Chapter 7: Calculations with Chemical Formulas and Chemical Reactions

Chemical reactions are written showing a few individual atoms or molecules reacting to form a few atoms or molecules of products. However, individual atoms and molecules are extremely small, too small to be physically handled as individual particles. As a practical matter, we manipulate many, many more molecules than just one or two.

This is a fundamental problem: While reactions involve small numbers of individual particles, we must manipulate extremely large numbers of these particles. We need some way of bridging the gulf between the "real world" of our ability to manipulate and measure materials, and the "atomic/molecular world" where small particles interact as described by the balanced chemical reaction. The way we bridge this gap is to use a collective (or count) noun called the ***mole.***

English already has many collective nouns for fixed, given numbers of objects. Some of the more common collective nouns are shown in Table 7.1.

Counting Numbers:		Numerical value
	"hundred"	100
	"thousand"	1000
	"million"	1,000,000
	"billion"	1,000,000,000
Special Numbers:		
	"Couple", "pair"."brace"	2
	"dozen"	12
	"gross"	144
	"great gross"	1728 (12 gross)
	"score"	20
Numbers of babies:		
	"twins"	2
	"triplets"	3
	"quadruplets"	4
Numbers of musicians:		
	"duet"	2
	"trio"	3
	"quartet"	4

Table 7.1. Common English collective (count) nouns for groups of objects.

The English word "dozen" means twelve (12) items. It makes no difference what the specific object is, one dozen of the object always means 12 objects. Likewise we can talk about a pair of shoes, or a score of years, and know that we are talking about 2 shoes and 20 years. Regardless of the exact identity of the item, the count noun tells us the number of items.

The mole is a count noun having a value of 6.022 141 5 x 10^{23} or 602,214,150,000,000,000,000,000. This is called ***Avogadro's number***, and we often say, "A mole contains Avogadro's number of particles". As you might expect, if we can't manipulate an individual molecule, it is just as impossible to manipulate 602,214,150,000,000,000,000,000 molecules. Or is it?

Chemists have defined the ***formula weight*** (FW) or the ***molecular weight*** (MW) of a substance as the mass in grams of the substance containing ***1 mole*** (6.022 x 10^{23}) of particles of the substance. This allows us to manipulate huge numbers of particles by their collective mass, instead of manipulating them as individual objects. This is the same basic idea used by banks and casinos handling large amounts of money – it is more efficient and just as accurate to weigh it than to count individual coins or bills.

The term *molecular weight* is generally reserved for substances that exist in water solution as discrete molecules. *Formula weight* is used for substances that ionize or dissociate when dissolved in water, but can also be used in place of molecular weight. Typically, when we deal with acids, bases, salts or other ionic compounds, we use the formula weight. However, it is not difficult to find examples of the two terms used interchangeably. The units for either formula or molecular weight are grams/mole.

The calculation of either weight is straightforward; it is the sum of the individual ***atomic weights*** of all atoms or ions present in one particle of the substance. The average atomic weight of an element is generally found at the bottom of the element block (Figure 7.1). The chemical formula of the substance clearly indicates how many atoms or ions of each element are present. For example, the formula for methane (CH_4) indicates that one molecule contains one carbon atom and four hydrogen atoms. The formula for sodium chloride (NaCl) indicates one sodium ion and one chlorine ion. Using the average atomic weight values from the periodic table, we calculate the molecular weight of methane by adding 12.011 for the carbon atom and 4 x 1.0079 for the four hydrogen atoms, for a total of 16.043 grams/mole. Similarly, the formula weight for sodium chloride is 22.98977 for the sodium ion and 35.453 for the chloride ion, for a total of 58.443 grams/mole.

Note: Different periodic tables may have slightly different values for average atomic weight. As a consequence, it is possible for two people using two different periodic tables to calculate two slightly different values for the molecular or formula weight of a substance. These small differences are negligible; so don't have a fit if atomic weights from your periodic table give you slightly different answers than those I present.

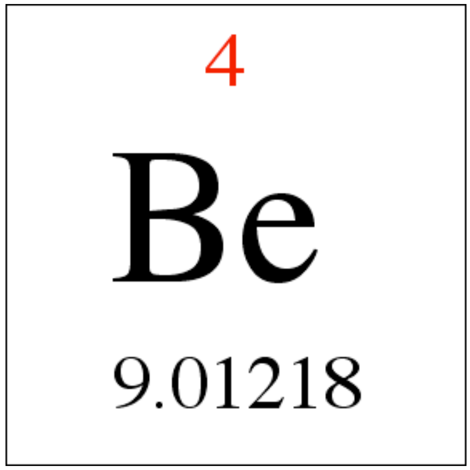

Figure 7.1. The element block for beryllium. Average atomic weight (9.01218) is at the bottom of the block.

There is no significant difference in the mass of an ion compared to the mass of the corresponding atom; sodium atoms have the same mass as sodium ions, and chloride ions have the same mass as chlorine atoms. The loss or gain of one or more electrons represents an extremely tiny change in mass. (The electron has a mass approximately 1100 times smaller than a single proton. Oxygen, for example, would need to gain ~1100 electrons for its average atomic weight to change by 1 unit, from 15.9994 to 16.9994).

Percentage composition by mass.

Once we calculate the molecular or formula weight of a substance, we can make other calculations based on the molecular or formula weight. One type of calculation is ***percentage composition by mass*** - the portion of the total mass of a substance due to one particular component of the substance. Percentage composition by mass is the basis for the law of constant composition.

The chemical formula of a substance indicates the number and kinds of atoms making up the substance. The formula for water, H_2O, clearly indicates two hydrogen atoms are combined with one oxygen atom in each molecule of water. Two out of three atoms are hydrogen, and so two-thirds of the atoms in water are hydrogen, while one-third of the atoms are oxygen.

However, the mass of a hydrogen atom is substantially smaller than the mass of an oxygen atom. A hydrogen atom weighs 1.0079; an oxygen atom weighs 15.9994. By mass, hydrogen contributes a small amount to the total mass of a water molecule, while oxygen contributes a large amount of mass to the water molecule.

Determining percentage composition is relatively straightforward. First you calculate the molecular or formula weight of the substance. Then you determine the total mass due to a particular element. Finally, you divide the elements total mass by the molecular (or formula) weight and multiply the result by 100 to express the result as a percentage.

For water, the molecular weight is 18.0152. There are two hydrogen atoms, each contributing 1.0079 to the molecular weight of water, or 2.0158. The single oxygen contributes 15.9994 to the water molecule. The percent hydrogen is (2.0158 ÷ 18.0152) x 100 = 11.189%. The percent oxygen is (15.9994 ÷ 18.0152) x 100 = 88.8106%. If you have calculated the individual percentages properly, then the sum of these percentages should total to 100%, within round off error. In this example, the total is 99.9996%, which rounds to 100.000%.

Notice that I haven't included any units with the weights. I can choose units of u (unified atomic mass units), or Da (Daltons), or grams/mole. It doesn't really matter which units I choose, so long as I use the same units for all values. Of course, once I perform the division, the result is dimensionless: Daltons ÷ Daltons = no unit. Most of the time, when calculating percentage composition, I don't specify a unit for the molecular or formula weight. For other calculations, the units will be very important. Experience will tell you when the unit is important, and when you can be a little less strict with the units.

Mass to moles, and moles to mass.

When we use the atomic weight, the formula weight, or the molecular weight, with units of grams, we have the ***gram atomic weight*** (GAW), the ***gram formula weight*** (GFW), and the ***gram molecular weight*** (GMW).

If I need one mole of carbon dioxide (CO_2), I must weigh out 44.010 grams of carbon dioxide. If I wanted two moles of carbon dioxide, the mass must be twice as great (88.020 grams). Likewise, if I need 0.25 moles of carbon dioxide, I only need 11.025 grams. In general:

$$\text{mass (grams)} = \text{\# of moles} \times \text{gram molecular weight}$$

It is also possible to calculate the specific number of moles of a substance for any given mass of substance – we simply re-arrange the equation:

$$\frac{\text{mass (grams)}}{\text{gram molecular weight}} = \text{\# of moles}$$

For example, if I have 9.00 grams of carbon dioxide, I have:

$$\frac{9.00\ grams}{44.010\ grams/mole} = 0.204\ moles\ CO_2$$

Similarly:

25.00 grams of Na_2SO_4 is $\dfrac{25.00\ grams}{142.04\ g/mole} = 0.1760\ moles\ Na_2SO_4$

5.00 grams of CH_3CO_2H is $\dfrac{5.00\ grams}{60.052\ grams/mole} = 0.0833\ moles\ CH_3CO_2H$

210 grams of NH_4OH is $\dfrac{210\ grams}{35.0456\ grams/mole} = 5.99\ moles\ NH_4OH$

Stoichiometry.

Stoichiometry is the exact whole number relationship between the numbers of atoms and molecules reacting to form products, as shown in a balanced chemical equation.

Consider the following unbalanced chemical equation:

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

This equation provides us some information, specifically the identity of the reacting molecules (methane and oxygen) and of the product molecules (carbon dioxide and water). However, since the chemical equation is unbalanced, it does not tell us *how many* molecules of each substance are produced and consumed. Only a balanced chemical equation can answer the question "How many?"

If you haven't mastered the art of balancing chemical equations, go back to Chapter 6 and master this art, **NOW!**

Consider our equation, now correctly balanced:

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

Now you know how many molecules of each substance react, and how many molecules are produced. The balanced chemical equation clearly says, "One molecule of methane combines with two molecules of oxygen to produce one molecule of carbon dioxide and two molecules of water." and saves a lot of writing in the process.

From the coefficients in the balanced chemical equation, we can write a set of equivalencies:

$$1\ CH_4 = 2\ O_2$$

$$1\ CH_4 = 1\ CO_2$$

$$1\ CH_4 = 2\ H_2O$$

$$2\ O_2 = 1\ CO_2$$

$$2\ O_2 = 2\ H_2O$$

$$1\ CO_2 = 2\ H_2O$$

In all cases, the "=" is read as "is chemically equivalent to". We can write 2 conversion factors for each equivalency, and use these conversion factors to determine the amounts of reactants and products used in the reaction. This is exactly the same procedure used in Chapter 1 for writing conversion factors.

Are you confused?

Let's look at some examples. If you have 4 methane molecules, how many oxygen molecules are needed to completely react? You can use the equivalency $1\ CH_4 = 2\ O_2$ and calculate:

$$4\ CH_4 \times \frac{2\ O_2}{1\ CH_4} = 8\ O_2$$

You need 8 oxygen molecules to completely react with 4 methane molecules.

Similarly, if 1 methane molecule reacts, how many carbon dioxide molecules are produced?

$$1\ CH_4 \times \frac{1\ CO_2}{1\ CH_4} = 1\ CO_2$$

Through stoichiometry, all you need is the mass of a single substance to determine the masses of all other substances participating in the reaction. Using the methane example from above, and starting with 5.00 grams of methane, how much oxygen is consumed, and how much carbon dioxide and water will be produced?

The first step is to balance the chemical reaction:

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

Not only is this the first step, it is also a critically important step. It is possible to make all kinds of mistakes, and being human, sooner or later you will make some sort of calculation mistake. **But if you start with a wrong chemical equation ALL of our calculations will be wrong!**

The second step is to determine the mass relationships between reactants and products in our equation. The balanced chemical equation tells what is happening on the molecular level, but it also tells what is happening on the "real world" level, through the use of gram molecular and gram formula weights. I can readily calculate the molecular weights of all reactants and products, and I can write the chemical reaction in terms of mass.

The molecular weight of methane is 16.0426 grams/mole, of oxygen is 31.9988 g/mole, of carbon dioxide is 44.0098 g/mole, and of water is 18.0152 g/mole. Substituting these values into the chemical reaction we get:

$$16.0426 \text{ g } CH_4 + 63.9976 \text{ g } O_2 \rightarrow 44.0098 \text{ g } CO_2 + 36.0304 \text{ g } H_2O$$

Notice what I did; I multiplied each molecular weight by the number of moles of that substance, indicated by the coefficient in the balanced chemical equation. The mass of oxygen used in the reaction is 63.9976 grams, which is 2× the gram molecular weight of oxygen (31.9988 g/mole); the mass of water produced is 36.0304 grams, which is also 2× the gram molecular weight of water (18.0152 g/mole).

When re-writing the equation in terms of mass, the mass of each reactant and product is the gram molecular (or formula) weight multiplied by the coefficient from the balanced chemical equation.

Before going any farther, let's make an important check. According to the law of conservation of mass, there should be no detectable change in mass between the reactants and products (although there may have some very tiny differences, due to round-off errors). Add up the total mass of reactants and compare it with the total mass of products for our reaction: 80.0402 grams vs. 80.0402 g.

If the total mass of reactants vs. products isn't the same (or very, very close), then maybe you have miscalculated the molecular weights, or didn't correctly balance the equation, or didn't correctly multiply the molecular weight by the coefficient, or maybe you have done something simple, like accidentally hitting the wrong key on the calculator. Whatever the mistake, you can check your work by comparing the total mass of reactants to products to see if everything is OK.

Once we know our math is OK, we can write conversion factors using the masses of individual reactants and products. Some examples will help you understand the process. Image I have 5.00 grams of methane: how many grams of oxygen are needed to completely react with the methane?

$$5.00 \text{ g } CH_4 \times \frac{63.9976 \text{ g } O_2}{16.0426 \text{ g } CH_4} = 19.95 \text{ g } O_2$$

How much carbon dioxide is produced?

$$5.00 \text{ g } CH_4 \times \frac{44.0098 \text{ g } CO_2}{16.0426 \text{ g } CH_4} = 13.72 \text{ g } CO_2$$

How much water is produced?

$$5.00 \text{ g } CH_4 \times \frac{36.0304 \text{ g } H_2O}{16.0426 \text{ g } CH_4} = 11.23 \text{ g } H_2O$$

Finally, we can write our results in the form of a chemical reaction using masses:

$$5.00 \text{ g } CH_4 + 19.95 \text{ g } O_2 \rightarrow 13.72 \text{ g } CO_2 + 11.23 \text{ g } H_2O$$

Adding up the mass of reactants and products we get 24.95 g of reactants vs. 24.95 g of products. Everything checks, and we are confident that our work is accurate. (NOTE: the total mass of reactants and products must be equal, but some small differences can occur due to rounding off final calculated values.)

For all stoichiometric calculations, the following steps must be followed:

1. Balance the chemical equation.

2. Calculate the molecular or formula weights of each substance.

3. Using the coefficients of the balanced chemical equation and the molecular or formula weights of substances, re-write the chemical reaction in terms of mass.

4. Use mass based conversion factors, and the given mass of one of the substances, to calculate the masses of all other substances.

5. Check that the total mass of reactants is equal (within round-off error) to the total mass of products.

One more example problem, and then you should be ready for the homework! Consider the following chemical reaction:

$$AgNO_3 + K_2CrO_4 \rightarrow Ag_2CrO_4 + KNO_3$$

Imagine we want to make 5.00 grams of silver chromate (Ag_2CrO_4). How much silver nitrate and potassium chromate will we need? How much potassium nitrate will be formed?

The first step is to balance the chemical equation:

$$2AgNO_3 + K_2CrO_4 \rightarrow Ag_2CrO_4 + 2KNO_3$$

The next step is to calculate the molecular/formula weights of all substances. These are shown below:

$AgNO_3$	169.8731 g/mole
K_2CrO_4	194.1903 g/mole
Ag_2CrO_4	331.7301 g/mole
KNO_3	101.1032 g/mole

The third step is to re-write the chemical reaction in terms of mass:

$$339.7462 \text{ g } AgNO_3 + 194.1903 \text{ g } K_2CrO_4 \rightarrow 331.7301 \text{ g } Ag_2CrO_4 + 202.2064 \text{ g } KNO_3$$

(The total mass of reactants is 533.9365 grams, vs. 533.9365 grams for total products.)

You can now use conversion factors to calculate the masses of all other substances.

How much silver nitrate ($AgNO_3$) do you need to make 5.00 grams of silver chromate (Ag_2CrO_4)?:

$$5.00 \text{ g } Ag_2CrO_4 \times \frac{339.7462 \text{ g } AgNO_3}{331.7301 \text{ g } Ag_2CrO_4} = 5.12 \text{ g } AgNO_3$$

How much potassium chromate (K_2CrO_4) is needed?:

$$5.00 \text{ g } Ag_2CrO_4 \times \frac{194.1903 \text{ g } K_2CrO_4}{331.7301 \text{ g } Ag_2CrO_4} = 2.93 \text{ g } K_2CrO_4$$

How much potassium nitrate (KNO_3) is formed?:

$$5.00 \text{ g } Ag_2CrO_4 \times \frac{202.2064 \text{ g } KNO_3}{331.7301 \text{ g } Ag_2CrO_4} = 3.05 \text{ g } KNO_3$$

Last step: check the total masses of reactants and products. You have 5.12 grams of silver nitrate and 2.93 grams of potassium chromate (8.05 grams total) reacting to produce 5.00 grams of silver chromate and 3.05 grams of potassium nitrate (8.05 grams total). Mass of reactants equals mass of products, so you are confident that you haven't made any mistakes in your calculations.

Many students find stoichiometry problems "hard", because they want a simple, one-step method to find the answer. There isn't a one-step method, so stop wanting one.

Limiting reactant calculations.

Sometimes when we combine reactants, we have too much of one reactant (or not enough of the other). A ***limiting reactant*** is the one reactant in a chemical reaction that is completely used up before any other reactant. The most common use of a limiting reactant is to cause all of the (limiting) reactant to be consumed by a chemical reaction, by supplying an excess of other reactants. When the limiting reactant is completely exhausted, the reaction stops, regardless of how much of the other reactant(s) are present.

Consider the combustion of methane with oxygen, forming carbon dioxide and water. The balanced chemical equation for this reaction is:

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

Suppose we start with 10.00 grams of methane and 55.00 grams of oxygen. Eventually, one of the reactants will run out, and the reaction stops. Which material runs out first (or for that matter, will both run out at the same time)?

The simplest way of answering this question is to treat this problem like any other stoichiometry calculation. First, balance the chemical reaction. Then calculate the molecular or formula weights for all reactants (since you are trying to see which reactant runs out first, don't worry about the products, for now). Next, calculate the mass of each reactant needed, based on the starting amount of one of the reactants. Finally, compare the calculated amounts of reactants with the starting amounts: which one runs out first?

Let's apply this procedure to our problem above. We already have a balanced chemical equation. The molecular weights of the reactants are 16.0426 g/mole for methane (CH_4), and 31.9988 g/mole for oxygen. Now re-write the chemical equation in terms of mass:

$$16.0426 \text{ g } CH_4 + 63.9976 \text{ g } O_2 \rightarrow X \text{ g } CO_2 + 2Y \text{ g } H_2O$$

(Note: I used X and Y for carbon dioxide and water, because for now I don't care about the products. If you prefer, you can calculate the molecular weights of the products and substitute them into the equation. I won't be using these values right now, but will later.)

We have two reactants, and one of them will (probably) run out before the other. Pick one of the reactants, and calculate how much of the other reactant is needed to completely react with the one you picked. In this example, I pick methane: how much oxygen do I need to completely react with 10.00 grams of methane?:

$$10.00 \text{ g } CH_4 \times \frac{63.9976 \text{ g } O_2}{16.0426 \text{ g } CH_4} = 39.89 \text{ g } O_2$$

I need 39.89 grams of oxygen to completely react with 10.00 grams of methane. I started with 55.00 grams of oxygen; clearly I have more than enough oxygen for the reaction. I will have oxygen left over when all of the methane has reacted; therefore methane is the limiting reactant.

What if I picked oxygen instead of methane? Then the question would be "How much methane do I need to completely react with 55.00 grams of oxygen?"

$$55.00 \text{ g } O_2 \times \frac{16.0426 \text{ g } CH_4}{63.9976 \text{ g } O_2} = 13.78 \text{ g } CH_4$$

I need 13.78 grams of methane to completely react with 55.00 grams of oxygen. Since I only have 10.00 grams of methane, clearly the methane runs out first, and I have oxygen left over. Methane is still the limiting reactant.

The amount of carbon dioxide and water that forms is limited by the amount of methane available. When the methane runs out, no more carbon dioxide and water are produced, even though unused oxygen is available. The methane is said to be a ***limiting reactant,*** because it limits "how far" the reaction proceeds.

In order to identify the limiting reactant, it is absolutely vital that you have a balanced chemical equation (Chapter 6), and that you know how to perform stoichiometric calculations. If you are uncertain about this material, go back and master this material **NOW**!

No matter how complex the reaction, you will usually have only 1 limiting reactant.

For example, consider the following rather complicated chemical reaction:

$$NaBrO_3 + 2CrCl_3 + 4H_2O \rightarrow Br^- + Cr_2O_7^{-2} + 8H^+ + Na^+ + 6Cl^-$$

The reaction begins with 16.00 grams of sodium bromate ($NaBrO_3$), 9.00 grams of chromium (III) chloride ($CrCl_3$), and 10.00 grams of water. Which reactant is the limiting reactant?

Calculate the molecular/formula weights of all reactants, and re-write the balanced chemical equation in terms of mass:

$$150.89197 \text{ g } NaBrO_3 + 316.7102 \text{ g } CrCl_3 + 72.0608 \text{ g } H_2O \rightarrow$$

$$V \text{ g } Br^- + W \text{ g } Cr_2O_7^{-2} + 8X \text{ g } H^+ + Y \text{ g } Na^+ + 6Z \text{ g } Cl^-$$

Pick one of the three reactants, and calculate the amounts of the other two reactants needed to react with the first. I pick sodium bromate:

$$16.00 \text{ g } NaBrO_3 \times \frac{316.7102 \text{ g } CrCl_3}{150.89197 \text{ g } NaBrO_3} = 33.58 \text{ g } CrCl_3$$

I need 33.58 grams of $CrCl_3$, but I only have 9.00 grams, so clearly chromium (III) chloride will run out before the sodium bromate, but is the chromium (III) chloride the limiting reactant?

What about the water? Do I have enough water to react with the sodium bromate?:

$$16.00 \text{ g } NaBrO_3 \times \frac{72.0608 \text{ g } H_2O}{150.89197 \text{ g } NaBrO_3} = 7.64 \text{ g } H_2O$$

I started the reaction with 10.00 grams of water, so I have enough water to react with the sodium bromate. I can therefore say that chromium (III) chloride is the limiting reactant.

For all questions involving the identification of the limiting reactant, the following steps must be followed:

1. Examine the chemical equation and balance it if it isn't already balanced.

2. Calculate the molecular/formula weight of the reactants. Re-write the chemical equation in terms of mass.

3. Pick one of the reactants, and calculate the mass of all other reactants necessary to completely react with your chosen substance. Compare the calculated amount of each reactant, with the amount specified in the problem. The substance requiring more mass (based on calculation) than is available (specified in the problem) is the limiting reactant.

Theoretical yield.

So far, we have been ignoring the masses of the products in our limiting reactant calculations. It is critical that you recognize that the maximum mass of products formed depends on the mass of the limiting reactant!! Let's examine this idea by looking at our sodium bromate problem in a little more detail.

We have the following equation written in terms or mass:

150.89197 g $NaBrO_3$ + 316.7102 g $CrCl_3$ + 72.0608 g H_2O →

V g Br^- + W g $Cr_2O_7^{-2}$ + 8X g H^+ + Y g Na^+ + 6Z g Cl^-

We didn't need the masses of the products to determine which reactant was limiting. In order to calculate the ***theoretical yield***, we need these masses. The weight of bromide is 79.904 g, the weight of dichromate is 215.9887 g, the total weight of hydrogen ion is 8.06376 g, the weight of sodium is 22.9898g, and the total weight of chloride is 212.718g. Including these masses into the equation gives us:

150.89197 g $NaBrO_3$ + 316.7102 g $CrCl_3$ + 72.0608 g H_2O →

79.904 g Br^- + 215.9887 g $Cr_2O_7^{-2}$ + 8.06376 g H^+ + 22.9898 g Na^+ + 212.718 g Cl^-

We've already determined that chromium (III) chloride is the limiting reactant, and we have 9.00 grams of it. We can now calculate the masses of the products of this reaction:

$$9.00 \text{ g } CrCl_3 \times \frac{79.904 \text{ g } Br^-}{316.7102 \text{ g } CrCl_3} = 2.27 \text{ g } Br^-$$

$$9.00 \text{ g } CrCl_3 \times \frac{215.9887 \text{ g } Cr_2O_2^{-2}}{316.7102 \text{ g } CrCl_3} = 6.14 \text{ g } Cr_2O_7^{-2}$$

$$9.00 \text{ g } CrCl_3 \times \frac{8.06376 \text{ g } H^+}{316.7102 \text{ g } CrCl_3} = 0.229 \text{ g } H^+$$

$$9.00 \text{ g } CrCl_3 \times \frac{22.9898 \text{ g } Na^+}{316.7102 \text{ g } CrCl_3} = 0.653 \text{ g } Na^+$$

$$9.00 \text{ g CrCl}_3 \times \frac{212.718 \text{ g Cl}^-}{316.7102 \text{ g CrCl}_3} = 6.04 \text{ g Cl}^-$$

Before proceeding, let's check the mass balance. We have 16.00 grams sodium bromate, 9.00 grams chromium (III) chloride, and 10.00 grams water for a total of 35.00 grams of reactants. We produced 2.27 grams bromide, 6.14 grams dichromate, 0.229 grams hydrogen ion, 0.653 grams sodium ion, and 6.04 grams chloride ion, for a total of 15.332 grams of products. The difference between these masses is 19.668 grams, which is much too high to be due to round-off error.

What happened?

Chromium (III) chloride limits how far the reaction proceeds. We start with 16.00 grams of sodium bromate, but not all of the sodium bromate reacts with the chromium (III) chloride. For 9.00 grams of chromium (III) chloride we only need:

$$9.00 \text{ g CrCl}_3 \times \frac{150.89197 \text{ g NaBrO}_3}{316.7102 \text{ g CrCl}_3} = 4.29 \text{ g NaBrO}_3$$

This means we have 11.71 grams of unreacted sodium bromate. Similarly, we will use:

$$9.00 \text{ g CrCl}_3 \times \frac{72.0608 \text{ g H}_2\text{O}}{316.7102 \text{ g CrCl}_3} = 2.05 \text{ g H}_2\text{O}$$

and we will have 7.95 grams of leftover water. The sum of the leftover reactants (7.95 g + 11.71 g = 19.66 g) matches the 19.668 g mass difference, within round-off error.

Theoretical yield is the maximum amount of a given product that can be formed from a given amount of reactants.

Imagine we go into the laboratory, and we carefully weigh out 4.29 g sodium bromate, 9.00 grams of chromium (III) chloride, and 2.05 grams water. We combine these substances and allow them time to completely react. Finally, by some kind of procedure (we don't need to worry about the exact procedure), we measure the actual masses of our products.

In a perfect world, where there are never any unforeseen circumstances, and where everything works exactly the way it is written on paper, we will get 2.27 grams of bromide. However, in the real world, where we deal with real chemical substances, there are all sorts of factors that may affect the total mass of substance we produce. Let's look at some of them.

First, we are assuming that our reactants are 100% pure. In the real world, manufacturers rarely claim that their sodium bromate is 100% pure. Many solids readily absorb water from the atmosphere. Water can be removed (in principle) by drying, but other impurities can't be eliminated this way, and might not be detected.

Second, in order to measure the mass of bromide, we can't weigh just bromide ion. Bromide ion only exists in water solution – to measure its weight we have to make a known compound containing bromide, weight the compound, and calculate bromide by difference. Making the bromide compound introduces more chances for contamination. More measurements – more chances for errors to creep into the final values.

Third, we are assuming that the only products made by this reaction are the products shown, no other substances. While this is a good assumption with our current example, with other reactions it may not be a particularly good assumption at all.

Fourth, we are assuming an almost inhuman level of precision in making all of our measurements and in conducting our experiment. However, as you are learning in your laboratory work, it is extremely rare to be totally precise in the chemistry lab.

For these reasons, and others, it is entirely possible that the mass of our product(s) is different from the calculated mass. We define the ***percent (or percentage) yield*** as the measured mass of product divided by the theoretical yield, and multiplied by 100:

$$\%\ \text{yield} = \frac{\text{measured mass of product, g}}{\text{theoretical yield of product, g}} \times 100$$

Sometimes the percent yield will be less than 100%, sometimes it will be more than 100%. Don't worry about the actual percent yield that you calculate – instead worry about calculating it correctly. In our example, if I find that I actually prepared 2.15 grams of bromide, then the percent yield is:

$$\frac{2.15\ \text{g}}{2.27\ \text{g}} \times 100 = 94.71\%$$

On the other hand, if I weigh my product and get 2.31 grams, the percent yield is:

$$\frac{2.31\text{ g}}{2.27\text{ g}} \times 100 = 101.8\%$$

I know just as well as anyone else that you can't have more than 100% of anything. I also know that reporting something different than what I measured is a lie. I am not a liar, and if asked how I got more than 100% yield, I will be happy to answer, "I don't know". Maybe some water was still in the product. Maybe it is contaminated with one of the other products, or something else unexpected. Whatever happened, I'm not going to make up some percentage value different than what I calculated.

Why should I? What value is there in concealing the truth? Who benefits from that?

Finally, there is not a single value for theoretical yield for our reaction. Each product will have its own theoretical yield, and depending on the product we care about, this reaction can have 5 theoretical yields and 5 percentage yields. The 5 percentage yields could be very similar to each other, or they could be dramatically different.

Vocabulary. The following terms are defined and explained in the text. Make sure that you are familiar with the meanings of the terms as used in chemistry. Understand that you may have been given incomplete or mistaken meanings for these terms in earlier courses. The meanings given in the text are correct and proper.

Mole	**Avogadro's number**	**(gram) formula weight**
(gram) molecular weight	**(gram) atomic weight**	**Stoichiometry**
Limiting reactant	**Theoretical yield**	**Percent(age) yield**
Percent composition by mass		

Homework:

Molecular/formula weight. Calculate the molecular or formula weights of the following substances.

1. CO_2
2. $C_6H_{12}O_6$
3. $La(IO_3)_3$
4. Na_2SO_4
5. H_2O
6. C_6H_5Cl
7. $C_{10}H_{20}N_2S_4Cu$
8. $Ca_3(PO_4)_2$
9. CH_3CO_2H
10. $NaKLiPO_4$

Percent composition. Calculate the percent composition by mass for the following compounds.

1. CO_2
2. $C_6H_{12}O_6$

3. $La(IO_3)_3$

4. Na_2SO_4

5. H_2O

6. C_6H_5Cl

7. $C_{10}H_{20}N_2S_4Cu$

8. $Ca_3(PO_4)_2$

9. CH_3CO_2H

10. $NaKLiPO_4$

Moles to grams, grams to moles. Perform the indicated calculation.

1. How many moles of sodium chloride (NaCl) are in 39.5 grams of sodium chloride?

2. How many moles of water (H_2O) are in 15.00 grams of water?

3. How many moles of nitric acid (HNO_3) are in 0.51 grams of nitric acid?

4. How many moles of sugar ($C_6H_{12}O_6$) are in 100 grams of sugar?

5. How many moles of carbon dioxide (CO_2) are in 14.22 grams of carbon dioxide?

6. How many moles of sodium sulfate (Na_2SO_4) are in 17.18 grams of sodium sulfate?

7. How many moles of nickel (II) nitrate {$Ni(NO_3)_2$} are in 30.15 grams of nickel (II) nitrate?

8. How many moles of iron (III) oxide are in 55.9 grams of Fe_2O_3?

9. How many moles of silver chloride (AgCl) are in 77.93 grams of silver chloride?

10. How many moles of zinc oxide (ZnO) are in 10.00 grams of zinc oxide?

11. How many grams are in 0.117 moles of $NaKLiPO_4$?

12. How many grams are in 1.58 moles of CH_3CO_2H?

13. How many grams are in 0.004558 moles of $Ca_3(PO_4)_2$?

14. How many grams are in 24.66 moles of $C_{10}H_{20}N_2S_4Cu$?

15. How many grams are in 0.055 moles of C_6H_5Cl?

16. How many grams are in 1.19 moles of H_2O?

17. How many grams are in 0.250 moles of Na_2SO_4?

18. How many grams are in 5.00 moles of $La(IO_3)_3$?

19. How many grams are in 0.36 moles of $C_6H_{12}O_6$?

20. How many grams are in 15.00 moles of CO_2?

Stoichiometry. For the reactions shown below, calculate the total masses of all materials participating in the reaction. You may have to balance the chemical reactions. In all cases, assume that the starting mass of the first substance shown in the reaction is 5.00 grams.

1. $H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O$

2. $H_2CO_3 \rightarrow CO_2 + H_2O$

3. $Fe + O_2 \rightarrow Fe_2O_3$

4. $Zn + HCl \rightarrow ZnCl_2 + H_2$

5. $6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 12O_2$

6. $NH_4OH + HNO_3 \rightarrow NH_4NO_3 + H_2O$

7. $C_2H_2 + 2Cl_2 \rightarrow C_2H_2Cl_4$

8. $CaCO_3 \rightarrow CaO + CO_2$

9. $C_4H_{10} + O_2 \rightarrow CO_2 + H_2O$

10. $BaCO_3 + 2HCl \rightarrow BaCl_2 + CO_2 + H_2O$

Limiting reactant. For the following equations, determine which of the reactants is the limiting reactant. You may have to balance the chemical equation before completing the problem.

1. $Cu(NO_3)_2 + Na_2SO_4 \Rightarrow CuSO_4 + 2NaNO_3$

   $Cu(NO_3)_2$ = 5.00 grams
   Na_2SO_4 = 10.00 grams

2. $C_4H_{10} + O_2 \Rightarrow CO_2 + H_2O$

   C_4H_{10} = 2.00 grams
   O_2 = 30.00 grams

3. $AgNO_3 + HCl \Rightarrow AgCl + HNO_3$

   $AgNO_3$ = 5.00 grams
   HCl = 2.00 grams

4. $CH_3CO_2H + Ca(OH)_2 \Rightarrow Ca(CH_3CO_2)_2 + H_2O$

   CH_3CO_2H = 40.00 grams
   $Ca(OH)_2$ = 25.00 grams

5. $4Fe + 3O_2 \Rightarrow 2Fe_2O_3$

   Fe = 5.00 grams
   O_2 = 5.00 grams

Theoretical yield. Homework: For limiting reactant problems 1 - 5, calculate the theoretical yield of all products, based on the given masses of reactants and the limiting reactant.

Answers.

Molecular/formula weight answers:

1. The formula indicates 1 carbon atom and 2 oxygen atoms.

   (1 x 12.011) + (2 x 15.9994) = 44.010 grams/mole

2. The formula indicates 6 carbon atoms, 12 hydrogen atoms and 6 oxygen atoms.

   (6 x 12.011) + (12 x 1.0079) + (6 x 15.9994) = 180.157 grams/mole

3. The formula indicates 1 lanthanum atom, 3 iodine atoms and 9 oxygen atoms. Note: when portions of the formula appear within parenthesis, such as $(IO_3)_3$ multiply the number of atoms shown inside the parenthesis by the subscript number appearing outside of the parenthesis.

   (1 x 138.9055) + (3 x 126.9045) + (9 x 15.9994) = 663.6136 grams/mole

4. The formula indicates 2 sodium atoms, 1 sulfur atom and 4 oxygen atoms.

   (2 x 22.98977) + (1 x 32.06) + (4 x 15.9994) = 142.04 grams/mole

5. The formula indicates 2 hydrogen atoms and 1 oxygen atom.

   (2 x 1.0079) + (1 x 15.9994) = 18.0152 grams/mole

6. The formula indicates 6 carbon atoms, 5 hydrogen atoms and 1 chlorine atom.

   (6 x 12.011) + (5 x 1.0079) + (1 x 35.453) = 112.558 grams/mole

7. The formula indicates 10 carbon atoms, 20 hydrogen atoms, 2 nitrogen atoms, 4 sulfur atoms and 1 copper atom.

   (10 x 12.011) + (20 x 1.0079) + (2 x 14.0067) + (4 x 32.06) + (1 x 63.546) = 360.07 grams/mole

8. The formula indicates 3 calcium atoms, 2 phosphorous atoms and 8 oxygen atoms.

   (3 x 40.08) + (2 x 30.97376) + (8 x 15.9994) = 310.18 grams/mole

9. The formula indicates 2 carbon atoms, 4 hydrogen atoms and 2 oxygen atoms.

   (2 x 12.011) + (4 x 1.0079) + (2 x 15.9994) = 60.052 grams/mole

10. The formula indicates 1 sodium atom, 1 potassium atom, 1 lithium atom, 1 phosphorous atom and 4 oxygen atoms.

    (1 x 22.98977) + (1 x 39.098) + (1 x 6.941) + (1 x 30.97376) + (4 x 15.9994) = 164.000 grams/mole

Percent composition answers:

1. The formula indicates 1 carbon atom and 2 oxygen atoms.

   (1 x 12.011) + (2 x 15.9994) = 44.010

   % carbon = (12.011 ÷ 44.010) x 100 = 27.292%

   % oxygen = (31.9988 ÷ 44.010) x 100 = 72.708%

   Total of % = 100.000%

2. The formula indicates 6 carbon atoms, 12 hydrogen atoms and 6 oxygen atoms.

   (6 x 12.011) + (12 x 1.0079) + (6 x 15.9994) = 180.157

   % carbon = (72.066 ÷ 180.157) x 100 = 40.002%

   % hydrogen = (12.0948 ÷ 180.157) x 100 = 6.71348%

   % oxygen = (95.9964 ÷ 180.157) x 100 = 53.2849%

   Total of % = 100.000%

3. The formula indicates 1 lanthanum atom, 3 iodine atoms and 9 oxygen atoms. Note: when portions of the formula appear within parenthesis, such as $(IO_3)_3$ multiply the number of atoms shown inside the parenthesis by the subscript number appearing outside of the parenthesis.

   (1 x 138.9055) + (3 x 126.9045) + (9 x 15.9994) = 663.6136

   % lanthanum = (138.9055 ÷ 663.6236) x 100 = 20.93137%

% iodine = (380.7135 ÷ 663.6236) x 100 = 57.36889%

% oxygen = (143.9946 ÷ 663.6236) x 100 = 21.69823%

Total of % = 99.99849%

4. The formula indicates 2 sodium atoms, 1 sulfur atom and 4 oxygen atoms.

   (2 x 22.98977) + (1 x 32.06) + (4 x 15.9994) = 142.04

   % sodium = (45.97954 ÷ 142.04) x 100 = 32.371%

   % sulfur = (32.06 ÷ 142.04) x 100 = 22.57%

   % oxygen = (63.9976 ÷ 142.04) x 100 = 45.056%

   Total of % = 100.00%

5. The formula indicates 2 hydrogen atoms and 1 oxygen atom.

   (2 x 1.0079) + (1 x 15.9994) = 18.0152

   % hydrogen = (2.0158 ÷ 18.0152) x 100 = 11.189%

   % oxygen = (15.9994 ÷ 18.0152) x 100 = 88.8106%

   Total of % = 100.000%

6. The formula indicates 6 carbon atoms, 5 hydrogen atoms and 1 chlorine atom.

   (6 x 12.011) + (5 x 1.0079) + (1 x 35.453) = 112.558

   % carbon = (72.066 ÷ 112.558) x 100 = 64.026%

   % hydrogen = (5.0395 ÷ 112.558) x 100 = 4.4772%

   % chlorine = (35.453 ÷ 112.558) x 100 = 31.498%

   Total of % = 100.001%

7. The formula indicates 10 carbon atoms, 20 hydrogen atoms, 2 nitrogen atoms, 4 sulfur atoms and 1 copper atom.

(10 x 12.011) + (20 x 1.0079) + (2 x 14.0067) + (4 x 32.06) + (1 x 63.546) = 360.07

% carbon = (120.11 ÷ 360.07) x 100 = 33.357%

% hydrogen = (20.1580 ÷ 360.07) x 100 = 5.5984%

% nitrogen = (28.0134 ÷ 360.07) x 100 = 7.7800%

% sulfur = (128.24 ÷ 360.07) x 100 = 35.615%

% copper = (63.546 ÷ 360.07) x 100 = 17.648%

Total of % = 99.998%

8. The formula indicates 3 calcium atoms, 2 phosphorous atoms and 8 oxygen atoms.

   (3 x 40.08) + (2 x 30.97376) + (8 x 15.9994) = 310.18

   % calcium = (120.24 ÷ 310.18) x 100 = 38.765 %

   % phosphorous = (61.94752 ÷ 310.18) x 100 = 19.972%

   % oxygen = (127.9952 ÷ 310.18) x 100 = 41.265%

   Total of % = 100.002%

9. The formula indicates 2 carbon atoms, 4 hydrogen atoms and 2 oxygen atoms.

   (2 x 12.011) + (4 x 1.0079) + (2 x 15.9994) = 60.052

   % carbon = (24.022 ÷ 60.052) x 100 = 40.002%

   % hydrogen = (4.0316 ÷ 60.052) x 100 = 6.7135%

   % oxygen = (31.9988 ÷ 60.052) x 100 = 53.285%

   Total of % = 100.001%

10. The formula indicates 1 sodium atom, 1 potassium atom, 1 lithium atom, 1 phosphorous atom and 4 oxygen atoms.

    (1 x 22.98977) + (1 x 39.098) + (1 x 6.941) + (1 x 30.97376) + (4 x 15.9994) = 164.000

% sodium = (22.98977 ÷ 164.000) x 100 = 14.0182%

% potassium = (39.098 ÷ 164.000) x 100 = 23.840%

% lithium = (6.941 ÷ 164.000) x 100 = 4.232%

% phosphorous = (30.97376 ÷ 164.000) x 100 = 18.8864%

% oxygen = (63.9976 ÷ 164.000) x 100 = 39.0229%

Total of % = 100.000%

Moles to grams, grams to moles answers: Note – if you have trouble calculating the molecular or formula weights, go back to the previous homework sets and master this skill.

1. $\frac{39.5 \text{ g sodium chloride}}{58.443 \text{ g/mole}} = 0.676 \text{ moles sodium chloride}$

2. $\frac{15.00 \text{ g water}}{18.0152 \text{ g/mole}} = 0.8326 \text{ moles water}$

3. $\frac{0.51 \text{ g nitric acid}}{63.0128 \text{ g/mole}} = 0.0081 \text{ moles nitric acid}$

4. $\frac{100 \text{ g sugar}}{180.157 \text{ g/mole}} = 0.555 \text{ moles sugar}$

5. $\frac{14.22 \text{ g carbon dioxide}}{44.010 \text{ g/mole}} = 0.3231 \text{ moles carbon dioxide}$

6. $\frac{17.18 \text{ g sodium sulfate}}{142.04 \text{ g/mole}} = 0.1210 \text{ moles sodium sulfate}$

7. $\frac{30.15 \text{ g nickel (II) nitrate}}{182.70 \text{ g/mole}} = 0.1650 \text{ moles nickel (II) nitrate}$

8. $\frac{55.9 \text{ g iron (III) oxide}}{159.662 \text{ g/mole}} = 0.350 \text{ moles iron (III) oxide}$

9. $\frac{77.93 \text{ g silver chloride}}{143.321 \text{ g/mole}} = 0.5437 \text{ moles silver chloride}$

10. $\frac{10.00 \text{ g zinc oxide}}{79.59 \text{ g/mole}} = 0.1256 \text{ moles zinc oxide}$

11. 0.117 moles $NaKLiPO_4$ ×164.000 g/mole = 19.2 g $NaKLiPO_4$

12. 1.58 moles CH_3CO_2H × 60.052 g/mole = 94.9 g CH_3CO_2H

13. 0.004 558 moles $Ca_3(PO_4)_2$ × 310.18 g/mole = 1.414 g $Ca_3(PO_4)_2$

14. 24.66 moles $C_{10}H_{20}N_2S_4Cu$ × 360.07 g/mole = 8879 g $C_{10}H_{20}N_2S_4Cu$

15. 0.055 moles C_6H_5Cl × 112.558 g/mole = 6.2 g C_6H_5Cl

16. 1.19 moles H_2O × 18.0152 g/mole = 21.4 g H_2O

17. 0.0250 moles Na_2SO_4 × 142.04 g/mole = 35.5 g Na_2SO_4

18. 5.00 moles $La(IO_3)_3$ × 663.6136 g/mole = 3.32 × 10^3 g $La(IO_3)_3$

19. 0.36 moles $C_6H_{12}O_6$ × 180.157 g/mole = 65 g $C_6H_{12}O_6$

20. 15.00 moles CO_2 × 44.010 g/mole = 660.2 g CO_2

Stoichiometry answers:

1. $H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O$

   The equation is already balanced.

   The molecular weight of sulfuric acid (H_2SO_4) is 98.0794 g/mole, the formula weight of sodium hydroxide is 39.99707 g/mole, the formula weight of sodium sulfate is 142.04314 g/mole, and the molecular weight of water is 18.0152 g/mole.

Balancing the reaction by mass gives us:

98.0794 g H_2SO_4 + 79.99414 g NaOH → 142.04314 g Na_2SO_4 + 36.0304 g H_2O

Calculate the masses of all other materials:

$$5.00\text{ g }H_2SO_4 \times \frac{79.99414\text{ g NaOH}}{98.0794\text{ g }H_2SO_4} = 4.08\text{ g NaOH}$$

$$5.00\text{ g }H_2SO_4 \times \frac{142.04314\text{ g }Na_2SO_4}{98.0794\text{ g }H_2SO_4} = 7.24\text{ g }Na_2SO_4$$

$$5.00\text{ g }H_2SO_4 \times \frac{36.0304\text{ g }H_2O}{98.0794\text{ g }H_2SO_4} = 1.84\text{ g }H_2O$$

Finally, compare the mass of all reactants to all products: 9.08 grams of reactants vs. 9.08 grams of products.

2. H_2CO_3 → CO_2 + H_2O

The equation is balanced.

The molecular weight of carbonic acid is 62.025 g/mole, the molecular weight of carbon dioxide is 44.010 g/mole, and the molecular weight of water is 18.0152 g/mole.

Balancing the reaction by mass gives us:

62.025 g H_2CO_3 → 44.010 g CO_2 + 18.0152 g H_2O

Calculate the mass of all other materials:

$$5.00\text{ g }H_2CO_3 \times \frac{44.010\text{ g }CO_2}{62.025\text{ g }H_2CO_3} = 3.55\text{ g }CO_2$$

$$5.00\text{ g }H_2CO_3 \times \frac{18.0152\text{ g }H_2O}{62.025\text{ g }H_2CO_3} = 1.45\text{ g }H_2O$$

Finally, compare the mass of all reactants to all products: 5.00 grams of reactants vs. 5.00 grams of products.

3. $Fe + O_2 \rightarrow Fe_2O_3$

From inspection, we see that this equation is not balanced. However, we can readily balance this equation to produce:

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3$$

The atomic weight of iron is 55.847 g/mole, the molecular weight of oxygen is 31.9988 g/mole, and the formula weight of iron (III) oxide is 159.6922 g/mole.

Write the balanced equation in terms of mass:

223.388 g Fe + 95.9964 g $O_2 \rightarrow$ 319.3844 g Fe_2O_3

Calculate the mass of all other substances:

$$5.00 \text{ g Fe} \times \frac{95.9964 \text{ g O}_2}{223.388 \text{ g Fe}} = 2.15 \text{ g O}_2$$

$$5.00 \text{ g Fe} \times \frac{319.3884 \text{ g Fe}_2\text{O}_3}{223.388 \text{ g Fe}} = 7.15 \text{ g Fe}_2\text{O}_3$$

Finally, compare the total mass of reactants to the total mass of products: 7.15 grams of reactants vs. 7.15 grams of products.

4. $Zn + 2HCl \rightarrow ZnCl_2 + H_2$

From inspection we see that the equation is balanced as written.

The atomic weight of zinc is 65.39 g/mole, the molecular weight of hydrochloric acid is 36.4609 g/mole, the formula weight of zinc chloride is 136.296 g/mole, and the molecular weight of hydrogen is 2.0158 g/mole.

We can re-write the equation in terms of mass as:

65.39 g Zn + 72.9218 g HCl $\rightarrow$ 136.296 g $ZnCl_2$ + 2.0158 g H_2

We calculate the masses of the other substances:

$$5.00 \text{ g Zn} \times \frac{72.9218 \text{ g HCl}}{65.39 \text{ g Zn}} = 5.58 \text{ g HCl}$$

$$5.00 \text{ g Zn} \times \frac{136.296 \text{ g ZnCl}_2}{65.39 \text{ g Zn}} = 10.42 \text{ g ZnCl}_2$$

$$5.00 \text{ g Zn} \times \frac{2.0158 \text{ g } H_2}{65.39 \text{ g Zn}} = 0.15 \text{ g } H_2$$

Finally, compare the masses of reactants to products: 10.58 g of reactants vs. 10.57 g of products (off slightly due to rounding).

5. $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

   From inspection we see that this equation is balanced.

   The molecular weight of carbon dioxide is 44.010 g/mole, the molecular weight of water is 18.0152 g/mole, the molecular weight of sugar is 180.1572 g/mole, and the molecular weight of oxygen is 31.9988 g/mole.

   Re-writing the chemical equation in terms of mass gives us:

   264.060 g CO_2 + 108.0912 g H_2O $\rightarrow$ 180.1572 g $C_6H_{12}O_6$ + 191.9928 g O_2

   Now we calculate:

$$5.00 \text{ g } CO_2 \times \frac{108.0912 \text{ g } H_2O}{264.060 \text{ g } CO_2} = 2.05 \text{ g } H_2O$$

$$5.00 \text{ g } CO_2 \times \frac{180.1572 \text{ g } C_6H_{12}O_6}{264.060 \text{ g } CO_2} = 3.41 \text{ g } C_6H_{12}O_6$$

$$5.00 \text{ g } CO_2 \times \frac{191.9928 \text{ g } O_2}{264.060 \text{ g } CO_2} = 3.64 \text{ g } O_2$$

   Finally we compare the total mass of reactants to products: 7.05 g of reactants vs. 7.05 g products.

6. $NH_4OH + HNO_3 \rightarrow NH_4NO_3 + H_2O$

   The reaction is balanced as written.

   Ammonium hydroxide has a molecular weight of 35.0456 g/mole, the molecular weight of nitric acid is 63.0128 g/mole, the molecular weight of ammonium nitrate is 80.0432 g/mole, and the molecular weight of water is 18.0152 g/mole.

   We re-write the chemical equation as:

35.0456 g NH_4OH + 63.0128 g HNO_3 → 80.0432g NH_4NO_3 + 18.0152 g H_2O

We calculate the mass of all other substances:

$$5.00 \text{ g } NH_4OH \times \frac{63.0128 \text{ g } HNO_3}{35.0456 \text{ g } NH_4OH} = 8.99 \text{ g } HNO_3$$

$$5.00 \text{ g } NH_4OH \times \frac{80.0432 \text{ g } NH_4NO_3}{35.0456 \text{ g } NH_4OH} = 11.42 \text{ g } NH_4NO_3$$

$$5.00 \text{ g } NH_4OH \times \frac{18.0152 \text{ g } H_2O}{35.0456 \text{ g } NH_4OH} = 2.57 \text{ g } H_2O$$

Total reactants = 13.99 grams. Total products = 13.99 grams.

7. $C_2H_2 + 2Cl_2 \rightarrow C_2H_2Cl_4$

The reaction is balanced as written.

Ethyne (C_2H_2) has a molecular weight of 26.0378 g/mole, the molecular weight of chlorine is 70.906 g/mole, and the molecular weight of tetrachloroethane is 167.8498 g/mole.

The chemical reaction is re-written as:

26.0378 g C_2H_2 + 141.812 g Cl_2 → 167.8498 g $C_2H_2Cl_4$

$$5.00 \text{ g } C_2H_2 \times \frac{141.82 \text{ g } Cl_2}{26.0378 \text{ g } C_2H_2} = 27.33 \text{ g } Cl_2$$

$$5.00 \text{ g } C_2H_2 \times \frac{167.8498 \text{ g } C_2H_2Cl_2}{26.0378 \text{ g } C_2H_2} = 32.23 \text{ g } C_2H_2Cl_2$$

Total reactants = 32.23 grams; total products = 32.23 grams.

8. $CaCO_3 \rightarrow CaO + CO_2$

The equation is written as balanced.

The formula weight of calcium carbonate ($CaCO_3$) is 100.0872 g/mole, the formula weight of calcium oxide is 56.0774 g/mole, and the molecular weight of carbon dioxide is 44.010 g/mole.

The re-written equation is:

$100.0872 \text{ g } CaCO_3 \rightarrow 56.0774 \text{ g } CaO + 44.010 \text{ g } CO_2$

$$5.00 \text{ g } CaCO_3 \times \frac{56.0774 \text{ g } CaO}{100.0872 \text{ g } CaCO_3} = 2.80 \text{ g } CaO$$

$$5.00 \text{ g } CaCO_3 \times \frac{44.010 \text{ g } CO_2}{100.0872 \text{ g } CaCO_3} = 2.20 \text{ g } CO_2$$

The total mass of products is equal to the total mass of reactants.

9. $C_4H_{10} + O_2 \rightarrow CO_2 + H_2O$

This equation is not balanced; it must be balanced before any calculations are performed.

The balanced chemical equation is:

$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$

The molecular weight of butane (C_4H_{10}) is 58.123 g/mole, the molecular weight of oxygen is 31.9988 g/mole, the molecular weight of carbon dioxide is 44.010 g/mole, and the molecular weight of water is 18.0152 g/mole.

Re-writing the equation gives:

$116.246 \text{ g } C_4H_{10} + 415.9844 \text{ g } O_2 \rightarrow 352.080 \text{ g } CO_2 + 180.152\text{g } H_2O$

$$5.00 \text{ g } C_4H_{10} \times \frac{415.9844 \text{ g } O_2}{116.246 \text{ g } C_4H_{10}} = 17.89 \text{ g } O_2$$

$$5.00 \text{ g } C_4H_{10} \times \frac{352.080 \text{ g } CO_2}{116.246 \text{ g } C_4H_{10}} = 15.14 \text{ g } CO_2$$

$$5.00 \text{ g } C_4H_{10} \times \frac{180.152 \text{ g } H_2O}{116.246 \text{ g } C_4H_{10}} = 7.57 \text{ g } H_2O$$

The total mass of products (22.89 g) equals the total mass of reactants, 22.89g.

10. $BaCO_3 + 2HCl \rightarrow BaCl_2 + CO_2 + H_2O$

The equation is balanced as written.

The formula weight of barium carbonate ($BaCO_3$) is 197.3392 g/mole, the molecular weight of hydrochloric acid is 36.4609 g/mole, the formula weight of barium chloride is 208.236 g/mole, the molecular weight of carbon dioxide is 44.010 g/mole, and the molecular weight of water is 18.0152 g/mole.

Re-writing the equation in terms of mass gives us:

197.3392 g $BaCO_3$ + 72.9218 g HCl → 208.236 g $BaCl_2$ + 44.010 g CO_2 + 18.0152 g H_2O

Now we calculate the masses for the other substances:

$$5.00 \text{ g BaCO}_3 \times \frac{72.9218 \text{ g HCl}}{197.3392 \text{ g BaCO}_3} = 1.85 \text{ g HCl}$$

$$5.00 \text{ g BaCO}_3 \times \frac{208.236 \text{ g BaCl}_2}{197.3392 \text{ g BaCO}_3} = 5.28 \text{ g BaCl}_2$$

$$5.00 \text{ g BaCO}_3 \times \frac{44.010 \text{ g CO}_2}{197.3392 \text{ g BaCO}_3} = 1.12 \text{ g CO}_2$$

$$5.00 \text{ g BaCO}_3 \times \frac{18.0152 \text{ g H}_2\text{O}}{197.3392 \text{ g BaCO}_3} = 0.46 \text{ g H}_2\text{O}$$

The total reactant mass is 5.00 grams of barium carbonate and 1.85 grams of hydrochloride acid for a total of 6.85 grams.

The total product mass is 5.28 grams of barium chloride plus 1.12 grams of carbon dioxide plus 0.46 grams of water for a total of 6.86 grams. The difference of 0.01 grams is due to round-off error.

Limiting reactant answers:

1. $Cu(NO_3)_2 + Na_2SO_4 \rightarrow CuSO_4 + 2NaNO_3$

   $Cu(NO_3)_2$ = 5.00 grams
   Na_2SO_4 = 10.00 grams

   The equation is balanced as written.

   The formula weight of copper nitrate ($Cu(NO_3)_2$) is 187.5558 g/mole, the formula weight of sodium sulfate (Na_2SO_4) is 142.04314 g/mole.

Re-writing the equation by mass:

187.5558 g $Cu(NO_3)_2$ + 142.04314 g Na_2SO_4 → X g $CuSO_4$ + 2Y g $NaNO_3$

For 5.00 grams of copper (II) nitrate we need:

$$5.00 \text{ g } Cu(NO_3)_2 \times \frac{142.04314 \text{ g } Na_2SO_4}{187.5558 \text{ g } Cu(NO_3)_2} = 3.79 \text{ g } Na_2SO_4$$

We have 10.00 grams of sodium sulfate; therefore copper (II) nitrate will run out before the sodium sulfate. Copper (II) nitrate is the limiting reactant.

2. $C_4H_{10} + O_2 \rightarrow CO_2 + H_2O$

   C_4H_{10} = 2.00 grams
   O_2 = 30.00 grams

   The equation is not balanced as written. The balanced equation is:

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$$

   The molecular weight of butane (C_4H_{10}) is 58.123 g/mole, and the molecular weight of oxygen is 31.9988 g/mole.

   Re-writing the equation in mass gives us:

   116.246 g C_4H_{10} + 415.9844 g O_2 → 8X g CO_2 + 10Y g H_2O

   For 2.00 grams of butane, we need:

$$2.00 \text{ g } C_4H_{10} \times \frac{415.9844 \text{ g } O_2}{116.246 \text{ g } C_4H_{10}} = 7.16 \text{ g } O_2$$

   We have 30.00 grams of oxygen, which is much more than the 7.16 grams required to react with 2.00 grams of butane. Therefore, butane is the limiting reactant.

3. $AgNO_3 + HCl \rightarrow AgCl + HNO_3$

   $AgNO_3$ = 10.00 grams
   HCl = 2.00 grams

The equation is balanced as written.

The formula weight of silver nitrate ($AgNO_3$) is 169.8731 g/mole. The molecular weight of hydrogen chloride (HCl) is 36.4609 g/mole.

Re-writing the equation gives us:

169.8731 g $AgNO_3$ + 36.4609 g HCl → X g AgCl + Y g HNO_3

For 10.00 grams of silver nitrate we need:

$$10.00 \text{ g } AgNO_3 \times \frac{36.4609 \text{ g HCl}}{169.8731 \text{ g } AgNO_3} = 2.15 \text{ g HCl}$$

We need 2.15 grams of HCl, but only have 2.00 grams. HCl is the limiting reactant.

4. $CH_3CO_2H + Ca(OH)_2 \rightarrow Ca(CH_3CO_2)_2 + H_2O$

CH_3CO_2H = 40.00 grams
$Ca(OH)_2$ = 25.00 grams

The chemical equation given is not balanced. Balancing the equation is our first task.

$$2CH_3CO_2H + Ca(OH)_2 \rightarrow Ca(CH_3CO_2)_2 + 2H_2O$$

The molecular weight of acetic acid (CH_3CO_2H) is 60.0524 g/mole.
The formula weight of calcium hydroxide ($Ca(OH)_2$) is 74.0926 g/mole.

Re-write the equation:

120.1048 g CH_3CO_2H + 74.0926 g $Ca(OH)_2$ → X g $Ca(CH_3CO_2)_2$ + 2Y g H_2O

How much calcium hydroxide is needed, to react with 40.00 grams of acetic acid?

$$40.00 \text{ g } CH_3CO_2H \times \frac{74.0926 \text{ g } Ca(OH)_2}{120.1048 \text{ g } CH_3CO_2H} = 24.68 \text{ g } Ca(OH)_2$$

We have 25.00 grams of calcium hydroxide, so acetic acid is the limiting reactant.

5. $4Fe + 3O_2 \rightarrow 2Fe_2O_3$

   Fe = 5.00 grams
   O_2 = 5.00 grams

   The equation is balanced as written.

   The atomic weight of iron is 55.847 g/mole, and the molecular weight of oxygen (O_2) is 31.9988 g/mole.

   Re-writing the equation gives:

   223.388 g Fe + 95.9964 g $O_2 \rightarrow$ 2X g Fe_2O_3

   What mass of oxygen is required to react with 5.00 grams of iron?

$$5.00\,\text{g Fe} \times \frac{95.9964\ \text{g O}_2}{223.388\ \text{g Fe}} = 2.15\ \text{g O}_2$$

   We have 5.00 grams of oxygen, so the iron is the limiting reactant.

<u>Theoretical yield answers:</u>

1. The formula weight of copper sulfate is 159.6096 g/mole, and the formula weight of sodium nitrate is 84.99437 g/mole. Including these values in our mass equation gives us:

   187.5558 g $Cu(NO_3)_2$ + 142.04314 g $Na_2SO_4 \rightarrow$

   159.6096 g $CuSO_4$ + 169.98934 g $NaNO_3$

   For 5.00 grams of copper (II) nitrate we produce:

$$5.00\ \text{g Cu(NO}_3)_2 \times \frac{159.6096\ \text{g CuSO}_4}{187.5558\ \text{g Cu(NO}_3)_2} = 4.25\ \text{g CuSO}_4$$

$$5.00\ \text{g Cu(NO}_3)_2 \times \frac{169.98934\ \text{g NaNO}_3}{187.5558\ \text{g Cu(NO}_3)_2} = 4.53\ \text{g NaNO}_3$$

2. The molecular weight of carbon dioxide is 44.010 g/mole, and the molecular weight of water is 18.0152 g/mole. Including these values in our mass equation gives us:

   116.246 g C_4H_{10} + 415.9844 g $O_2 \rightarrow$ 352.080 g CO_2 + 180.152 g H_2O

For 2.00 grams of butane, we produce:

$$2.00 \text{ g } C_4H_{10} \times \frac{352.080 \text{ g } CO_2}{116.246 \text{ g } C_4H_{10}} = 6.06 \text{ g } CO_2$$

$$2.00 \text{ g } C_4H_{10} \times \frac{180.152 \text{ g } H_2O}{116.246 \text{ g } C_4H_{10}} = 3.10 \text{ g } H_2O$$

3. The formula weight of silver chloride is 143.3212 g/mole, and the formula weight of nitric acid is 63.0128 g/mole. Including these values in our mass equation gives us:

   169.8731 g $AgNO_3$ + 36.4609 g HCl → 143.3212 g AgCl + 63.0128 g HNO_3

   Hydrochloric acid is the limiting reactant, so we need to make all of our calculations based on the mass of hydrochloric acid (2.00 grams).

$$2.00 \text{ g HCl} \times \frac{143.3212 \text{ g AgCl}}{36.4609 \text{ g HCl}} = 7.86 \text{ g AgCl}$$

$$2.00 \text{ g HCl} \times \frac{63.0128 \text{ g } HNO_3}{36.4609 \text{ g HCl}} = 3.46 \text{ g } HNO_3$$

4. The formula weight for calcium acetate is 158.16982 g/mole, and the formula weight for water is 18.0152 g/mole. Including these values in our mass equation gives:

   120.1048 g CH_3CO_2H + 74.0926 g $Ca(OH)_2$ →
   158.16982 g $Ca(CH_3CO_2)_2$ + 36.0304 g H_2O

   Acetic acid was the limiting reactant (40.00 grams) so we can produce:

$$40.00 \text{ g } CH_3CO_2H \times \frac{158.16982 \text{ g } Ca(CH_3CO_2)_2}{120.1048 \text{ g } CH_3CO_2H} = 52.68 \text{ g } Ca(CH_3CO_2)_2$$

$$40.00 \text{ g } CH_3CO_2H \times \frac{36.0304 \text{ g } H_2O}{120.1048 \text{ g } CH_3CO_2H} = 12.00 \text{ g } H_2O$$

5. The formula weight of iron (III) oxide is 159.6922 g/mole. Inserting this value into the mass equation gives us:

   223.388 g Fe + 95.9964 g O_2 → 319.3844 g Fe_2O_3

   Iron was the limiting reagent, so 5.00 grams of iron produces:

$$5.00 \text{ g Fe} \times \frac{319.3844 \text{ g } Fe_2O_3}{223.388 \text{ g Fe}} = 7.15 \text{ g } Fe_2O_3$$