Chapter 6: Writing and Balancing Chemical Equations.

It is convenient to classify chemical reactions into one of several general types. Some of the more common, important, reactions are shown below.

<u>Decomposition reactions</u>.

These reactions follow the pattern:

$$AB \rightarrow A + B$$

"A" and "B" are typically molecules, although sometimes they are individual atoms. One common decomposition reaction is that of calcium carbonate:

$$CaCO_3 \rightarrow CaO + CO_2$$

Generally, decomposition reactions are readily identified, because they tend to have a single reactant, and two or more products.

<u>Combination reactions</u>.

Combination reactions are essentially the reverse of decomposition reactions: two materials unite to form a single molecule. Combination reactions follow the pattern:

$$A + B \rightarrow C$$

There are many examples of these reactions; one is the combination of ammonia with sulfuric acid to form ammonium sulfate:

$$2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$$

Generally, combination reactions have fewer products than reactants.

<u>Single replacement reactions.</u>

In these reactions, one atom or complex ion is replaced with a second atom or complex ion. Single replacement reactions follow the pattern:

$$AB + C \rightarrow AC + B$$
$$(\text{or } AB + C \rightarrow CB + A)$$

For example, iron replaces copper in copper sulfate, as shown in the reaction:

$$3CuSO_4 + 2Fe \rightarrow Fe_2(SO_4)_3 + 3Cu$$

Double replacement (metathesis) reactions.

Double replacement or ***metathesis*** reactions follow the pattern:

$$AB + CD \rightarrow AD + CB$$

There are many examples of double replacement reactions, such as the reaction between lithium nitride and ammonium nitrate:

$$Li_3N + 3NH_4NO_3 \rightarrow 3LiNO_3 + (NH_4)_3N$$

Precipitation reactions.

If one or more of the products are insoluble, then we have a precipitation reaction. Most precipitation reactions are also single or double replacement reactions. One classic example is the reaction between sodium chloride and silver nitrate:

$$NaCl(aq) + AgNO_3(aq) \rightarrow AgCl(s) + NaNO_3(aq)$$

In this reaction, (aq) means that the substance is dissolved in water: the sodium chloride, silver nitrate, and sodium nitrate are in solution as anions and cations. The (s) means that the material is a solid: silver chloride is not in solution as silver cations and chloride anions. The material produced by the reaction and designated as (s) is a ***precipitate***.

In the laboratory, precipitation reactions can be quite impressive. Two solutions, each colorless and for all practical purposes identical to plain water, are poured together, and instantaneously, the solution becomes cloudy. Eventually, the cloudy material settles to the bottom of the container (Figure 6.1). Many precipitates are white, but some are highly colored. The liquid above the precipitate may be clear and colorless, like water, or it might be colored. This liquid is called the ***supernatant liquid*** – the liquid left after a precipitate has settled.

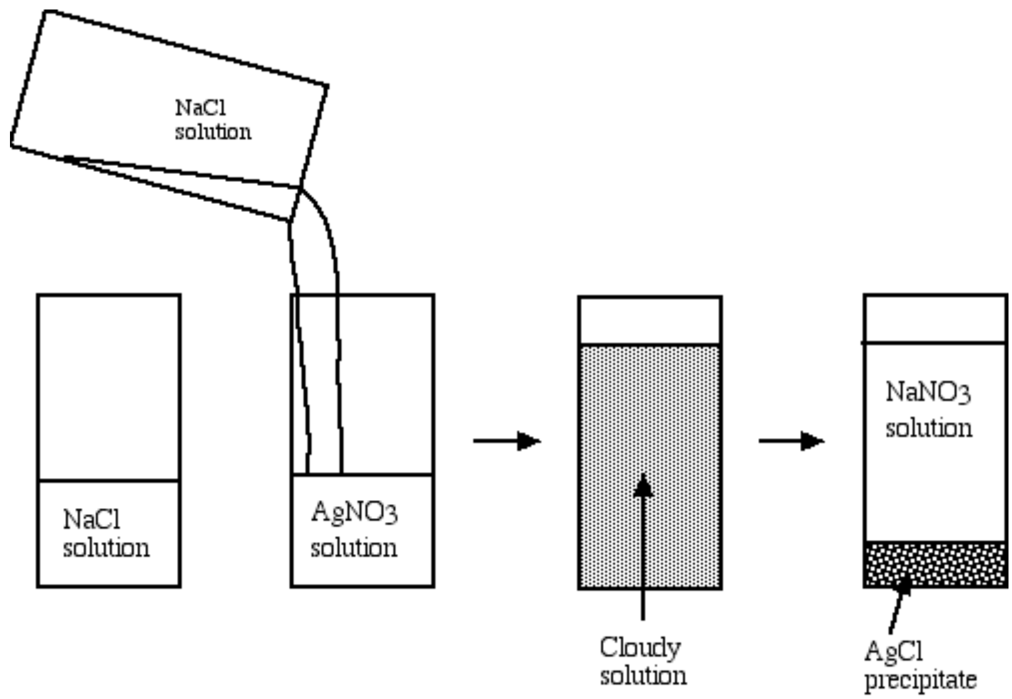

Figure 6.1. Mixing sodium chloride and silver nitrate solutions produces a cloudy solution of silver chloride. The silver chloride eventually settles out of solution, leaving a clear, colorless liquid on top and a white solid on the bottom.

Combustion reactions.

Combustion reactions describe the combination of oxygen with a second reactant, typically producing carbon dioxide and water, and releasing large amounts of energy as heat and light. Any substance that burns is undergoing a combustion reaction:

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O$$

While the products of combustion reactions are often carbon dioxide and water, the products depend on the specific substance combining with oxygen. Sulfur burns in oxygen to produce sulfur dioxide:

$$S + O_2 \rightarrow SO_2$$

Combustion reactions are one example of a more general type of reaction called oxidation-reduction (redox) reactions. All combustions reactions are redox reactions (but not all redox reactions are combustion reactions).

Balanced chemical equations.

A ***balanced chemical equation*** is a representation of a chemical reaction using the chemical formulas of the ***reactants*** and ***products***, and indicating the number of molecules or atoms of each substance.

By convention, reactants are shown first, an arrow is drawn from left to right, and products are shown last. The pattern is illustrated below.

$$\text{Reactants} \rightarrow \text{Products}$$

The identities of the individual reactants and products are given by the specific chemical formulas of these substances.

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

The specific compound methane (CH_4) reacts with the specific element oxygen (O_2) to produce the specific compounds, carbon dioxide (CO_2) and water (H_2O). Since each substance has one chemical formula ***any change in the chemical formula changes the specific compound(s) involved in the reaction!***

NEVER!

NEVER!!

NEVER CHANGE THE CHEMICAL FORMULAS OF THE COMPOUNDS!!!!

To balance a chemical equation, two absolute requirements must be met. The first requirement is "The same kinds of elements must be present in the reactants and the products." In our reaction, we have the elements carbon (C), hydrogen (H), and oxygen (O) in the reactants and these same elements appear in the products. We have no other elements appearing on either side of the equation.

But what if we did? What if we had this situation?

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

This indicates that someone has made some sort of mistake. The mistake is probably something simple, either accidentally including sodium as a product, or omitting sodium as a reactant. But regardless of the cause of the mistake, it is definite that a mistake was made in writing the equation. As a consequence of this mistake, this chemical equation can never be balanced as it is written.

Returning to our earlier, mistake free equation:

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

We are ready for the second absolute requirement: "The number of atoms of each element must be the same on both sides of the equation." In our equation, we have one atom of carbon on both sides – that is good. We have four atoms of hydrogen as reactants, and only two atoms of hydrogen as products – that is not good. We have two atoms of oxygen as reactants and three atoms of oxygen as products – that is also not good.

Element	Reactant	Product
C	1	1
H	4	2
O	2	3

So, what we must now do is clear: we must equalize the number of hydrogen and oxygen atoms. How to do this? Well, there are two ways.

The wrong way is to change the compounds. We could erase the 4 beside the hydrogen in methane and write in a 2. Then we could erase the 2 beside the oxygen in carbon dioxide and we would have the following (changes in red):

$$CH_2 + O_2 \rightarrow CO + H_2O$$

There are only two things wrong with this. Methane is **NOT** CH_2: it is CH_4. Carbon dioxide is **NOT** CO: it is CO_2. **Any change in the chemical formula changes the specific compound(s) involved in the reaction!**

NEVER!

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So, if we can't change the subscript numbers to balance the reaction, what can we do?

The right way is to put numbers in front of the chemical formulas. If we write "$2O_2$", we haven't changed the identity of the compound; instead we are saying there are 2 molecules of O_2. This is our method for balancing a chemical equation – we manipulate the ***coefficients*** (the numbers in front of the formulas) changing the number of molecules or atoms that react or are produced.

There is no single, definitive order in which to change these coefficients to get the final balanced equation. It is a trial and error procedure. It does not matter which material you choose to balance first. Generally, the easiest way is to balance those elements that are in only one reactant and one product first.

Here is our equation:

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

We have one carbon atom in methane and one carbon atom in carbon dioxide, so there is nothing for us to do with carbon. Hydrogen is present in one reactant (methane) and one product (water), so let's balance hydrogen next. With 4 hydrogen atoms in methane and 2 hydrogen atoms in water, if we multiply water by 2 (put 2 in front of water), we end up with 4 hydrogen atoms on both sides of the equation.

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

All that's left is oxygen. We have two oxygen atoms on the left, and 4 oxygen atoms on the right (2 from carbon dioxide, and 2 more from 2 molecules of water). Putting a 2 in front of oxygen gives us 4 oxygen atoms on each side of the equation.

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

Are we done? To answer this question, we simply compare the number of atoms of each element on the reactant and product sides. We have 1 carbon atom on each side. We have 4 hydrogen atoms on each side. Both sides have 4 oxygen atoms. Since the kinds of atoms are the same, and the numbers of atoms of each kind are the same, the equation is balanced.

What is that you say? "Too much fooling around, isn't there an easier way?"

No, there isn't. But with practice, the process becomes easier. Another exercise that may help is to draw some pictures of the atoms or molecules involved in the reaction. Figure 6.1 shows the initial equation and the balanced equation using pictures of the atoms and molecules. If you have trouble balancing equations, try drawing some pictures to help you visualize what is happening. Eventually, you'll be able to balance the equations without the pictures.

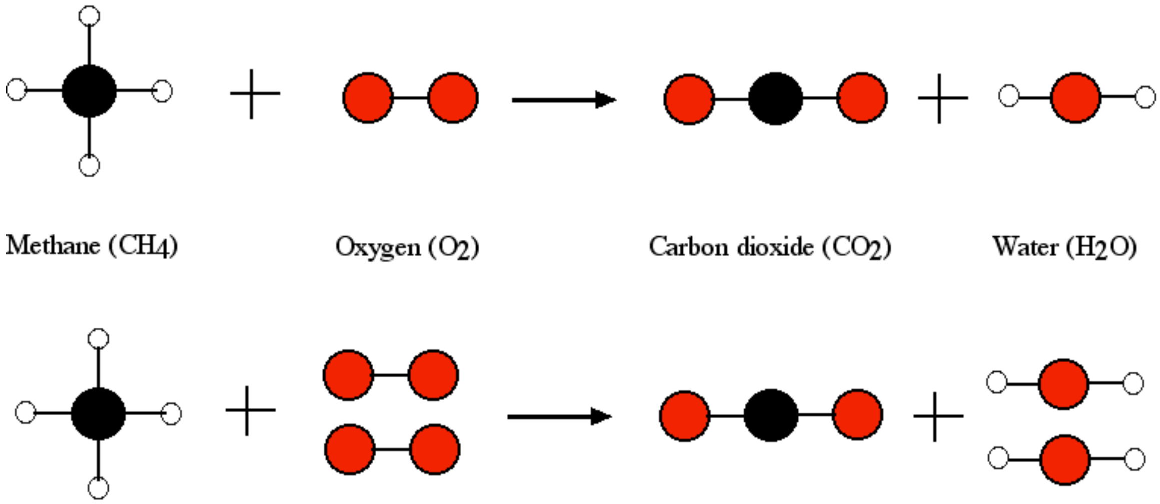

Figure 6.1. Picture method of balancing chemical equations. The initial, unbalanced equation is at the top, while the balanced equation is at the bottom. Carbon atoms are black balls, hydrogen atoms are white, and oxygen atoms are red.

Sometimes, we run into little problems while balancing the equation. Let's look at a reaction similar to our first.

$$C_2H_6 + O_2 \rightarrow CO_2 + H_2O$$

There are 2 carbon atoms as reactants, but only 1 carbon atom as products, so multiplying the carbon product by 2 balances the carbon atoms.

$$C_2H_6 + O_2 \rightarrow 2CO_2 + H_2O$$

There are 6 hydrogen atoms as reactants and 2 hydrogen atoms as products, so multiplying the hydrogen product by 3 balances the hydrogen atoms.

$$C_2H_6 + O_2 \rightarrow 2CO_2 + 3H_2O$$

There are 2 oxygen atoms as reactants, and a total of 7 oxygen atoms as products, so multiplying the oxygen reactant by 3.5 balances the oxygen atoms.

$$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$$

We see there are 2 carbon atoms on each side, 6 hydrogen atoms on each side, and 7 oxygen atoms (2 x 3.5 = 7) on each side. The kinds of atoms are the same, the numbers of each kind of atom are the same, the reaction is balanced and we are done, yes?

No.

Look at what has been done to oxygen (O_2) in our reaction. What are we describing?

Three oxygen molecules (O_2) are: O=O O=O O=O.

Three and a half oxygen molecules would be: O=O O=O O=O O.

We do not have any isolated oxygen atoms (O) in our reactants!!!! All of the oxygen came in the form of oxygen molecules!!!! By writing 3.5 O_2, we have changed the chemical equation to say "3 molecules of oxygen and 1 oxygen atom". **We have changed the specific chemical compounds in the reaction by changing the formulas of the compounds.**

NEVER!

NEVER!!

NEVER CHANGE THE CHEMICAL FORMULAS OF THE COMPOUNDS!!!!

What to do, what to do? Well, how about this – since we are changing the coefficients of the individual compounds, why not change the coefficients again to get rid of "1/2" of an oxygen molecule? The simplest way is to multiply the entire equation by 2 to get:

$$2C_2H_6 + 7O_2 \Rightarrow 4CO_2 + 6H_2O$$

We see there are 4 carbon atoms on each side, 12 hydrogen atoms on each side, and 14 oxygen atoms on each side. None of the formulas have been changed. This is a correctly balanced chemical equation. ***In a properly balanced chemical equation the coefficients are the smallest possible whole number values***.

There is another way of handling this problem. Let's pretend we were balancing this equation, and got to the step where we saw that we had 2 oxygen atoms on the left and 7 on the right. We could stop balancing the reaction right here, take a step backwards, and use the following method.

First, start over using the original equation:

$$C_2H_6 + O_2 \rightarrow CO_2 + H_2O$$

Next, multiply every substance in the equation by 2:

$$2C_2H_6 + 2O_2 \rightarrow 2CO_2 + 2H_2O$$

Now balance the equation as normal. We have 4 carbon atoms on the left and 2 on the right, so we need to increase the coefficient in front of carbon dioxide to balance the carbon atoms:

$$2C_2H_6 + 2O_2 \rightarrow 4CO_2 + 2H_2O$$

We have 12 hydrogen atoms on the left and 4 on the right, so we need to increase the coefficient in front of water to balance hydrogen atoms:

$$2C_2H_6 + 2O_2 \rightarrow 4CO_2 + 6H_2O$$

Finally, we have 4 oxygen atoms on the left and 14 on the right (8 from four molecules of carbon dioxide and 6 from water molecules), so we need to increase the coefficient in front of oxygen to balance oxygen atoms:

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O$$

As a final check, we can compare number of atoms of each element on the left and right sides. We have 4 carbon, 12 hydrogen, and 14 oxygen atoms on each side, so the reaction is balanced.

Sometimes, when we balance one element in a reaction, another element that was already balanced becomes unbalanced. The final check allows us to catch these kinds of errors.

Balancing equations with reactants and products containing polyatomic ions is very easy if you recognize the ions in the chemical formulas. Let's balance an equation between aluminum chlorate and magnesium chromate:

$$Al(ClO_3)_3 + MgCrO_4 \rightarrow Al_2(CrO_4)_3 + Mg(ClO_3)_2$$

It would be easy to panic and flounder around, worrying about all the different elements that have to balance, but instead look at the equation calmly. We have chlorate (ClO_3^-) in the reactant and in the product, just as we have chromate (CrO_4^{-2}) on both sides. Chlorate and chromate can be treated as if they were single atoms, because they aren't being converted into new substances.

Once we recognize that the polyatomic ions aren't being converted into anything different, balancing the equation is relatively simple. First, we increase the coefficient in front of aluminum chlorate to balance the aluminum atoms (one atom on the left, 2 on the right):

$$2Al(ClO_3)_3 + MgCrO_4 \rightarrow Al_2(CrO_4)_3 + Mg(ClO_3)_2$$

Next, we balance the chlorate. We have 6 chlorate ions on the left, and 2 on the right, so the coefficient in front of magnesium chlorate needs to be increased:

$$2Al(ClO_3)_3 + MgCrO_4 \rightarrow Al_2(CrO_4)_3 + 3Mg(ClO_3)_2$$

Balancing the magnesium requires that we increase the coefficient in front of magnesium chromate to 3:

$$2Al(ClO_3)_3 + 3MgCrO_4 \rightarrow Al_2(CrO_4)_3 + 3Mg(ClO_3)_2$$

All that is left is to balance chromate. We have 3 chromate ions on the left, and 3 on the right, so there is nothing more to do except a final check:

Element	Left side	Right side
Al	2	2
Cl	6	6
O	30	30
Mg	3	3
Cr	3	3

We have the same number and kinds of atoms on both sides of the equation – it is balanced.

Optional symbols.

Sometimes, additional information is included in a balanced chemical equation by using additional optional symbols. These symbols aren't needed for balancing the reactions, but provide additional information that might be useful for other calculations or applications. These symbols and their meanings are shown in Table 6.2.

Symbol	Meaning
(s)	Solid
(l)	Liquid
(g)	Gas
(↑)	Gas is produced
(↓)	Precipitate (solid substance) comes out of solution
(aq)	Aqueous – substance dissolved in water
Δ (above or below reaction arrow)	Heat required
$h\upsilon$ (above or below reaction arrow)	Light required
cat. or Pt	Catalyst required

Table 6.2. Additional symbols seen in chemical reactions.

Chapter 6 Homework:

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.

Decomposition reaction	**Combination reaction**	**Single replacement reaction**
Double replacement (metathesis) reaction	**Precipitation reaction**	**Supernatant liquid**
Precipitate	**Combustion reaction**	**Balanced chemical equation**
Reactant(s)	**Product(s)**	**Coefficients**
Optional symbols		

Homework:

A. Balance the following chemical equations.

1. $Fe + O_2 \rightarrow Fe_2O_3$
2. $C_2H_4 + O_2 \rightarrow CO_2 + H_2O$
3. $P_2O_5 + H_2O \rightarrow H_3PO_4$
4. $Al_4C_3 + H_2O \rightarrow Al(OH)_3 + CH_4$
5. $NH_4NO_3 \rightarrow N_2 + O_2 + H_2O$
6. $Na_2O + H_2O \rightarrow NaOH$
7. $Na_2SiO_3 + HF \rightarrow H_2SiO_3 + NaF$
8. $C_3H_5N_3O_9 \rightarrow CO_2 + N_2 + O_2 + H_2O$
9. $NaHCO_3 + H_3C_6H_5O_7 \rightarrow CO_2 + H_2O + Na_3C_6H_5O_7$
10. $KClO_3 \rightarrow KCl + O_2$

B. For the ten chemical equations given in part A, identify which are decomposition, combination, single replacement, double replacement, or combustion reactions. (It is possible for one chemical reaction to fit into two categories).

Answers:

A. Balance the following chemical equations.

1. $Fe + O_2 \rightarrow Fe_2O_3$

   Balance Fe: $2Fe + O_2 \rightarrow Fe_2O_3$

   Balance O: $2Fe + 1.5O_2 \rightarrow Fe_2O_3$

   Final: $4Fe + 3O_2 \Rightarrow 2Fe_2O_3$

   Check: 4 Fe, 6 O vs. 4 Fe, 6 O

2. $C_2H_4 + O_2 \rightarrow CO_2 + H_2O$

   Balance C: $C_2H_4 + O_2 \rightarrow 2CO_2 + H_2O$

   Balance H: $C_2H_4 + O_2 \rightarrow 2CO_2 + 2H_2O$

   Balance O: $C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$

   Check: 2 C, 4 H, 6 O vs. 2 C, 4 H, 6 O

3. $P_2O_5 + H_2O \rightarrow H_3PO_4$

   Balance P: $P_2O_5 + H_2O \rightarrow 2H_3PO_4$

   Balance O: $P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$

   Balance H: $P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$

   Check: 2 P, 8 O, 6 H vs. 2 P, 8 O, 6 H

4. $Al_4C_3 + H_2O \rightarrow Al(OH)_3 + CH_4$

Balance Al:	$Al_4C_3 + H_2O \rightarrow 4Al(OH)_3 + CH_4$
Balance C:	$Al_4C_3 + H_2O \rightarrow 4Al(OH)_3 + 3CH_4$
Balance O:	$Al_4C_3 + 12H_2O \rightarrow 4Al(OH)_3 + 3CH_4$
Balance H:	$Al_4C_3 + 12H_2O \rightarrow 4Al(OH)_3 + 3CH_4$
Check:	4 Al, 3 C, 12 O, 24 H vs. 4 Al, 3 C, 12 O, 24 H

5. $NH_4NO_3 \rightarrow N_2 + O_2 + H_2O$

Balance N:	$NH_4NO_3 \rightarrow N_2 + O_2 + H_2O$
Balance O:	$NH_4NO_3 \rightarrow N_2 + O_2 + H_2O$
Balance H:	$NH_4NO_3 \rightarrow N_2 + O_2 + 2H_2O$
Balance O:	$NH_4NO_3 \rightarrow N_2 + 1/2O_2 + 2H_2O$
Final:	$2NH_4NO_3 \rightarrow 2N_2 + O_2 + 4H_2O$
Check:	4 N, 6 O, 8 H vs. 4 N, 6 O, 8 H

6. $Na_2O + H_2O \rightarrow NaOH$

Balance Na:	$Na_2O + H_2O \rightarrow 2NaOH$
Balance O:	$Na_2O + H_2O \rightarrow 2NaOH$
Balance H:	$Na_2O + H_2O \rightarrow 2NaOH$
Check:	2 Na, 2 O, 2 H vs. 2 Na, 2 O, 2 H

7. $Na_2SiO_3 + HF \rightarrow H_2SiO_3 + NaF$

   Notice: SiO_3^{-2} present on both sides. Treat as a single unit.

   Balance SiO_3: $Na_2SiO_3 + HF \rightarrow H_2SiO_3 + NaF$

   Balance Na: $Na_2SiO_3 + HF \rightarrow H_2SiO_3 + 2NaF$

   Balance F: $Na_2SiO_3 + 2HF \rightarrow H_2SiO_3 + 2NaF$

   Balance H: $Na_2SiO_3 + 2HF \rightarrow H_2SiO_3 + 2NaF$

   Check: 2 Na, 1 Si, 3 O, 2 H, 2 F vs. 2 Na, 1 Si, 3 O, 2 H, 2 F

8. $C_3H_5N_3O_9 \rightarrow CO_2 + N_2 + O_2 + H_2O$

   Balance C: $C_3H_5N_3O_9 \rightarrow 3CO_2 + N_2 + O_2 + H_2O$

   Balance N: $C_3H_5N_3O_9 \rightarrow 3CO_2 + 1.5N_2 + O_2 + H_2O$

   Balance O: $C_3H_5N_3O_9 \rightarrow 3CO_2 + 1.5N_2 + O_2 + H_2O$

   Balance H: $C_3H_5N_3O_9 \rightarrow 3CO_2 + 1.5N_2 + O_2 + 2.5H_2O$

   Balance O: $C_3H_5N_3O_9 \rightarrow 3CO_2 + 1.5N_2 + 0.25O_2 + 2.5H_2O$

   Final: $4C_3H_5N_3O_9 \Rightarrow 12CO_2 + 6N_2 + O_2 + 10H_2O$

   Check: 12 C, 20 H, 12 N, 36 O vs. 12 C, 20 H, 12 N, 36 O

9. $NaHCO_3 + H_3C_6H_5O_7 \rightarrow CO_2 + H_2O + Na_3C_6H_5O_7$

   Notice: $C_6H_5O_7^{-3}$ present on both sides. Treat as a single unit.

   Balance $C_6H_5O_7$: $NaHCO_3 + H_3C_6H_5O_7 \rightarrow CO_2 + H_2O + Na_3C_6H_5O_7$

   Balance Na: $3NaHCO_3 + H_3C_6H_5O_7 \rightarrow CO_2 + H_2O + Na_3C_6H_5O_7$

   Balance C: $3NaHCO_3 + H_3C_6H_5O_7 \rightarrow 3CO_2 + H_2O + Na_3C_6H_5O_7$

   Balance O: $3NaHCO_3 + H_3C_6H_5O_7 \rightarrow 3CO_2 + 3H_2O + Na_3C_6H_5O_7$

   Balance H: $3NaHCO_3 + H_3C_6H_5O_7 \rightarrow 3CO_2 + 3H_2O + Na_3C_6H_5O_7$

   Check: 3 Na, 11 H, 9 C, 16 O vs. 3 Na, 11 H, 9 C, 16 O

10. $KClO_3 \rightarrow KCl + O_2$

    Balance K: $KClO_3 \rightarrow KCl + O_2$

    Balance Cl: $KClO_3 \rightarrow KCl + O_2$

    Balance O: $KClO_3 \rightarrow KCl + 1.5O_2$

    Final: $2KClO_3 \rightarrow 2KCl + 3O_2$

    Check: 2 K, 2 Cl, 6 O vs. 2 K, 2 Cl, 6 O

B. For the ten chemical equations given in part A, identify which are decomposition, combination, single replacement, double replacement, or combustion reactions. (It is possible for one chemical reaction to fit into two categories).

1. $Fe + O_2 \rightarrow Fe_2O_3$ — Combination and combustion reaction
2. $C_2H_4 + O_2 \rightarrow CO_2 + H_2O$ — Combustion reaction
3. $P_2O_5 + H_2O \rightarrow H_3PO_4$ — Combination reaction
4. $Al_4C_3 + H_2O \rightarrow Al(OH)_3 + CH_4$ — Double replacement reaction
5. $NH_4NO_3 \rightarrow N_2 + O_2 + H_2O$ — Decomposition reaction
6. $Na_2O + H_2O \rightarrow NaOH$ — Combination reaction

7. $Na_2SiO_3 + HF \rightarrow H_2SiO_3 + NaF$ Double replacement reaction

8. $C_3H_5N_3O_9 \rightarrow CO_2 + N_2 + O_2 + H_2O$ Decomposition reaction

9. $NaHCO_3 + H_3C_6H_5O_7 \rightarrow CO_2 + H_2O + Na_3C_6H_5O_7$ Single replacement and Decomposition reaction

10. $KClO_3 \rightarrow KCl + O_2$ Decomposition reaction