2.1 *Compounds and Chemical Change*

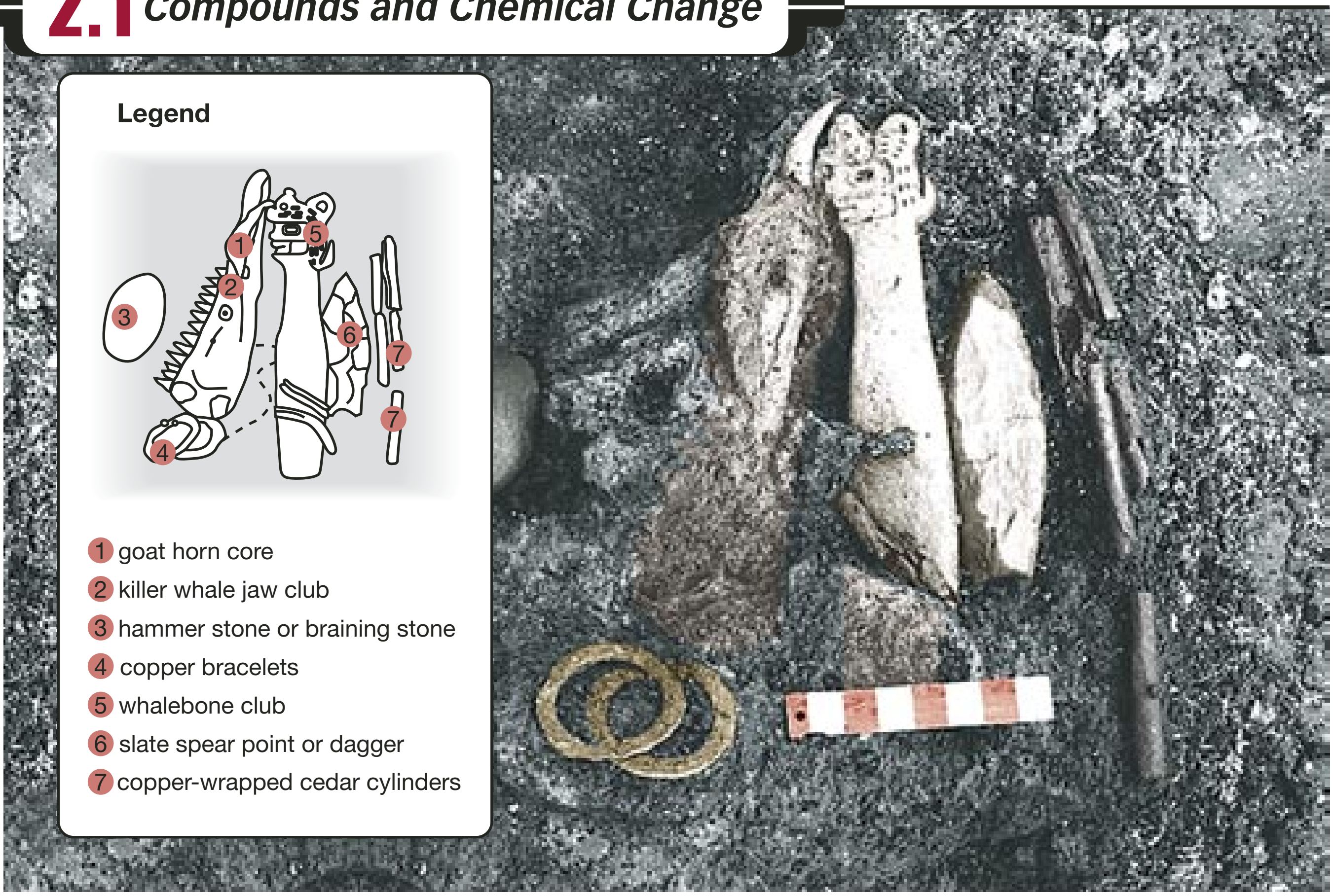


Figure A2.1: Copper bracelets were among the items found in an ancient site near Prince Rupert Harbour.

The objects in Figure A2.1 were found hidden in an ancient site near Prince Rupert Harbour. Archaeologists suspect that these objects were a cache of weapons and other objects that once belonged to a warrior who lived approximately 1800 years ago. Of particular interest are the copper bracelets and the copper-wrapped cedar cylinders that were a form of rod armour. The source of the copper was likely 1200 km north of Prince Rupert in the Copper River area of Alaska, where copper occurs as nuggets in the gravel of the river bed.

This evidence suggests that the ancestors of the First Nations people in Canada were not only identifying, collecting, and trading copper metal, they were also applying metallurgy—heating and hammering copper into shapes.

In Alberta, First Nations people also made use of copper; but, in this case, the source of the copper was likely from the area around Lake Superior—over 1500 km east of Alberta—which also has excellent deposits of copper. Archaeologists have dated some of the manufactured copper artifacts from this area to be nearly 7000 years old. This suggests that the ancestors of the First Nations people may have been among the first metal workers in the world. The technological details about how the copper was heated and hammered into shape remain a mystery because archaeologists have not located kilns or crucibles capable of melting or smelting copper needed for the manufacturing process.

Archaeologists studying artifacts, like the copper bracelets in Figure A2.2, often use chemical analysis to help determine the likely source of the copper. This can provide insights into the extent of trade routes among different regions.

Figure A2.2: The copper bracelets were found at a site along the Columbia River.

Practice

1. Ancient copper artifacts are rarely unearthed in shiny or lustrous condition. Usually, these objects tend to have a dull green surface. The change in colour of the copper artifacts indicates that a process has occurred. Identify the name of this process.

2. Archaeological evidence suggests that the ancient ancestors of the First Nations people in Alberta had access to copper from the Lake Superior area, sea shells from the Gulf of Mexico, and obsidian (a type of volcanic glass) from Wyoming. What does this evidence suggest about the movement of goods and materials on the North American continent in ancient times?
3. When copper artifacts were first discovered in eastern North America over a hundred years ago, it was assumed by archaeologists of the day that these objects were created by First Nations people using copper obtained through trade with European settlers.
   - **a.** Explain how this assumption led to the mistaken conclusion that some archaeological sites were hundreds of years old when, in reality, many sites were thousands of years old.
   - **b.** Copper nuggets from the Lake Superior area have exceptional purity: about 99.9%. The purest copper from Europe is only about 98% pure. Explain how a chemical analysis of ancient artifacts could determine the original source of the copper.

Tarnishing of Metal Jewellery

Ancient copper artifacts often have a dull green appearance when they are discovered. Even jewellery from modern times can sometimes start to tarnish and lose its lustre. Silver, in particular, has a tendency to turn black over time. Why does this happen?

Figure A2.3: Silver sulfide is the black substance that coats silverware.

When metal begins to tarnish, the colour change is evidence of a chemical reaction occurring. Silver has the tendency to react with molecules in the air, such as hydrogen sulfide in the presence of oxygen. The products of this reaction are silver sulfide, Ag_2S, and water. Silver sulfide is what gives tarnished silverware its black colour. The process of developing a balanced chemical equation for this reaction from a word description is as follows.

Writing a Balanced Chemical Equation

(solid silver) + (hydrogen sulfide gas) + (oxygen gas) → (solid silver sulfide) + (liquid water)

Translate the words into chemical formulas.

$$\square\ Ag(s) + \square\ H_2S(g) + \square\ O_2(g) \rightarrow \square\ Ag_2S(s) + \square\ H_2O(l)$$

Add coefficients to balance the equation.

$$\boxed{4}\ Ag(s) + \boxed{2}\ H_2S(g) + \boxed{1}\ O_2(g) \rightarrow \boxed{2}\ Ag_2S(s) + \boxed{2}\ H_2O(l)$$

Coefficients of 1 are not recorded.

$$4\ Ag(s) + 2\ H_2S(g) + O_2(g) \rightarrow 2\ Ag_2S(s) + 2\ H_2O(l)$$

The coefficients ensure that the equation is balanced. Even though new products were produced, these new compounds were formed by simply rearranging the atoms that were available in the reactants. Atoms were not created nor destroyed—they were simply rearranged. You can use a table similar to the following to check whether chemical equations are, in fact, balanced.

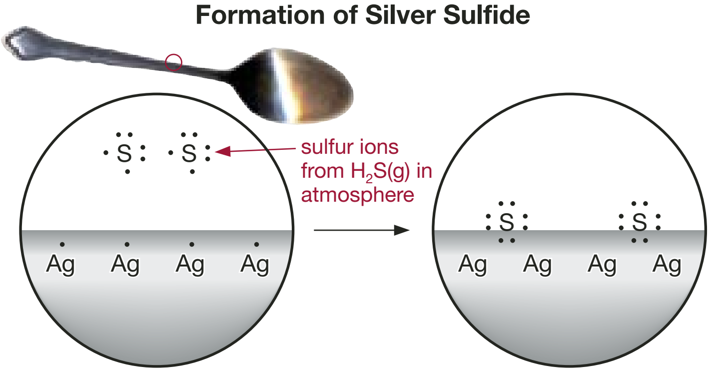
CHECKING A BALANCED CHEMICAL EQUATION

Atom	Number of Atoms Before Reaction	Number of Atoms After Reaction
Ag	4	4
H	4	4
S	2	2
O	2	2

Since the total of each kind of atom before the reaction is equal to the total of each kind of atom after the reaction, this equation is balanced. Matter is conserved.

In addition to balancing the equation, the coefficients indicate the relative ratios of one compound to another. For example, when silver reacts to form silver sulfide, for every four atoms of silver, there are only two units of silver sulfide crystal produced. The reasons for this 4-to-2 ratio lie within the silver sulfide crystal.

Lewis Dot Diagram Showing Formation of Silver Sulfide



Each sulfur atom acquires two electrons to fill its outer energy level to become an ion with a charge of 2–. To obtain a full outer energy level, each silver atom loses one electron to become an ion with a charge of 1+. As the graphic illustrates, it will always take four silver atoms to produce two units of silver sulfide. The ratio of these coefficients in the balanced chemical equation describing this reaction is called the **mole ratio**.

mole ratio: the ratio of the coefficients in a balanced chemical equation

$$\frac{n_r}{n_g} = \frac{coefficient_r}{coefficient_g}$$

number of moles of required substance (n_r)
coefficient of required substance ($coefficient_r$)
number of moles of given substance (n_g)
coefficient of given substance ($coefficient_g$)

It is called a ratio because it communicates proportion. Whether it is 8 dozen to 4 dozen, 600 to 300, or 4 mol to 2 mol, there will always be double the number of silver atoms to units of silver sulfide. Mole ratios are very useful because they can be used to solve problems.

Example Problem 2.1

Determine the amount of silver required to make 0.876 mol of silver sulfide.

Solution

$n_{Ag_2S} = 0.876 \text{ mol}, n_{Ag} = ?$

First, determine the mole ratio.

Balanced chemical equation

$$4\,Ag(s) + 2\,H_2S(g) + O_2(g) \rightarrow 2\,Ag_2S(s) + 2\,H_2O(l)$$

Mole ratio

$$\frac{n_{Ag}}{n_{Ag_2S}} = \frac{coefficient_{Ag}}{coefficient_{AgS}}$$
$$= \frac{4}{2}$$

Now, calculate the number of moles of silver required.

$$\frac{n_{Ag}}{n_{Ag_2S}} = \frac{4}{2}$$
$$n_{Ag} = \frac{4}{2} \times n_{Ag_2S}$$
$$= \frac{4}{2} \times 0.876 \text{ mol}$$
$$= 1.75 \text{ mol}$$

The amount of silver required is 1.75 mol.

Note: When no coefficient is written, the coefficient is assumed to be 1. Since a ratio can be stated a number of different ways, it is convenient to place the required substance in the numerator.

Practice

4. Determine the amount of oxygen required to react with 0.533 mol of silver in the formation of silver tarnish.
5. Determine the amount of hydrogen sulfide required to produce 1.45 mol of silver sulfide.
6. If you use a silver spoon to eat a hard-boiled egg, the spoon will develop tarnish on its surface much sooner than usual. Suggest a reason for this effect.

Ratios in Balanced Chemical Equations and Recipes

In Example Problem 2.1, the solution was separated into two steps. The first step was to determine the mole ratio for two of the chemicals in the reaction. Many students do not record this step because they are able to do this mentally. This cuts the length of the solution in half. If you think of a balanced chemical reaction like a recipe, you might be able to do this step in your head.

In the recipe for homemade iced tea, what is the ratio of tea bags to lemons? What is the ratio of granulated sugar to lemon juice? If you immediately said 24 tea bags to 4 lemons and 600 mL of sugar to 60 mL of lemon juice, you may want to start answering the next Practice questions by simply stating the ratio. As before, to keep the calculation straightforward, continue to set up the mole ratio with the required substance in the numerator.

Example Problem 2.2

When aluminium metal is exposed to air, the metal reacts with oxygen in the air to form aluminium oxide.

$$4\ \mathrm{Al(s)} + 3\ \mathrm{O_2(g)} \rightarrow 2\ \mathrm{Al_2O_3(s)}$$

a. If you react 6.25 mol of aluminium with a sufficient amount of oxygen, determine how many moles of aluminium oxide will be formed.

b. Determine the number of moles of oxygen required to react with 6.25 mol of aluminium.

Solution

a. $n_{\mathrm{Al}} = 6.25\ \mathrm{mol}$

$n_{\mathrm{Al_2O_3}} = ?$

$$\frac{n_{\mathrm{Al_2O_3}}}{n_{\mathrm{Al}}} = \frac{\mathit{coefficient}_{\mathrm{Al_2O_3}}}{\mathit{coefficient}_{\mathrm{Al}}}$$

$$\frac{n_{\mathrm{Al_2O_3}}}{n_{\mathrm{Al}}} = \frac{2}{4}$$

$$\begin{aligned} n_{\mathrm{Al_2O_3}} &= \frac{2}{4} \times n_{\mathrm{Al}} \\ &= \frac{2}{4} \times 6.25\ \mathrm{mol} \\ &= 3.13\ \mathrm{mol} \end{aligned}$$

There will be 3.13 mol of aluminium oxide formed.

b. $n_{\mathrm{Al}} = 6.25$

$n_{\mathrm{O_2}} = ?$

$$\frac{n_{\mathrm{O_2}}}{n_{\mathrm{Al}}} = \frac{\mathit{coefficient}_{\mathrm{O_2}}}{\mathit{coefficient}_{\mathrm{Al}}}$$

$$\frac{n_{\mathrm{O_2}}}{n_{\mathrm{Al}}} = \frac{3}{4}$$

$$\begin{aligned} n_{\mathrm{O_2}} &= \frac{3}{4} \times n_{\mathrm{Al}} \\ &= \frac{3}{4} \times 6.25\ \mathrm{mol} \\ &= 4.69\ \mathrm{mol} \end{aligned}$$

The reaction will require 4.69 mol of oxygen.

Practice

Use the following information to answer questions 7 and 8.

The Coppermine River in Nunavut has many copper deposits along its banks that were used by the ancestors of the Inuit people who live there. The copper was used to make jewellery, knives (such as the one shown in Figure A2.4), and other tools. Prior to restoration, the copper blade of this knife had the characteristic green colour of weathered copper metal.

The process of corrosion for copper artifacts is a complex one that involves many stages. The following description is a simplified version of the key steps in this process:

step 1: The process usually involves carbon dioxide dissolved in atmospheric moisture to form carbonic acid.

$$CO_2(g) + H_2O(l) \rightarrow H_2CO_3(aq)$$

Figure A2.4: The Inuit people made tools from copper found along the Coppermine River.

step 2: The carbonic acid then reacts with the copper to form basic copper(II) carbonate (an ionic crystal), which gives the artifact its green colour. The following equation is a simplification of this process:

$$H_2CO_3(aq) + 2\ Cu(s) + 2\ H_2O(l) \rightarrow Cu_2(OH)_2CO_3(s) + 2\ H_2(g)$$

This same process is what often gives the copper roof of Canada's Parliament buildings their renowned green colour. When new pieces are added to the Parliament buildings' copper roofs, they start off with their characteristic reddish-brown lustre. It takes about 15 years for the chemical reaction to convert the copper in the roof to basic copper carbonate. The process can also be seen on the roof of the University of Calgary's MacEwan Hall. Recent additions are not the same colour as the original portions of the roof.

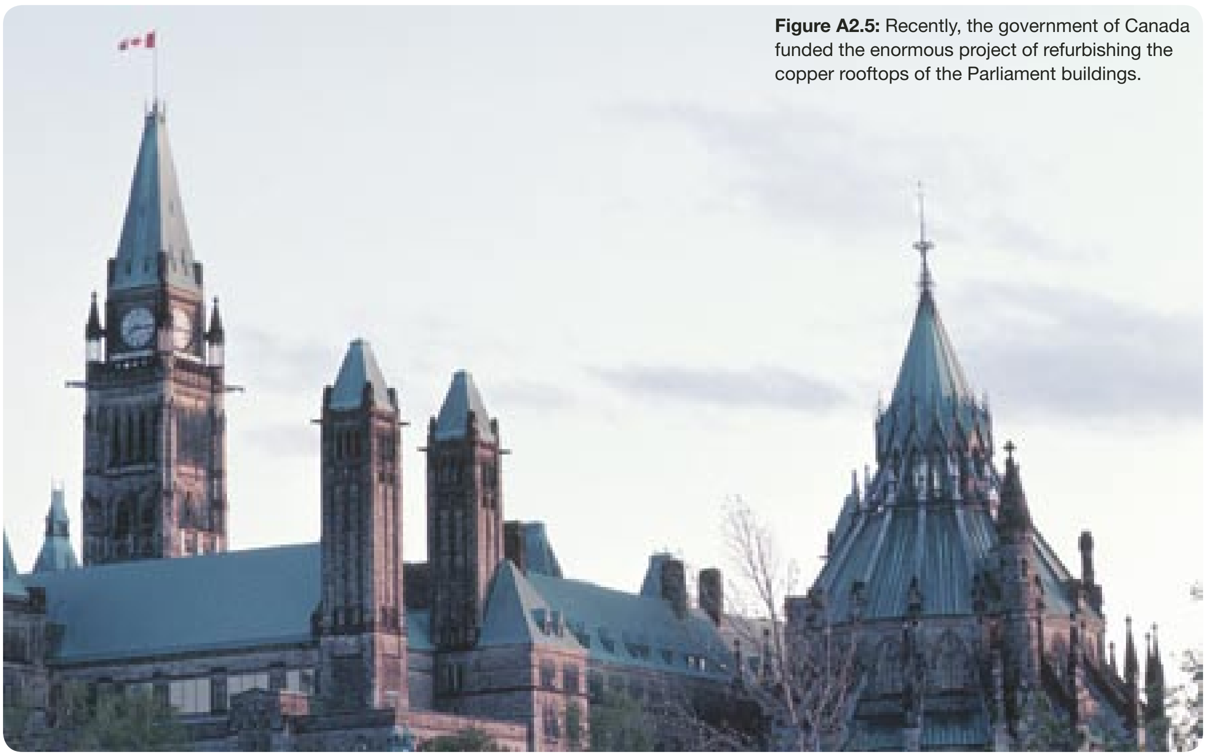


Figure A2.5: Recently, the government of Canada funded the enormous project of refurbishing the copper rooftops of the Parliament buildings.

7. Consider the reaction that produces the carbonic acid.
   a. If the reaction involved 3.87 mol of carbon dioxide, how many moles of carbonic acid is expected to be produced?
   b. Explain why a copper roof obtains its outer coating of basic copper carbonate in less time if the surrounding environment is humid and rich with the emissions from the burning of fossil fuels.
8. Consider the reaction that produces basic copper(II) carbonate. Suppose this reaction involves 3.89 mol of copper.
   a. How many moles of carbonic acid will be used in the chemical reaction?
   b. How many moles of basic copper carbonate will be produced?

Use the following information to answer questions 9 to 11.

If the amount of tarnish is light, you can make silver items shiny again by removing the thin, dark coating of silver sulfide. One way to do this is by reversing the chemical reaction that produced the silver sulfide. This simple process can be done at home.

step 1: Line the bottom of a large pan with aluminium foil, shiny side up.

step 2: Carefully pour boiling water into the pan from a kettle.

step 3: Add about 125 mL of baking soda, $NaHCO_3(s)$ (sodium bicarbonate), for every litre of water.

step 4: Use tongs to place the tarnished silver item in the pan so it is touching the aluminium foil and is submerged in the solution of hot water and baking soda.

step 5: Wait a few minutes for the tarnish to be removed.

step 6: Remove the silver item with tongs, rinse under cool water, and dry thoroughly.

Figure A2.6: Removing tarnish from silver is a very simple process.

The balanced chemical equation for this process is

$$3\ Ag_2S(s) + 2\ Al(s) + 3\ H_2O(l) \rightarrow 6\ Ag(s) + Al_2O_3(s) + 3\ H_2S(aq)$$

The baking soda, $NaHCO_3(aq)$, acts to remove impurities on the surface of the aluminium foil and to improve the conductivity of the solution. The baking soda also reacts with the hydrogen sulfide from the first chemical equation (as shown in the following equation).

$$NaHCO_3(aq) + H_2S(aq) \rightarrow NaHS(aq) + H_2O(l) + CO_2(g)$$

9. You have 4.29×10^{-3} mol of silver tarnish, $Ag_2S(s)$, on a spoon.
   a. How many moles of aluminium are necessary to change these moles of $Ag_2S(s)$ back into silver?
   b. How many moles of water are required in the reaction that converts the tarnish back into silver?
   c. How many moles of silver will be produced during the reaction?
   d. How many moles of aluminium oxide will be produced during the reaction?
10. During the process of removing tarnish from a fork, 5.76×10^{-3} mol of hydrogen sulfide, $H_2S(aq)$, completely reacts with the baking soda.
    a. How many moles of baking soda, $NaHCO_3(aq)$, are required for this reaction?
    b. How many moles of sodium hydrosulfide, NaHS, are produced in this reaction?
    c. Explain how an understanding of mole ratio eliminates the need for calculations.
11. Tiny bubbles of gas can be observed leaving the silver piece during the tarnish-removal process. Consider both chemical equations in the tarnish-removal process as you answer the parts of this question.
    a. Hydrogen sulfide gas has a distinctive rotten-egg odour. Why isn't this odour noticeable during the tarnish-removal process?
    b. Identify the compound forming the tiny gas bubbles on the silver item during the process.

Investigation

Mole Ratios in Chemical Reactions

Purpose

You will collect data for the following chemical reaction:

$$2\,NaOH(aq) + CaCl_2(aq) \rightarrow 2\,NaCl(aq) + Ca(OH)_2(s)$$

The data you collect will allow you to compare the theoretical number of moles of calcium hydroxide produced to the actual number of moles produced.

Science Skills

✓ Performing and Recording

✓ Analyzing and Interpreting

Materials

- 1.50 g of sodium hydroxide, $NaOH(s)$
- 2.10 g of calcium chloride, $CaCl_2(s)$
- distilled water
- 2, 100-mL beakers
- filter paper
- funnel
- ring stand
- drying oven
- analytical balance

CAUTION!

Exercise extreme caution to minimize exposure to the solids or solutions produced in this investigation. Use gloves, safety glasses, and lab aprons for this investigation.

Pre-Lab Analysis

1. Use the periodic table to determine the molar mass of sodium hydroxide, calcium chloride, and calcium hydroxide.
2. Using the masses given in the materials, calculate the number of moles of sodium hydroxide and calcium chloride that will be used in this experiment.
3. Use the mole ratio of calcium hydroxide to sodium hydroxide to predict the theoretical number of moles of calcium hydroxide that should be produced.
4. Use the mole ratio of calcium hydroxide to calcium chloride to predict the theoretical number of moles of calcium hydroxide that should be produced.
5. Consider your answers to questions 3 and 4. Explain which value is the best estimate of the amount of calcium hydroxide that will be produced.

Procedure

step 1: Copy the following data sheet into your notebook or into a spreadsheet. Insert the values from the pre-lab analysis to your data sheet.

Predicted/Theoretical Value

Moles of Calcium Hydroxide Produced = ________________

Measured/Experimental Values

Mass of Filter Paper and Calcium Hydroxide = ________________

Mass of Filter Paper = ________________

Chemical	Molar Mass (g/mol)	Mass (g)	Amount (mol)
sodium hydroxide $NaOH(s)$			
calcium chloride $CaCl_2(s)$			
calcium hydroxide $Ca(OH)_2(s)$			

step 2: Use an analytical balance to determine the mass of the filter paper. Record this mass on your data sheet.

step 3: Dissolve 1.50 g of sodium hydroxide, $NaOH(s)$, into a sufficient amount of water that just dissolves the crystals (no more than 20 mL). Record this mass on your data sheet.

step 4: Dissolve 2.10 g of calcium chloride, $CaCl_2(s)$, into a sufficient amount of water that just dissolves the crystals (no more than 20 mL). Record this mass on your data sheet.

step 5: Combine the solutions from steps 3 and 4. Gently swirl the solutions to encourage thorough mixing. A precipitate should be observable.

step 6: Support the funnel on the ring stand, and line the funnel with the filter paper.

step 7: Pour the solution from step 5 through the filter paper to collect all of the precipitate. Rinse any remaining precipitate into the funnel.

step 8: Dry the resulting precipitate overnight in a drying oven. (If no drying oven is available, you may leave it to air dry.)

step 9: Use an analytical balance to determine the mass of the filter paper and calcium hydroxide. Record your results.

Analysis

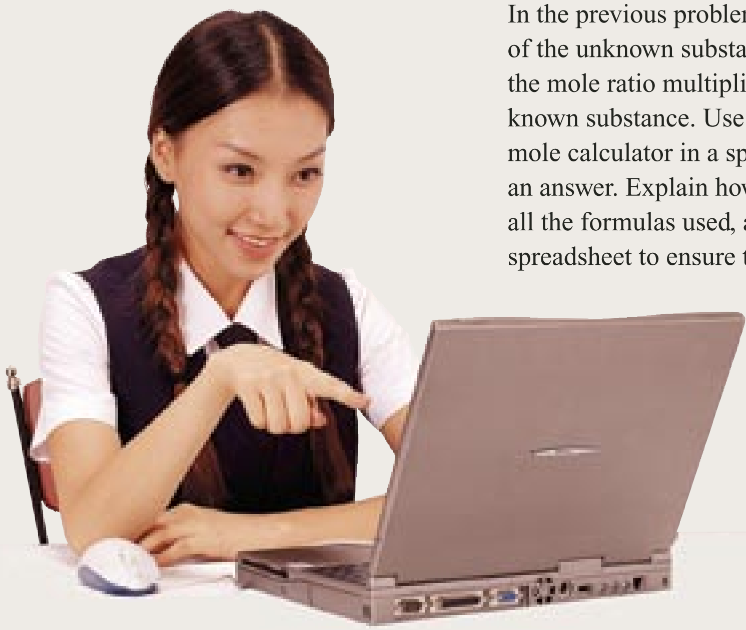
6. Calculate the mass of calcium hydroxide produced by this reaction. Record this value in your data sheet.
7. Calculate the number of moles of calcium hydroxide that were produced in this investigation. Record this value in your data sheet.

Evaluation

8. Compare your experimental value for the number of moles of calcium hydroxide to the theoretical value you calculated in the pre-lab analysis.
9. What difficulties did you encounter that may have affected the accuracy of your results?
10. Describe some steps you could take to minimize difficulties and make this investigation more accurate.

Utilizing Technology

Building an Automatic Mole Calculator Spreadsheet



In the previous problems, calculating the number of moles of the unknown substance always ended up being the same: the mole ratio multiplied by the number of moles of the known substance. Use this fact to construct an automatic mole calculator in a spreadsheet that will convert entered data into an answer. Explain how you constructed the spreadsheet. Include all the formulas used, and provide an example of how you tested the spreadsheet to ensure that it works appropriately.

Science Skills

✓ Initiating and Planning
✓ Analyzing and Interpreting

Using Chemistry to Preserve Artifacts

The warrior cache described at the beginning of the lesson represents a special discovery. It is rare for objects like the bone tools and copper artifacts to be so well preserved in a heavily forested area. Decaying forest vegetation normally creates an acidic soil environment that results in the rapid deterioration of these objects. In this case, the artifacts were surrounded by layers of shells. The shells represented hundreds of years of debris from the First Nations people who inhabited this site. As rainwater dissolved the shells, it created a solution that neutralized the effects of the acid. Thankfully, the naturally acidic soil chemistry was altered by the layers of shells, helping prevent further deterioration of these objects.

Chemistry is also used by experts who preserve and display these valuable artifacts. An understanding of chemical reactions ensures that these objects are maintained under optimum conditions. Such conditions include

- handling artifacts with gloves to prevent the transfer of sweat and oils from the skin
- packing, shipping, and storing artifacts in special acid-free tissue and acid-free boxes
- displaying artifacts in climate-controlled cabinets, ensuring stable temperatures, low humidity, and an environment free of harmful substances

2.1 Summary

Chemical reactions occur due to a rearrangement of atoms—the number of each atom involved in a chemical reaction is conserved. The balanced chemical equation is the result of this principle and provides the key values for determining the mole ratio. Mole ratio is useful because it allows you to determine the amount of reactants or products that will be involved in a chemical reaction.

2.1 Questions

Knowledge

1. Define *mole ratio* and *mass*.

2. Provide a step-by-step outline describing how to use the concept of mole ratio to determine the following.

a. the amount of a reactant required to produce a specific amount of a product

b. the amount of a product that will be produced given a certain amount of a reactant

3. Describe a useful situation for predicting the amount of product in a chemical reaction.

4. Describe a useful situation for calculating the amount of reactant required for a specific amount of product.

Applying Concepts

5. To make pure iron metal from its ore, iron(III) oxide must react with carbon monoxide. The products of this reaction are iron metal and carbon dioxide gas. The balanced chemical equation for this reaction is

$$Fe_2O_3(s) + 3\ CO(g) \rightarrow 2\ Fe(s) + 3\ CO_2(g)$$

Answer the following if 1.5×10^3 mol of iron(III) oxide reacted with a sufficient amount of carbon monoxide.

a. How many moles of pure iron metal will be produced?

b. How many moles of carbon dioxide will be released into the air?

c. How many moles of carbon monoxide will be required to fully change the ore into its metal?

6. Many fertilizers are formed from chemical reactions involving nitric acid because the nitrate within the acid helps make plants green. Several different reactions are required to make nitric acid within an industry. The first step is to react ammonia, $NH_3(g)$, with oxygen from the air. This will produce nitrogen monoxide gas and water. The balanced chemical equation for this reaction is

$$4\ NH_3(g) + 5\ O_2(g) \rightarrow 4\ NO(g) + 6\ H_2O(l)$$

You need to make 2.8×10^3 mol of nitrogen monoxide.

a. How many moles of ammonia will you need?

b. How many moles of oxygen will you need?

c. How many moles of water will be produced?

7. During photosynthesis, carbon dioxide and water react in the presence of light energy to form glucose and oxygen.

$$6\ CO_2(g) + 6\ H_2O(g) \rightarrow C_6H_{12}O_6(aq) + 6\ O_2(g)$$

In a particular reaction, 9.00 mol of glucose are produced.

a. How many moles of water were required?

b. How many moles of oxygen were produced?

c. Without using pencil and paper, predict the number of moles of carbon dioxide needed. Explain.

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Legend: t = top, m = middle, b = bottom, l = left, r = right

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