6.5 Mass and Number of Entities

How many molecules of water are there in a drop of water? Even the smallest visible drop of water contains more molecules than you can count in a lifetime. Because molecules are so small, chemists use mass as a convenient way to estimate the number of molecules in a sample. For example, chemists know that water has a molar mass of 18.0 g/mol. Therefore, they know that 18.0 g of water contains 1.00 mol or 6.02×10^{23} molecules of water (**Figure 1**). Similarly 36.0 g of water contains 2.00 mol of water molecules. In this section, you will see how Avogadro's constant, N_A, serves as the link, or bridge, between the mass of a pure substance and the number of entities present.

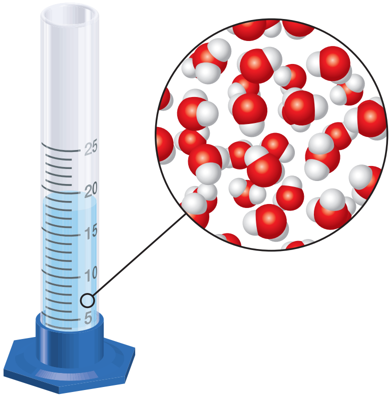

Figure 1 A mole of water has a mass of 18.0 g. Since water has a density of 1.0 g/mL at room temperature, 18.0 mL (1.00 mol) of water contains 6.02×10^{23} water molecules.

Determining the Number of Entities

We often use counting units to specify a number of entities. A dozen is a counting unit. It means "12." We can represent a larger number using dozens as the unit. For example, 5 dozen doughnuts contain 60 doughnuts. Mathematically, this can be determined using the following calculation:

$$\text{number of doughnuts} = (5\ \cancel{\text{dozen}})\left(\frac{12\ \text{doughnuts}}{1\ \cancel{\text{dozen}}}\right)$$
$$= 60\ \text{doughnuts}$$

In general:

$$\text{number of doughnuts} = (\text{number of}\ \cancel{\text{dozen}})\left(\frac{12\ \text{doughnuts}}{1\ \cancel{\text{dozen}}}\right)$$

Similarly, the number of molecules of water in 5.00 mol of water is:

$$\text{number of water molecules} = (5.00\ \cancel{\text{mol}})\left(\frac{6.02 \times 10^{23}\ \text{molecules}}{1\ \cancel{\text{mol}}}\right)$$
$$= 30.1 \times 10^{23}\ \text{molecules}$$
$$= 3.01 \times 10^{24}\ \text{molecules}$$

The number o.f entities in a sample, N, is determined by multiplying the amount, n, by Avogadro's constant, N_A:

$N = nN_A$ (**Figure 2**)

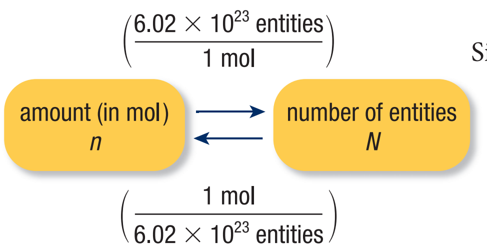

Figure 2 Avogadro's constant is the conversion factor linking an amount to the number of entities in a sample.

Tutorial 1 Calculating the Number of Entities in a Sample

A pure substance can consist of atoms, molecules, or ions. To find the number of these entities in a sample of a substance, we first need to know the amount of the substance. Then, we can find the number of entities by multiplying by a conversion factor.

Sample Problem 1: Calculating the Number of Atoms in a Sample

Calculate the number of atoms in a 1.00 kg bar of gold.

Given: $m_{Au} = 1.00$ kg

Required: number of atoms of gold, N_{Au}

Solution:

Step 1. Look up the molar mass of the element gold in the periodic table.

$$M_{Au} = 196.97\ \frac{\text{g}}{\text{mol}}$$

Step 2. Determine the amount of gold by multiplying the mass of gold (given) by an appropriate conversion factor derived from the molar mass of gold.

$$n_{Au} = (1.00 \times 10^3\ \cancel{\text{g}})\left(\frac{1\ \text{mol}}{196.97\ \cancel{\text{g}}}\right)$$

$$n_{Au} = 5.0760\ \text{mol}\ [2\ \text{extra digits carried}]$$

Step 3. Calculate the number of atoms of gold in 5.0760 mol of gold. To do this, note that 1 mol of gold contains 6×10^{23} atoms of gold, which gives two possible conversion factors:

$$\frac{6.02 \times 10^{23}\ \text{atoms}}{1\ \text{mol}} \quad \text{or} \quad \frac{1\ \text{mol}}{6.02 \times 10^{23}\ \text{atoms}}$$

Also note that the following equation may be used to calculate the number of atoms in an entity, given the amount of entity (in moles):

Since you want to solve for the number of atoms, multiply by the factor that has "number of atoms" in the numerator.

$$N_{Au} = (5.0760\ \cancel{\text{mol}})\left(6.02 \times 10^{23}\ \frac{\text{atoms}}{\cancel{\text{mol}}}\right)$$

$$= 30.56 \times 10^{23}\ \text{atoms}$$

$$= 3.056 \times 10^{24}\ \text{atoms}$$

$$N_{Au} = 3.06 \times 10^{24}\ \text{atoms}$$

Statement: A 1.00 kg bar of gold contains 3.06×10^{24} atoms of gold.

COMBINING STEPS IN THE CALCULATION

SKILLS HANDBOOK A6.3

Notice in Sample Problem 1 that, after determining the molar mass of gold, we calculated the number of gold atoms in two successive steps: Step 2 and Step 3. By combining these two steps we can calculate the number of atoms of gold from the given mass in one step as follows:

$$N_{Au} = (1.00 \times 10^{-3}\ \cancel{\text{g}})\left(\frac{1\ \text{mol}}{196.97\ \cancel{\text{g}}}\right)\left(\frac{6.02 \times 10^{23}\ \text{atoms}}{\cancel{1\ \text{mol}}}\right)$$

$$N_{Au} = 3.06 \times 10^{24}\ \text{atoms}$$

Sample Problem 2: Calculating the Number of Molecules in a Sample

Ammonia is a pungent gas released from smelling salts. Calculate the number of molecules in a 4.00 mg sample of ammonia, NH_3.

Given: $m_{NH_3} = 4.00$ mg

$m_{NH_3} = 4.00 \times 10^{-3}$ g

Required: number of molecules of ammonia, N_{NH_3}

Solution:

Step 1. Look up the molar mass of nitrogen and hydrogen in the periodic table and calculate the molar mass of ammonia.

$$M_{NH_3} = M_N + 3M_H$$

$$= \left(14.01\ \frac{\text{g}}{\text{mol}}\right) + 3\left(1.01\ \frac{\text{g}}{\text{mol}}\right)$$

$$M_{NH_3} = 17.04\ \frac{\text{g}}{\text{mol}}$$

Step 2. Calculate the amount of ammonia by multiplying the mass of ammonia (given) by an appropriate conversion factor derived from the molar mass of ammonia.

$$n_{NH_3} = (4.00 \times 10^{-3}\ \cancel{\text{g}})\left(\frac{1\ \text{mol}}{17.04\ \cancel{\text{g}}}\right)$$

$$n_{NH_3} = 2.3474 \times 10^{-4}\ \text{mol}\ [2\ \text{extra digits carried}]$$

Step 3. Calculate the number of molecules of ammonia in 2.3474×10^{-4} mol of ammonia using an appropriate conversion factor. In this case, use the conversion factor with amount in the denominator.

$$N_{NH_3} = (2.3474 \times 10^{-4}\ \cancel{mol})\left(6.02 \times 10^{23}\ \frac{\text{molecules}}{\cancel{mol}}\right)$$
$$= 14.1 \times 10^{19}\ \text{molecules}$$
$$N_{NH_3} = 1.41 \times 10^{20}\ \text{molecules}$$

Statement: A sample containing 4.00 mg of ammonia contains 1.41×10^{20} ammonia molecules.

We could perform the calculation in Sample Problem 2 in one step as follows:

$$N_{NH_3} = (4.00 \times 10^{-3}\ \cancel{g})\left(\frac{1\ \cancel{mol}}{17.04\ \cancel{g}}\right)\left(6.02 \times 10^{23}\ \frac{\text{molecules}}{1\ \cancel{mol}}\right)$$
$$= 14.1 \times 10^{19}\ \text{molecules}$$
$$N_{NH_3} = 1.41 \times 10^{20}\ \text{molecules}$$

Practice

SKILLS HANDBOOK A6.5

1. A typical car battery contains 8.16 kg of lead. Determine the number of lead atoms in this battery. T/I [ans: 2.37×10^{25} atoms]
2. A one-carat diamond has a mass of 2.00×10^{-1} g. Assuming the diamond is made of pure carbon, determine the number of carbon atoms in a one-carat diamond. T/I [ans: 1.00×10^{22} atoms]
3. Determine the number of ethylene molecules, C_2H_4, in a 7.3 g sample of ethylene. T/I [ans: 1.6×10^{23} molecules]
4. Find the number of formula units of $CaCl_2$ in a 1.5 kg pail of calcium chloride (used to melt sidewalk ice). T/I [ans: 8.1×10^{24} formula units]

Determining the Number of Entities in Compounds

Each molecular compound has a unique chemical formula, which gives the exact number of atoms of each element in a molecule. Therefore, if the number of molecules in a sample is known, chemists can calculate the number of atoms of each element present. For example, the chemical formula H_2O tells us that 1 water molecule contains 1 oxygen atom and 2 hydrogen atoms (**Figure 3**). Therefore, *x* water molecules contain *x* oxygen atoms and 2*x* hydrogen atoms.

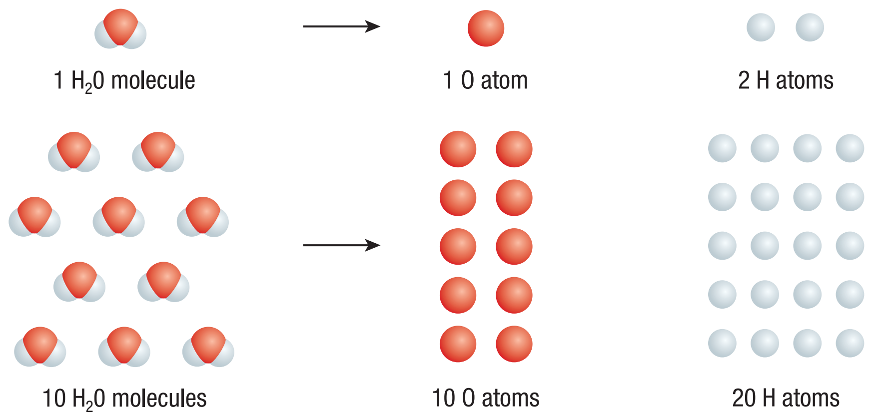

Figure 3 The number of atoms of an element in a sample of molecules is determined by multiplying the number of molecules by the number of atoms of the element per molecule.

We describe the number of ions in an ionic compound in a similar manner. The difference is that we specify the ratios of ions in a formula unit of the compound. For example, the chemical formula $Al_2(SO_4)_3$ states that there are 2 aluminum ions for every 3 sulfate ions in a formula unit of aluminum sulfate. (Remember that each sulfate ion is a polyatomic ion. It is considered a single entity within the formula unit.) Regardless of the number of aluminum sulfate formula units, aluminum ions and sulfate ions always occur in a 2:3 ratio (**Table 1**).

Table 1 Ratio of Ions in Aluminum Sulfate, $Al_2(SO_4)_3$

Number of formula units	Number of Al^{3+} cations	Number of SO_4^{2-} anions
1	$1 \times 2 = 2$	$1 \times 3 = 3$
10	$10 \times 2 = 20$	$10 \times 3 = 30$
2 000 000	$2\,000\,000 \times 2 = 4\,000\,000$	$2\,000\,000 \times 3 = 6\,000\,000$
$1 \text{ mol} = 6.02 \times 10^{23}$	$2 \text{ mol}_{Al^{3+}} = \frac{2 \text{ aluminum ions}}{1 \cancel{\text{formula unit}}}(6.02 \times 10^{23} \cancel{\text{formula unit}})$ $= 1.204 \times 10^{24}$ aluminum ions	$3 \text{ mol}_{SO_4^{2-}} = \frac{3 \text{ sulfate ions}}{1 \cancel{\text{formula unit}}}(6.02 \times 10^{23} \cancel{\text{formula unit}})$ $= 1.806 \times 10^{24}$ sulfate ions

Tutorial 2 Calculating the Number of Atoms or Ions in a Sample

Calculating the number of atoms or ions in a compound follows the same strategy as outlined in Tutorial 1. The only difference is that you now must consider the number of atoms or ions per molecule or formula unit of the compound.

Sample Problem 1: Calculating the Number of Atoms

Benzaldehyde, C_6H_5CHO, is a compound used to give prepared foods an almond flavour. Find the number of carbon, hydrogen, and oxygen atoms in a 26.5 g sample of benzaldehyde.

Given: $m_{C_6H_5CHO} = 26.5 \text{ g}$

Required: number of atoms of carbon, hydrogen and oxygen, N_C, N_H, and N_O

Solution:

Step 1. Look up the molar mass of carbon, hydrogen, and oxygen in the periodic table and calculate the molar mass of benzaldehyde.

$$M_{C_6H_5CHO} = 7M_C + 6M_H + M_O$$
$$= \left(7 \times 12.01 \frac{\text{g}}{\text{mol}}\right) + \left(6 \times 1.01 \frac{\text{g}}{\text{mol}}\right) + \left(16.00 \frac{\text{g}}{\text{mol}}\right)$$
$$M_{C_6H_5CHO} = 106.13 \frac{\text{g}}{\text{mol}}$$

Step 2. Calculate the amount of benzaldehyde by multiplying the mass of the sample (given) by an appropriate conversion factor derived from the molar mass of benzaldehyde.

$$n_{C_6H_5CHO} = 26.5 \cancel{\text{g}} \times \frac{1 \text{ mol}}{106.13 \cancel{\text{g}}}$$
$$n_{C_6H_5CHO} = 0.24969 \text{ mol [extra digits carried]}$$

Step 3. Calculate the number of molecules of benzaldehyde in the 26.5 g sample using an appropriate conversion factor. In this case, use the conversion factor with amount in the denominator.

$$N_{C_6H_5CHO} = (0.24969 \cancel{\text{mol}})\left(6.02 \times 10^{23} \frac{\text{molecules}}{1 \cancel{\text{mol}}}\right)$$
$$N_{C_6H_5CHO} = 1.503 \times 10^{23} \text{ molecules [extra digits carried]}$$

LEARNING TIP

When to Round Off Answers
Whenever the answer to one calculation will be used in a later calculation, rounding off early introduces unnecessary errors in the answer. Always round off after the last calculation.

Step 4. Determine the number of each type of atom present by multiplying the number of molecules by the number of each type of atom per molecule.

$$N_C = (1.503 \times 10^{23} \text{ ~~molecules of benzaldehyde~~})\left(\frac{7 \text{ atoms of carbon}}{1 \text{ ~~molecule of benzaldehyde~~}}\right)$$

$$= 10.522 \times 10^{23} \text{ atoms}$$

$$N_C = 1.05 \times 10^{24} \text{ atoms}$$

$$N_H = (1.503 \times 10^{23} \text{ ~~molecule of benzaldehyde~~})\left(\frac{6 \text{ atoms of hydrogen}}{1 \text{ ~~molecule of benzaldehyde~~}}\right)$$

$$N_H = 9.02 \times 10^{23} \text{ atoms}$$

$$N_O = (1.503 \times 10^{23} \text{ ~~molecules of benzaldehyde~~})\left(\frac{1 \text{ atoms of oxygen}}{1 \text{ ~~molecule of benzaldehyde~~}}\right)$$

$$N_O = 1.50 \times 10^{23} \text{ atoms}$$

Statement: A 26.5 g sample of benzaldehyde contains 1.05×10^{24} atoms of carbon, 9.02×10^{23} atoms of hydrogen, and 1.50×10^{23} atoms of oxygen.

Practice

1. Find the number of hydrogen and oxygen atoms present in 15.0 g of pure hydrogen peroxide, H_2O_2. T/I [ans: 5.31×10^{23} hydrogen atoms and 5.31×10^{23} oxygen atoms]
2. Find the number of calcium ions in 2.5 g of calcium phosphate, $Ca_3(PO_4)_2$ (a nutrient in milk). T/I [ans: 1.5×10^{22} Ca^{2+} ions]
3. Calculate the mass of 8.4×10^{24} molecules of carbon dioxide (dry ice) (Hint: first calculate the number of molecules.) T/I [ans: 6.1×10^2 g]

Mini Investigation

Determining Numbers of Everyday Entities

Skills: Planning, Performing, Observing, Analyzing, Communicating — SKILLS HANDBOOK A3.2, A3.3, A6

In this activity you will determine the number of molecules or formula units in samples of common objects.

Equipment and Materials: lab apron; blackboard; balance; dropper; graduated cylinder; chalk; water; disposable cups; penny

1. Plan procedures to determine the following quantities of matter:
   (i) the mass of chalk required to write your name. Assume that chalk is pure calcium carbonate, $CaCO_3$.
   (ii) the mass of water that you can hold in your hand
   (iii) the mass of water drops that will fit on a penny without overflowing
2. With your teacher's approval, carry out your procedures. Record your observations.

A. Calculate the amount of each substance. T/I

B. Calculate the number of molecules or formula units in each substance. T/I

6.5 Summary

- In general, the number of entities in a sample, N, is determined by multiplying the amount, n, by Avogadro's constant, N_A.
  $N = n\,N_A$
- The number of atoms or ions in a sample of a compound equals the number of atoms or ions per molecule or formula unit times the number of molecules or formula units in the sample.

6.5 Questions

1. Calculate the number of molecules present in each of the following samples: T/I
   (a) 2.0 mol of ammonia, NH_3
   (b) 1.6 mg of water, H_2O
2. Calculate the amount of substance in each of the following samples: T/I
   (a) 3.01×10^{23} atoms of copper
   (b) 6.02×10^{25} molecules of hydrogen chloride (in hydrochloric acid)
   (c) 42.0 g of calcium carbonate, $CaCO_3$ (in shellfish)
3. A sample of carbon dioxide contains 4.2×10^{24} molecules. T/I
   (a) How many atoms of carbon and how many atoms of oxygen are in the sample?
   (b) What is the mass of the sample?
4. Sodium hypochlorite, NaClO, is the active ingredient in chlorine bleaches. A sample of chlorine bleach contains 120.0 g of sodium hypochlorite. How many formula units of NaClO are in the sample? T/I
5. Acetylsalicylic acid, $C_9H_8O_4$, is the pain reliever in many headache medications. A typical tablet contains 250.0 mg of acetylsalicylic acid. T/I
   (a) Calculate the amount of acetylsalicylic acid in the tablet.
   (b) Calculate the number of hydrogen atoms in the amount of acetylsalicylic acid in the tablet determined in (a).
6. A 2.00 L birthday balloon contains 0.327 g of helium. T/I
   (a) Calculate the number of helium atoms in the balloon.
   (b) A blimp occupies a volume of 5.74×10^{6} L. (**Figure 4**) Assuming that the blimp has the same number of atoms per litre as the party balloon under the same conditions, how many helium atoms are in the blimp?

Figure 4 A helium-filled blimp

7. Arsenic(III) oxide, As_2O_3, is a toxic compound once used as a wood preservative. Recently, however, this compound has been used in experimental cancer treatments. The toxicity of this compound in humans is not known. However, 14 mg of As_2O_3 is known to be lethal to half of the laboratory rats in a typical group. T/I
   (a) Calculate the number of formula units of As_2O_3 in this mass.
   (b) What number of oxide ions is present in this mass?
8. Sodium monofluorophosphate, Na_2FPO_3, is a common additive in toothpastes to help prevent tooth decay. Analysis indicates that 0.76 % of the mass of a 120.0 g tube of toothpaste is sodium monofluorophosphate. T/I
   (a) Calculate the amount of sodium monofluorophosphate in the tube.
   (b) Calculate the number of sodium ions and monofluorophosphate ions in the tube.
9. Gold medals from the 2010 Vancouver Olympic and Paralympic Games were made of silver with a thin coating of gold (**Figure 5**). A typical "gold" medal contains 509.0 g of silver and 6.0 g of gold. T/I
   (a) Calculate the number of silver atoms and the number of gold atoms in a gold medal.
   (b) Compare the costs of a gold-plated medal and a solid gold medal, each with a total mass of 515 g. Research today's cost of gold and silver on the stock market.

Figure 5 Gold medal from the 2010 Vancouver Paralympic winter games

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