Chemical Equations

Here is a good site that introduces chemical equations and related topics, from Dr. Peter Chieh's website at the University of Waterloo.

Overview

Chemical equations show a number of important features of a reaction. The formulas of the reactants and products are given, and through the use of coefficients in front of the formulas, the relative amounts of the substances that react and form are given. It is important to realize that the amounts given by the coefficients are not masses, but rather are numbers of atoms, molecules, or formula units of the substances in the reaction, such as the moles of them. For simplicity, the coefficients are written in their simplest whole-number values. Thus we can say that chemical equations are "in" mole units by default, which is why we must always convert amounts such as grams or kilograms to moles when using a chemical equation in calculations.

"Reactants Yield Products"
This is the standard order of writing reactions. On the left side go the starting substances, or reactants, and on the right side go the substances that form in the reaction, which are the products. In between the reactant and product sides goes the "yield sign" which is the familiar arrow ——>.

Besides the normal yield sign, there are other arrows used in writing reactions, but these have different meanings:

$\rightleftharpoons$ This is the equilibrium double arrow for reversible reactions.

$\longleftrightarrow$ This is the resonance arrow which is used to indicate the different resonance structures of a substance.

$\not\longrightarrow$ This means "does not yield" in case you need to make the point!

Other information may be placed above or below the yield sign to save space. For example,

$\xrightarrow{\Delta}$ means "yields with heating" (temperature not specified).

$\xrightarrow{25°C}$ means "yields" at 25 degrees Celsius.

$\xrightarrow[H_2SO_4]{}$ means "yields in the presence of sulfuric acid."

$\xrightarrow[25\ atm]{}$ means "yields at 25 atmospheres pressure."

Physical States
More information that is given in a properly written reaction are the physical states of the reactants and products. These are specified by the following abbreviations after the formulas:

(s) means "solid"
(l) means "liquid"
(g) means "gas"
(aq) means "aqueous solution" or "dissolved in water"

Thus H_2O (s) is water in the solid state (ice), H_2O (l) is water in the liquid state, and H_2O (g) is gaseous water vapor.

Common Reaction Types

It is convenient to be familiar with about five "standard" types of reactions which are very common. Recognizing the reaction type enables us to be able to predict the outcome of the reaction if we do not initially know what the products are. The five types are

1. **Combination** (or "composition" or "synthesis"). Two reactants combine to form a single product.
$A + B \longrightarrow C$

Examples
$2\,Mg\,(s) + O_2\,(g) \longrightarrow 2\,MgO\,(s)$
$CO_2\,(aq) + H_2O\,(l) \longrightarrow H_2CO_3\,(aq)$

2. **Decomposition**. A single reactant breaks down to give two or more products.
$A \longrightarrow B + C$

Examples
$CaCO_3\,(s) \xrightarrow{\Delta} CaO\,(s) + CO_2\,(g)$
$H_2CO_3\,(aq) \longrightarrow CO_2\,(g) + H_2O\,(l)$

$2\,KClO_3\,(s) \xrightarrow[MnO_2]{\Delta} 2\,KCl\,(s) + 3\,O_2\,(g)$

3. **Single Displacement** (or single replacement). An element displaces another element from a compound.
$A + BX \longrightarrow B + AX$ Element A must be "more active" than element B

Examples
$Zn\,(s) + CuSO_4\,(aq) \longrightarrow Cu\,(s) + ZnSO_4\,(aq)$
$Ni\,(s) + 2\,HCl\,(aq) \longrightarrow H_2\,(g) + NiCl_2\,(aq)$

4. **Double Displacement** (or double replacement or "metathesis"). Usually in ionic reactions, ions "exchange partners."

AX + BY ——> BX + AY

Examples

$AgNO_3$ (aq) + NaCl (aq) ——> $NaNO_3$ (aq) + AgCl (s)

$Pb(NO_3)_2$ (aq) + 2 KI (aq) ——> 2 KNO_3 (aq) + PbI_2 (s)

HCl (aq) + NaOH (aq) ——> NaCl (aq) + H_2O (l)

We need to be familiar with the solubility rules of common ionic compounds in order to write the ionic and net ionic reactions. In aqueous solution, soluble ionic compounds are completely separated into their positive and negative ions. "$Pb(NO_3)_2$ (aq)" would be written "Pb^{2+} (aq) + 2 NO_3^- (aq)". The formulas of insoluble ionic solids and weak and non-electrolytes are not separated like this because that does not happen in these cases.

Formula equation:

$Pb(NO_3)_2$ (aq) + 2 KI (aq) ——> 2 KNO_3 (aq) + PbI_2 (s)

Ionic equation:

Pb^{2+} (aq) + 2 NO_3^- (aq) + 2 K^+ (aq) + 2 I^- (aq) ——> 2 K^+ (aq) + 2 NO_3^- (aq) + PbI_2 (s)

"Canceling" the soluble "spectator ions" that appear on both sides gives the net ionic equation:

Pb^{2+} (aq) + 2 I^- (aq) ——> PbI_2 (s)

Note that ionic and net ionic equations can be written for single displacement reactions as well.

5. **Combustion** of a hydrocarbon in an oxygen atmosphere.
Complete combustion gives carbon dioxide and water as the only products.

Examples

CH_4 (g) + 2 O_2 (g) ——> CO_2 (g) + 2 H_2O (g)

2 C_4H_{10} (g) + 13 O_2 (g) ——> 8 CO_2 + 10 H_2O (g)

Balance the carbons first, then the hydrogens, and lastly the oxygens. The coefficient in front of O_2 may be a fraction, such as 13/2. In that case, multiply all the coefficients through by two so that you have the simplest whole-number coefficients.

Balancing Reactions

When we balance chemical reactions, we want to have the same number of atoms of each element on each side of the equation. If we have eight carbons on the left, we should have a total of eight carbons on the right, and so on. Normally this is a trial and error process, although complex reactions can be very difficult to balance this way. For such reactions, an algebraic approach can be incorporated into a computer program which will balance the reaction for you. There are several such "equation balancers" on the Internet to use for free or purchase. But most of the time, the reactions in your textbook can be balanced by the trial and error method.

Number One Rule in balancing reactions: First, before balancing, be sure the formulas of the substances are written correctly! Watch out for mistakes like "Na_2Cl_2" and "$K_2(NO_3)_2$." The correct formulas are NaCl and KNO_3. If you need two of them, use coefficients, don't change a correct formula: 2 NaCl and 2 KNO_3. Check the charges of the ions from a table if necessary, to avoid writing things like "$NaSO_4$" when it should be Na_2SO_4.

When working problems based on a chemical equation (stoichiometry problems), it is very important that the reaction be balanced correctly, or the results of the calculations will almost certainly be wrong.

Reactions involving ionic substances are usually easier to balance than they may first appear. Look at the following unbalanced reaction, for example:

$$Ca(NO_3)_2\ (aq) + Na_3PO_4\ (aq) \longrightarrow NaNO_3\ (aq) + Ca_3(PO_4)_2\ (s)$$

Rather than counting the oxygens individually, just balance the ions, NO_3^- and PO_4^{3-}. Since there are two nitrates on the left, we need two nitrates on the right:

$$Ca(NO_3)_2\ (aq) + Na_3PO_4\ (aq) \longrightarrow \mathbf{2}\ NaNO_3\ (aq) + Ca_3(PO_4)_2\ (s)$$

Since there are two phosphates on the right, we need two phosphates on the left:

$$Ca(NO_3)_2\ (aq) + \mathbf{2}\ Na_3PO_4\ (aq) \longrightarrow 2\ NaNO_3\ (aq) + Ca_3(PO_4)_2\ (s)$$

Now for the calciums. There are three Ca on the right, so we need three on the left. But that will unbalance the nitrates. So after putting a coefficient of 3 in front of $Ca(NO_3)_2$, we will need to multiply the coefficient in front of $NaNO_3$ by three also, making it 6.

$$\mathbf{3}\ Ca(NO_3)_2\ (aq) + 2\ Na_3PO_4\ (aq) \longrightarrow \mathbf{6}\ NaNO_3\ (aq) + Ca_3(PO_4)_2\ (s)$$

And that does it. Part method and part luck!

Balancing Net Ionic Equations: Charge-Balancing

Consider this net ionic reaction:

$$Cu\ (s) + Ag^+\ (aq) \longrightarrow Ag\ (s) + Cu^{2+}\ (aq)$$

It is balanced with respect to elements, but not with respect to charge. There is a total of +1 charge of ions on the left but +2 on the right. We have to put a coefficient of 2 in front of Ag^+ (aq) (and in front of Ag (s) also to keep the silvers balanced) in order balance this reaction correctly:

$$Cu\ (s) + 2\ Ag^+\ (aq) \longrightarrow 2\ Ag\ (s) + Cu^{2+}\ (aq)$$

Now the charge of the ions on both sides is the same, +2.

This will make more sense if we look at the original formula equation (with spectator nitrate ions present) before simplifying it to the net ionic equation:

$Cu\ (s)\ +\ AgNO_3\ (aq)\ \longrightarrow\ Ag\ (s)\ +\ Cu(NO_3)_2\ (aq)$

Now we can easily see that the nitrate ions are not balanced; we need to have two NO_3^- on each side:

$Cu\ (s)\ +\ 2\ AgNO_3\ (aq)\ \longrightarrow\ 2\ Ag\ (s)\ +\ Cu(NO_3)_2\ (aq)$

Balancing Oxidation-Reduction ("Redox") Reactions

These kinds of reactions often require a more methodical approach to balancing. In aqueous solution, these can also be balanced in acidic solution or basic solution. They are part of the general topic of oxidation and reduction, oxidation numbers, half-reactions, and electrochemistry which we won't go into here, except to outline the steps.

In the method of half-reactions, you first break down the reaction into the unbalanced oxidation and reduction half-reactions. Then you balance each half-reaction separately by the following procedure:

First do steps 1-4 to each half-reaction:
1. Balance the elements other than O and H.
2. Balance the oxygens by adding H_2Os to the appropriate side.
3. Balance the hydrogens by adding H^+ to the appropriate side.
4. Balance the charge by adding electrons (e^-) to the appropriate side.

Then you are ready to do steps 5 & 6:
5. Balance the electrons lost and gained by multiplying one or both half-reactions through by an integer (so the electrons cancel when the half-reactions are added together).
6. Add the half-reactions together and combine like terms, if necessary.

By default, this gives the balanced reaction in acidic aqueous solution (since H^+ ions are used to balance the hydrogens). To convert to basic solution, if asked for, simply add the same number of hydroxide ions, OH^-, as you have H^+ ions in the balanced reaction in acidic solution, to both sides of the equation (so it remains balanced). Convert each $H^+ + OH^-$ to H_2O and simplify the number of water molecules in the reaction to get the final reaction in basic solution. You could also do this to each balanced half-reaction before adding them together in step 6 if you prefer.

Unbalanced reaction:
$MnO_4^-\ (aq)\ +\ ClO_2^-\ (aq)\ \longrightarrow\ MnO_2\ (s)\ +\ OH^-\ (aq)\ +\ ClO_4^-\ (aq)$

Balanced reaction in acidic aqueous solution:
$3\ ClO_2^-\ (aq)\ +\ 4\ MnO_4^-\ (aq)\ +\ 4\ H^+\ (aq)\ \longrightarrow\ 3\ ClO_4^-\ (aq)\ +\ 4\ MnO_2\ (s)\ +\ 2\ H_2O\ (l)$

Balanced reaction in basic aqueous solution:
$4\ MnO_4^-\ (aq)\ +\ 3\ ClO_2^-\ (aq)\ +\ 2\ H_2O\ (l)\ \longrightarrow\ 4\ MnO_2\ (s)\ +\ 4\ OH^-\ (aq)\ +\ 3\ ClO_4^-\ (aq)$

Exercises

For practice in balancing reactions, try the problems here (under "Reactions") from Dr. Sergei Smirnov's site at New Mexico State University.

Exercises in completing reactions may also be found here at the Virtual Chemistry Lab (under "Introduction to Chemical Reactions"). From Deepa Godambe, Harper College, Palatine, IL.

Classify the following reactions as combination, decomposition, single displacement, double displacement, or combustion:

1. $Mg\ (s) + Ni(NO_3)_2\ (aq) \longrightarrow Ni\ (s) + Mg(NO_3)_2\ (aq)$

2. $H_2SO_4\ (aq) + 2\ NaOH\ (aq) \longrightarrow Na_2SO_4\ (aq) + 2\ H_2O\ (l)$

3. $2\ HgO\ (s) \xrightarrow{\Delta} 2\ Hg\ (l) + O_2\ (g)$

4. $2\ Fe\ (s) + 3\ Cl_2\ (g) \longrightarrow 2\ FeCl_3\ (s)$

5. $Fe\ (s) + 2\ HCl\ (aq) \longrightarrow H_2\ (g) + FeCl_2\ (aq)$

6. $C_5H_{12}\ (l) + 8\ O_2\ (g) \longrightarrow 5\ CO_2\ (g) + 6\ H_2O\ (g)$

7. $BaCl_2\ (aq) + Na_2SO_4\ (aq) \longrightarrow 2\ NaCl\ (aq) + BaSO_4\ (s)$

8. $P_4O_{10}\ (s) + 6\ H_2O\ (l) \longrightarrow 4\ H_3PO_4\ (l)$

9. $N_2O_3\ (g) \longrightarrow NO\ (g) + NO_2\ (g)$

10. $NaHCO_3\ (s) + HC_2H_3O_2\ (aq) \longrightarrow CO_2\ (g) + H_2O\ (l) + NaC_2H_3O_2\ (aq)$ (two steps)

Balance the following reactions:

11. $Fe_2O_3\ (s) + H_2\ (g) \longrightarrow Fe\ (s) + H_2O\ (l)$

12. $Al\ (s) + O_2\ (g) \longrightarrow Al_2O_3\ (s)$

13. $Zn(NO_3)_2\ (aq) + NaOH\ (aq) \longrightarrow NaNO_3\ (aq) + Zn(OH)_2\ (s)$

14. $CCl_4\ (g) + O_2\ (g) \longrightarrow COCl_2\ (g) + Cl_2\ (g)$

15. $N_2O_5\ (g) + H_2O\ (l) \longrightarrow HNO_3\ (aq)$

16. $PCl_5\ (l) + H_2O\ (l) \longrightarrow H_3PO_4\ (aq) + HCl\ (aq)$

17. C_6H_{14} (l) + O_2 (g) ——> CO_2 (g) + H_2O (l)

18. NO_2 (g) + H_2O (l) ——> HNO_3 (aq) + NO (g)

19. CH_3CH_2OH (l) + O_2 (g) ——> CO_2 (g) + H_2O (g)

20. Cu (s) + HNO_3 (aq) ——> $Cu(NO_3)_2$ (aq) + NO (g) + H_2O (l)

Complete and balance the following reactions:

21. Al (s) + $CuSO_4$ (aq) ——>

22. $CdCl_2$ (aq) + Na_2S (aq) ——>

23. SO_3 (g) + H_2O (l) ——>

24. H_2O_2 (aq) ——>

25. $Pb(NO_3)_2$ (aq) + NaCl (aq) ——>

26. $C_{40}H_{82}$ (s) + O_2 (g) ——>

27. H_2 (g) + O_2 (g) ——>

28. Na (s) + H_2O (l) ——>

29. $Al(OH)_3$ (s) + H_2SO_4 (aq) ——>

30. Mg (s) + N_2 (g) $\xrightarrow{\Delta}$

Answers to Exercises

1. single displacement
2. double displacement
3. decomposition
4. combination
5. single displacement
6. combustion
7. double displacement
8. combination
9. decomposition

10. a) double displacement: $NaHCO_3$ (s) + $HC_2H_3O_2$ (aq) ——> H_2CO_3 (aq) + $NaC_2H_3O_2$ (aq)
    b) decomposition: H_2CO_3 (aq) ——> CO_2 (g) + H_2O (l)
    (See note at bottom)

11. Fe_2O_3 (s) + 3 H_2 (g) ——> 2 Fe (s) + 3 H_2O (l)

12. 4 Al (s) + 3 O_2 (g) ——> 2 Al_2O_3 (s)

13. $Zn(NO_3)_2$ (aq) + 2 NaOH (aq) ——> 2 $NaNO_3$ (aq) + $Zn(OH)_2$ (s)

14. 2 CCl_4 (g) + O_2 (g) ——> 2 $COCl_2$ (g) + 2 Cl_2 (g)

15. N_2O_5 (g) + H_2O (l) ——> 2 HNO_3 (aq)

16. PCl_5 (l) + 4 H_2O (l) ——> H_3PO_4 (aq) + 5 HCl (aq)

17. 2 C_6H_{14} (l) + 19 O_2 (g) ——> 12 CO_2 (g) + 14 H_2O (l)

18. 3 NO_2 (g) + H_2O (l) ——> 2 HNO_3 (aq) + NO (g)

19. 2 CH_3CH_2OH (l) + 6 O_2 (g) ——> 4 CO_2 (g) + 6 H_2O (g)

20. 3 Cu (s) + 8 HNO_3 (aq) ——> 3 $Cu(NO_3)_2$ (aq) + 2 NO (g) + 4 H_2O (l)

21. Single Displacement: 2 Al (s) + 3 $CuSO_4$ (aq) ——> 3 Cu (s) + $Al_2(SO_4)_3$ (aq)

22. Double Displacement: $CdCl_2$ (aq) + Na_2S (aq) ——> 2 NaCl (aq) + CdS (s)

23. Combination: SO_3 (g) + H_2O (l) ——> H_2SO_4 (aq)

24. Decomposition: 2 H_2O_2 (aq) ——> 2 H_2O (l) + O_2 (g)

25. Double Displacement: $Pb(NO_3)_2$ (aq) + 2 NaCl (aq) ——> 2 $NaNO_3$ (aq) + $PbCl_2$ (s)

26. Combustion: 2 $C_{40}H_{82}$ (s) + 121 O_2 (g) ——> 80 CO_2 (g) + 82 H_2O (g)

27. Combination: 2 H_2 (g) + O_2 (g) ——> 2 H_2O (l)

28. Single Displacement: 2 Na (s) + 2 H_2O (l) ——> H_2 (g) + 2 NaOH (aq)

29. Double Displacement: 2 $Al(OH)_3$ (s) + 3 H_2SO_4 (aq) ——> 6 H_2O (l) + $Al_2(SO_4)_3$ (aq)

30. Combination: 3 Mg (s) + N_2 (g) $\xrightarrow{\Delta}$ Mg_3N_2 (s)

Note for Question 10
The following products are unstable and decompose immediately upon formation:

carbonic acid, H_2CO_3 (aq) ——> CO_2 (g) + H_2O (l)
sulfurous acid, H_2SO_3 (aq) ——> SO_2 (g) + H_2O (l)
ammonium hydroxide, NH_4OH (aq) ——> NH_3 (g) + H_2O (l)

When you form any of these compounds, write the decomposition products instead, since these are what will actually be formed in the reaction.