CHAPTER 11

The Mole

Moles and One Step Problems (Part I)

What You'll Learn

- You will use the mole and molar mass to make conversions among moles, mass, and number of representative particles.
- You will determine the percent composition of the components of compounds.
- You will calculate the empirical and molecular formulas for compounds and determine the formulas for hydrates.

Why It's Important

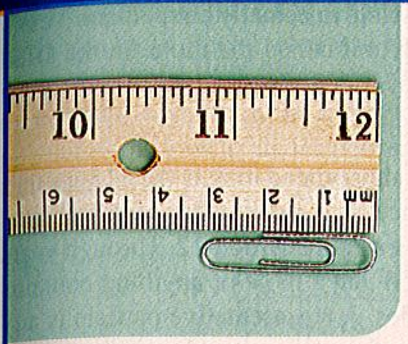
New materials, new products, new consumer goods of all kinds come on the market regularly. But before manufacturing begins on most new products, calculations involving the mole must be done.

ChemistryOnline

Visit the Chemistry Web site at **chemistrymc.com** to find links to the mole.

Florists often sell flowers, such as roses, carnations, and tulips, by the dozen. A dozen is a counting unit for 12 items.

DISCOVERY LAB



Materials

centimeter ruler
paper clip

How much is a mole?

Counting large numbers of items is easier when you use counting units like the dozen. Chemists use a counting unit called the mole.

Procedure

1. Measure the length of a paper clip to the nearest 0.1 cm.
2. If a mole is 6.02×10^{23} items, how far will a mole of paper clips, placed end to end lengthwise, reach into space?

Analysis

How many light-years (ly) would the paper clips extend into space? (1 light-year = 9.46×10^{15} m). How does the distance you calculated compare with the following astronomical distances: nearest star (other than the sun) = 4.3 ly, center of our galaxy = 30 000 ly, nearest galaxy = 2×10^{6} ly?

Section 11.1

Measuring Matter

Objectives

- **Describe** how a mole is used in chemistry.
- **Relate** a mole to common counting units.
- **Convert** moles to number of representative particles and number of representative particles to moles.

Vocabulary

mole
Avogadro's number

If you were buying a bouquet of roses for a special occasion, you probably wouldn't ask for 12 or 24; you'd ask for one or two dozen. Similarly, you might buy a pair of gloves, a ream of paper for your printer, or a gross of pencils. Each of the units shown in **Figure 11-1**—a pair, a dozen, a gross, and a ream—represents a specific number of items. These units make counting objects easier. It's easier to buy and sell paper by the ream—500 sheets—than by the individual sheet.

Counting Particles

Each of the counting units shown in **Figure 11-1** is appropriate for certain kinds of objects depending primarily on their size and the use they serve. But regardless of the object—boots, eggs, pencils, paper—the number that the unit represents is always constant.

Figure 11-1

A pair is always two objects, a dozen is 12, a gross is 144, and a ream is 500. Can you think of any other counting units?

Chemists also need a convenient method for counting accurately the number of atoms, molecules, or formula units in a sample of a substance. As you know, atoms and molecules are extremely small. There are so many of them in even the smallest sample that it's impossible to actually count them. That's why chemists created their own counting unit called the mole. In the **DISCOVERY LAB**, you found that a mole of paper clips is an enormous number of items.

What is a mole? The **mole**, commonly abbreviated mol, is the SI base unit used to measure the amount of a substance. It is the number of representative particles, carbon atoms, in exactly 12 g of pure carbon-12. Through years of experimentation, it has been established that a mole of anything contains $6.022\,136\,7 \times 10^{23}$ representative particles. A representative particle is any kind of particle such as atoms, molecules, formula units, electrons, or ions. The number $6.022\,136\,7 \times 10^{23}$ is called **Avogadro's number** in honor of the Italian physicist and lawyer Amedeo Avogadro who, in 1811, determined the volume of one mole of a gas. In this book, Avogadro's number will be rounded to three significant figures—6.02×10^{23}.

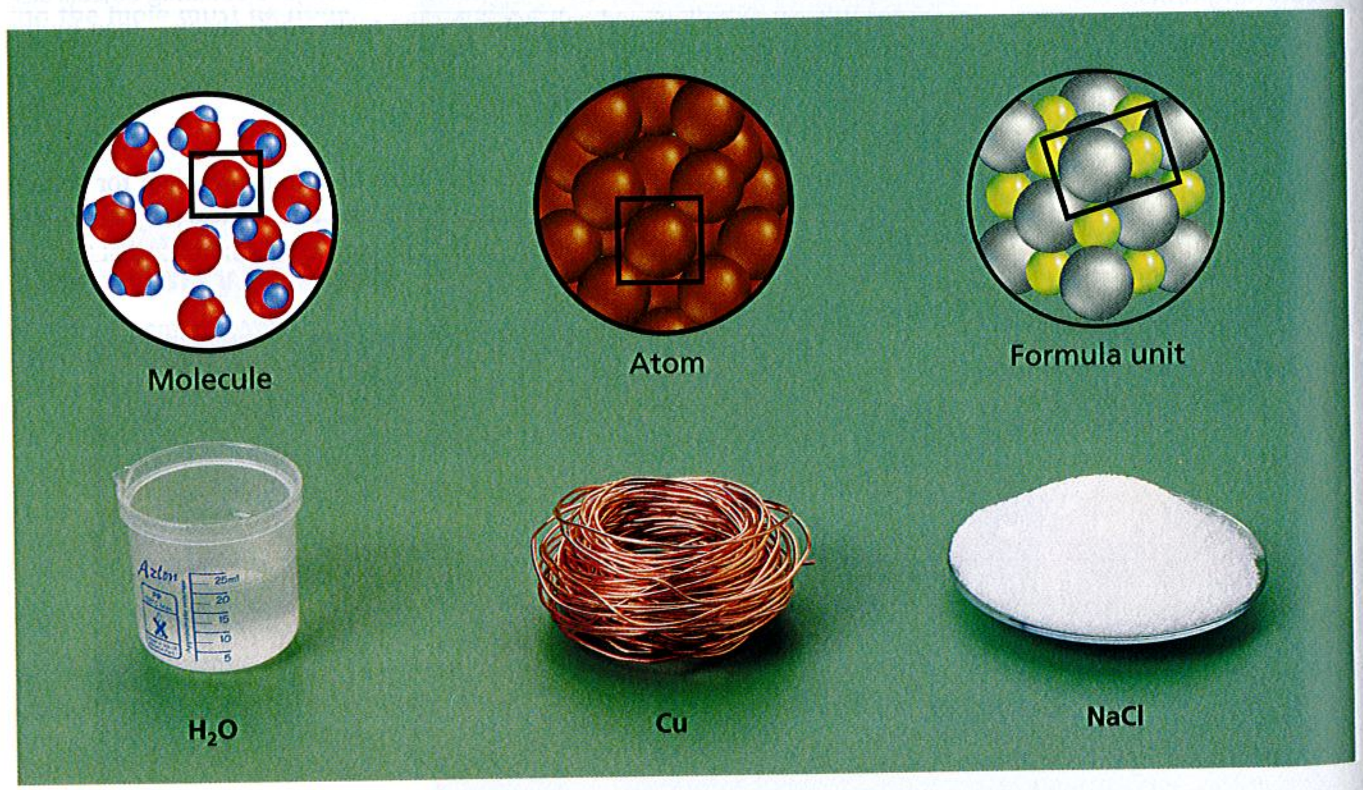
If you write out Avogadro's number, it looks like this.

602 000 000 000 000 000 000 000

Avogadro's number is an enormous number, as it must be in order to count extremely small particles. As you can imagine, Avogadro's number would not be convenient for measuring a quantity of marbles. Avogadro's number of marbles would cover the surface of Earth to a depth of more than six kilometers! But you can see in **Figure 11-2** that it is convenient to use the mole to measure substances. One-mole quantities of three substances are shown, each with a different representative particle. The representative particle in a mole of water is the water molecule, the representative particle in a mole of copper is the copper atom, and the representative particle in a mole of sodium chloride is the formula unit.

Figure 11-2

The amount of each substance shown is 6.02×10^{23} or one mole of representative particles. The representative particle for each substance is shown in a box. Refer to **Table C-1** in Appendix C for a key to atom color conventions.



Converting Moles to Particles and Particles to Moles

Suppose you buy three and a half dozen roses and want to know how many roses you have. Recall what you have learned about conversion factors. You can multiply the known quantity (3.5 dozen roses) by a conversion factor to express the quantity in the units you want (number of roses). You must set up your calculation as shown here so that all units cancel except those required for the answer.

Note: Multiply the numbers as you move up

	Roses
Item #	42
Item#/Dozen	12
Dozen	3.5

↑ multiply

Note that the units cancel and the answer tells you that 42 roses are in 3.5 dozen.

Now, suppose you want to determine how many particles of sucrose are in 3.50 moles of sucrose. You know that one mole contains 6.02×10^{23} representative particles. Therefore, you can write a conversion factor, Avogadro's number, that relates representative particles to moles of a substance.

$$\text{Conversion factor: } \frac{6.02 \times 10^{23} \text{ representative particles}}{1 \text{ mole}}$$

You can find the number of representative particles in a number of moles just as you found the number of roses in 3.5 dozen.

Particles	
Particles/Mole	6.02×10^{23}
Moles	

↑ multiply

For sucrose, the representative particle is a molecule, so the number of molecules of sucrose is obtained by multiplying 3.50 moles of sucrose by the conversion factor, Avogadro's number.

	Sucrose
Molecules	2.11×10^{24}
Molecules/Mole	6.02×10^{23}
Moles	3.50

↑ multiply

There are 2.11×10^{24} molecules of sucrose in 3.50 moles.

PRACTICE PROBLEMS

1. Determine the number of atoms in 2.50 mol Zn.

3. Calculate the number of molecules in 11.5 mol H_2O.

Now, suppose you want to find out how many moles are represented by a certain number of representative particles. You can use the inverse of Avogadro's number as a conversion factor.

Note: Divide the numbers as you move down

Particles	
Particles/Mole	6.02×10^{23}
Moles	

History CONNECTION

Lorenzo Romano Amedeo Carlo Avogadro, Conte di Quaregna e Ceretto was born in Turin, Italy in 1776 and was educated as a church lawyer. During the early 1800s, he studied mathematics and physics and was appointed to a professorship at the Royal College of Vercelli where he produced his hypothesis on gases. From 1820 until his death, Avogadro was professor of physics at the University of Turin where he conducted research on electricity and the physical properties of liquids.

Avogadro's hypothesis did not receive recognition for more than fifty years. Although Avogadro did nothing to measure the number of particles in equal volumes of gases, his hypothesis did lead to the eventual calculation of the number, 6.02×10^{23}.

National Mole Day is celebrated on October 23 (10/23) from 6:02 A.M. to 6:02 P.M. to commemorate Avogadro's contribution to modern chemistry.

Practice!

For more practice converting from moles to representative particles, go to **Supplemental Practice Problems** in Appendix A.

The number of moles of substance is obtained by multiplying the number of particles by this factor, as you will see in Example Problem 11-1.

EXAMPLE PROBLEM 11-1

Converting Number of Representative Particles to Moles

Zinc is used as a corrosion-resistant coating on iron and steel. It is also an essential trace element in your diet. Calculate the number of moles that contain 4.50×10^{24} atoms of zinc (Zn).

1. Analyze the Problem

You are given the number of atoms of zinc and must find the equivalent number of moles. If you compare 4.50×10^{24} atoms Zn with 6.02×10^{23}, the number of atoms in one mole, you can predict that the answer should be less than 10 moles.

Known

number of atoms = 4.50×10^{24} atoms Zn

1 mol Zn = 6.02×10^{23} atoms Zn

Unknown

mol Zn = ? mol

2. Solve for the Unknown

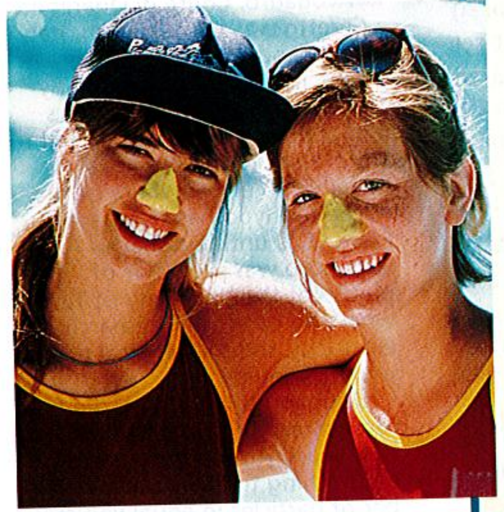
Multiply the number of zinc atoms by the conversion factor that is the inverse of Avogadro's number.

	Zn
atoms	4.50×10^{24}
atoms/mol	6.02×10^{23}
mol	7.48

↓ Divide

3. Evaluate the Answer

The number of atoms of zinc and Avogadro's number have three significant figures. Therefore, the answer is expressed correctly with three digits. The answer is less than 10 moles, as predicted, and has the correct unit.



Ointments containing zinc oxide provide protection from sunburn and are used to treat some skin diseases.

Practice!

For more practice converting from representative particles to moles, go to **Supplemental Practice Problems** in Appendix A.

PRACTICE PROBLEMS

4. How many moles contain each of the following?

a. 5.75×10^{24} atoms Al

b. 3.75×10^{24} molecules CO_2

c. 3.58×10^{23} formula units $ZnCl_2$

d. 2.50×10^{20} atoms Fe

Section 11.1 Assessment

5. How is a mole similar to a dozen?

7. Explain how you can convert from the number of representative particles of a substance to moles of that substance.

9. **Thinking Critically** Arrange the following from the smallest number of representative particles to the largest number of representative particles: 1.25×10^{25} atoms Zn; 3.56 mol Fe; 6.78×10^{22} molecules glucose ($C_6H_{12}O_6$).

10. **Using Numbers** Determine the number of representative particles in each of the following and identify the representative particle: 11.5 mol Ag; 18.0 mol H_2O; 0.150 mol NaCl.

chemistrymc.com/self_check_quiz

Section 11.2 Mass and the Mole

Objectives

- **Relate** the mass of an atom to the mass of a mole of atoms.
- **Calculate** the number of moles in a given mass of an element and the mass of a given number of moles of an element.
- **Calculate** the number of moles of an element when given the number of atoms of the element.
- **Calculate** the number of atoms of an element when given the number of moles of the element.

Vocabulary

molar mass

You wouldn't expect a dozen limes to have the same mass as a dozen eggs. Eggs and limes differ in size and composition, so it's not surprising that they have different masses, as **Figure 11-3** shows. Moles of substances also have different masses for the same reason—the substances have different compositions. If you put a mole of carbon on a balance beside a mole of metallic copper, you would see a difference in mass just as you do for a dozen eggs and a dozen limes. Carbon atoms differ from copper atoms. Thus, the mass of 6.02×10^{23} atoms of carbon does not equal the mass of 6.02×10^{23} atoms of copper. How do you determine the mass of a mole?

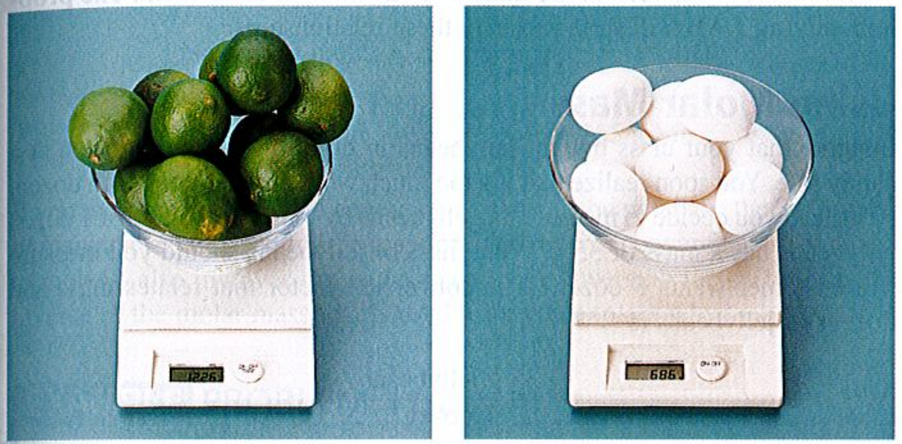


Figure 11-3

A dozen limes has approximately twice the mass of a dozen eggs. The difference in mass is reasonable because limes are different from eggs in composition and size.

The Mass of a Mole

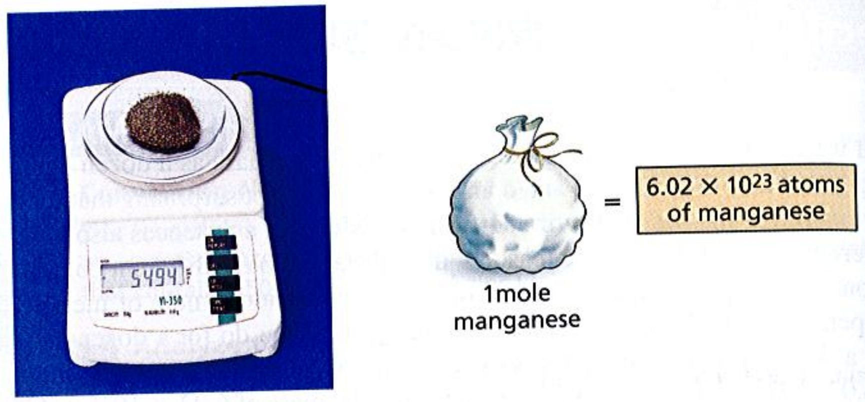
In Chapter 4, you learned that the relative scale of atomic masses uses the isotope carbon-12 as the standard. Each atom of carbon-12 has a mass of 12 atomic mass units (amu). The atomic masses of all other elements are established relative to carbon-12. For example, an atom of hydrogen-1 has a mass of 1 amu. The mass of an atom of helium-4 is 4 amu. Therefore, the mass of one atom of hydrogen-1 is one-twelfth the mass of one atom of carbon-12. The mass of one atom of helium-4 is one-third the mass of one atom of carbon-12.

You can find atomic masses on the periodic table, but notice that the values shown are not exact integers. For example, you'll find 12.011 amu for carbon, 1.008 amu for hydrogen, and 4.003 amu for helium. These differences occur because the recorded values are weighted averages of the masses of all the naturally occurring isotopes of each element.

How does the mass of one atom relate to the mass of a mole of that atom? You know that the mole is defined as the number of representative particles, or carbon-12 atoms, in exactly 12 g of pure carbon-12. Thus, the mass of one mole of carbon-12 atoms is 12 g. What about other elements? Whether you are considering a single atom or Avogadro's number of atoms (a mole), the masses of all atoms are established relative to the mass of carbon-12. The mass of a mole of hydrogen-1 is one-twelfth the mass of a mole of carbon-12 atoms, or 1.0 g. The mass of a mole of helium-4 atoms is one-third the mass of a mole of carbon-12 atoms, or 4.0 g. The mass in grams of one mole of any pure substance is called its **molar mass**. The molar mass of any element is numerically equal to its atomic mass and has the units g/mol. An atom of manganese has an atomic mass of 54.94 amu. Therefore, the molar mass of manganese is 54.94 g/mol. When you measure 54.94 g of manganese on a balance,

Figure 11-4

One mole of manganese, represented by a bag of particles, contains Avogadro's number of atoms and has a mass equal to its atomic mass in grams. The same is true for all the elements.



you indirectly count 6.02 × 10^{23} atoms of manganese. **Figure 11-4** shows the relationship between molar mass and one mole of an element. The **problem-solving LAB** will further clarify these relationships.

The Molar Mass of Compounds

The mass of your backpack is the sum of the mass of the pack plus the masses of the books, notebooks, pencils, lunch, and miscellaneous items you put into it. You could find its mass by determining the mass of each item separately and adding them together. Similarly, the mass of a mole of a compound equals the sum of the masses of every particle that makes up the compound. You know how to use the molar mass of an element as a conversion factor in calculations. You also know that a chemical formula indicates the number of moles of each element in a compound. With this information, you can now determine the molar mass of a compound.

Suppose you want to determine the molar mass of potassium chromate (K_2CrO_4). Using the periodic table, the mass of one mole of each element present in potassium chromate can be determined. That mass is then multiplied by the number of moles of that element in the chemical formula. Adding the masses of all elements present will yield the molar mass of K_2CrO_4.

$$\text{number of moles} \times \text{molar mass} = \text{number of grams}$$

$$2.000\ \cancel{\text{mol K}} \times \frac{39.10\ \text{g K}}{1\ \cancel{\text{mol K}}} = 78.20\ \text{g}$$

$$1.000\ \cancel{\text{mol Cr}} \times \frac{52.00\ \text{g Cr}}{1\ \cancel{\text{mol Cr}}} = 52.00\ \text{g}$$

$$4.000\ \cancel{\text{mol O}} \times \frac{16.00\ \text{g O}}{1\ \cancel{\text{mol O}}} = \underline{64.00\ \text{g}}$$

$$\text{molar mass } K_2CrO_4 = 194.20\ \text{g}$$

PRACTICE PROBLEMS

25. Determine the molar mass of each of the following ionic compounds: NaOH, $CaCl_2$, $KC_2H_3O_2$, $Sr(NO_3)_2$, and $(NH_4)_3PO_4$.

26. Calculate the molar mass of each of the following molecular compounds: C_2H_5OH, $C_{12}H_{22}O_{11}$, HCN, CCl_4, and H_2O.

Practice!

For more practice calculating the molar mass of a compound, go to **Supplemental Practice Problems** in Appendix A.

The molar mass of a compound demonstrates the law of conservation of mass. The sum of the masses of the elements that reacted to form the compound equals the mass of the compound. **Figure 11-7** shows 194 g, or one mole, of K_2CrO_4 and masses equal to one mole of two other substances.

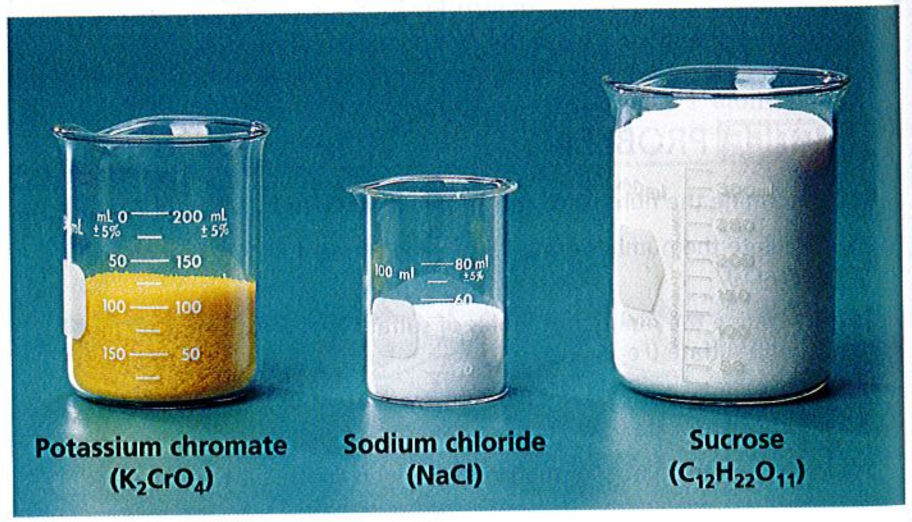


Figure 11-7

Each substance contains different numbers and kinds of atoms so their molar masses are different. The molar mass of each compound is the sum of the masses of all the elements contained in the compound.