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# Chemistry 11

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# BC SCIENCE
# CHEMISTRY 11


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# 3 The Mole — The Central Unit of Chemistry

By the end of this chapter, you should be able to do the following:

- Explain the significance and use of the mole
- Perform calculations involving the mole
- Determine relationships between molar quantities of gases at STP
- Perform calculations involving molecular and empirical formulas to identify a substance
- Describe concentration in terms of molarity
- Perform calculations involving molarity

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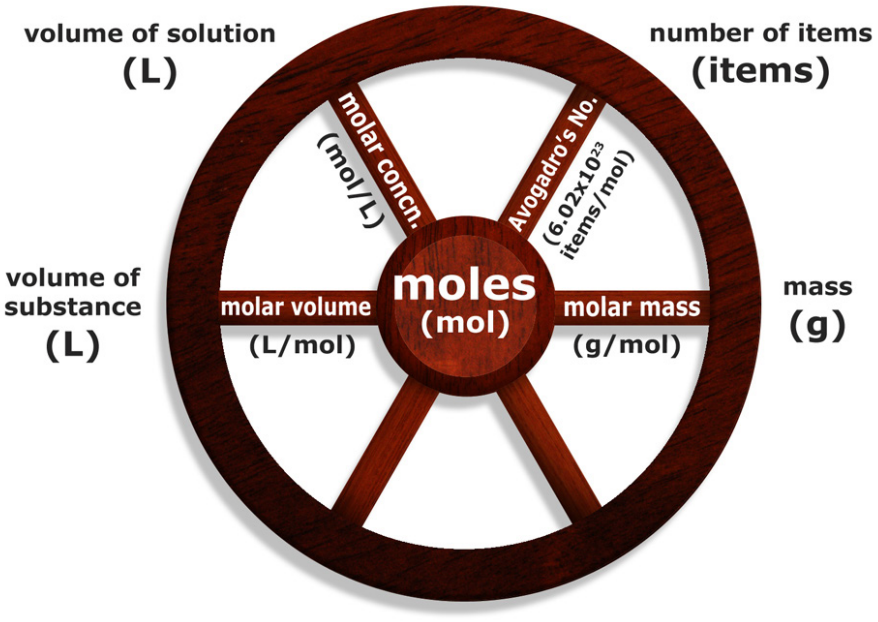
By the end of this chapter you should know the meaning of these **key terms**:

- empirical formula
- molarity
- molar mass
- molar solution
- molar volume
- mole
- molecular formula
- molecular mass
- percentage composition
- relative atomic mass
- standard solution
- stoichiometry
- STP



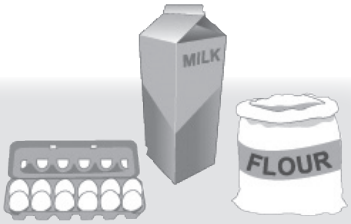

*The mole is at the centre of the chemical measurement.*

# 3.1 Relative Atomic Mass

## Warm Up

1. Complete the grocery list by filling in the missing units (Figure 3.1a).
   One _____ eggs, Two _____milk, Three _____flour
2. From your answer to #1, what are the three ways that we typically express amounts of materials?

   (a) number of items (b) _____ (c) _____




*We express amounts of materials in different ways.*

### Relative Mass

Experimental chemistry is essentially figuring out things about matter that cannot be observed directly. The joy of experimental chemistry lies in figuring out how to figure it out. Consider the following ingenious method for determining the relative masses of objects without needing to know their actual masses. **Mass** is the amount of matter. When you say that one object has twice as much mass as another you are expressing the object's **relative mass**. You are comparing one object's mass to the other's.

Suppose you wanted to determine the relative mass of a staple and a grain of rice, each of which is too small to register a mass on your balance (Figure 3.1.1). Why not weigh 100 of each? If 100 identical staples weigh twice as much as 100 identical grains of rice then one staple will weigh twice as much as one grain of rice. The nifty aspect of this technique is that we don't even need to know how many objects we are weighing: we just need to know that we're weighing the same number of each. If some number of staples weighs twice as much as the same number of rice grains then any number of staples will weigh twice as much as that number of rice grains.


**Figure 3.1.1** *One hundred staples and one hundred grains of rice have the same mass ratio as one staple and one grain of rice, 2:1.*

This technique for determining relative mass still works even if the items being weighed are not identical. If the items being weighed for comparison are not identical, then the ratio provided is that of their average masses rather than the ratio of the masses of the individual items since this would depend on which individual items. For example, if a variety of pens weighs 1.52 times as much as the same number of a variety of pencils then the average mass of these pens is 1.52 times the average mass of these pencils.

> The mass ratio of any equal number of items equals the average mass ratio of those individual items.

While you should never confuse the terms "weight" and "mass," the word "weigh" serves double duty. To **weigh** is to find the weight or compare the weights of. Since scales work by comparing weights, you are by definition "weighing" objects and materials with a scale. In fact, a **weighing scale** is a measuring instrument for determining the mass or weight of an object.

## Quick Check

1. What does "relative mass" mean? _____
2. You have two bags of candy from a bulk food store: a bag of gumdrops and a bag of jujubes. You intend to determine the relative masses of a jujube and a gumdrop by weighing the contents of each bag. What condition is necessary for this to work? _____

## Law of Constant Composition

In this book, as in most chemistry textbooks, much of our current chemical knowledge will be presented in historical context. Instead of just telling you what we know (or think we know), we'll tell you how chemists came to this understanding. This is because chemistry is more than just an accumulated list of facts about matter: it is also the processes that lead us to such information. By learning and assessing these processes, as well as the facts, some of you will decide to continue this quest. In addition, people often acquire a better understanding of a concept by learning the concept in the same manner that it was originally developed.

To use the technique just described to determine the relative masses of different types of atoms, chemists needed to be able to weigh an equal number of different types of atoms. In the early 1800s, chemists discovered that all samples of a given compound have the same mass ratio of their constituent elements. For example, there are 8 g of oxygen for every 1 g of hydrogen in every sample of water. This is called the **law of constant composition**. In 1804, John Dalton, a scientist in England, argued that the law of constant composition not only supported the concept of atoms but also provided their relative masses. He reasoned that the mass ratios in which different elements combine are the mass ratios of their individual atoms or a simple multiple thereof. If one atom of magnesium weighs 1.5 times as much as one atom of oxygen then any number of magnesium atoms would weigh 1.5 times as much as the same number of oxygen atoms. Dalton argued that this was the reason all samples of a compound contained the same mass ratio of its elements.

### Sample Problem — Determining Relative Atomic Mass

A chemist carefully heats 0.350 g of magnesium powder in a crucible. The magnesium reacts with atmospheric oxygen to produce 0.580 g of magnesium oxide (MgO). What is the mass of a magnesium atom relative to the mass of an oxygen atom?

**What to Think about**

1. 0.350 g Mg must have combined with 0.230 g O to produce 0.580 g MgO.
2. Since magnesium oxide has the formula MgO, 0.350 g of magnesium and 0.230 g of oxygen contain equal numbers of atoms.
3. If some number of Mg atoms weighs 1.52 times as much as the same number of O atoms then any number of Mg atoms weighs 1.52 times as much as the same number of O atoms, even one of each.

**How to Do It**

0.580 g MgO − 0.350 g Mg = 0.230 g O

$$\frac{\text{mass of Mg atoms}}{\text{mass of O atoms}} = \frac{0.350\ \text{g}}{0.230\ \text{g}} = 1.52$$

A Mg atom weighs 1.52 times as much as an O atom.

### Practice Problems — Determining Relative Atomic Mass

1. A dozen identical AA batteries have a mass of 276 g and a dozen identical watch batteries have a mass of only 26.4 g. The mass of an AA battery is _____ times the mass of a watch battery.

2. A sample of strontium oxide (SrO) is found to contain 2.683 g Sr and 0.490 g O. What is the mass of a strontium atom relative to that of an oxygen atom?

3. A 4.218 g sample of daltonium bromide (DBr) is decomposed and 0.337 g of D is recovered.
   (a) What is the atomic mass of daltonium given that the atomic mass of bromine is 79.9 u?
   _____
   (b) This question uses the fictitious element, daltonium, so you can't just look up the element's atomic mass.
   What element does daltonium represent? _____

## Relative Masses of Atoms

According to the sample problem, if all the atoms of an element are identical then the mass of a magnesium atom is 1.52 times the mass of an oxygen atom. If all the atoms of an element do not have the same mass then the average mass of a magnesium atom is 1.52 times the average mass of an oxygen atom. The issue of whether all the atoms of an element are identical wasn't resolved for another century but, as described, we need only insert the word, "average" if they are not.

The element hydrogen was discovered to have the least massive atoms so its atoms were originally assigned an atomic mass of 1 u (atomic mass unit) and the mass of all the other types of atoms were expressed relative to this. The discussion of atomic mass and atomic mass units will continue in chapter 5. Oxygen's atomic mass of 16 u means that the mass of an oxygen atom is 16 times the mass of a hydrogen atom (or that the average mass of an oxygen atom is 16 times the average mass of a hydrogen atom) (Figure 3.1.2). If the mass of a magnesium atom is 1.52 times the mass of an oxygen atom then the mass of a magnesium atom is 1.52 × 16.0 u = 24.3 u. The periodic table of the elements confirms that magnesium has a relative atomic mass of 24.3 u.

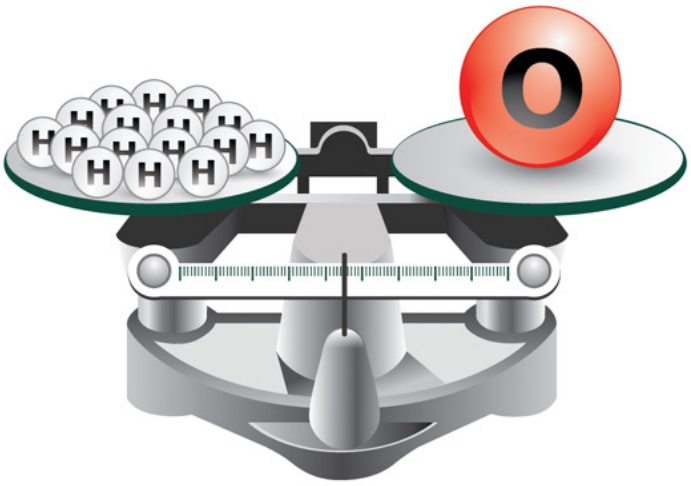



**Figure 3.1.2** *The mass of an oxygen atom is equal to the mass of 16 hydrogen atoms.*

Determining the relative masses of the basic units of matter was a remarkable feat. Dalton bridged the gap between the world we experience and the invisible world of atoms by deriving the relative masses of atoms from laboratory observations. But how did Dalton know that the formula of magnesium oxide was MgO? Recall Dalton's important qualification: "or a simple multiple thereof." If the formula of magnesium oxide is $MgO_2$ then the mass ratio of Mg to O in the compound would need to be doubled to determine their atomic mass ratio. This is necessary because we are weighing half as many magnesium atoms. Therefore, the same number of magnesium atoms would weigh twice as much. Similar adaptations would be required for other possible formulas.

### Sample Problem — Determining Relative Atomic Mass (Non 1:1 Formulas)

Barium chloride has a mass ratio of 1.934 g Ba:1.000 g Cl. Chlorine has an atomic mass of 35.5 u.
What is the atomic mass of barium if the formula of barium chloride is $BaCl_2$?

| What to Think about | How to Do It |
|---|---|
| If the formula is $BaCl_2$ then we need to double the mass of barium so that we can compare the masses of equal numbers of atoms. | $2(1.934) \times 35.5\ u = 137.3\ u$ |

### Practice Problems — Determining Relative Atomic Mass (Non 1:1 Formulas)

Aluminum iodide has a mass ratio of 1.000 g Al: 14.100 g I. Given that the atomic mass of iodine is 126.9 u, what is the atomic mass of aluminum if the formula of aluminum iodide is:

1. $AlI_3$? _____

2. $Al_2I_3$? _____

## Cannizzaro's Paper

Dalton assumed that atoms combined in the simplest manner possible. He believed that if a pair of elements (A + B) formed only one compound, the formula for the compound would be AB. If they formed a second compound, its formula would be either $A_2B$ or $AB_2$. Dalton was well aware that he had no evidence for his "rules of simplicity." He conceded that some of his formulas and resulting atomic mass determinations might be incorrect. As you may recall from earlier science classes, the formulas of ionic compounds are simple ratios, but not quite as simple as Dalton supposed.

On September 3, 1860, many of Europe's leading chemists met in Karlsruhe, Germany. At this meeting, the Italian chemist Stanislao Cannizzaro presented a remarkable paper in which he solved the mystery of atomic masses. For example, Dalton hadn't understood how two particles of hydrogen gas could react with one particle of oxygen gas to produce two particles of water vapor. He thought that couldn't happen because it would require splitting the oxygen particle, which he thought was an atom. Cannizzaro showed that Dalton's atomic model was still valid if the hydrogen and oxygen gas particles were made up of pairs of atoms. Hydrogen and oxygen molecules are called **diatomic molecules** because they are formed of two atoms of the same element ("di" means 2).

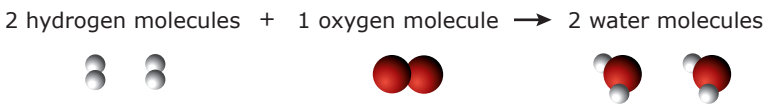
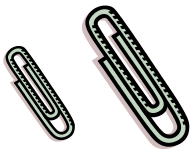



**Figure 3.1.3** *Diatomic molecules of hydrogen and oxygen combine to form water molecules.*

Cannizzaro's paper went on to describe and explain three other techniques for determining atomic mass: one for metals, one for liquid or gaseous non-metals, and one for solid non-metals.

Dalton is called the father of the atomic theory because he explained how the law of constant composition provided support for the concept of atoms. However, additional methods were required to determine the relative atomic masses. These atomic masses were, in turn, used to determine the correct formulas of compounds. Dmitri Mendeleev, who published his first periodic table of the elements in 1869, was at Karlsruhe. The correct atomic masses were a prerequisite to Mendeleev's famous table.

# 3.1 Activity: The Relative Mass of Paper Clips



## Question

What is the mass of a large paper clip relative to that of a small paper clip?
(We'll answer this question without weighing only one paper clip of either type.)

## Background

If some number of large paper clips weighs twice as much as the same number of small paper clips then any number of large paper clips will weigh twice as much as the same number of small paper clips, including one of each. Remember we don't need to know how many paper clips we are weighing; we just need to know that we're weighing the same number of each. The mass ratio of any equal number of identical items equals the mass ratio of the individual items.

## Procedure

1. Weigh a pile of small paper clips. Record this mass in the table provided below.
2. Attach a large paper clip to each small paper clip and measure the total mass of these coupled clips. Record this mass in the table provided below.
3. Calculate the total mass of the attached large paper clips and record this mass in the table below.

## Results and Discussion

| Objects | Mass (g) |
|---|---|
| Small paper clips | |
| Coupled paper clips | |
| Large paper clips | |

1. $$\frac{\text{mass of some number of large paper clips}}{\text{mass of the same number of small paper clips}} = \frac{\qquad\qquad\text{g}}{\text{g}} = \_\_\_\_\_$$

   The mass of a large paper clip is _____ times the mass of a small paper clip.

2. If we assign a small paper clip a mass of 1.00 smu (stationary mass unit), what is the mass of a large paper clip?

3. Let's check this result by weighing one small paper clip and one large paper clip.

   $$\frac{\text{mass of one large paper clip}}{\text{mass of one small paper clip}} = \frac{\qquad\qquad\text{g}}{\text{g}} = \_\_\_\_\_$$

4. Why might the ratios calculated in steps 1 and 3 be slightly different?

## 3.1 Review Questions

1. A certain number of identical glass marbles has a mass of 825 g. The same number of identical steel marbles has a mass of 2245 g.
   (a) Assigning a glass marble a mass of 1.00 mmu (marble mass unit), calculate the mass of a steel marble.

   (b) Why don't you need to know the number of marbles that were weighed?

2. 1.965 g of sodium is placed in a flask containing chlorine gas. 5.000 g of NaCl is produced in the resulting reaction.
   (a) A sodium atom's mass is _____ times a chlorine atom's mass.

   (b) Chlorine has an atomic mass of 35.5 u. What is the atomic mass of sodium?

3. A 10.000 g sample of zubenium fluoride (ZuF) is decomposed and 8.503 g of Zu is recovered.
   (a) What is the atomic mass of zubenium?

   (b) This question uses the fictitious element zubenium so you can't just look up the element's atomic mass. What element does zubenium represent?

4. Zinc sulfide has a mass ratio of 2.037 g Zn: 1.000 g S. Given that the atomic mass of sulfur is 32.1 u, what is the atomic mass of zinc if the formula of zinc sulfide is:
   (a) ZnS?

   (b) $ZnS_2$?

   (c) $Zn_3S_2$?

5. A compound of copper and oxygen contains 13.073 g Cu and 1.647 g O. Oxygen has an atomic mass of 16.0 u.
   (a) What is the atomic mass of copper if the formula of the above compound is CuO?

   (b) What is the atomic mass of copper if the formula of the above compound is $Cu_2O$?

   (c) What is the atomic mass of copper if the formula of the above compound is $CuO_2$?

6. In 1819, Dulong and Petit noted a relationship between the presumed atomic mass of most metals and their specific heats. The specific heat of a metal divided into 25.0 provides the approximate atomic mass of the metal. The specific heat of a substance is the amount of heat required to raise 1 g of the substance by 1°C. The specific heat of copper is 0.3864 J/g°C.
   (a) Calculate the approximate atomic mass of copper using Dulong and Petit's method.

   (b) Knowing the approximate atomic mass of the metal allowed chemists to determine which of the more accurate atomic masses derived by composition analysis was correct. Which of the atomic masses and corresponding formulas calculated in question 5 is correct for the compound that was analyzed?

7. Determine the percent error of Dulong and Petit's method of approximating a metal's atomic mass for aluminum (0.903 J/g°C), magnesium (1.05 J/g°C) and silver (0.23772 J/g°C).

8. In 1811 Amedeo Avogadro proposed that equal volumes of any gas at the same temperature and pressure contain *the same number of particles*. Cannizzaro realized this allows scientists to weigh equal numbers of atoms of different gaseous elements and determine their relative atomic masses. Complete the following data table showing the mass of equal volumes of two different gases at the same temperature and pressure.

| Element | Mass of Gas (g) | Relative Atomic Mass (u) |
|---|---|---|
| H | 0.210 | 1.0 |
| | 7.455 | |

9. Potassium has an atomic mass of 39.1 u. What does this mean?

10. Look up the following elements in the periodic table and report each element's atomic mass.

    (a) P _____

    (b) Ca _____

    (c) U _____

11. Eight identical forks have a mass of 213.1 g. Eight identical knives have a mass of 628.2 g.

    (a) What is the mass of a knife relative to that of a fork?

    (b) Why did you not need to divide the supplied masses by 8 to answer 11(a)?

    (c) What could you conclude from these data if the utensils of each type were not identical?

12. A mint is advertising a special set of silver coins containing a 10 g coin, a 20 g coin and a 30 g coin. One of these coins is accidentally being made 1 g lighter than its advertised mass. You have two sets of these coins and have been challenged to identify the undersized coin by weighing only one pile of coins. The single pile may include any combination of the coins that you wish. What combination of the coins would you weigh? How can you use that mass to identify the undersized coin?