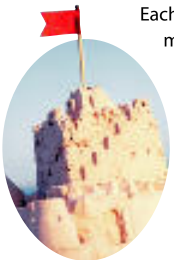
10.1 The Mole: A Measurement of Matter

Connecting to Your World Every year, contestants from all over the world travel to Harrison Hot Springs in British Columbia, Canada, to compete in the world championship sand sculpture contest. Each contestant creates a beautiful work of art out of millions of tiny grains of sand. You could measure the amount of sand in a sculpture by counting the grains of sand. But wouldn't it be much easier to weigh the sand? In this section, you'll discover how chemists measure the amount of a substance using a unit called a mole.



Guide for Reading

Key Concepts

- What are three methods for measuring the amount of something?
- How is Avogadro's number related to a mole of any substance?
- How is the atomic mass of an element related to the molar mass of an element?
- How is the mass of a mole of a compound calculated?

Vocabulary

mole
Avogadro's number
representative particle
molar mass

Reading Strategy

Relating Text and Visuals As you read, look closely at Table 10.2. Explain how the information in the table helps you understand the basis for the molar masses of the elements.

Measuring Matter

You live in a quantitative world. The grade you got on your last exam, the number of times you heard your favorite song on the radio yesterday, and the cost of a bicycle you would like to own are all important quantities to you. These are quantities that answer questions such as "How much?" or "How many?" Scientists answer similar questions. How many kilograms of iron can be obtained from one hundred kilograms of iron ore? How many grams of hydrogen and nitrogen must be combined to make 200 grams of the fertilizer ammonia (NH_3)? Questions like these illustrate that chemistry is a quantitative science. In your study of chemistry, you will analyze the composition of samples of matter and perform chemical calculations that relate quantities of reactants in a chemical reaction to quantities of products. To solve these and other problems, you will have to be able to measure the amount of matter you have.

How do you measure matter? One way is to count how many of something you have. For example, you can count the CDs in your collection or the number of pins you knock down when bowling. Another way to measure matter is to determine its mass. You can buy potatoes by the kilogram or pound and gold by the gram or ounce. You can also measure matter by volume. For instance, people buy gasoline by the liter or the gallon and take cough medicine by the milliliter or the teaspoon. **You often measure the amount of something by one of three different methods—by count, by mass, and by volume.** For example, you can buy soda by the six-pack or by the liter. Figure 10.1 shows how you might measure the amount of grapes you want to buy.

Figure 10.1 A grocer's scale measures the weight of the grapes you buy.

10.1

Some of the units used for measuring indicate a specific number of items. For example, a pair always means two. A pair of shoes is two shoes, and a pair of aces is two aces. Similarly, a dozen always means 12. A dozen eggs is 12 eggs and a dozen pens is 12 pens.

Apples are measured in three different ways. At a fruit stand, they are often sold by the count (3 for \$2.40). In a supermarket, you usually buy apples by weight (\$1.29/pound) or mass (\$2.79/kg). At an orchard, you can buy apples by volume (\$12.00/bushel). Each of these different ways to measure apples can be equated to a dozen apples.

By count: 1 dozen apples = 12 apples

For average-sized apples the following approximations can be used.

By mass: 1 dozen apples = 2.0 kg apples

By volume: 1 dozen apples = 0.20 bushel apples

Figure 10.2 shows other items sold by count, weight, and volume.

Knowing how the count, mass, and volume of apples relate to a dozen apples allows you to convert among these units. For example, based on the unit relationships given above, you could calculate the mass of a bushel of apples or the mass of 90 average-sized apples using conversion factors such as the following.

$$\frac{1\text{ dozen apples}}{12\text{ apples}} \qquad \frac{2.0\text{ kg apples}}{1\text{ dozen apples}} \qquad \frac{1\text{ dozen apples}}{0.20\text{ bushel apples}}$$

Checkpoint ***What are three ways of measuring the amount of a substance?***

Figure 10.2 You can buy items by different types of measurements, such as a count, a weight or mass, or a volume. **Classifying** ***Which of these common items are being sold by weight? By volume? By count?***

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SAMPLE PROBLEM 10.1

Finding Mass from a Count

What is the mass of 90 average-sized apples if 1 dozen of the apples has a mass of 2.0 kg?

1 Analyze ***List the knowns and the unknown.***

Knowns
- number of apples = 90 apples
- 12 apples = 1 dozen apples
- 1 dozen apples = 2.0 kg apples

Unknown
- mass of 90 apples = ? kg

You can use dimensional analysis to convert the number of apples to the mass of apples. Carry out this conversion by performing the following sequence of conversions:

Number of apples $\longrightarrow$ dozens of apples $\longrightarrow$ mass of apples.

2 Calculate ***Solve for the unknown.***

The first conversion factor is $\dfrac{1 \text{ dozen apples}}{12 \text{ apples}}$.

The second conversion factor is $\dfrac{2.0 \text{ kg apples}}{1 \text{ dozen apples}}$.

Multiplying the original number of apples by these two conversion factors gives the answer in kilograms.

$$\text{mass of apples} = 90 \cancel{\text{apples}} \times \frac{1 \cancel{\text{dozen apples}}}{12 \cancel{\text{apples}}} \times \frac{2.0 \text{ kg apples}}{1 \cancel{\text{dozen apples}}}$$
$$= 15 \text{ kg apples}$$

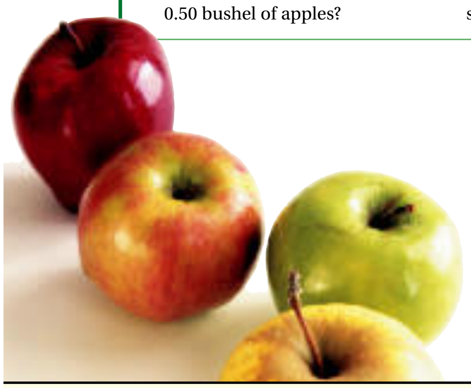
The mass of 90 average-sized apples is 15 kg.

3 Evaluate ***Does the result make sense?***

Because a dozen apples has a mass of 2.0 kg, and 90 apples is less than 10 dozen apples, the mass should be less than 20 kg of apples (10 dozen × 2.0 kg/dozen).

Practice Problems

1. If 0.20 bushel is 1 dozen apples and a dozen apples has a mass of 2.0 kg, what is the mass of 0.50 bushel of apples?
2. Assume 2.0 kg of apples is 1 dozen and that each apple has 8 seeds. How many apple seeds are in 14 kg of apples?



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Dimensional Analysis

Dimensional analysis is a tool for solving conversion problems—problems in which a measurement must be expressed in a different unit.

To solve a simple one-step conversion problem (for example, How many grams is 34 kg?), you must know the relationship between the unit of the known measurement (kg) and the unit of the desired answer (g). The relationship is: 1 kg = 1000 g.

Write this equality as a ratio (conversion factor). When you multiply the known measurement by the conversion factor, the unit kg cancels and the resulting answer has the unit g.

In more complex problems, you may need to use more than one conversion factor to obtain the answer, but the principle is the same.

Math Handbook

For help with dimensional analysis, go to page R66.

Interactive Textbook

Problem-Solving 10.1
Solve Problem 1 with the help of an interactive guided tutorial.

with ChemASAP

Figure 10.3 Words other than *mole* are used to describe a number of something—for example, a *ream* of paper (500 sheets), a *gross* of pencils (144), and a *dozen* eggs (12).

What Is a Mole?

Counting objects as big as apples is a reasonable way to measure the amount of apples. But imagine trying to count the grains of sand in a sand sculpture. That would be an endless job. Recall that matter is composed of atoms, molecules, and ions. These particles are much smaller than grains of sand and an extremely large number of them are in even a small sample of a substance. Obviously, counting particles one by one is not practical. However, think about counting eggs. It's easier when the eggs are grouped into dozens. A dozen is a specified number, 12, of things. Other common groupings of items are shown in Figure 10.3. Chemists also use a unit that is a specified number of particles. The unit is called a mole. Just as a dozen eggs is 12 eggs, a **mole** (mol) of a substance is 6.02×10^{23} representative particles of that substance and is the SI unit for measuring the amount of a substance. The number of representative particles in a mole, 6.02×10^{23}, is called **Avogadro's number.** It was named in honor of the Italian scientist Amedeo Avogadro di Quaregna (1776–1856) who helped clarify the difference between atoms and molecules.

The term **representative particle** refers to the species present in a substance: usually atoms, molecules, or formula units. The representative particle of most elements is the atom. Iron is composed of iron atoms. Helium is composed of helium atoms. Seven elements, however, normally exist as diatomic molecules (H_2, N_2, O_2, F_2, Cl_2, Br_2, and I_2). The representative particle of these elements and of all molecular compounds is the molecule. The molecular compounds water (H_2O) and sulfur dioxide (SO_2) are composed of H_2O and SO_2 molecules, respectively. For ionic compounds, such as calcium chloride, the representative particle is the formula unit $CaCl_2$. **A mole of any substance contains Avogadro's number of representative particles, or 6.02×10^{23} representative particles.** Table 10.1 summarizes the relationship between representative particles and moles of substances.

Converting Number of Particles to Moles

The relationship, 1 mol = 6.02×10^{23} representative particles, is the basis for a conversion factor that you can use to convert numbers of representative particles to moles.

$$\text{moles} = \text{representative particles} \times \frac{1 \text{ mole}}{6.02 \times 10^{23} \text{ representative particles}}$$

Checkpoint ***How many representative particles are in one mole?***

Table 10.1

Representative Particles and Moles

Substance	Representative particle	Chemical formula	Representative particles in 1.00 mole
Atomic nitrogen	Atom	N	6.02×10^{23}
Nitrogen gas	Molecule	N_2	6.02×10^{23}
Water	Molecule	H_2O	6.02×10^{23}
Calcium ion	Ion	Ca^{2+}	6.02×10^{23}
Calcium fluoride	Formula unit	CaF_2	6.02×10^{23}
Sucrose	Molecule	$C_{12}H_{22}O_{11}$	6.02×10^{23}

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SAMPLE PROBLEM 10.2

Converting Number of Atoms to Moles

Magnesium is a light metal used in the manufacture of aircraft, automobile wheels, tools, and garden furniture. How many moles of magnesium is 1.25×10^{23} atoms of magnesium?

1 Analyze ***List the knowns and the unknown.***

Knowns
- number of atoms = 1.25×10^{23} atoms Mg
- 1 mol Mg = 6.02×10^{23} atoms Mg
- The desired conversion is: atoms $\longrightarrow$ moles

Unknown
- moles = ? mol Mg

2 Calculate ***Solve for the unknown.***

The conversion factor is $\dfrac{1 \text{ mol Mg}}{6.02 \times 10^{23} \text{ atoms Mg}}$.

Multiplying atoms of Mg by the conversion factor gives the answer.

$$\text{moles} = 1.25 \times 10^{23} \cancel{\text{atoms Mg}} \times \frac{1 \text{ mol Mg}}{6.02 \times 10^{23} \cancel{\text{atoms Mg}}}$$

$$\text{moles} = 2.08 \times 10^{-1} \text{ mol Mg} = 0.208 \text{ mol Mg}$$

3 Evaluate ***Does the result make sense?***

Because the given number of atoms is less than one-fourth of Avogadro's number, the answer should be less than one-fourth mole of atoms. The answer should have three significant figures.

Practice Problems

3. How many moles is 2.80×10^{24} atoms of silicon?

4. How many moles is 2.17×10^{23} representative particles of bromine?

Math Handbook

For help with dimensional analysis, go to page R66.

Interactive Textbook

Problem-Solving 10.4
Solve Problem 4 with the help of an interactive guided tutorial.
with ChemASAP

Converting Moles to Number of Particles Now suppose you want to determine how many atoms are in a mole of a compound. To do this, you must know how many atoms are in a representative particle of the compound. This number is determined from the chemical formula. Figure 10.4 illustrates this idea with marbles (atoms) in cups (molecules). The number of marbles in a dozen cups is (6×12), or 72 marbles. In the formula of a molecule of carbon dioxide (CO_2), the subscripts show that carbon dioxide is composed of three atoms: one carbon atom and two oxygen atoms. A mole of carbon dioxide contains Avogadro's number of CO_2 molecules. But each molecule contains three atoms. Thus a mole of carbon dioxide contains three times Avogadro's number of atoms. A molecule of carbon monoxide (CO) consists of two atoms, so a mole of carbon monoxide contains two times Avogadro's number of atoms.

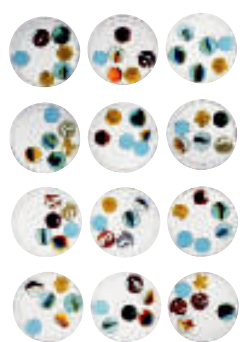

Figure 10.4 A dozen cups of marbles contain more than a dozen marbles. Similarly, a mole of molecules contains more than a mole of atoms. **Calculating** ***How many atoms are in one mole of molecules if each molecule consists of six atoms?***

To find the number of atoms in a mole of a compound, you must first determine the number of representative particles. You can use the following conversion factor to convert a number of moles of a compound to the number of representative particles (molecules or formula units).

$$\text{representative particles} = \text{moles} \times \frac{6.02 \times 10^{23} \text{ representative particles}}{1 \text{ mole}}$$

The next step is to multiply the number of representative particles by the number of atoms in each molecule or formula unit.

SAMPLE PROBLEM 10.3

Converting Moles to Number of Atoms

Propane is a gas used for cooking and heating. How many atoms are in 2.12 mol of propane (C_3H_8)?

1 Analyze ***List the knowns and the unknown.***

Knowns
- number of moles = 2.12 mol C_3H_8
- 1 mol C_3H_8 = 6.02×10^{23} molecules C_3H_8
- 1 molecule C_3H_8 = 11 atoms (3 carbon atoms and 8 hydrogen atoms)
- The desired conversion is: moles ⟶ molecules ⟶ atoms.

Unknown
- number of atoms = ? atoms

Use the relationships among units given above to write the desired conversion factors.

2 Calculate ***Solve for the unknown.***

The first conversion factor is $\frac{6.02 \times 10^{23} \text{ molecules } C_3H_8}{1 \text{ mol } C_3H_8}$.

The second conversion factor is $\frac{11 \text{ atoms}}{1 \text{ molecule } C_3H_8}$.

Multiply the moles of C_3H_8 by the proper conversion factors:

$$2.12 \text{ mol } C_3H_8 \times \frac{6.02 \times 10^{23} \text{ molecules } C_3H_8}{1 \text{ mol } C_3H_8} \times \frac{11 \text{ atoms}}{1 \text{ molecule } C_3H_8}$$

$$= 1.4039 \times 10^{25} \text{ atoms} = 1.40 \times 10^{25} \text{ atoms}$$

3 Evaluate ***Does the result make sense?***

Because there are 11 atoms in each molecule of propane and more than 2 mol of propane, the answer should be more than 20 times Avogadro's number of propane molecules. The answer has three significant figures based on the three significant figures in the given measurement.

Practice Problems

5. How many atoms are in 1.14 mol SO_3?

6. How many moles are in 4.65×10^{24} molecules of NO_2?

Math Handbook

For help with dimensional analysis, go to page R66.

Interactive Textbook

Problem-Solving 10.5
Solve Problem 5 with the help of an interactive guided tutorial.
with ChemASAP

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Perhaps you are wondering just how large a mole is. The SI unit, the mole, is not related to the small burrowing animal of the same name shown in Figure 10.5. But this little animal can help you appreciate the size of the number 6.02×10^{23}. Assume that an average animal-mole is 15 cm long, 5 cm tall, and has a mass of 150 g. Based on this information, the mass of 6.02×10^{23} animal-moles is 9.03×10^{22} kg. That means that the mass of Avogadro's number of animal-moles is equal to more than 60 times the combined mass of Earth's oceans. If spread over the entire surface of Earth, Avogadro's number of animal-moles would form a layer more than 8 million animal-moles thick. What about the length of 6.02×10^{23} animal-moles? If lined up end-to-end, 6.02×10^{23} animal-moles would stretch from Earth to the nearest star, Alpha Centauri, more than two million times. Are you beginning to understand how enormous Avogadro's number is?

Figure 10.5 An average animal-mole has a mass of 150 g. The mass of 6.02×10^{23} animal-moles is 9.03×10^{22} kg.

The Mass of a Mole of an Element

Remember that the atomic mass of an element (the mass of a single atom) is expressed in atomic mass units (amu). The atomic masses are relative values based on the mass of the most common isotope of carbon (carbon-12). Table 10.2 shows that an average carbon atom (C) with an atomic mass of 12.0 amu is 12 times heavier than an average hydrogen atom (H) with an atomic mass of 1.0 amu. Therefore, 100 carbon atoms are 12 times heavier than 100 hydrogen atoms. In fact, any number of carbon atoms is 12 times heavier than the same number of hydrogen atoms. The mass ratio of 12 carbon atoms to 1 hydrogen atom remains the same no matter what unit is used to express the masses. So 12.0 g of carbon atoms and 1.0 g of hydrogen atoms must contain the same number of atoms.

Interactive Textbook

Animation 11 Find out how Avogadro's number is based on the relationship between the amu and the gram.

with ChemASAP

Table 10.2

CARBON ATOMS		HYDROGEN ATOMS		MASS RATIO
Number	Mass (amu)	Number	Mass (amu)	$\frac{\text{Mass carbon}}{\text{Mass hydrogen}}$
	12		1	$\frac{12\text{ amu}}{1\text{ amu}} = \frac{12}{1}$
	24 [2 × 12]		2 [2 × 1]	$\frac{24\text{ amu}}{2\text{ amu}} = \frac{12}{1}$
	120 [10 × 12]		10 [10 × 1]	$\frac{120\text{ amu}}{10\text{ amu}} = \frac{12}{1}$
	600 [50 × 12]		50 [50 × 1]	$\frac{600\text{ amu}}{50\text{ amu}} = \frac{12}{1}$
Avogadro's number	$(6.02 \times 10^{23}) \times (12)$	Avogadro's number	$(6.02 \times 10^{23}) \times (1)$	$\frac{(6.02 \times 10^{23}) \times (12)}{(6.02 \times 10^{23}) \times (1)} = \frac{12}{1}$

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If you look at the atomic masses of the elements in the periodic table, you will notice that they are not whole numbers. For example, the atomic mass of carbon is not exactly 12 times the mass of hydrogen. Recall from Chapter 4 that this is because atomic masses are weighted average masses of the isotopes of each element.

Quantities measured in grams are convenient for working in the laboratory, so chemists have converted the relative scale of masses of the elements in amu to a relative scale of masses in grams. **The atomic mass of an element expressed in grams is the mass of a mole of the element.** The mass of a mole of an element is its **molar mass**. For carbon, the molar mass is 12.0 g. For atomic hydrogen, the molar mass is 1.0 g. Figure 10.6 shows one molar mass of mercury, carbon, iron, and sulfur. Compare the molar masses in the figure to the atomic masses in your periodic table. Notice that the molar masses were rounded off to one place after the decimal point. All the examples and problems in this text use molar masses that are rounded off in this way. If your teacher uses a different rounding rule for molar masses, your answers to problems may differ slightly from the answers given in the text.

If you were to compare 12.0 g of carbon atoms with 16.0 g of oxygen atoms, you would find they contain the same number of atoms. The molar masses of any two elements must contain the same number of atoms. How many atoms are contained in the molar mass of an element? You already know. The molar mass of any element contains 1 mol or 6.02×10^{23} atoms of that element.

The mole can now be further defined as the amount of substance that contains as many representative particles as the number of atoms in 12.0 g of carbon-12. You know that 12.0 g is the molar mass of carbon-12, so 12.0 g is 1 mol of carbon. The same relationship applies to hydrogen: 1.0 g of hydrogen is 1 mol of hydrogen atoms. Similarly, because 24.3 g is the molar mass of magnesium, 1 mol of magnesium (or 6.02×10^{23} atoms of magnesium) has a mass of 24.3 g. Molar mass is the mass of 1 mol of atoms of any element.

Checkpoint ***How many atoms are in one mole of magnesium?***

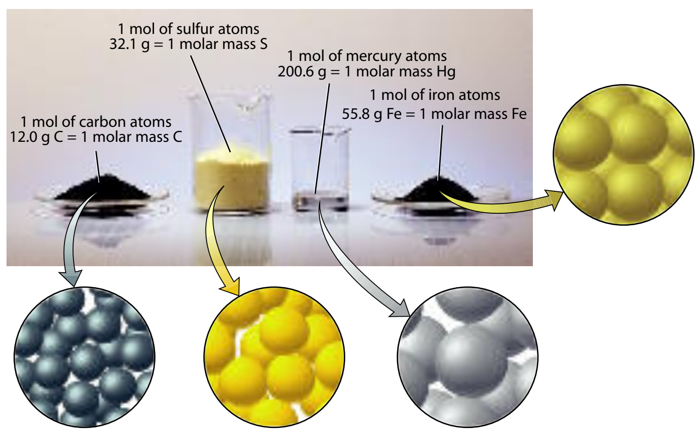

Figure 10.6 One molar mass of carbon, sulfur, mercury, and iron are shown. Each of the quantities contains one mole of the element. **Applying Concepts** ***How many atoms of each element are shown?***

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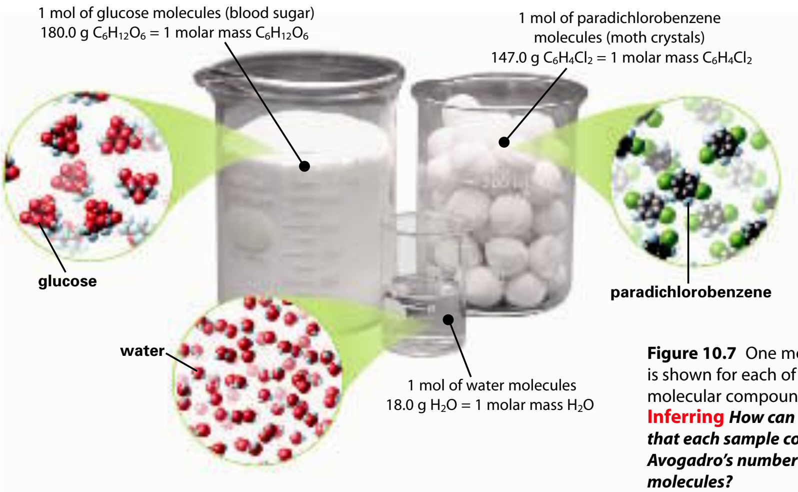
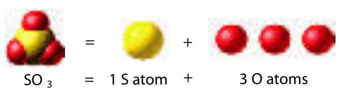


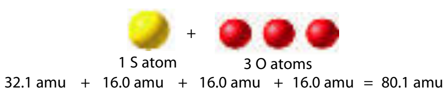
Figure 10.7 One molar mass is shown for each of three molecular compounds.
Inferring ***How can you know that each sample contains Avogadro's number of molecules?***

The Mass of a Mole of a Compound

To find the mass of a mole of a compound, you must know the formula of the compound. The formula of sulfur trioxide is SO_3. A molecule of SO_3 is composed of one atom of sulfur and three atoms of oxygen.

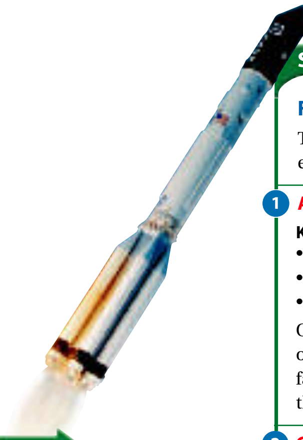


You can calculate the mass of a molecule of SO_3 by adding the atomic masses of the atoms making up the molecule. From the periodic table, the atomic mass of sulfur (S) is 32.1 amu. The mass of three atoms of oxygen is three times the atomic mass of a single oxygen atom (O): 3×16.0 amu = 48.0 amu. So, the molecular mass of SO_3 is 32.1 amu + 48.0 amu = 80.1 amu.



Now substitute the unit grams for atomic mass units to find the molar mass of SO_3. The molar mass (g/mol) of any compound is the mass in grams of 1 mol of that compound. Thus 1 mol of SO_3 has a mass of 80.1 g. This is the mass of 6.02×10^{23} molecules of SO_3.

To calculate the molar mass of a compound, find the number of grams of each element in one mole of the compound. Then add the masses of the elements in the compound. This method for calculating molar mass applies to any compound, molecular or ionic. The molar masses of glucose ($C_6H_{12}O_6$, 180.0 g), water (H_2O, 18.0 g), and paradichlorobenzene ($C_6H_4Cl_2$, 147.0 g) in Figure 10.7 were obtained in this way.



SAMPLE PROBLEM 10.4

Finding the Molar Mass of a Compound

The decomposition of hydrogen peroxide (H_2O_2) provides sufficient energy to launch a rocket. What is the molar mass of hydrogen peroxide?

1 Analyze ***List the knowns and the unknown.***

Knowns
- molecular formula = H_2O_2
- 1 molar mass H = 1 mol H = 1.0 g H
- 1 molar mass O = 1 mol O = 16.0 g O

Unknown
- molar mass = ? g

One mol of hydrogen peroxide has 2 mol of hydrogen atoms and 2 mol of oxygen atoms. Convert moles of atoms to grams by using conversion factors (g/mol) based on the molar mass of each element. The sum of the masses of the elements is the molar mass.

2 Calculate ***Solve for the unknown.***

Convert moles of hydrogen and oxygen to grams of hydrogen and oxygen. Then add the results.

$$2\ \cancel{\text{mol H}} \times \frac{1.0\ \text{g H}}{1\ \cancel{\text{mol H}}} = 2.0\ \text{g H}$$

$$2\ \cancel{\text{mol O}} \times \frac{16.0\ \text{g O}}{1\ \cancel{\text{mol O}}} = 32.0\ \text{g O}$$

$$\text{molar mass of } H_2O_2 = 34.0\ \text{g}$$

3 Evaluate ***Does the result make sense?***

The answer is the sum of two times the molar mass of hydrogen and oxygen. The answer is expressed to the tenth's place because the numbers being added are expressed to the tenth's place.

Practice Problems

7. Find the molar mass of PCl_3.

8. What is the mass of 1.00 mol of sodium hydrogen carbonate?

Math Handbook

For help with significant figures, go to page R59.

Interactive Textbook

Problem-Solving 10.7 Solve Problem 7 with the help of an interactive guided tutorial.

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10.1 Section Assessment

9. **Key Concept** What are three ways to measure the amount of something?

10. **Key Concept** Describe the relationship between Avogadro's number and one mole of any substance.

11. **Key Concept** How is the atomic mass of an element related to the molar mass of the element?

12. **Key Concept** How can you calculate the mass of a mole of a compound?

13. How many moles is 1.50×10^{23} molecules NH_3?

14. How many atoms are in 1.75 mol $CHCl_3$?

15. What is the molar mass of $CaSO_4$?

Writing Activity

Report Research the history of Avogadro's number. What elements other than carbon have been used to define a mole? Write a report that summarizes your findings.

Interactive Textbook

Assessment 10.1 Test yourself on the concepts in Section 10.1.

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