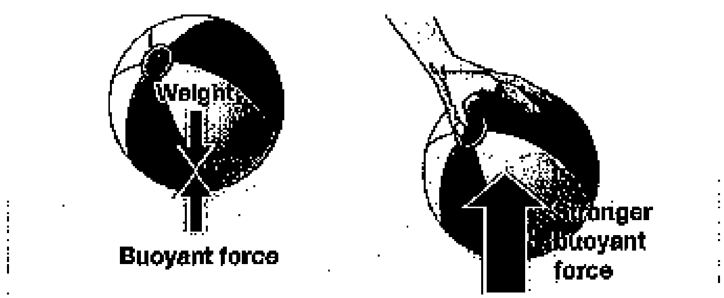
Weight and mass are not the same

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.

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.

VOCABULARY

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

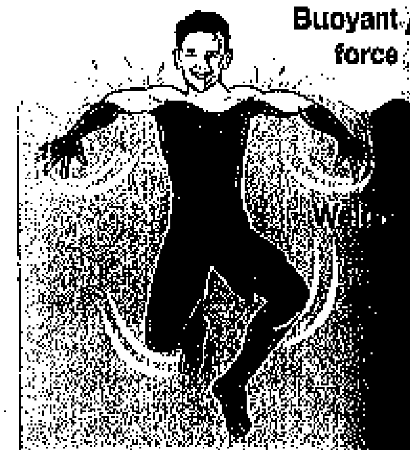


Figure 10.20: *The water in the [...] exerts an upward force on your bo[...] the net force on you is lessened.*

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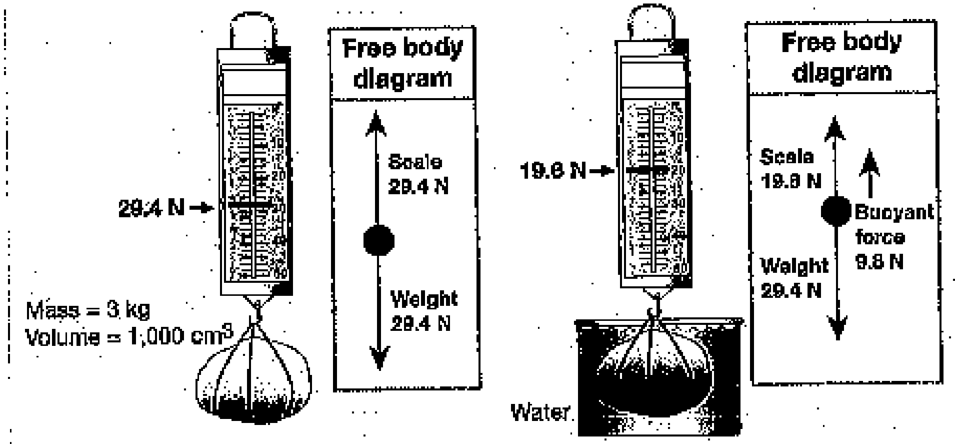
What is rchimedes' principle?

A simple uoyancy xperiment

ating the uoyant force

himedes' 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.

lculating 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.

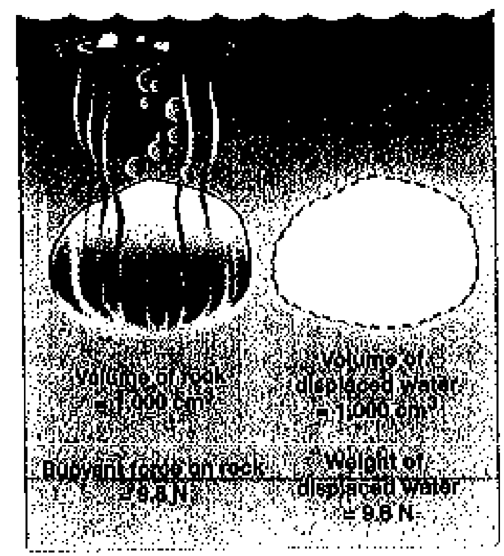
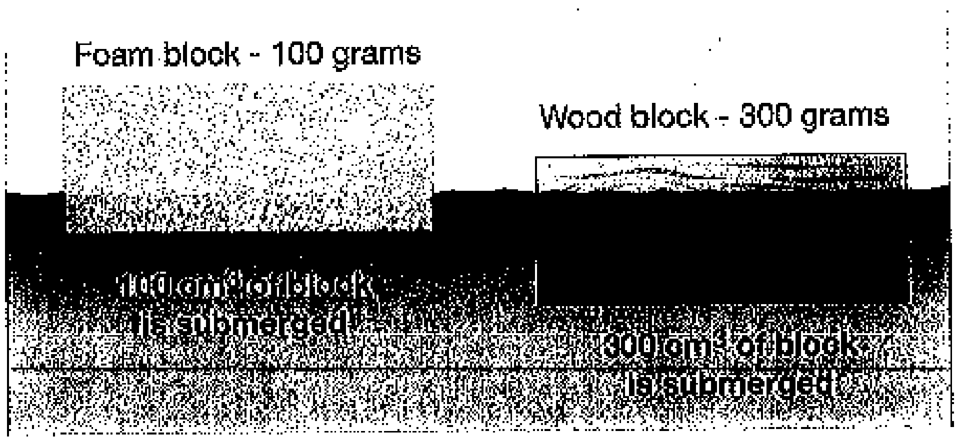


Figure 10.21: *A rock with a volume of 1,000 cm^3 experiences a buoyant force of 9.8 newtons.*

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.

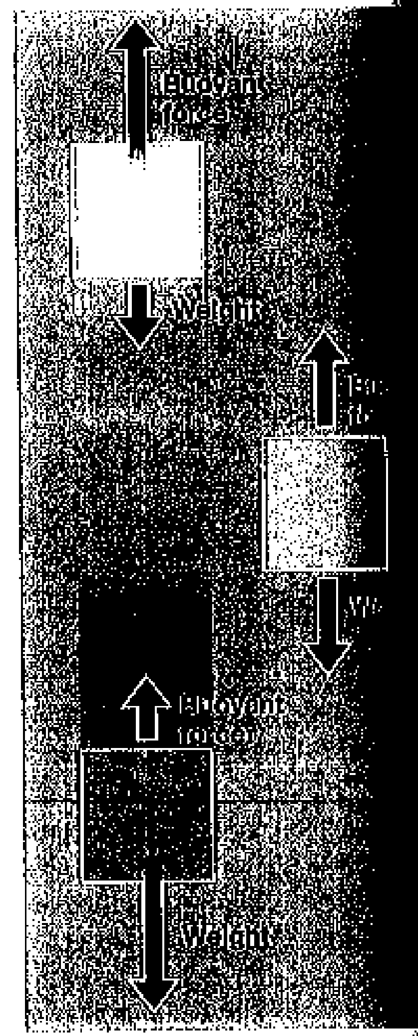


Figure 10.22: *Whether an object sinks or floats depends on how the buoyant force compares with the object's weight.*

ty and buoyancy

Comparing densities

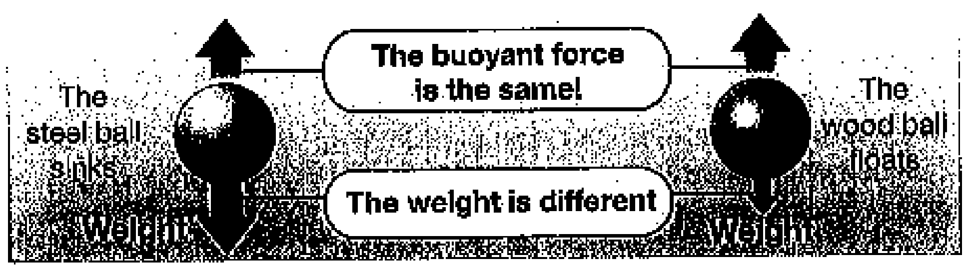
If you know an object's density, you can immediately predict whether it will sink or float—without measuring its weight. An object sinks if its density is greater than that of the liquid it is submerged into. It floats if its density is less than that of the surrounding fluid.

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.

one sinks 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.

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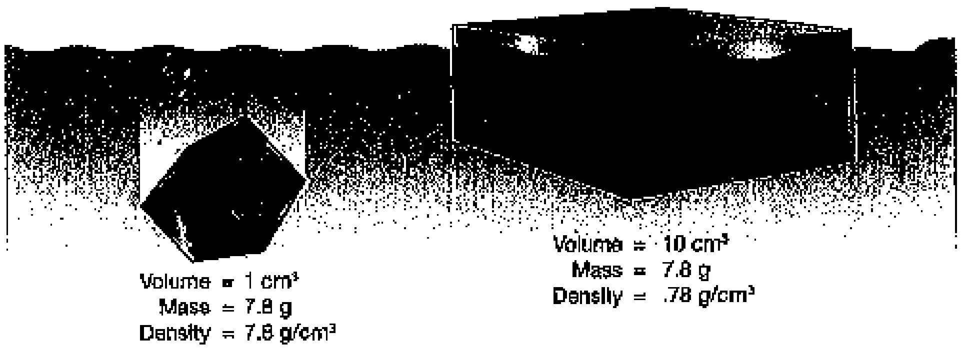
Boats and apparent density

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 m[...] divided by the total volume of an object that is made up of more th[...] one material including air.

An object with an appa[...] density GREATER than [...] density of water will si[...]

An object with an appa[...] density LESS than th[...] density of water will flo[...]

Apparent Density
Apparent density is the total ma[...] divided by the total volume.

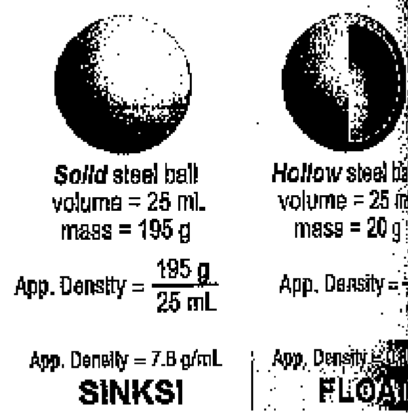


Figure 10.23: *The meaning of* apparent density. *Note: 1 mL = 1 c*

yancy, volume, temperature, and pressure of gases

ing 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.

ing 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.

arles'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.

essure 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.

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 psi × 568 K) ÷ 294 K = 580 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.

CONVERTING CELSIUS TO KELVIN

$$T_{Kelvin} = T_{Celsius} + 2$$

Figure 10.26: *To convert degr[ees] Celsius to Kelvins, simply add 273 [to the] Celsius temperature.*

Figure 10.27: *NEVER put spr[ay] cans near heat!*

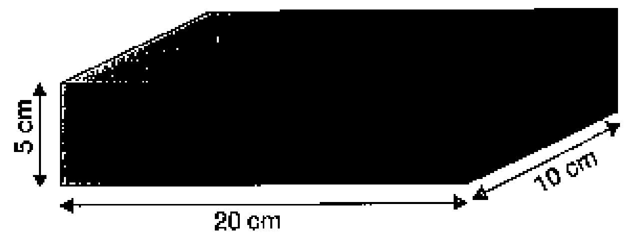
SOLVE FIRST LOOK L[ATER]

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.

The Periodic Table of the Elements

ny elements make up the universe? The only way to tell if a substance is an element is to emically break it down into other substances by any possible means. A substance that can ically broken apart cannot be an element. As of this writing, scientists have identified 117 ed elements. Only about 90 of these elements occur naturally. The others are made in ries.

VOCABULARY

periodic table - a chart that organizes the elements by their chemical properties and increasing atomic number.

period - a row of the periodic table.

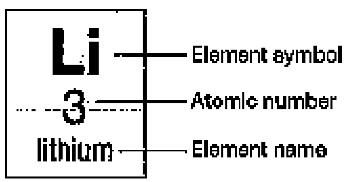
group - a column of the periodic table.

eriodic table

The modern riodic table

As chemists worked on identifying the true elements, they noticed that some elements acted like other elements. For example, the soft metals lithium, sodium, and potassium always combine with oxygen in a ratio of two atoms of metal to one atom of oxygen (Figure 12.17). By keeping track of how each element combined with other elements, scientists began to recognize repeating patterns. From this data, they developed the first periodic table of the elements. The **periodic table** organizes the elements according to how they combine with other elements due to their chemical properties.

ization of the periodic table



The periodic table is organized in order of increasing atomic number. The lightest element (hydrogen) is at the upper left. The heaviest is on the lower right. Each element corresponds to one box in the periodic table, identified with the element symbol.

The periodic table is further divided into periods and groups. Each horizontal row is called a **period**. Across any period, the properties of the elements gradually change. Each vertical column is called a **group**. Groups of elements have similar properties. The *main group elements* are Groups 1 and 2 and Groups 13 through 18 (the tall columns of the periodic table). Elements in Groups 3 through 12 are called the *transition elements*. The inner transition elements, called *lanthanides* and *actinides*, are often shown below the bottom row of the chart in order for the chart to fit on a page.

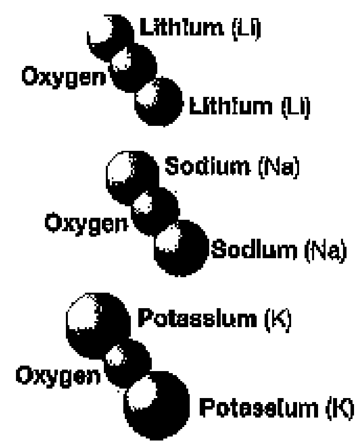


Figure 12.17: *The metals lithium, sodium, and potassium all form compounds with a ratio of two atoms of the metal to one atom of oxygen. All the elements in Group 1 of the periodic table form similar compounds.*

Reading the periodic table

Metals, nonmetals, and metalloids

Most of the elements are **metals.** A metal is typically shiny, opaque, and a good conductor of heat and electricity as a pure element. Metals are also ductile, which means they can be bent into different shapes without breaking. **Nonmetals** are poor conductors of heat and electricity. Solid nonmetals are brittle and appear dull. With the exception of hydrogen, the nonmetals are on the right side of the periodic table. The elements on the border between metals and nonmetals are called *metalloids*. Silicon is an example of a metalloid element with properties in between those of metals and nonmetals.

Periodic Table of the Elements

Main Group Elements | Non metals | Transition Elements | Metals

ROWS = PERIODS COLUMNS = GROUPS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
[illegible]																	[illegible]
Li 3 lithium	Be 4 beryllium											[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Na 11 sodium	Mg 12 magnesium											Al 13 aluminum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
K 19 potassium	Ca 20 calcium	Sc 21 scandium	Ti 22 titanium	V 23 vanadium	Cr 24 chromium	Mn 25 manganese	Fe 26 iron	Co 27 cobalt	Ni 28 nickel	Cu 29 copper	Zn 30 zinc	Ga 31 gallium	Ge 32 germanium	[illegible]	[illegible]	[illegible]	[illegible]
Rb 37 rubidium	Sr 38 strontium	Y 39 yttrium	Zr 40 zirconium	Nb 41 niobium	Mo 42 molybdenum	Tc 43 technetium	Ru 44 ruthenium	Rh 45 rhodium	Pd 46 palladium	Ag 47 silver	Cd 48 cadmium	In 49 indium	Sn 50 tin	Sb 51 antimony	[illegible]	[illegible]	[illegible]
Cs 55 cesium	Ba 56 barium		Hf 72 hafnium	Ta 73 tantalum	W 74 tungsten	Re 75 rhenium	Os 76 osmium	Ir 77 iridium	Pt 78 platinum	Au 79 gold	Hg 80 mercury	Tl 81 thallium	Pb 82 lead	Bi 83 bismuth	Po 84 polonium	[illegible]	[illegible]
Fr 87 francium	Ra 88 radium		Rf 104 rutherfordium	Db 105 dubnium	Sg 106 seaborgium	Bh 107 bohrium	Hs 108 hassium	Mt 109 meitnerium	Ds 110 darmstadtium	Rg 111 roentgenium	Uub 112 ununbium	Uut 113 ununtrium	Uuq 114 ununquadium	Uup 115 ununpentium	Uuh 116 ununhexium	Uus 117 ununseptium	[illegible]

La 57 lanthanum	Ce 58 cerium	Pr 59 praseodymium	Nd 60 neodymium	Pm 61 promethium	Sm 62 samarium	Eu 63 europium	Gd 64 gadolinium	Tb 65 terbium	Dy 66 dysprosium	Ho 67 holmium	Er 68 erbium	Tm 69 thulium	Yb 70 ytterbium	Lu 71 lutetium
Ac 89 actinium	Th 90 thorium	Pa 91 protactinium	U 92 uranium	Np 93 neptunium	Pu 94 plutonium	Am 95 americium	Cm 96 curium	Bk 97 berkelium	Cf 98 californium	Es 99 einsteinium	Fm 100 fermium	Md 101 mendelevium	No 102 nobelium	Lr 103 lawrencium

VOCABULARY

metals - elements that are typ... shiny and good conductors of h... and electricity.

nonmetals - elements that a... conductors of heat and electric...

...mass

Atomic mass units

Atomic mass and isotopes

...number review

ic mass

mic mass units

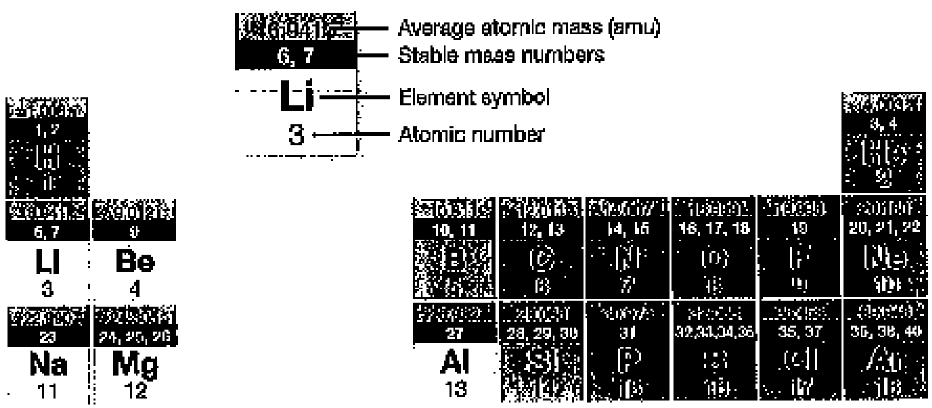
The mass of individual atoms is so small that the numbers are difficult to work with. To make calculations easier, scientists came up with the **atomic mass unit** (amu). One atomic mass unit is about the mass of a single proton (or neutron). In laboratory units, 1 amu is 1.66×10^{-24} grams. That's 0.00000000000000000000000166 grams!

mic mass nd isotopes

The **atomic mass** is the *average* mass (in amu) of an atom of each element. Atomic masses differ from mass numbers because most elements in nature contain more than one isotope (see chart below). For example, the atomic mass of lithium is 6.94 amu. That does *not* mean there are 3 protons and 3.94 neutrons in a lithium atom! On average, out of every 100 atoms of lithium, 6 atoms are Li-6 and 94 atoms are Li-7 (Figure 12.18). The *average* atomic mass of lithium is 6.94 because of the mixture of isotopes.

ic number review

As you learned earlier, the atomic number is the number of protons all atoms of that element have in their nuclei. If the atom is neutral, it will have the same number of electrons as well.



VOCABULARY

atomic mass unit - a unit of mass equal to 1.66×10^{-24} grams.

atomic mass - the average mass of all the known isotopes of an element, expressed in amu.

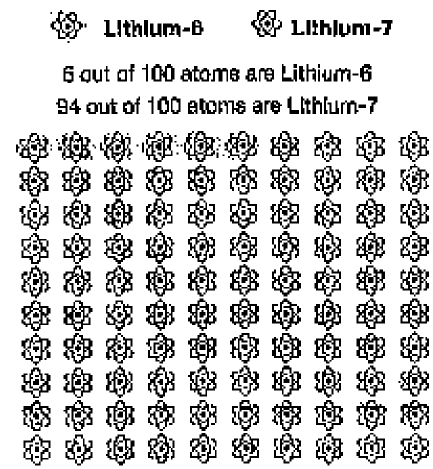
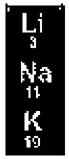


Figure 12.18: *Naturally-occurring elements have a mixture of isotopes.*

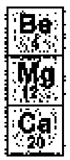
Groups of the periodic table

Alkali metals



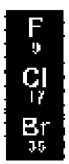
All of the elements in the different groups of the periodic table have similar chemical properties. The first group is known as the **alkali metals**. Some examples of this group are the elements lithium (Li), sodium (Na), and potassium (K). The alkali metals are soft and silvery in their pure form and are highly reactive. Each of them combines in a ratio of two to one with oxygen. For example, lithium oxide has two atoms of lithium per atom of oxygen.

Group 2 metals



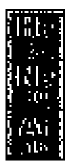
Some examples of Group 2 metals are beryllium (Be), magnesium (Mg), and calcium (Ca). These metals also form oxides, however, they combine one-to-one with oxygen. For example, beryllium oxide has one beryllium atom per each oxygen atom.

Halogens



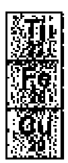
The **halogens** are on the right-hand side of the periodic table. These elements tend to be toxic in their pure form. Some examples are fluorine (F), chlorine (Cl), and bromine (Br). The halogens are also very reactive and are rarely found in pure form. When combined with alkali metals, they form salts, such as sodium chloride (NaCl) and potassium chloride (KCl).

Noble gases



On the far right of the periodic table are the **noble gases**. Some examples of this group are the elements helium (He), neon (Ne), and argon (Ar). These elements do not naturally form chemical bonds with other atoms and are almost always found in their pure state. They are sometimes called *inert gases* for this reason.

Transition metals



In the middle of the periodic table are the transition metals, including titanium (Ti), iron (Fe), and copper (Cu). These elements are usually good conductors of heat and electricity. For example, the wires that carry electricity in your school are made of copper. Figure 12.19 shows the location of the groups of elements on the periodic table.

VOCABULARY

alkali metals - elements in th
group of the periodic table.

halogens - elements in the gr
containing fluorine, chlorine, an
bromine, among others.

noble gases - elements in th
group containing helium, neon,
argon, among others.

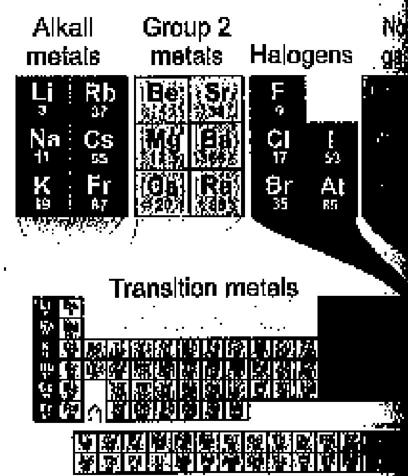


Figure 12.19: *Groups of the p*
table.

...gy levels and the periodic table

...iod 1 is the ...energy level

The periods (rows) of the periodic table correspond to the energy levels in the Bohr model of the atom (Figure 12.20). The first energy level can accept up to two electrons. Hydrogen (H) has one electron and helium (He) has two. These two elements complete the first period.

...iod 2 is the ...ond energy level

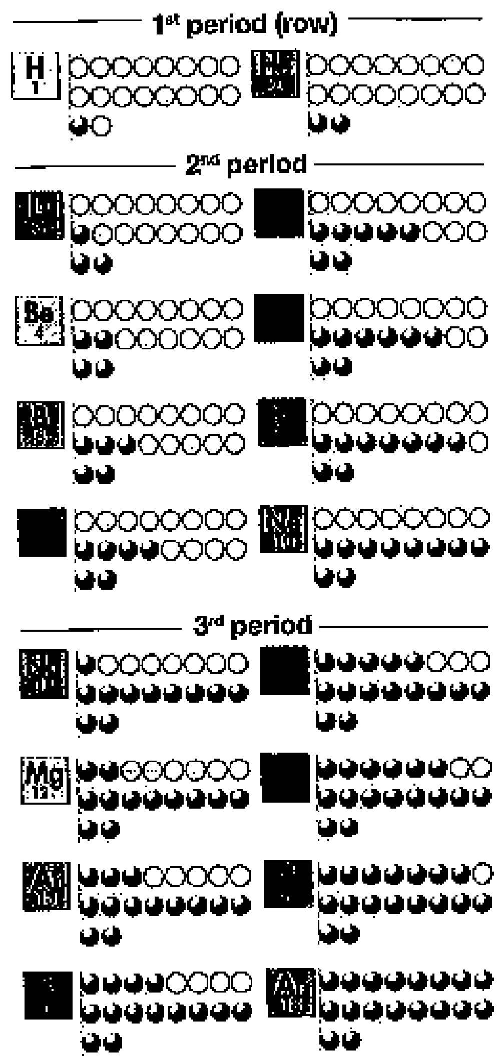
The next element, lithium (Li), has three electrons. Lithium begins the second period because the third electron goes into the second energy level. The second energy level can hold eight electrons, so there are eight elements in the second row of the periodic table, ending with neon (Ne). Neon has 10 electrons, which completely fill the second energy level.

...iod 3 is the third energy level

Sodium (Na) has 11 electrons, and starts the third period because the eleventh electron goes into the third energy level. We know of elements with up to 118 electrons. These elements have their outermost electrons in the seventh energy level.

...electrons

As we will see in the next chapter, the outermost electrons in an atom are the ones that interact with other atoms. The outer electrons are the ones in the highest energy level. Electrons in the completely filled inner energy levels do not participate in forming chemical bonds.



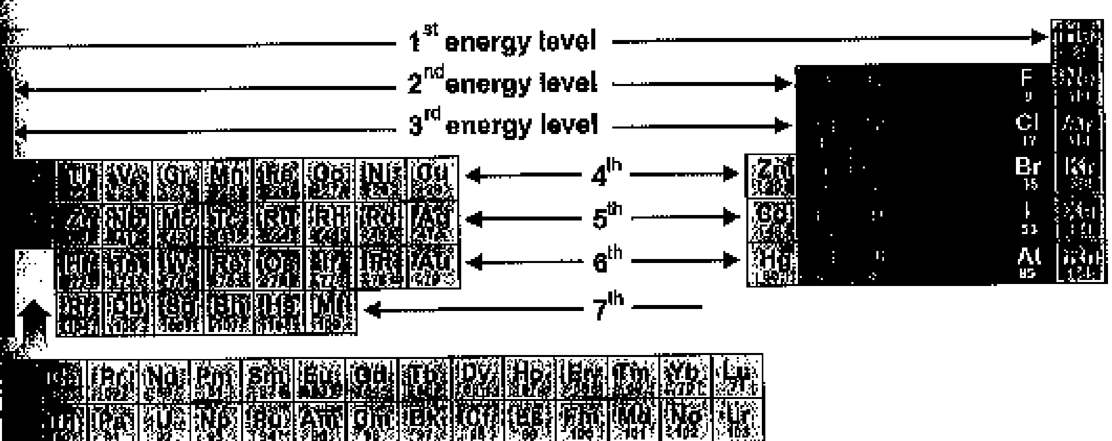


Figure 12.20: *The rows (periods) of the periodic table correspond to the energy levels for the electrons in an atom.*

Section 12.3 Review

1. Groups of the periodic table correspond to elements with:
   a. the same mass number
   b. the same atomic number
   c. similar chemical properties
   d. similar numbers of neutrons
2. Which element is the atom shown in Figure 12.21?
3. Name three elements that have similar chemical properties to oxygen.
4. The atomic mass unit (amu) is:
   a. the mass of a single atom of carbon
   b. one-millionth of a gram
   c. approximately the mass of a proton
   d. approximately the mass of an electron
5. Which element belongs in the empty space in Figure 12.22?
6. The outermost electrons of the element vanadium (atomic #23) are in which energy level of the atom? How do you know?
7. The elements fluorine, chlorine, and bromine are in which group of the periodic table?
   a. the alkali metals
   b. the oxygen-like elements
   c. the halogens
   d. the noble gases
8. Which three metals are in the third period (row) of the periodic table?

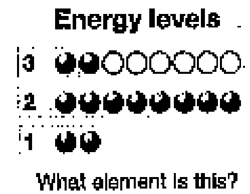


Figure 12.21: *Question 2.*

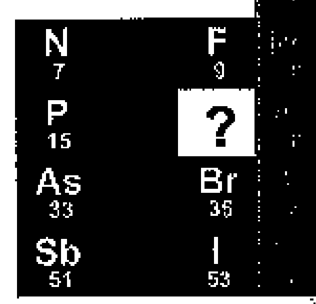


Figure 12.22: *Question 5.*

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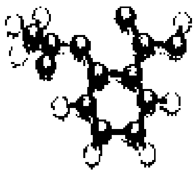
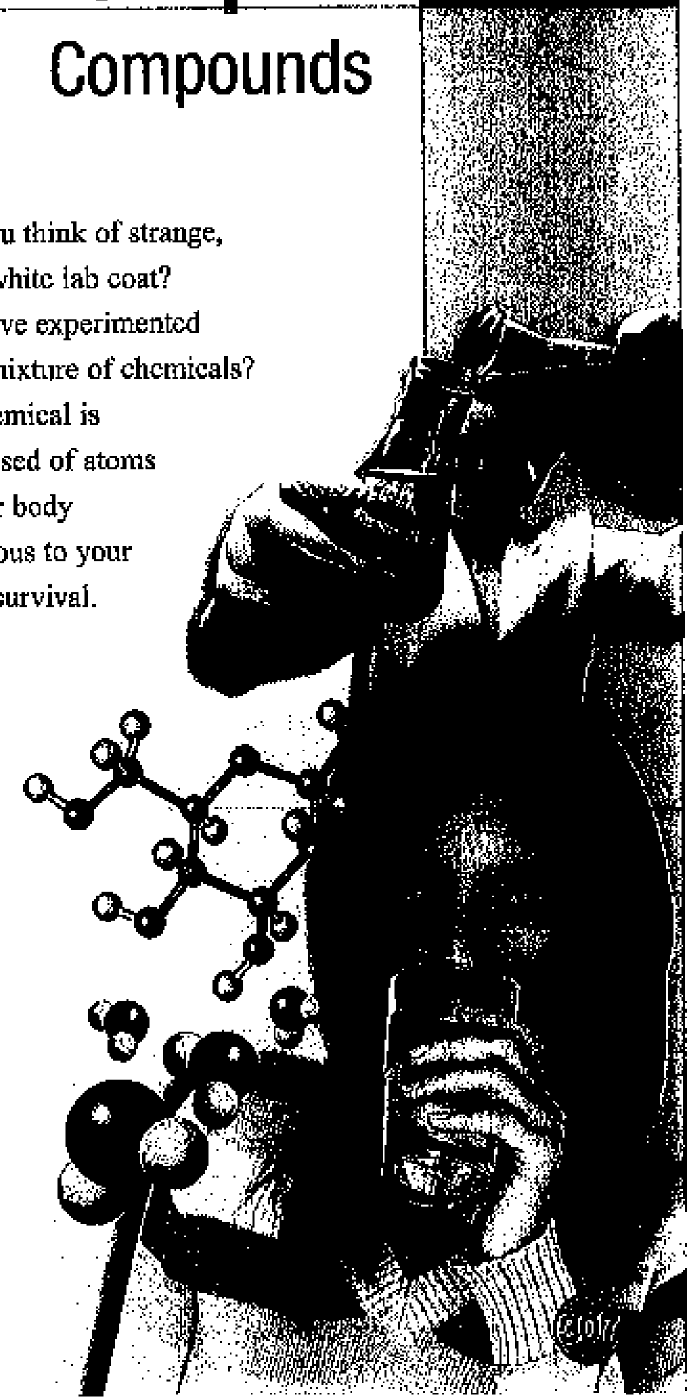
Chapter 13
Compounds



What does the word *chemical* mean to you? Does it make you think of strange, bubbling concoctions in test tubes, mixed by a scientist in a white lab coat? You might have heard or read about a hazardous chemical spill, or you might have experimented with chemicals in a science lab. Would it surprise you to know that YOU are a mixture of chemicals? So are a block of wood and a glass of orange juice. The scientific term for a chemical is *compound*. The word *compound* is used to describe any substance that is composed of atoms bonded together. Water (H_2O) and sodium chloride (NaCl) are compounds. Your body contains thousands of different compounds. While some compounds are hazardous to your health, many such as proteins and carbohydrates, are necessary for growth and survival.

All of the millions upon millions of different compounds are made of only 92 elements combined in different ways. Just as you can spell thousands of words with the same 26 letters, you can make all the compounds from 92 elements.



Key Questions

✔ *What does the chemical formula H_2O mean?*

✔ *Why do elements tend to combine to form compounds?*

✔ *What compounds is your body made of?*

13.1 Chemical Bonds and Electrons

Most matter exists as compounds, not as pure elements. That's because most pure elements are chemically unstable. They quickly form *chemical bonds* with other elements to make compounds. For example, water (H_2O) is a compound of hydrogen and oxygen. The salt used in food is a compound that contains two elements, sodium and chlorine, that are poisonous by themselves. In this section, you will learn why and how the atoms of elements form compounds.

Covalent bonds

Electrons form chemical bonds

A **chemical bond** forms when atoms transfer or share electrons. Almost all elements form chemical bonds easily. This is why most of the matter you experience is in the form of compounds.

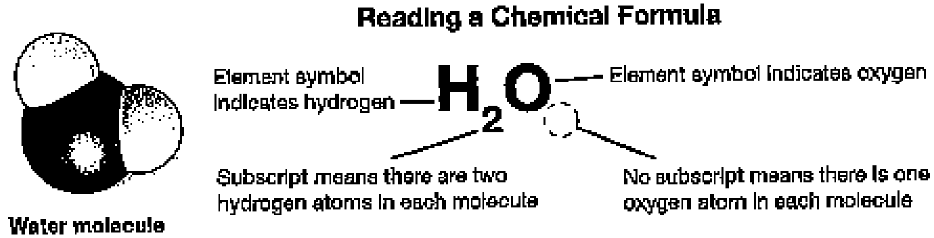
Covalent bonds

A **covalent bond** forms when atoms share electrons. A group of atoms held together by covalent bonds is called a *molecule*. The bonds between oxygen and hydrogen in a water molecule are covalent bonds (Figure 13.1). There are two covalent bonds in a water molecule, between the oxygen and each of the hydrogen atoms. Each bond represents a shared electron pair.

Chemical formulas

A molecule's **chemical formula** tells you the ratio of atoms of each element in the compound. For example, the chemical formula for water is H_2O. The subscript 2 indicates there are two hydrogen atoms in a water molecule. No subscript after the O indicates there is only one oxygen atom for every two hydrogen atoms in the molecule.

Reading a Chemical Formula



Ratio of two hydrogen atoms to one oxygen atom in the compound

VOCABULARY

chemical bond - a bond that ... when atoms transfer or share ... electrons.

covalent bond - a chemical ... formed by atoms that are shari... or more electrons.

chemical formula - a representation of a compound th... includes the symbols and ratios ... atoms of each element in the compound.

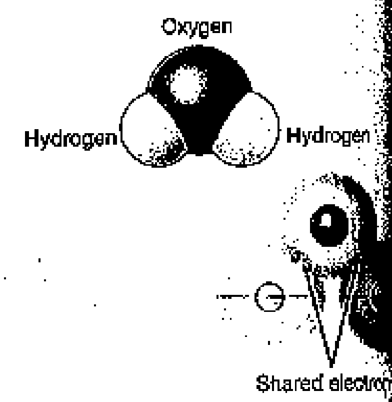


Figure 13.1: *In a covalent bo... electrons are shared between atom...*

bonds

An ion is a charged atom

Not all compounds are made of molecules. For example, sodium chloride (NaCl) is a compound of sodium (Na) and chlorine (Cl) in a ratio of one sodium atom per chlorine atom. The difference is that in sodium chloride, the electron is transferred (instead of shared) from the sodium atom to the chlorine atom. When atoms gain or lose an electron, they become **ions**. An ion is a charged atom. By losing an electron, the sodium atom becomes a sodium ion with a charge of +1. By gaining an electron, the chlorine atom becomes a chloride ion with a charge of –1. (Note that when chlorine becomes an ion, the name changes to chlor*ide*.)

Ionic bonds

Sodium and chlorine form an **ionic bond** because the positive sodium ion is attracted to the negative chloride ion. Ionic bonds are bonds in which one or more electrons are transferred from one atom to another.

Ionic compounds do not form molecules

Unlike covalent bonds, ionic bonds are not limited to a single pair of atoms. In sodium chloride, each positive sodium ion is attracted to all of the neighboring chloride ions (Figure 13.2). Likewise, each chloride ion is attracted to all the neighboring sodium ions. Because the bonds are not just between pairs of atoms, ionic compounds do not form molecules. In an ionic compound, each atom bonds with *all* of its neighbors through attraction between positive and negative charges.

The chemical formula for ionic compounds

Like covalent compounds, ionic compounds have fixed ratios of elements. For example, there is one sodium ion per chloride ion in sodium chloride (NaCl). This means we can use chemical formulas for ionic compounds just like we do for covalent compounds.

Ions might be multiply charged

Sodium chloride involves the transfer of one electron. However, ionic compounds may also be formed by the transfer of two or more electrons. A good example is magnesium chloride ($MgCl_2$). The magnesium atom gives up two electrons to become a magnesium ion with a charge of +2. Each chlorine atom gains one electron to become a chloride ion with a charge of –1. The ion charge is written as a superscript after the element symbol (Mg^{2+}, Cl^-, Fe^{3+}, etc.).

VOCABULARY

ion - an atom (or group of atoms) that has an electric charge other than zero, created when an atom (or group of atoms) gains or loses electrons.

ionic bond - a bond that transfers one or more electrons from one atom to another, resulting in attraction between oppositely charged ions.

Sodium and Chlorine Form an Ionic Compound

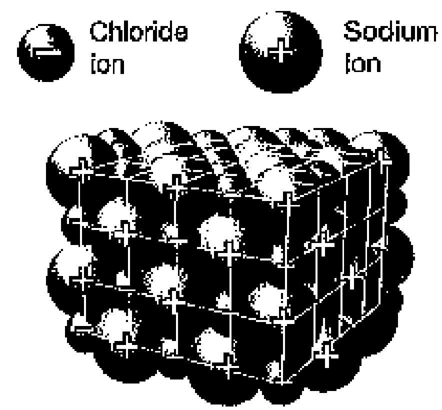


Figure 13.2: *Sodium chloride is an ionic compound in which each positive sodium ion is attracted to all of its negative chloride ion neighbors and vice versa.*

Why chemical bonds form

Atoms form bonds to reach a lower energy state It takes energy to pull the tape off of a surface. Similarly, it also takes energy to separate atoms that are bonded together. If it takes energy to separate bonded atoms, then the same amount of energy must be released when the bond forms. *Energy is released when chemical bonds form.* Energy is released because atoms that have bonded together have less total energy than the same atoms separately. Like a ball rolling downhill, atoms form compounds because the atoms have lower energy when they are together in compounds. For example, one carbon atom and four hydrogen atoms have more total energy apart than they do when combined in a methane molecule (Figure 13.3).

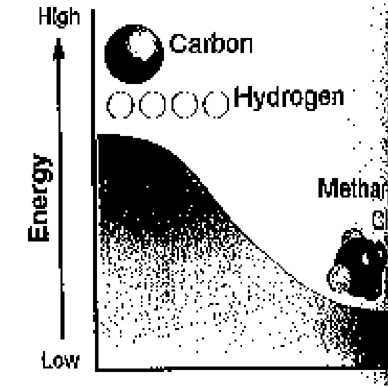
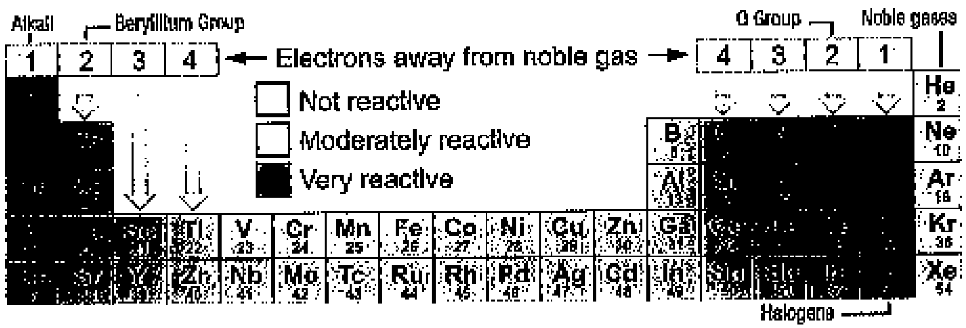


Figure 13.3: *The methane (CH... molecule has lower total energy th... four separate hydrogen atoms and separate carbon atom.*

Chemical reactivity All elements, except the noble gases, form chemical bonds. However, some elements are much more reactive than others. In chemistry, *reactive* means an element easily forms chemical bonds, often releasing energy. For example, sodium is a highly reactive metal. Chlorine is a highly reactive gas. If pure sodium and pure chlorine are placed together, a violent explosion occurs as the sodium and chlorine combine. The energy of the explosion is the energy given off by the formation of the chemical bonds.



CHALLENGE

The noble gases (He, Ne, Ar, et... called *inert* because they do no... ordinarily react with anything. Yo... put sodium in an atmosphere o... helium and nothing will happen... However, scientists have found ... few noble gases *do* form compo... in very special circumstances. Research this topic and see if yo... find a compound involving a no... gas.

Some elements are more reactive than others The closer an element is to having the same number of electrons as a noble gas, the more reactive the element is. The alkali metals are very reactive because they are just one electron away from the noble gases. The halogens are also very reactive because they are also one electron away from the noble gases. The beryllium group and the oxygen group are less reactive because each element in these groups is two electrons away from a noble gas.

...ce electrons

Compounds contain ...icular ratios ...of elements

The discovery of energy levels in the atom solved a 2,000-year-old mystery. Why do elements combine with other elements only in particular ratios (or not at all)? For example, why do two hydrogen atoms bond with one oxygen atom to make water? Why isn't there a molecule with three (H_3O) or even four (H_4O) hydrogen atoms? Why does sodium chloride have a precise ratio of one sodium ion to one chloride ion? Why don't helium, neon, and argon form compounds with any other elements? The answers have to do with the electrons in the outermost energy levels.

What are valence electrons?

Chemical bonds are formed only between the electrons in the highest unfilled energy level. These electrons are called **valence electrons**. You can think of valence electrons as the outer "skin" of an atom. Electrons in the inner (filled) energy levels do not interact with other atoms because they are shielded by the valence electrons. For example, chlorine has seven valence electrons. The first 10 of chlorine's 17 electrons are in the inner (filled) energy levels (Figure 13.4).

...t elements ...d to reach ...ht valence electrons

It turns out that eight is the stable number for chemical bonding. All the elements heavier than boron form chemical bonds to acquire a configuration with eight valence electrons. For example, sodium and chlorine form an ionic bond so each can have a configuration of eight valence electrons (Figure 13.5). Eight is a stable number because eight electrons completely fill a part of the outermost energy level. The noble gases already have a stable number of eight valence electrons. They don't form chemical bonds because they don't need to react to achieve this stable number.

...t elements ...d to reach ...wo valence electrons

For elements with an atomic number of five (boron) or less, the stable number is two instead of eight. For these light elements, two valence electrons completely fill the *first* energy level. The elements H, He, Li, Be, and B form bonds to reach the stable number of two valence electrons.

Hydrogen is special

Because of its single electron, hydrogen can also have zero valence electrons. Zero is a stable number for hydrogen, as well as two. This flexibility makes hydrogen a very "friendly" element; hydrogen can bond with almost any other element.

VOCABULARY

valence electrons - the electrons in the highest unfilled energy level of an atom.

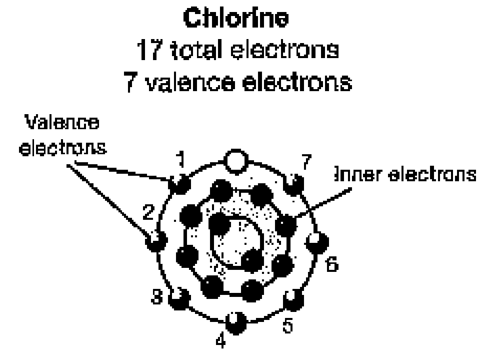


Figure 13.4: *Chlorine has 7 valence electrons. The other 10 electrons are in filled (inner) energy levels.*

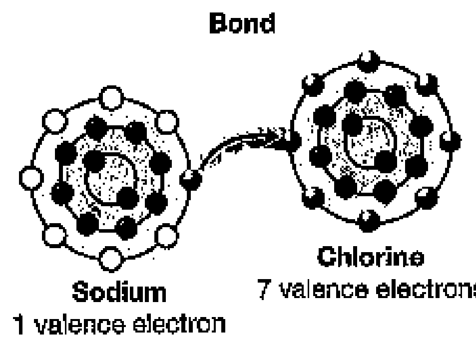
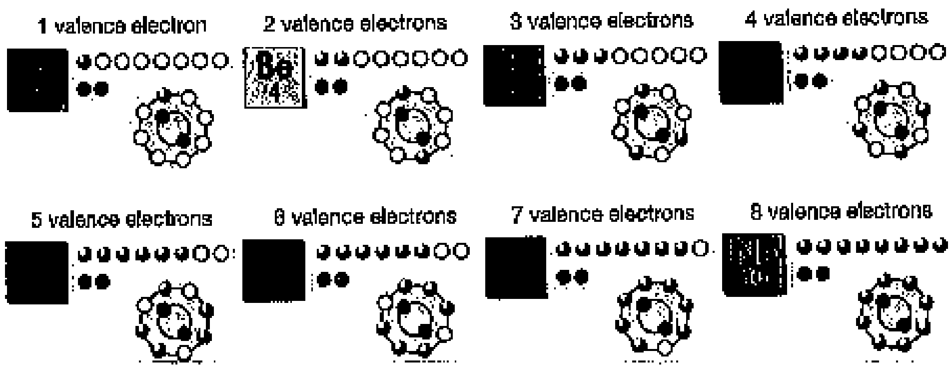


Figure 13.5: *Chlorine and sodium bond so each can reach a configuration with eight valence electrons.*

Valence electrons and the periodic table

Period 2 elements The illustration below shows how the electrons in the elements in the second period (lithium to neon) fill the energy levels. Two of lithium's three electrons go in the first energy level. Lithium has one valence electron because its third electron is the only one in the second energy level.

Each successive element has one more valence electron Going from left to right across a period, each successive element has one more valence electron. Beryllium has two valence electrons, boron has three, and carbon has four. Each element in the second period adds one more electron until all eight spots in the second energy level are full at atomic number 10, which is neon, a noble gas. Neon has eight valence electrons.



Bonding Oxygen has six valence electrons. To get to the magic number of eight, oxygen needs to add two electrons. Oxygen forms chemical bonds that provide these two extra electrons. For example, a single oxygen atom combines with two hydrogen atoms because each hydrogen can supply only one electron (Figure 13.6).

Double bonds share two electrons Carbon has four valence electrons. That means two oxygen atoms can bond with a single carbon atom, with each oxygen sharing two of carbon's four valence electrons. The bonds in carbon dioxide (CO_2) are *double bonds* because each bond involves four electrons (Figure 13.7), two from carbon and two from oxygen. Each oxygen has two lone pairs of electrons (see the in-text diagram on the next page).

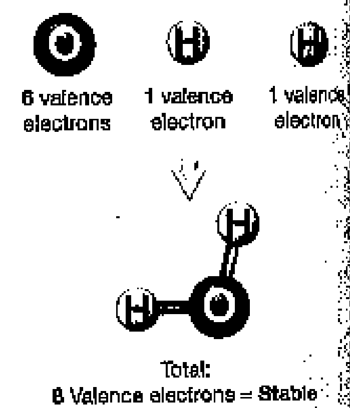


Figure 13.6: *Oxygen has six va... electrons and hydrogen has two. I... water molecule, each hydrogen su... one electron to make a total of eig... valence electrons.*

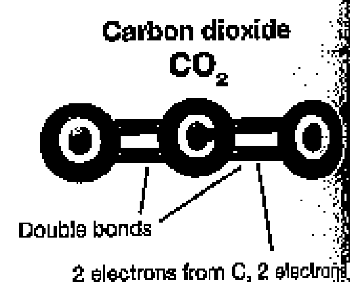


Figure 13.7: *Carbon forms t... double bonds with oxygen to ma... carbon dioxide.*

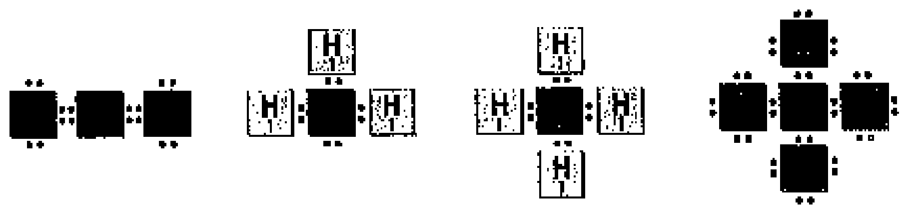
dot diagrams

diagrams of the elements

A **Lewis dot diagram** is a way to represent an atom's valence electrons. A dot diagram shows the element symbol surrounded by one to eight dots representing its valence electrons. Each dot represents one electron. Lithium has one dot, beryllium has two, boron has three, etc. Figure 13.8 shows dot diagrams for some of the elements.

diagrams of molecules

Each element forms bonds to reach one of the stable numbers of valence electrons: two or eight. In dot diagrams of a complete molecule, each element symbol has either two or eight dots around it. Both configurations correspond to completely filled (or empty) energy levels.



Example dot diagrams

Carbon has four dots and hydrogen has one. One carbon atom bonds with four hydrogen atoms because this allows the carbon atom to have eight valence electrons (eight dots)—four of its own and four shared with four hydrogen atoms. The picture above shows dot diagrams for carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4), and carbon tetrachloride (CCl_4).

Formation of an ionic bond

A sodium atom is neutral with 11 positively charged protons and 11 negatively charged electrons. When sodium loses one electron, it has 11 protons (+) and 10 electrons (–) and becomes an ion with a net charge of +1. This is because it now has one more positive charge than its negative charges. A chlorine atom is neutral with 17 protons and 17 electrons. When chlorine gains one electron to have a stable eight electrons, it has 17 protons (+) and 18 electrons (–) and becomes an ion with a charge of –1. This is because it has gained one negative charge. When sodium and chlorine form an ionic bond, the resulting compound is neutral (+1) + (–1) = 0.

VOCABULARY

Lewis dot diagram - a method for representing an atom's valence electrons using dots around the element symbol.

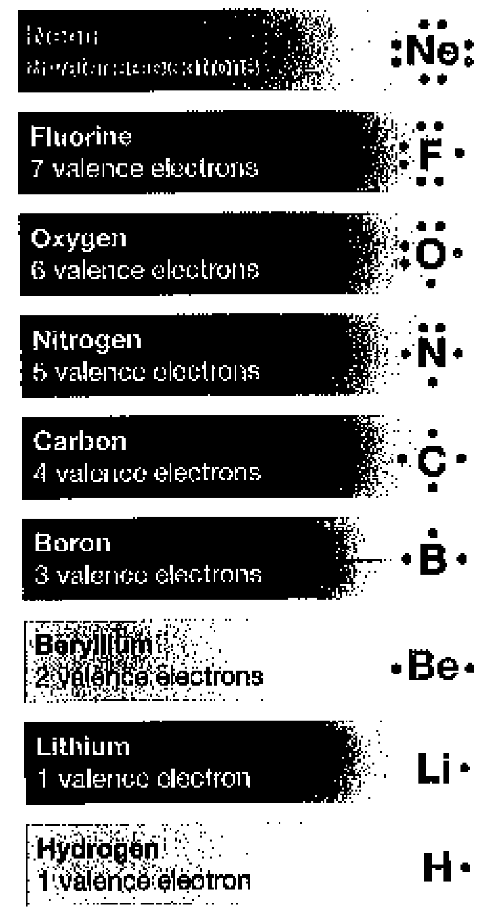
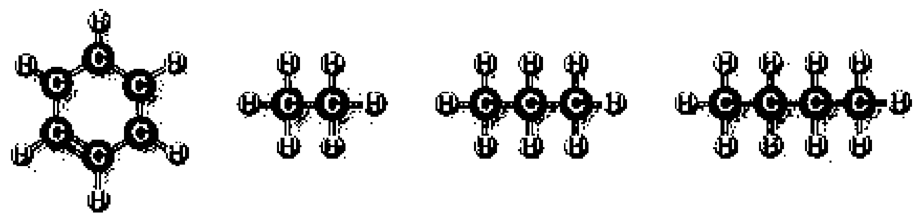


Figure 13.8: *Dot diagrams for some of the elements.*

Section 13.1 Review

1. Molecules are held together by:
   a. ionic bonds
   b. covalent bonds
   c. both a and b
2. How many atoms of chlorine (Cl) are in the carbon tetrachloride molecule (CCl_4)?
3. Which of the compounds below has a chemical formula of C_3H_8?



A B C D

4. True or False: Ionic compounds do not form molecules.
5. Atoms form chemical bonds using:
   a. electrons in the innermost energy level.
   b. electrons in the outermost energy level.
   c. protons and electrons.
6. Which of the diagrams in Figure 13.9 shows an element with three valence electrons? What is the name of this element?
7. Name two elements that have the Lewis dot diagram shown in Figure 13.10.
8. Draw dot diagrams for the following.
   a. silicon
   b. xenon
   c. calcium
   d. H_2O

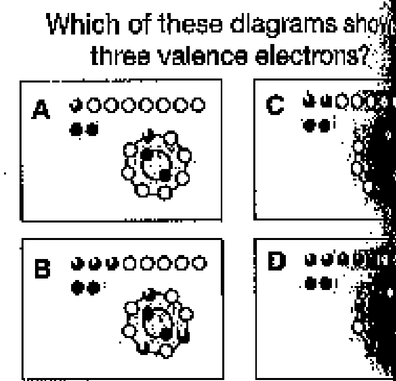


Figure 13.9: *Question 6.*

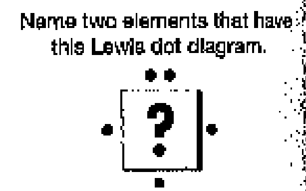


Figure 13.10: *Question 7.*

Chemical Formulas

...vious section, you learned how and why atoms form chemical bonds with one another. ...learned that atoms combine in certain ratios with other atoms. These ratios determine the ...formula for a compound. In this section, you will learn how to write the chemical ...for compounds. You will also learn how to name compounds based on their chemical

...ical formulas and oxidation numbers

Ionic compounds Recall that the chemical formula for sodium chloride is NaCl. This formula indicates that every formula unit of sodium chloride contains one atom of sodium and one atom of chlorine; it's a 1:1 ratio. Why do sodium and chlorine combine in a 1:1 ratio? When sodium loses an electron, it becomes an ion with a charge of +1. When chlorine gains an electron, it becomes an ion with a charge of –1. When these two ions combine to form an ionic bond, the net electrical charge is zero (Figure 13.11). This is because (+1) + (–1) = 0.

All compounds have an electrical charge of zero. This means they are neutral.

Oxidation numbers A sodium atom always ionizes to become Na^{+} (a charge of +1) when it combines with other atoms to make a compound. Therefore, we say that sodium has an oxidation number of 1+. An **oxidation number** indicates the electric charge on an atom when electrons are lost, gained, or shared during chemical bond formation. Notice that the convention for writing oxidation numbers is the opposite of the convention for writing the charge. When writing the oxidation number, the positive (or negative) symbol is written *after* the number, not *before* it.

What is chlorine's oxidation number? If you think it is 1–, you are right. This is because chlorine gains one electron, one negative charge, when it bonds with other atoms. Figure 13.12 shows the oxidation numbers for some of the elements.

VOCABULARY

oxidation number - a quantity that indicates the charge on an atom when it gains, loses, or shares electrons during bond formation.

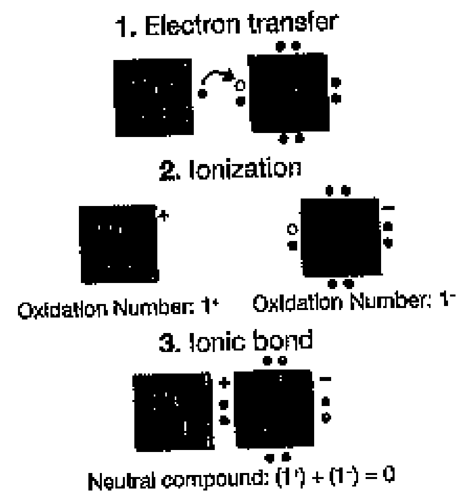


Figure 13.11: *Sodium and chlorine combine in a 1:1 ratio.*

Atom	Electrons Gained or Lost	Oxidation Number
K	loses 1	1+
Mg	loses 2	2+
Al	loses 3	3+
P	gains 3	3–
Se	gains 2	2–
Br	gains 1	1–

Figure 13.12: *Oxidation numbers of some common elements.*

Predicting oxidation numbers from the periodic table

Valence electrons and oxidation numbers

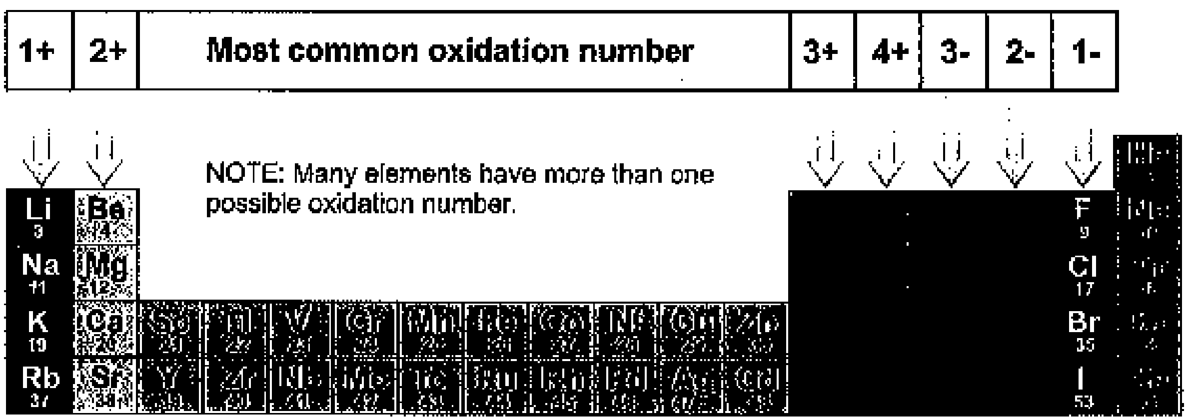
In the last section, you learned that you can tell how many valence electrons an element has by its location on the periodic table. If you can determine how many valence electrons an element has, you can predict its oxidation number. An oxidation number corresponds to the need of an atom to gain or lose electrons (Figure 13.13).

Beryllium has an oxidation number of 2+

For example, locate beryllium (Be) on the periodic table below. It is in the second column, or Group 2, which means beryllium has two valence electrons. Will beryllium get rid of two electrons, or gain six in order to obtain a stable number? Of course, it is easier to lose two electrons. When these two electrons are lost, beryllium becomes an ion with a charge of +2. Therefore, the most common oxidation number for beryllium is 2+. In fact, the most common oxidation number for all elements in Group 2 is 2+.

The periodic table

The periodic table below shows the most common oxidation numbers of most of the elements. The elements known as *transition metals* (in the middle of the table) have variable oxidation numbers.



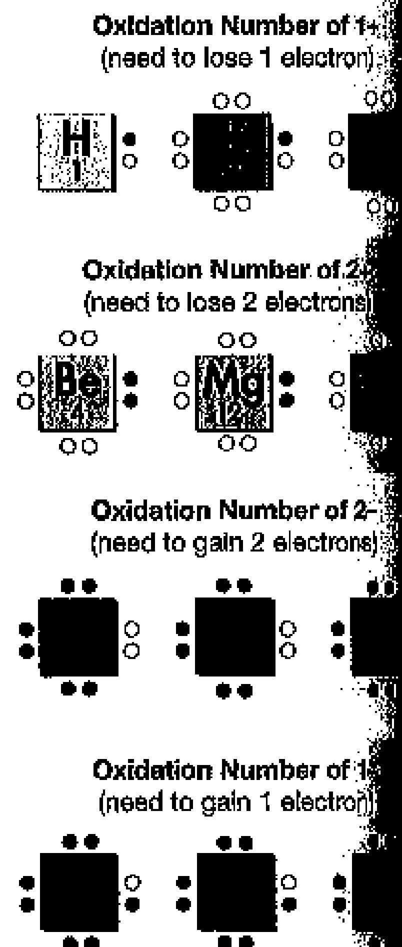


Figure 13.13: *Oxidation numbers correspond to the need to gain or lose electrons.*

...cting ionic and covalent bonds

...bonds are ...or covalent

Whether a compound is ionic or covalently bonded depends on how much each element "needs" an electron to get to a magic number (two or eight). Elements that are very close to the noble gases tend to give or take electrons rather than share them. These elements often form ionic bonds rather than covalent bonds.

...m chloride is ionic

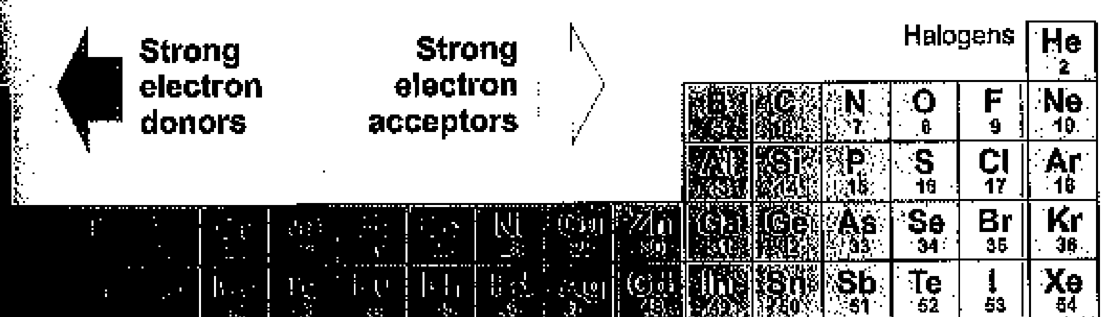
As an example, sodium has one electron more than the noble gas neon. Sodium has a very strong tendency to give up that electron and become a positive ion. Chlorine has one electron less than argon. Therefore, chlorine has a very strong tendency to accept an electron and become a negative ion. Sodium chloride is an ionic compound because sodium has a strong tendency to give up an electron, and chlorine has a strong tendency to accept an electron.

...ing ionic ...mpounds

On the periodic table, strong electron donors are on the left side (alkali metals). Strong electron acceptors are on the right side (halogens). The farther separated two elements are on the periodic table, the more likely they are to form an ionic compound.

Forming covalent ...mpounds

Covalent compounds form when elements have roughly equal tendency to accept electrons. Elements that are nonmetals and therefore close together on the periodic table tend to form covalent compounds with each other because they have approximately equal tendency to accept electrons. Compounds involving carbon, silicon, nitrogen, and oxygen are often covalent.



SOLVE IT!

You can use the periodic table to predict whether two elements will form ionic or covalent compounds. For example, potassium combines with bromine to make potassium bromide (KBr). Are the chemical bonds in this compound likely to be ionic or covalent? To solve this problem, look at the periodic table at the left.

K is a strong electron donor and Br is a strong electron acceptor. KBr is an ionic compound because K and Br are from opposite sides of the periodic table.

Now you try the following.

1. Are the chemical bonds in silica (SiO_2) likely to be ionic or covalent?
2. Are the chemical bonds in calcium fluoride (CaF_2) likely to be ionic or covalent?

Oxidation numbers and chemical formulas

Oxidation numbers in a compound add up to zero

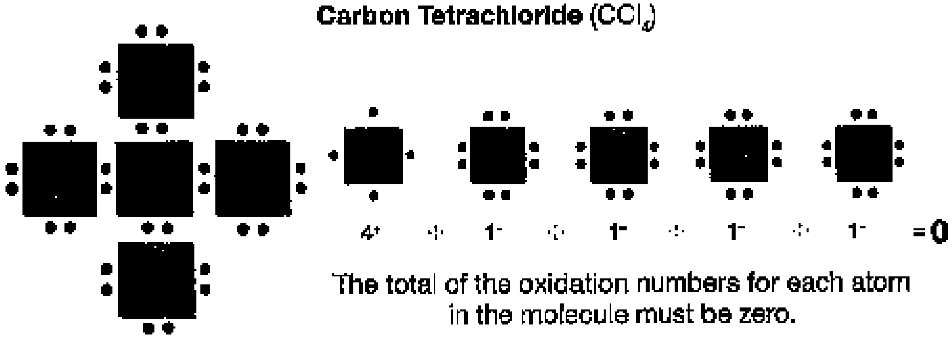
When elements combine in molecules and ionic compounds, the total electric charge is always zero. This is because any electron donated by one atom is accepted by another. The rule of zero charge is easiest to apply using oxidation numbers. The total of all the oxidation numbers for all the atoms in a compound must be zero. This important rule allows you to predict many chemical formulas.

The oxidation numbers for all the atoms in a compound must add up to zero.

Example: carbon tetrachloride

To see how this works, consider the compound carbon tetrachloride (CCl_4). Carbon has an oxidation number of 4+. Chlorine has an oxidation number of 1–. It takes four chlorine atoms to cancel carbon's 4+ oxidation number.

Carbon Tetrachloride (CCl_4)



The total of the oxidation numbers for each atom in the molecule must be zero.

Most elements have more than one possible oxidation number

Some periodic tables list multiple oxidation numbers for most elements. This is because more complex bonding is possible. When multiple oxidation numbers are shown, the most common one is usually in bold type. For example, nitrogen has possible oxidation numbers of 5+, 4+, 3+, 2+, and 3–, even though 3– is the most common (shown at the right). In some reference materials, roman numerals are used to distinguish the oxidation number. Figure 13.14 shows a few of these elements.

5+, 4+, 3+ 2+, 3-
N
7
nitrogen

Element	Oxidati Numb
copper (I)	Cu
copper (II)	Cu^{2}
iron (II)	Fe^{2}
iron (III)	Fe
chromium (II)	Cr^{2}
chromium (III)	Cr
lead (II)	Pb^{2}
lead (IV)	Pb

Figure 13.14: *In some cases, numerals are used to distinguish oxidation number for an element multiple numbers.*

Rules for predicting chemical formulas

...ting chemical formulas for binary compounds

Rules for predicting chemical formulas

Once you know how to find the oxidation numbers of the elements, you can predict the chemical formulas of binary compounds (Figure 13.15). A **binary compound** is a compound that consists of two elements. Sodium chloride (NaCl) is a binary compound. To predict and write the chemical formula of a binary compound, use the following rules.

1. Write the symbol for the element that has a positive oxidation number first. Do not write the oxidation number.
2. Write the symbol for the element that has a negative oxidation number second. Do not write the oxidation number.
3. Find the least common multiple between the oxidation numbers to make the sum of their charges equal zero. Use the numbers you multiply the oxidation numbers by as subscripts.

Solving Problems: Binary Compounds

Iron (III) (3+) and oxygen (2–) combine to form a compound. Predict the chemical formula of this compound.

...ing for: Chemical formula for a binary compound

...: Elements and oxidation numbers: Fe (III) = 3+ and O = 2–

...ionships: Write the subscripts so that the sum of the oxidation numbers equals zero.

...ion: The least common multiple between 3 and 2 is 6.
For iron (III): 2 × (3+) = 6+. For oxygen: 3 × (2–) = 6–
(6+) + (6–) = 0. The chemical formula is Fe_2O_3 because it took 2 Fe atoms and 3 O atoms to make a neutral compound.

Your turn...

a. Predict the chemical formula of the compound containing beryllium (2+) and fluorine (1–).

b. Predict the chemical formula of the compound containing lead (IV) and sulfur (2–).

VOCABULARY

binary compound - a chemical compound that consists of two elements.

Predict the chemical formula for a compound made from iron (oxidation number 3+) and oxygen (oxidation number 2–).

1. Write the symbol for the element that has a positive oxidation number first. Do not write the oxidation number.

Fe

2. Write the symbol for the element that has a negative oxidation number second. Do not write the oxidation number.

O

3. Add subscripts so that the sum of the oxidation numbers of all the atoms in the formula is zero.

$2 \times Fe^{3+} = 6+$

$3 \times O^{2-} = 6-$

$(6+) + (6-) = 0$

Chemical formula: Fe_2O_3

Figure 13.15: *The steps to predict the chemical formula of a binary compound.*

SOLVE FIRST LOOK LATER

a. BeF_2

b. PbS_2

Compounds with more than two elements

Not all compounds are made of only two types of atoms

Have you ever taken an antacid for an upset stomach? Many antacids contain calcium carbonate, or $CaCO_3$. How many types of atoms does this compound contain? You are right if you said three: calcium, carbon, and oxygen. Some compounds contain more than two elements. Some of these types of compounds contain polyatomic ions. A **polyatomic ion** contains more than one atom. The prefix *poly-* means "many." Figure 13.16 lists some common polyatomic ions. The example below illustrates how to write chemical formulas for these types of compounds.

Solving Problems: More Chemical Formulas

Aluminum (3+) combines with sulfate (SO_4^{2-}) or the sulfate ion to make aluminum sulfate. Write the chemical formula for aluminum sulfate.

1. Looking for: Chemical formula for a compound containing more than two elements

2. Given: Al^{3+} and SO_4^{2-}

3. Relationships: The oxidation numbers for all of the atoms in the compound must add up to zero.

4. Solution: Two aluminum ions have a charge of 6+. It takes three sulfate ions to get a charge of 6–. To write the chemical formula, parentheses must be placed around the polyatomic ion. The subscript is placed on the outside of the parentheses. The formula is: $Al_2(SO_4)_3$

Your turn...

a. Write the chemical formula for hydrogen (1+) peroxide (O_2^{2-}).

b. Write the chemical formula for calcium (2+) phosphate (PO_4^{3-}).

VOCABULARY

polyatomic ion - an ion that contains more than one atom

Oxidation Number	Name of Ion	Formula
1+	ammonium	[illegible]
1–	acetate	[illegible]
2–	carbonate	[illegible]
2–	chromate	[illegible]
1–	hydrogen carbonate	[illegible]
1+	hydronium	[illegible]
1–	hydroxide	[illegible]
1–	nitrate	[illegible]
2–	peroxide	[illegible]
3–	phosphate	[illegible]
2–	sulfate	[illegible]
2–	sulfite	[illegible]

Figure 13.16: *Oxidation nu... some common polyatomic ions.*

SOLVE FIRST LOOK

a. H_2O_2

b. $Ca_3(PO_4)_2$

...ing compounds

...ing binary ionic compounds

By using the following rules, you can name a binary ionic compound if you are given its chemical formula. A *binary ionic compound* is held together by ionic bonds. *Binary molecular compounds* consist of covalently bonded atoms. Naming binary molecular compounds is discussed in the *Solve It!* on the next page. To name a binary ionic compound:

1. Write the name of the first element.
2. Write the root name of the second element.
3. Add the suffix *-ide* to the root name.

What is the ... of $MgBr_2$?

$MgBr_2$ is *magnesium* (name of first element) plus *-brom* (root name of second element) plus *-ide* = magnesium bromide (Figure 13.17, top).

If the positive element has more than one oxidation number, you must first figure out that number. Then, use a roman numeral to indicate the oxidation number. For example, $FeCl_3$ = iron (III) chloride because iron (III) has a charge of 3+. It would take three chloride ions (oxidation number = 1–) to make the sum of the oxidation numbers equal zero.

Naming ...unds with ...omic ions

Naming compounds with polyatomic ions is easy.

1. Write the name of the first element or polyatomic ion first. Use the periodic table or ion chart (Figure 13.16, previous page) to find its name.
2. Write the name of the second element or polyatomic ion second. Use the periodic table or ion chart (Figure 13.16, previous page) to find its name. If the second one is an element, use the root name of the element with the suffix *-ide*.

What is the ... of NH_4Cl?

NH_4Cl is *ammonium* (the name of the polyatomic ion from Figure 13.16) plus *-chlor* (root name of the second element) plus *-ide* = ammonium chloride (Figure 13.17, bottom).

Again, if an element has more than one oxidation number, you must figure out that number. For example, Cu_2SO_3 would be named copper (I) sulfite and $CuSO_3$ would be copper (II) sulfite.

Naming a Binary Compound

$MgBr_2$

1. Write the name of the first element.

Mg = magnesium

2. Write the root name of the second element.

Br = bromine = brom-

3. Add the suffix *-ide* to the root name.

brom + -ide = bromide

Name of the compound:

Magnesium bromide

Naming Compounds with Polyatomic Ions

NH_4Cl

1. Write the name of the first element or polyatomic ion first. Use the periodic table or ion chart to find its name.

NH_4 = ammonium

2. Write the name of the second element or polyatomic ion second. Use the periodic table or ion chart to find its name. If the second one is an element, use the root name of the element with the suffix *-ide*.

Cl = chloride

Name of the compound:

ammonium chloride

Figure 13.17: *Naming compounds.*

Section 13.2 Review

1. The oxidation number is:
   a. the number of oxygen atoms an element bonds with.
   b. the positive or negative charge acquired by an atom in a chemical bond.
   c. the number of electrons involved in a chemical bond.
2. Name three elements that have an oxidation number of 3+.
3. What is the oxidation number for the elements in Group 17?
4. When elements form a molecule, what is TRUE about the oxidation numbers of the atoms in the molecule?
   a. The sum of the oxidation numbers must equal zero.
   b. All oxidation numbers from the same molecule must be positive.
5. True or False: All oxidation numbers from the same molecule must be negative.
6. Which of the following elements will bond with oxygen, resulting in a 1:1 ratio of oxygen and the element?
   a. lithium
   b. boron
   c. beryllium
   d. nitrogen
7. Name the following compounds.
   a. $NaHCO_3$
   b. $BaCl_2$
   c. LiF
   d. $Al(OH)_3$
   e. SrI
8. Would a bond between potassium and iodine most likely be covalent or ionic? Explain your answer.

SOLVE IT!

Naming Binary Molecular Compounds

Naming binary molecular com[…] is similar to the methods used […] naming binary ionic compoun[…] described on the previous pa[…] However, in this case, the num[…] each type of atom (the subscri[…] also specified in the name of th[…] compound. From 1 to 10, the G[…] prefixes are: *mono, di, tri, tetr[…] hexa, hepta, octa, nona, deca*

To name a binary molecular compound, specify the numbe[…] each type of atom using the G[…] prefix. As with binary ionic compounds, the ending of the […] of the second element in the compound is modified by addi[…] suffix *-ide* as shown in the exa[…] below.

N_2O_4

dinitrogen tetr[…]oxi[…]

If the first element in the com[…] does not have a subscript, do[…] a Greek prefix for that elemen[…] use one for the second elem[…] example, CO_2 is carbon diox[…]

Name the following binary mo[…] compounds.

(a) CCl_4 (b) N_4O_6 (c)[…]