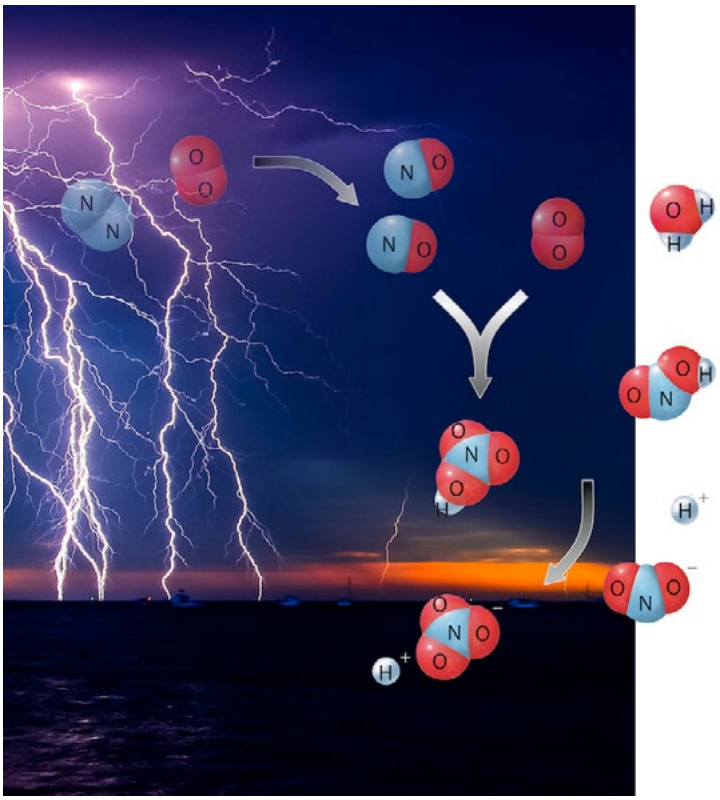


Chapter 9

How Chemicals React

THE MAIN IDEA

Atoms change partners during a chemical reaction.

9.3 Grams to Moles

Atoms and molecules react in specific ratios by number. In the laboratory, however, chemists work with bulk quantities of materials, which are measured by grams. Chemists therefore need to know the relationship between the grams of a given sample and the number of atoms or molecules contained in that mass. The key to this relationship is the *mole*. Recall from Section 7.3 that we use the word *mole* to indicate a number, much as we use the word *dozen* to indicate a number. While a dozen is equal to 12, a mole is equal to a number that is incredibly large: 6.02×10^{23}. This number is known as **Avogadro's number**, in honor of the 18th-century scientist Amedeo Avogadro. Again, for emphasis, one mole is equal to 6.02×10^{23}.

As **Figure 9.4** illustrates, if you express the numeric value of the atomic mass of any element in *grams*, the number of atoms in a sample of the element having this mass is always 6.02×10^{23}, which is 1 mole. For example, a 22.990-gram sample of sodium metal, Na (atomic mass = 22.990 amu), contains 6.02×10^{23} sodium atoms, and a 207.2-gram sample of lead, Pb (atomic mass = 207.2 amu), contains 6.02×10^{23} lead atoms.

The same concept holds for molecules (or any compound). Express the numeric value of the formula mass in *grams* and a sample having that mass contains 6.02×10^{23} molecules. For example, there are 6.02×10^{23} O_2 molecules in 31.998 grams of molecular oxygen, O_2 (formula mass = 31.998 amu), and 6.02×10^{23} CO_2 molecules in 44.009 grams of carbon dioxide, CO_2 (formula mass = 44.009 amu).

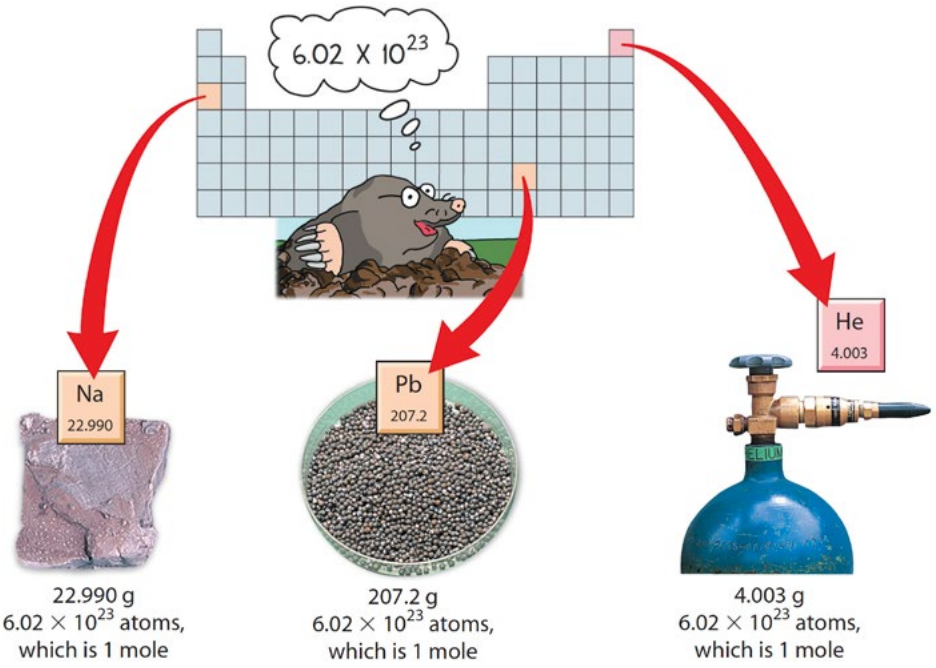
The **molar mass** of any substance, be it element or compound, is defined as the mass of 1 mole of the substance. Thus, the units of molar mass are *grams per mole*. For instance, the atomic mass of carbon is 12.011 amu, which means that 1 mole of carbon has a mass of 12.011 grams, and we say

FOR YOUR INFORMATION

An Avogadro's number of grains of sand would cover the United States to a depth of about 2 meters. A stack of an Avogadro's number of pennies would be about 800,000 trillion kilometers tall, which is about the diameter of our galaxy. Placed side by side, these pennies would reach to the Andromeda galaxy, which is about 2.5 million light-years away. Avogadro's number is beyond huge, yet that's the number of water molecules found in a mere 18 grams of water. Water molecules are that small!

Figure 9.4 >

Express the numeric value of the atomic mass of any element in grams, and that many grams contain 6.02×10^{23} atoms.



that the molar mass of carbon is 12.011 grams per mole. The molar mass of molecular oxygen, O_2 (formula mass 31.998 amu), is 31.998 grams per mole. For convenience, values such as these are often rounded to the nearest whole number. The molar mass of carbon, therefore, might also be presented as 12 grams per mole and that of molecular oxygen as 32 grams per mole.

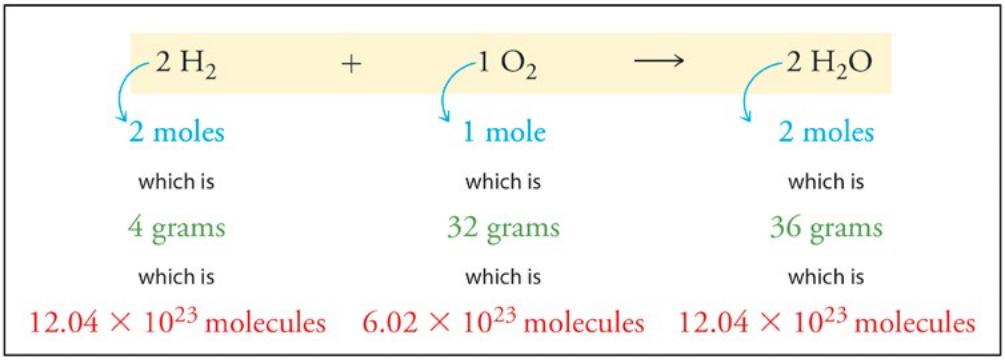
Because 1 mole of any substance always contains 6.02×10^{23} particles, the mole is an ideal unit for chemical reactions. For example, 1 mole of carbon (12 grams) reacts with 1 mole of molecular oxygen (32 grams) to give 1 mole of carbon dioxide (44 grams).

In many instances, the ratio in which chemicals react is not 1:1. As shown in **Figure 9.5**, for example, 2 moles (4 grams) of molecular hydrogen react with 1 mole (32 grams) of molecular oxygen to give 2 moles (36 grams) of water. Note how the coefficients of the balanced chemical equation can be conveniently interpreted as the number of moles of reactants or products. A chemist therefore need only convert these numbers of moles to grams in order to know how much mass of each reactant he should measure out to have the proper proportions.

Cooking and chemistry are similar in that both require measuring ingredients. Just as a cook looks to a recipe to find the necessary quantities measured by the cup or the tablespoon, a chemist looks to the periodic table to find the necessary quantities measured by the number of grams per mole for each element or compound.

Figure 9.5 >

Two moles of H_2 reacts with 1 mole of O_2 to give 2 moles of H_2O. This is the same as saying 4 grams of H_2 reacts with 32 grams of O_2 to give 36 grams of H_2O or, equivalently, that 12.04×10^{23} H_2 molecules react with 6.02×10^{23} O_2 molecules to give 12.04×10^{23} H_2O molecules.



CONCEPT **CHECK**

1. How many atoms are in a 6.941-gram sample of lithium, Li (atomic mass = 6.941 amu)?

2. How many molecules are in an 18.015-gram sample of water, H_2O (formula mass = 18.015 amu)?

CHECK YOUR ANSWER

1. Because this number of grams of lithium is numerically equal to the atomic mass, there are 6.02×10^{23} atoms in the sample, which is 1 mole of lithium atoms.

2. Because this number of grams of water is numerically equal to the formula mass, there are 6.02×10^{23} water molecules in the sample, which is 1 mole of water molecules.

CONCEPT **CHECK**

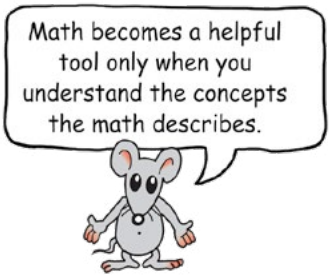
What is the molar mass of water (formula mass = 18 amu)?

CHECK YOUR ANSWER

From the formula mass, you know that 1 mole of water has a mass of 18 grams. Therefore, the molar mass is 18 grams per mole.

CHEMICAL CONNECTIONS

How are the atoms in your lungs connected to the atoms that were once in the lungs of Leonardo da Vinci?



FOR YOUR INFORMATION

Pi is the ratio of a circle's circumference to diameter. As the circumference gets bigger, so does the diameter. The ratio of the two remains the same, which is why the value of pi is constant. Similarly, Avogadro's number is the ratio of relative mass expressed in amu to mass expressed in grams. For example, a carbon atom has a relative mass of 12.011 amu. It's mass in grams is 1.99×10^{-23}. The ratio of these two numbers is 6.02×10^{23}. This is Avogadro's number, which stays constant because it is simply a ratio. An atom with a larger mass in amu will necessarily have a larger mass in grams. The value of Avogadro's number was not known until scientists were able to estimate the mass of single atoms and molecules.

Calculation Corner: Masses of Reactants and Products

The coefficients of a chemical equation tell us the ratio by which reactants react and products form. The following equation, for example, tells us that every 1 mole of methane, CH_4, reacts to produce 2 moles of water, H_2O.

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

If you were given 16 g of methane, CH_4, how many grams of water, H_2O, would form? From the text, you should know that 16 g of methane, CH_4, is 1 mole (formula mass 16 amu). So, 16 g of methane would yield 2 moles of water. But how many grams are 2 moles of water? Well, if 1 mole of water, H_2O, equals 18 g (formula mass 18 amu), then 2 moles equals 36 g. Thus, 16 g of methane, CH_4, would yield 36 g of water, H_2O. Let's look at this process from a step-by-step mathematical point of view.

SAMPLE PROBLEM 1

What mass of water is produced when 16 g of methane, CH_4 (formula mass 16 amu), reacts with an unlimted supply of oxygen, O_2, in the following reaction? $CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$

SOLUTION:

Step 1. Convert the given mass to moles:

$$\text{(16 g } \cancel{CH_4}\text{)}\left(\frac{\text{1 mole } CH_4}{\text{16 g } \cancel{CH_4}}\right) = \text{1 mole } CH_4$$

(Conversion factor)

Step 2. Use the coefficients of the balanced equation to find out how many moles of H_2O are produced from this many moles of CH_4:

$$\text{(1 } \cancel{\text{mole } CH_4}\text{)}\left(\frac{\text{2 moles } H_2O}{\text{1 } \cancel{\text{mole } CH_4}}\right) = \text{2 moles } H_2O$$

(Conversion factor)

Step 3. Now that you know how many moles of H_2O are produced, convert this value to grams of H_2O:

$$\text{(2 } \cancel{\text{moles } H_2O}\text{)}\left(\frac{\text{18 g } H_2O}{\text{1 } \cancel{\text{mole } H_2O}}\right) = \text{36 g } H_2O$$

(Conversion factor)

Steps 1 through 3 can be combined into a single equation that starts with what you are given (16 g of CH_4) and calculates that which is asked for:

$$\underset{\text{step 1}}{\text{(16 g } \cancel{CH_4}\text{)}\left(\frac{\text{1 mole } \cancel{CH_4}}{\text{16 g } \cancel{CH_4}}\right)}\underset{\text{step 2}}{\left(\frac{\text{2 moles } \cancel{H_2O}}{\text{1 mole } \cancel{CH_4}}\right)}\underset{\text{step 3}}{\left(\frac{\text{18 g } H_2O}{\text{1 } \cancel{\text{mole } H_2O}}\right)} = \text{36 g } H_2O$$

This technique of combining a series of conversion factors is an application of what you learned in the unit conversion Calculation Corner of Chapter 1. Also, within each conversion factor, the unit that you want to change goes in the denominator and that which you want to obtain goes in the numerator.

The method of converting grams of a substance to moles (step 1), then from moles of this substance to moles of that substance (step 2), followed by moles of that substance to grams (step 3) is called *stoichiometry*. Using stoichiometry, we can calculate the amounts of reactants or products in any chemical reaction.

The methods of stoichiometry are developed much further in upper level chemistry. For our current purposes, we're simply introducing the main idea, which how we keep tabs on atoms and molecules as they react to form products.

Nonetheless, for a special assignment, you might try your analytical thinking skills on the following problems. First, try to deduce the answer based on what you know about the law of mass conservation, and then follow the mathematical steps to check your answers.

SAMPLE PROBLEM 2

Show that 44 g of carbon dioxide, CO_2, is produced when 16 g of methane, CH_4, reacts with an unlimited supply of oxygen, O_2. How many grams of oxygen, O_2, are actually needed for this reaction?

SOLUTION:

The 16 g of methane, CH_4, is one mole, which reacts with oxygen to produce one mole of carbon dioxide, CO_2, which you know because of the coefficients in the balanced chemical equation shown previously. One mole of carbon dioxide (formula mass 44 amu) is 44 g. So, the 16 g of methane reacts with oxygen to produce 44 g of carbon dioxide plus 36 g of water. The mass of the products (44 g + 36 g = 80 g) must be equal to the mass of the reactants (16 g + ? = 80 g). We can calculate that the methane reacted with 64 g of oxygen, which, interestingly enough, is 2 moles, as we see from the balanced equation.

The mass of carbon dioxide produced can also be calculated as follows:

$$(16\ \text{g}\ \cancel{\text{CH}_4})\left(\frac{1\ \text{mole}\ \cancel{\text{CH}_4}}{16\ \text{g}\ \cancel{\text{CH}_4}}\right)\left(\frac{1\ \text{mole}\ \cancel{\text{CO}_2}}{1\ \text{mole}\ \cancel{\text{CH}_4}}\right)\left(\frac{44\ \text{g}\ \text{CO}_2}{1\ \text{mole}\ \cancel{\text{CO}_2}}\right) = 44\ \text{g}\ \text{CO}_2$$

Similarly, the mass of oxygen can be calculated as follows:

$$(16\ \text{g}\ \cancel{\text{CH}_4})\left(\frac{1\ \text{mole}\ \cancel{\text{CH}_4}}{16\ \text{g}\ \cancel{\text{CH}_4}}\right)\left(\frac{2\ \text{moles}\ \cancel{\text{O}_2}}{1\ \text{mole}\ \cancel{\text{CH}_4}}\right)\left(\frac{32\ \text{g}\ \text{O}_2}{1\ \text{mole}\ \cancel{\text{O}_2}}\right) = 64\ \text{g}\ \text{O}_2$$

SAMPLE PROBLEM 3

How many grams of ozone (O_3, 48 amu) can be produced from 64 g of oxygen (O_2, 32 amu) in the reaction shown?

$$3\ \text{O}_2 \rightarrow 2\ \text{O}_3$$

SOLUTION:

According to the law of mass conservation, the amount of mass in the products must equal the amount of mass in the reactants. Given that this reaction involves only one reactant and one product, you should not be surprised to learn that 64 g of reactant produces 64 g of product. Here are the stepwise calculations, which start with *grams* of oxygen and then finds the *moles* of oxygen. The moles of oxygen are then converted to moles of ozone using the coefficients of the equation. This is followed by a conversion of *moles* of ozone to *grams* of ozone:

$$(64\ \text{g}\ \cancel{\text{O}_2})\left(\frac{1\ \text{mole}\ \cancel{\text{O}_2}}{32\ \text{g}\ \cancel{\text{O}_2}}\right)\left(\frac{2\ \text{moles}\ \cancel{\text{O}_3}}{3\ \text{moles}\ \cancel{\text{O}_2}}\right)\left(\frac{48\ \text{g}\ \text{O}_3}{1\ \text{mole}\ \cancel{\text{O}_3}}\right) = 64\ \text{g}\ \text{O}_3$$

SAMPLE PROBLEM 4

What mass of nitrogen monoxide (NO, 30 amu) is formed when 28 g of nitrogen (N_2, 28 amu) reacts with 32 g of oxygen (O_2, 32 amu) in the reaction shown?

$$\text{N}_2 + \text{O}_2 \rightarrow 2\ \text{NO}$$

SOLUTION:

There are several ways to answer this question. One way would be to recognize that 28 g of N_2 is 1 mole of N_2 and 32 g of O_2 is 1 mole of O_2. According to the balanced equation, combining 1 mole of N_2 with 1 mole of O_2 yields 2 moles of NO. Because the mass of 1 mole of NO is 30 g, the mass of 2 moles of NO must be 30 g × 2 = 60 g, which is simply the sum of all the reactants (28 g + 32 g = 60 g). To calculate step-wise, you can start with either the 28 g of N_2 or the 32 g of O_2.

$$(28\ \text{g}\ \cancel{\text{N}_2})\left(\frac{1\ \text{mole}\ \cancel{\text{N}_2}}{28\ \text{g}\ \cancel{\text{N}_2}}\right)\left(\frac{2\ \text{moles}\ \cancel{\text{NO}}}{1\ \text{mole}\ \cancel{\text{N}_2}}\right)\left(\frac{30\ \text{g NO}}{1\ \text{mole}\ \cancel{\text{NO}}}\right) = 60\ \text{g NO}$$

In this reaction, N_2 and O_2 were combined in exactly the right amounts. Do you recognize that there would be too much oxygen if 28 g of N_2 were reacted with 40 g of O_2? If that were the case, then only 32 g of the 40 g of O_2 would react. There would be 8 g of unreacted O_2 left over. Stoichiometry is an area of chemistry rich in opportunities for analytical thinking.

YOUR TURN

1. How many grams of iron oxide, Fe_2O_3, can be produced from the reaction of 25.0 g of iron, Fe, with an unlimited amount of oxygen, O_2? (Not sure where to start? Here's a helpful rule: always start your calculation by writing down that which you are given, which in this case is 25.0 g of Fe. Then proceed with the conversions.)

$$4\ \text{Fe} + 3\ \text{O}_2 \rightarrow 2\ \text{Fe}_2\text{O}_3$$

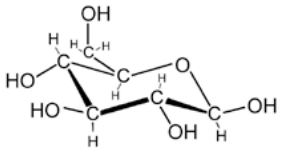
2. How many grams of iron oxide, Fe_2O_3, can be produced from the reaction of 25.0 g of oxygen, O_2, with an unlimited amount of iron, Fe?

3. How many grams of oxygen, O_2, are required to react with 25.0 g of iron, Fe, to form iron oxide, Fe_2O_3?

4. A 25.0-g sample of iron, Fe, powder is mixed with 25.0 g of oxygen, O_2, gas and heated until all of the Fe has reacted. How many grams of O_2 remain after the reaction is complete?

Empirical Formulas

Consider the glucose molecule, which has the following structure:



Glucose, $C_6H_{12}O_6$

The molecular formula for this molecule is obtained by counting the number of different types of atoms within that molecule. With six carbons, twelve hydrogens, and six oxygens the molecular formula is $C_6H_{12}O_6$.

Back in the day—over a century ago, before the advent of modern instruments—how exactly did chemists find the formula for a compound? One method was *combustion analysis*. They would burn the compound under carefully controlled conditions such that they could analyze relative amounts of the remaining elements, which is the percent composition. Combusting glucose, for example, would reveal experimental data looking something like this:

Percent Composition (Carbon): 40.123

Percent Composition (Hydrogen): 6.670

Percent Composition (Oxygen): 53.332

From this raw data, the chemist could calculate an *empirical formula*, which shows the lowest ratio of atoms. This calculation requires dividing the percent composition by the atomic mass of each atom. This provides the relative ratio of elements, looking something like this:

Relative Ratio (Carbon): 40.123/12.011 = 3.341

Relative Ratio (Hydrogen): 6.670/1.008 = 6.617

Relative Ratio (Oxygen): 53.332/15.999 = 3.333

The chemist would then divide each by the lowest number and then round off to the closest whole number. This rounding-off accommodated for experimental errors from the combustion analysis.

Relative Ratio (Carbon): 3.341/3.333 = 1

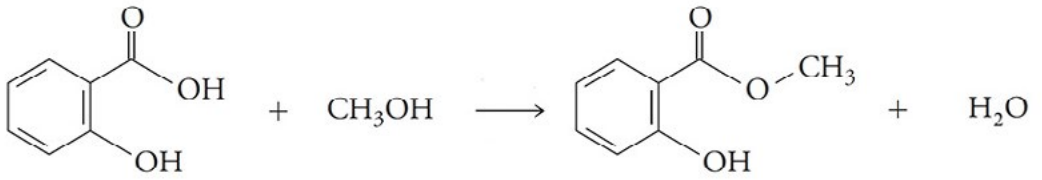
Relative Ratio (Hydrogen): 6.617/3.333 = 2

Relative Ratio (Oxygen): 3.333/3.333 = 1

The chemist would then know the empirical formula, which for glucose is $C_1H_2O_1$. The empirical formula shows the elements of a compound in their lowest whole-number ratio. Back in the day, it was a chemist's first step for discovering a compound's molecular formula, which would be some multiple of the empirical formula. To discern the molecular formula required other innovative techniques such as crystallography.

Percent Yield

Methyl salicylate is the compound responsible for the smell and taste of wintergreen, a common ingredient of many candies. It can be synthesized from the starting materials salicylic acid and methanol:



According to this equation, methyl salicylate forms from salicylic acid in a 1:1 mole ratio. Thus, if you were to start with 138 grams of salicylic acid (1 mole), then, ideally, a total of 152 grams of methyl salicylate (1 mole) can be obtained. The reality is that not all of the salicylic acid will be converted to methyl salicylate. Why not? There can be other reactions that occur instead. Chemists will usually have to control the conditions carefully to assure the reaction they want to occur is optimized. Also, some of the product might be lost as the chemist tries to isolate and purify it.

This is why chemists use the concept of **percent yield**, which is a measure of how much product was obtained relative to the amount of product that could be obtained under ideal conditions. For example, we know that from 138 grams of salicylic acid, the theoretical yield of methyl salicylate

is 152 grams. Let's say the actual yield was 142 grams. The percent yield is then calculated by this formula:

$$\text{Percent Yield} = \frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100$$

$$\text{Percent Yield} = (142/152) \times 100 = 93.4\%$$

Because of the reality of conditions in the laboratory, a 100% yield is not to be expected. That said, chemists will spend much time, energy, and thought to optimize their actual yields to be as close to 100% as is possible and practical.

FOR YOUR INFORMATION

If the molecular formula is already known, then the percent composition of each element can be calculated with no need for any experimental methods. Glucose has the molecular formula $C_6H_{12}O_6$ with a formula mass of 180.156 amu. Six carbons is 72.066 amu. Twelve hydrogens is 12.096 amu. Six oxygens is 95.994 amu. Thus:

Percent Composition (Carbon): $(72.066/180.156) \times 100 = 40.002$
Percent Composition (Hydrogen): $(12.096/180.156) \times 100 = 6.714$
Percent Composition (Oxygen): $(95.994/180.156) \times 100 = 53.284$