The Avogadro Constant and the Mole

5.2

In section 5.1, you learned how to use isotopic abundances and isotopic masses to find the average atomic mass of an element. You can use the average atomic mass, found in the periodic table, to describe the average mass of an atom in a large sample.

Why is relating average atomic mass to the mass of large samples important? In a laboratory, as in everyday life, we deal with macroscopic samples. These samples contain incredibly large numbers of atoms or molecules. Can you imagine a cookie recipe calling for six septillion molecules of baking soda? What if copper wire in a hardware store were priced by the atom instead of by the metre, as in Figure 5.5? What if we paid our water bill according to the number of water molecules that we used? The numbers involved would be ridiculously inconvenient. In this section, you will learn how chemists group large numbers of atoms into amounts that are easily measurable.

Section Preview/ Specific Expectations

In this section, you will

- **describe** the relationship between moles and number of particles
- **solve** problems involving number of moles and number of particles
- **explain** why chemists use the mole to group atoms
- **communicate** your understanding of the following terms: *mole, Avogadro constant*

Figure 5.5 Copper wire is often priced by the metre because the metre is a convenient unit. What unit do chemists use to work with large numbers of atoms?

Grouping for Convenience

In a chemistry lab, as well as in other contexts, it is important to be able to measure amounts accurately and conveniently. When you purchase headache tablets from a drugstore, you are confident that each tablet contains the correct amount of the active ingredient. Years of testing and development have determined the optimum amount of the active ingredient that you should ingest. If there is too little of the active ingredient, the tablet may not be effective. If there is too much, the tablet may be harmful. When the tablets are manufactured, the active ingredient needs to be weighed in bulk. When the tablets are tested, however, to ensure that they contain the right amount of the active ingredient, chemists need to know how many molecules of the substance are present. How do chemists group particles so that they know how many are present in a given mass of substance?

On its own, the mass of a chemical is not very useful to a chemist. The chemical reactions that take place depend on the number of atoms present, not on their masses. Since atoms are far too small and numerous to count, you need a way to relate the numbers of atoms to masses that can be measured.

When many items in a large set need to be counted, it is often useful to work with groups of items rather than individual items. When you hear the word "dozen," you think of the number 12. It does not matter what the items are. A dozen refers to the quantity 12 whether the items are eggs or pencils or baseballs. Table 5.1 lists some common quantities that we use to deal with everyday items.

Table 5.1 Some Common Quantities

Item	Quantity	Amount
gloves	pair	2
soft drinks	six-pack	6
eggs	dozen	12
pens	gross (12 dozen)	144
paper	ream	500

You do not buy eggs one at a time. You purchase them in units of a dozen. Similarly, your school does not order photocopy paper by the sheet. The paper is purchased in bundles of 500 sheets, called a ream. It would be impractical to sell sheets of paper individually.

Figure 5.6 **Certain items, because of their size, are often handled in bulk. Would you rather count reams of paper or individual sheets?**

The Definition of the Mole

Convenient, or easily measurable, amounts of elements contain huge numbers of atoms. Therefore chemists use a quantity that is much larger than a dozen or a ream to group atoms and molecules together. This quantity is the **mole** (symbol **mol**).

- One mole (1 mol) of a substance contains $6.022\ 141\ 99 \times 10^{23}$ particles of the substance. This value is called the **Avogadro constant**. Its symbol is N_A.
- The mole is defined as the amount of substance that contains as many elementary entities (atoms, molecules, or formula units) as exactly 12 g of carbon-12.

Language LINK

The term *mole* is an abbreviation of another word. What do you think this other word is? Check your guess by consulting a dictionary.

For example, one mole of carbon contains 6.02×10^{23} atoms of C. One mole of sodium chloride contains 6.02×10^{23} formula units of NaCl. One mole of hydrofluoric acid contains 6.02×10^{23} molecules of HF.

The Avogadro constant is an experimentally determined quantity. Chemists continually devise more accurate methods to determine how many atoms are in exactly 12 g of carbon-12. This means that the accepted value has changed slightly over the years since it was first defined.

The Chemist's Dozen

The mole is literally the chemist's dozen. Just as egg farmers and grocers use the dozen (a unit of 12) to count eggs, chemists use the mole (a much larger number) to count atoms, molecules, or formula units. When farmers think of two dozen eggs, they are also thinking of 24 eggs.

$$(2\ \cancel{\text{dozen}}) \times \left(\frac{12\ \text{eggs}}{\cancel{\text{dozen}}}\right) = 24\ \text{eggs}$$

Chemists work in a similar way. As you have learned above, 1 mol has 6.02×10^{23} particles. Thus 2 mol of aluminum atoms contain 12.0×10^{23} atoms of Al.

$$2\ \cancel{\text{mol}} \times (6.02 \times 10^{23}\ \frac{\text{atoms}}{\cancel{\text{mol}}}) = 1.20 \times 10^{24}\ \text{atoms of Al}$$

How Big Is the Avogadro Constant?

The Avogadro constant is a huge number. Its magnitude becomes easier to visualize if you imagine it in terms of ordinary items. For example, suppose that you created a stack of 6.02×10^{23} loonies, as in Figure 5.7. To determine the height of the stack, you could determine the height of one loonie and multiply by 6.02×10^{23}. The Avogadro constant needs to be this huge to group single atoms into convenient amounts. What does 1 mol of a substance look like? Figure 5.8 shows some samples of elements. Each sample contains 6.02×10^{23} atoms. Notice that each sample has a different mass. You will learn why in section 5.3. Examine the following Sample Problem to see how to work with the Avogadro constant.

Web LINK

www.school.mcgrawhill.ca/resources/
Chemists have devised various ways to determine the Avogadro constant. To learn more about how this constant has been found in the past and how it is found today, go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next. What are some methods that chemists have used to determine the number of particles in a mole? How has the accepted value of the Avogadro constant changed over the years?

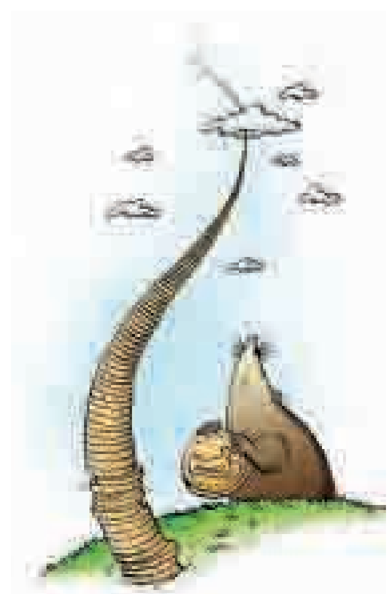

Figure 5.7 Measure the height of a pile of five loonies. How tall, in kilometres, would a stack of 6.02×10^{23} loonies be?

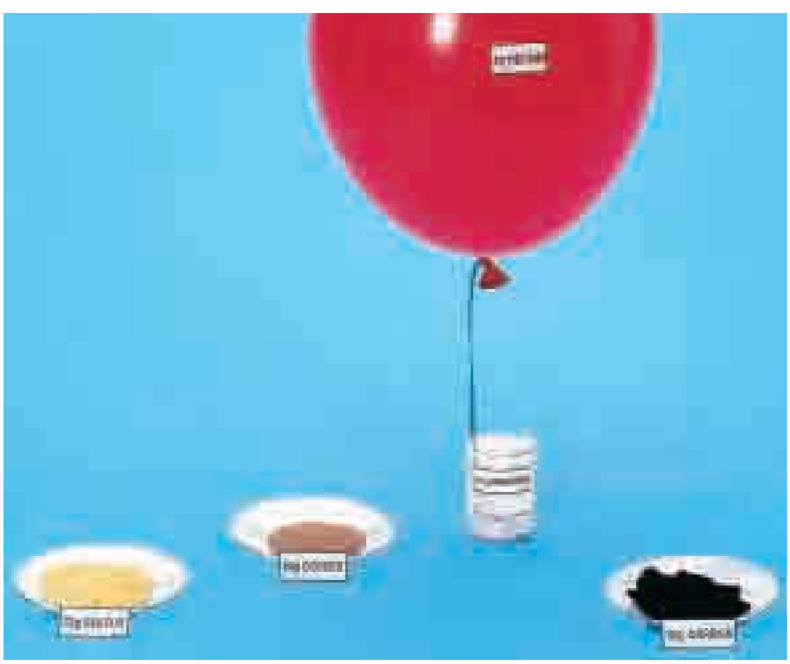

Figure 5.8 Each sample contains 1.00 mol, or 6.02×10^{23} atoms. Why do you think the mass of each sample is different?

Sample Problem

Using the Avogadro Constant

Problem

The distance "as the crow flies" from St. John's in Newfoundland to Vancouver in British Columbia is 5046 km. Suppose that you had 1 mol of peas, each of diameter 1 cm. How many round trips could be made between these cities, laying the peas from end to end?

What Is Required?

You need to find the number of round trips from St. John's to Vancouver (2×5046 km) that can be made by laying 6.02×10^{23} peas end to end.

What Is Given?

Each round trip is 2×5046 km or 10 092 km. A pea has a diameter of 1 cm.

Plan Your Strategy

First convert the round trip distance from kilometres to centimetres. Since each pea has a diameter of 1 cm, a line of 6.02×10^{23} peas is 6.02×10^{23} cm in length. Divide the length of the line of peas by the round-trip distance to find the number of round trips.

Act on Your Strategy

Converting the round-trip distance from kilometres to centimetres gives

$$(10\,092\ \cancel{\text{km}}) \times (10^5\ \text{cm}/\cancel{\text{km}}) = 1.01 \times 10^9\ \text{cm}$$

$$\text{Number of round trips} = \frac{6.02 \times 10^{23}\ \cancel{\text{cm}}}{(1.01 \times 10^9\ \cancel{\text{cm}}/\text{round trip})}$$

$$= 5.96 \times 10^{14}\ \text{round trips}$$

About 596 trillion round trips between St. John's and Vancouver could be made by laying one mole of peas end to end.

Check Your Solution

Looking at the magnitude of the numbers, you have $10^{23} \div 10^9$. This accounts for 10^{14} in the answer.

Practice Problems

9. The length of British Columbia's coastline is 17 856 km. If you laid 6.02×10^{23} metre sticks end to end along the coast of BC, how many rows of metre sticks would you have?

10. The area of Nunavut is 1 936 113 km^2. Suppose that you had 6.02×10^{23} sheets of pastry, each with the dimensions 30 cm × 30 cm. How many times could you cover Nunavut completely with pastry?

Continued ...

Math LINK

Suppose that you invested \$6.02 × 10^{23} so that it earned 1% compound interest annually. How much money would you have at the end of ten years?

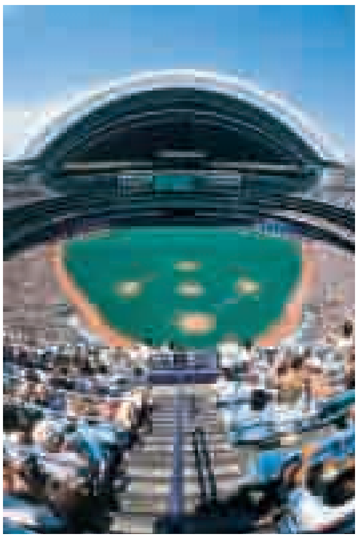

Figure 5.9 Toronto's SkyDome cost about \$500 million to build. Spending \$6.02 × 10^{23} at the rate of one billion dollars per second is roughly equivalent to building two SkyDomes per second for over 19 million years.

Continued ...
FROM PAGE 174

11. If you drove for 6.02×10^{23} days at a speed of 100 km/h, how far would you travel?

12. If you spent \$$6.02 \times 10^{23}$ at a rate of \$1.00/s, how long, in years, would the money last? Assume that every year has 365 days.

Converting Moles to Number of Particles

In the Thought Lab below, you can practise working with the mole by relating the Avogadro constant to familiar items. Normally the mole is used to group atoms and compounds. For example, chemists know that 1 mol of barium contains 6.02×10^{23} atoms of Ba. Similarly, 2 mol of barium sulfate contain $2 \times (6.02 \times 10^{23}) = 12.0 \times 10^{23}$ molecules of $BaSO_4$.

number of moles → Multiply by 6.02×10^{23} → number of particles (atoms, molecules, formula units)

The mole is used to help us "count" atoms and molecules. The relationship between moles, number of particles, and the Avogadro constant is

$$N = \text{number of particles}$$
$$n = \text{number of moles}$$
$$N_A = \text{Avogadro constant}$$
$$N = n \times N_A$$

Try the next Sample Problem to learn how the number of moles of a substance relates to the number of particles in the substance.

Technology LINK

Scientific calculators are made to accommodate scientific notation easily. To enter the Avogadro constant, for example, type 6.02, followed by the key labelled "EE" or "EXP." (The label on the key depends on the make of calculator you have.) Then enter 23. The 23 will appear at the far right of the display, *without* the exponential base of 10. Your calculator *understands* the number to be in scientific notation.

ThoughtLab: The Magnitude of the Avogadro Constant

This activity presents some challenges related to the magnitude of the Avogadro constant. These questions are examples of *Fermi problems*, which involve large numbers (like the Avogadro constant) and give approximate answers. The Italian physicist, Enrico Fermi, liked to pose and solve these types of questions.

Procedure

Work in small groups. Use any reference materials, including materials supplied by your teacher and information on the Internet. For each question, brainstorm to determine the required information. Obtain this information, and answer the question. Be sure to include units throughout your calculation, along with a brief explanation.

Analysis

1. If you covered Canada's land mass with 1.00 mol of golf balls, how deep would the layer of golf balls be?
2. Suppose that you put one mole of five-dollar bills end to end. How many round trips from Earth to the Moon would they make?
3. If you could somehow remove 6.02×10^{23} teaspoons of water from the world's oceans, would you completely drain the oceans? Explain.
4. What is the mass of one mole of apples? How does this compare with the mass of Earth?
5. How many planets would we need for one mole of people, if each planet's population were limited to the current population of Earth?

Language LINK

The term *order of magnitude* refers to the size of a number—specifically to its exponent when in scientific notation. For example, a scientist will say that 50 000 (5×10^4) is two orders of magnitude (10^2 times) larger than 500 (5×10^2). How many orders of magnitude is the Avogadro constant greater than one billion?

Sample Problem

Moles to Atoms

Problem

A sample contains 1.25 mol of nitrogen dioxide, NO_2.

(a) How many molecules are in the sample?

(b) How many atoms are in the sample?

What Is Required?

You need to find the number of atoms and molecules in the sample.

What Is Given?

The sample consists of 1.25 mol of nitrogen dioxide molecules.
Each nitrogen dioxide molecule is made up of three atoms:
1 N atom + 2 O atoms.

$$N_A = 6.02 \times 10^{23} \text{ molecules/mol}$$

Plan Your Strategy

(a) A molecule of NO_2 contains three atoms. Find the number of NO_2 *molecules* in 1.25 mol of nitrogen dioxide.

(b) Multiply the number of molecules by 3 to arrive at the total number of *atoms* in the sample.

Act on Your Strategy

(a) Number of molecules of NO_2

$$= (1.25 \cancel{\text{mol}}) \times \left(6.02 \times 10^{23} \frac{\text{molecules}}{\cancel{\text{mol}}}\right)$$

$$= 7.52 \times 10^{23} \text{ molecules}$$

Therefore there are 7.52×10^{23} molecules in 1.25 mol of NO_2.

(b) $$(7.52 \times 10^{23} \cancel{\text{molecules}}) \times \left(3 \frac{\text{atoms}}{\cancel{\text{molecule}}}\right) = 2.26 \times 10^{24} \text{ atoms}$$

Therefore there are 2.26×10^{24} atoms in 1.25 mol of NO_2.

Check Your Solution

Work backwards. One mol contains 6.02×10^{23} atoms. How many moles represent 2.2×10^{24} atoms?

$$2.2 \times 10^{24} \cancel{\text{atoms}} \times \frac{1 \text{ mol}}{6.02 \times 10^{23} \cancel{\text{atoms}}} = 3.7 \text{ mol}$$

There are 3 atoms in each molecule of NO_2

$$3.7 \cancel{\text{mol atoms}} \times \frac{1 \text{ mol molecule}}{3 \cancel{\text{mol atoms}}} = 1.2 \text{ molecules}$$

This is close to the value of 1.25 mol of molecules, given in the question.

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FROM PAGE 176

Practice Problems

13. A small pin contains 0.0178 mol of iron, Fe. How many atoms of iron are in the pin?

14. A sample contains 4.70×10^{-4} mol of gold, Au. How many atoms of gold are in the sample?

15. How many formula units are contained in 0.21 mol of magnesium nitrate, $Mg(NO_3)_2$?

16. A litre of water contains 55.6 mol of water. How many molecules of water are in this sample?

17. Ethyl acetate, $C_4H_8O_2$, is frequently used in nail polish remover. A typical bottle of nail polish remover contains about 2.5 mol of ethyl acetate.

(a) How many molecules are in the bottle of nail polish remover?

(b) How many atoms are in the bottle?

(c) How many carbon atoms are in the bottle?

18. Consider a 0.829 mol sample of sodium sulfate, Na_2SO_4.

(a) How many formula units are in the sample?

(b) How many sodium ions, Na^+, are in the sample?

Electronic Learning Partner

Go to the Chemistry 11 Electronic Learning Partner for a video clip that describes the principles behind the Avogadro constant and the mole.

Converting Number of Particles to Moles

Chemists very rarely express the amount of a substance in number of particles. As you have seen, there are far too many particles to work with conveniently. For example, you would never say that you had dissolved 3.21×10^{23} molecules of sodium chloride in water. You might say, however, that you had dissolved 0.533 mol of sodium chloride in water. When chemists communicate with each other about amounts of substances, they usually use units of moles (see Figure 5.10). To convert the number of particles in a substance to the number of moles, rearrange the equation you learned previously.

$$N = N_A \times n$$
$$n = \frac{N}{N_A}$$

To learn how many moles are in a substance when you know how many particles are present, find out how many times the Avogadro constant goes into the number of particles.

Try the next Sample Problem to practise converting the number of atoms, formula units, or molecules in a substance to the number of moles.

Figure 5.10 Chemists rarely use the number of particles to communicate how much of a substance they have. Instead, they use moles.

Sample Problem

Molecules to Moles

Problem

How many moles are present in a sample of carbon dioxide, CO_2, made up of 5.83×10^{24} molecules?

What Is Required?

You need to find the number of moles in 5.83×10^{24} molecules of carbon dioxide.

What Is Given?

You are given the number of molecules in the sample.

$$N_A = 6.02 \times 10^{23} \text{ molecules } CO_2/\text{mol } CO_2$$

Plan Your Strategy

$$n = \frac{N}{N_A}$$

Act on Your Strategy

$$n = \frac{5.83 \times 10^{24} \cancel{\text{ molecules } CO_2}}{(6.02 \times 10^{23} \cancel{\text{ molecules } CO_2}/\text{mol } CO_2)}$$
$$= 9.68 \text{ mol } CO_2$$

There are 9.68 mol of CO_2 in the sample.

Check Your Solution

5.83×10^{24} molecules is approximately equal to 6×10^{24} molecules. Since the number of molecules is about ten times larger than the Avogadro constant, it makes sense that there are about 10 mol in the sample.

Practice Problems

19. A sample of bauxite ore contains 7.71×10^{24} molecules of aluminum oxide, Al_2O_3. How many moles of aluminum oxide are in the sample?

20. A vat of cleaning solution contains 8.03×10^{26} molecules of ammonia, NH_3. How many moles of ammonia are in the vat?

21. A sample of cyanic acid, HCN, contains 3.33×10^{22} atoms. How many moles of cyanic acid are in the sample? **Hint:** Find the number of molecules of HCN first.

22. A sample of pure acetic acid, CH_3COOH, contains 1.40×10^{23} carbon atoms. How many moles of acetic acid are in the sample?

History LINK

The Avogadro constant is named to honour the Italian chemist Amedeo Avogadro. In 1811, Avogadro postulated what is now known as Avogadro's law: Equal volumes of gases, at equal temperatures and pressures, contain the same number of molecules. You will learn more about Avogadro's law in Unit 4.

Web LINK

www.school.mcgrawhill.ca/resources/
The International System of Units (SI) is based on seven base units for seven quantities. (One of these quantities is the mole.) The quantities are assumed to be all independent of each other. To learn about the seven base quantities, go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next. All other SI units are derived from the seven base units.