Chapter 10: Blowing Stuff Up – The Story of chemical Reactions

This is what it looks like when you use bombs to blow up other bombs. I totally wish I were there, because it would be like a Michael Bay movie, except without the dancing killer robots.

Chapter 10: Blowing Stuff Up – The Story of Chemical Reactions

Have you ever wanted to blow stuff up? If you just answered "no", you're a huge liar. Every human being lusts to watch explosions and to be the person who makes them happen. Scientists have shown that it's innate in our genetic makeup, just like the urge to find food or make fun of people who speak with a Swedish accent. Anyway, if you want to see stuff blow up, or to see other chemical reactions that may or may not be as interesting to watch, read on.

Section 10.1: Getting To Know Chemical Reactions

Whenever you're looking at some process taking place, it's handy to know whether or not it's a chemical process. After all, if it's *you* that's going to blow up, it would be nice to have some warning that something bad is in the process of happening.

So, how do you tell a chemical reaction from a physical process? Use the handy table below:

Chemical Reaction	Physical Process
The process spontaneously gives off heat and gets hot (is exothermic) or spontaneously absorbs heat and gets cold (is endothermic).	You may see a temperature change, but that's only if you directly did something to make it happen. For example, if you put a jar of pudding in the oven, it gets hot because you made it hot, not because it underwent a chemical reaction
It spontaneously gives off bubbles (think of vinegar + baking soda or the bubbles in soda)	No bubbles, unless you did something to specifically make them happen. For example, if you boil water, it bubbles because you made it hot, not because it's undergoing a chemical reaction.
There may be a color change	There's probably not a color change
The chemical properties (i.e. the way it reacts with other stuff) are changed. An example of this is burning wood, as wood burns but the ashes don't	The chemical properties don't change
A precipitate is a solid that's formed when two liquids are mixed together. A precipitate may show up as either chunks of solid, or more likely has a milky appearance due to the presence of very small solid flakes.	No precipitate forms

Some common examples of chemical reactions include burning, rusting, decomposing, and exploding. It's hard to come up with less common examples of chemical reactions because they're not very common.

Spotlight on Chemical Reactions

Figure 10.1: *What does this crackhead have in common with chemists? She understands how to harness the power of combustion reactions for her own purposes.*

http://commons.wikimedia.org/wiki/File:Smoking_Crack.jpg

Section 10.2: Writing Chemical Equations

If we want to explain to other people (or figure out for ourselves) what's going on in a chemical process, the best way to do this is to write a chemical equation that explains it. Basically, a chemical equation is a complete list of the reactants (the things you are reacting) and the products (the stuff you make), as well as a recipe for making them react.

Here's an example of a chemical equation:

$$CH_{4(g)} + 2O_{2(g)} \xrightarrow{\Delta} CO_{2(g)} + 2H_2O_{(g)}$$

$$\Delta H \text{ is negative}$$

Let's examine what the various features of this equation mean:

- The stuff at the left (CH_4 and O_2) are the reactants[1], and the products are CO_2 and H_2O.
- The (g) at the bottom of each compound indicates that they are in the gas state. If the compound is a solid, the letter is (s), if it's a liquid the letter is (l), and if it's dissolved in water it's (aq).[2]
- If you see something written around the arrow, this tells you what you need to do. For example, the Δ that's above the arrow in this equation indicates that energy needs to be added to the reaction to make it occur. Other things you might see include specific temperatures at which the reaction needs to occur or other specialized instructions.

[1] The term "reactant" is synonymous with "reagent", so if you see either one, don't freak out.
[2] (aq) stands for "aqueous", which simply means "dissolved in water."

- The ΔH term after the equation indicates whether the reaction is exothermic (in which case ΔH will be negative) or endothermic (in which case ΔH will be positive). There are numerical values which need to be added to this ΔH term, but we won't learn about how to come up with them until we talk about thermodynamics later in the book.

Now that we know what chemical equations are supposed to look like, we can start figuring out how to write the complete chemical equation for any chemical reaction. Let's use the following reaction, written out in word form:

"When nitrogen gas reacts with hydrogen gas at a pressure of 200 atmospheres (atm) and a temperature of 400^0 C, it forms ammonia gas. This reaction gives off heat."[3]

To make a useful equation out of this statement, let's do the following things:

1. Write down the formulas of the reactants and products. Using our skills at naming compounds, we know that nitrogen is N_2, hydrogen is H_2, and ammonia is NH_3.[4] Putting these into a rough equation, we come up with:

$$N_2 + H_2 \rightarrow NH_3$$

2. Indicate the states of matter of each compound. In this case, we were told that all three compounds are gases, which gives us the following:

$$N_{2(g)} + H_{2(g)} \rightarrow NH_{3(g)}$$

3. Put any necessary symbols around the arrow. In this case, we're told that we need to use a pressure of 200 atm and a temperature of 400^0 C, so let's write something to indicate this sort of thing around the arrow:

$$N_{2(g)} + H_{2(g)} \xrightarrow[400^0\ C]{200\ atm} NH_{3(g)}$$

4. Draw any ΔH terms that are needed after the equation. In this case, the reaction gives off heat, which indicates that it's exothermic and that ΔH should be negative:

$$N_{2(g)} + H_{2(g)} \xrightarrow[400^0\ C]{200\ atm} NH_{3(g)} \quad \Delta H = \text{negative}$$

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[3] This reaction is known as the Haber process and is responsible for the production of most of the fertilizer in the world today.

[4] You *did* remember that some elements are diatomic, didn't you? If not, the diatomic elements consist of the halogens, oxygen, nitrogen, and hydrogen.

5. The last step is to balance the equation. This is where you put numbers (called coefficients) in front of each of the compound formulas so that the number of atoms of each element is the same on both sides of the arrow. When you do this, you get the following final answer:

$$2\,N_{2(g)} + 3\,H_{2(g)} \xrightarrow[400^0\,C]{200\text{ atm}} 2\,NH_{3(g)} \quad \Delta H = \text{negative}$$

It's as easy as that!

What if it's not as easy as that? How to balance equations:

One of the things I didn't mention in step 5 was how to balance a chemical equation. If you're not sure about what to do, follow these steps to balance an equation:

- Write an inventory of all of the atoms on both sides of the unbalanced equation. In the unbalanced equation, we find the following:

Element	Atoms of the element on the reactant side	Atoms of the element on the product side
N	2	1
H	2	3

- Write a coefficient before one of the compounds in the reaction to balance the number of atoms of each element on both sides of the reaction. Writing coefficients multiplies the number of atoms of that element by the coefficient. In this case, we can see that there's one atom of nitrogen on the product side of the equation and two on the reactant, so let's put a "2" in front of the compound in the products that contains nitrogen:

$$N_{2(g)} + H_{2(g)} \xrightarrow[400^0\,C]{200\text{ atm}} 2\,NH_{3(g)} \quad \Delta H = \text{negative}$$

- Redo the inventory. When we do this, we find that:

Element	Atoms of the element on the reactant side	Atoms of the element on the product side
N	2	2
H	2	6

- If necessary, add another coefficient. In this case, the numbers in the inventory don't yet add up, so we need to add a "3" in front of the compound containing hydrogen on the reactants side to make the 2 into a 6. This gives us:

$$N_{2(g)} + 3\,H_{2(g)} \xrightarrow[400^0\,C]{200\text{ atm}} 2\,NH_{3(g)} \quad \Delta H = \text{negative}$$

Continued on next page →

- Do another inventory of the elements to see if they match up on the reactants and products side. (You should do this whenever you change any of the coefficients). When we do this, we find that:

Element	Atoms of the element on the reactant side	Atoms of the element on the product side
N	2	2
H	6	6

This indicates that the equation is balanced. It's as simple as that!

Section 10.3: The Six Types of Chemical Reaction

Let's say that you're some kind of hoodlum student who has found a couple of bottles of random chemicals. Fortunately for you, you're a *smart* hoodlum student who wants to figure out what sort of hell will be unleashed before you actually get started with the unleashing part. How will you figure out what's going to happen?

Well, before you can determine what terrible demons will come forth from your steaming chemistry cauldron, you need to know what type of chemical reaction will take place when these compounds are combined. After all, there are a bunch of different ways that chemicals can react, and if you just take a random guess, you probably won't pick the right one.

In any case, here are the six ways in which chemicals react with one another:[5]

Synthesis Reactions

Synthesis reactions occur when two chemicals combine to form one larger chemical. Examples include the Haber process from Section 10.2 and the following reaction that would be used to make water if water wasn't already all over the place:

$$2\ H_{2(g)} + O_{2(g)} \rightarrow 2\ H_2O_{(g)}$$

[5] Some people classify the chemical reactions differently. For example, they may refer to redox reactions as a separate type of reaction, or include nuclear processes as a type of reaction. However, since they're not writing this book, they're out of luck.

Decomposition Reactions

Decomposition reactions occur when one chemical breaks up to form two or more smaller chemicals (basically, they're the exact opposite of a synthesis reaction). You might be familiar with the decomposition reaction that occurs in soda, where carbonic acid breaks up into water and carbon dioxide:[6]

$$H_2CO_{3(aq)} \rightarrow H_2O_{(l)} + CO_{2(g)}$$

Combustion Reactions

If you've got something organic (i.e. something that contains both carbon and hydrogen atoms) reacting with oxygen to form carbon dioxide gas and water vapor (plus lots of energy). One combustion reaction that's particularly unpleasant is the combustion of benzene (C_6H_6):

$$2\ C_6H_{6(l)} + 15\ O_{2(g)} \rightarrow 12\ CO_{2(g)} + 6\ H_2O_{(g)} \qquad \Delta H = \text{negative}$$

Great Moments in Stuff on Fire

Figure 10.2: *Dr. Robert Goddard was the first guy to make a rocket that had a liquid propellant. That propellant: Benzene. There's no word on how it smelled, but I'm guessing that it smelled like a gasoline fire that spread to a family of squirrels.*

NASA file photo:
http://commons.wikimedia.org/wiki/File:Robert_Hutchins_GODDARD.jpg

[6] It's the carbon dioxide that's formed in this reaction that's responsible for the bubbles you see when you open a bottle of soda.

Single Displacement Reactions

Single displacement reactions[7] occur when the atoms of a pure element replace those of an element in a chemical compound. The pure element is usually, but not always, a metal. An example of this can be shown in the reaction between aluminum and copper (II) sulfate to form copper and aluminum sulfate:

$$2\ Al_{(s)} + 3\ CuSO_{4(aq)} \rightarrow Al_2(SO_4)_{3(aq)} + 3\ Cu_{(s)}$$

Double Displacement Reactions

If the cations of two ionic compounds switch places, you're looking at a double displacement reaction. When lead (II) nitrate reacts with potassium iodide to form lead (II) iodide[8] and potassium nitrate, you've got yourself a double displacement reaction:

$$Pb(NO_3)_2 + 2\ KI_{(aq)} \rightarrow PbI_{2(s)} + 2\ KNO_{3(aq)}$$

Acid-Base Reactions

Acid-base reactions (also known as "neutralization reactions") are just double displacement reactions in which water is formed. One example of this takes place when sodium hydroxide is used to neutralize sulfuric acid:

$$2\ NaOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + 2\ H_2O_{(l)}$$

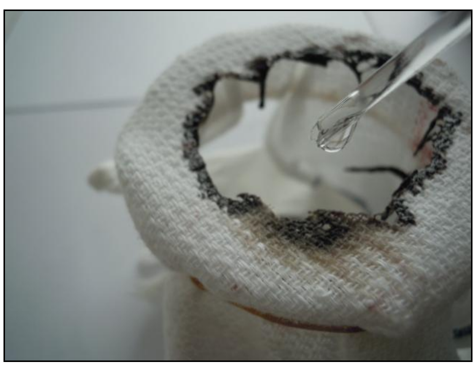

Figure 10.3: *Sulfuric acid is so spectacularly corrosive that it can even burn through a thin cotton towel.*

http://commons.wikimedia.org/wiki/File:Sulphuric_acid_on_a_piece_of_towel.JPG

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[7] The word "replacement" is sometimes used in place of "displacement." They're the same thing, so don't sweat it. Even Wikipedia calls it different things in different articles, and you can always completely trust them, right?

[8] Lead (II) iodide is a really bright yellow solid. If you ever see it, you'll totally be like "whoa."

A Recap: What Type of Reaction is it?

Because it can sometimes be challenging to figure out what type of reaction it taking place, just follow these steps to determine what type of reaction is taking place. Important: When you finally answer "yes" to any of these questions, you've identified the reaction in question:

- *Does something containing C and H react with O_2? If yes, it's a combustion reaction.*
- *Do simple compounds make a complicated one? If yes, it's a synthesis reaction.*
- *Does a complicated compound break down to make simpler ones? If yes, it's a decomposition reaction.*
- *Are there any pure elements in the reaction? If yes, it's a single displacement reaction.*
- *Is water formed in the reaction? If yes, it's an acid-base reaction. If no, it's a double displacement reaction.*

Section 10.4: Predicting Reaction Products

Sometimes, chemists like to mix a bunch of chemicals together to see what sort of hell will be unleashed. When this happens, they like to compare their predictions of the upcoming nightmare to the actual products of the nightmare that occurs. Chemists are a tricky bunch.[9]

So, how do you predict what will be made when two reagents are formed? Read on and see:

Synthesis Reactions

If you see two reactants that are either pure elements or very simple molecules, you're probably looking at a synthesis reaction. When reactions like this occur, they either form ionic compounds (if one of the elements is a metal and one is a nonmetal) or simple and familiar covalent compounds (such as CO_2, HCl, CH_4, H_2O, and so forth).

Given the following reagents, see if you can figure out what will be formed:

$$2\ H_2 + O_2 \rightarrow ?$$

The product in this reaction will be water (actually, "2 H_2O" when you're done balancing the equation. How do you know this? Because H_2O is probably the only compound you know of that contains both hydrogen and oxygen.[10]

[9] Knowing how to predict reaction products also helps chemists to figure out how to make some particular compound of interest. However, this is less fun to think about than the scenario I described.

[10] But what if you know about hydrogen peroxide, H_2O_2? Well, given the reactants, it would be entirely reasonable for you to predict that the following reaction occurs: $H_2 + O_2 \rightarrow H_2O_2$. Sometimes, there can be more than one right answer for these problems – as long as the product molecule actually exists, you're in good shape.

Decomposition Reactions

If you're looking at a reaction that contains only one compound and has an arrow after it, it's safe to say that you're looking at a decomposition reaction. To predict the product of this reaction, use your imagination to see if you can break apart the reactant into any reasonable-looking compounds that you're familiar with. Again, these include things like H_2O, CO_2, N_2, and so forth. An example of this can be seen below:

$$H_2CO_3 \rightarrow ?$$

Examination of this compound reveals that it contains water, and when we take away the water molecule we're left with CO_2. Thus, our final equation is $H_2CO_3 \rightarrow H_2O + CO_2$.

The Magical World of Decomposition Reactions

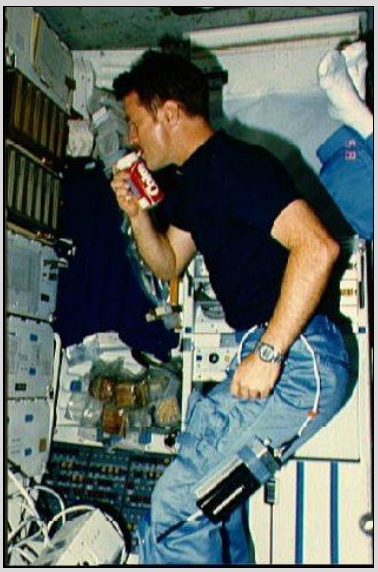

Figure 10.4: *Space shuttle astronauts used to bring soda with them on missions, and would bring them in specially-designed cans that would keep the stuff from going everywhere. Unfortunately, the carbonation in the soda (which is the result of the decomposition of carbonic acid as described above) made them burp, and the lack of gravity allowed food and drink to come out of the stomach along with the belch. If you want to imagine the majesty of space, imagine a bunch of astronauts puking soda all over each other.*

http://commons.wikimedia.org/wiki/File:NASA_shuttle_astronaut_drinks_from_a_specially_designed_Coke_beverage_can.jpg

Combustion Reactions

The products of combustion reactions are always CO_2, H_2O, and heat. Any time you something with carbon and hydrogen in it reacts with oxygen gas, you're looking at a combustion reaction.[11] When we burn methane, that's what we see:

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

[11] There are combustion reactions that occur without hydrocarbons (those compounds with C and H), but the vast majority of these reactions can be classified as one of the other types of reaction that I've mentioned here. In reality, it's not the name of the reaction that's important, but whether you can use this information to help you become a better chemist.

Single Displacement Reactions

When you're presented with a single element and a compound that contains two elements, you're probably looking at a single displacement reaction. In the vast majority of these reactions, the single element is a metal and the compound that contains two elements is ionic. An example of a problem like this would look like:

$$Cu + AgNO_3 \rightarrow ?$$

The products of these reactions consist of a different pure element and a different compound that's similar to the first. In this case, we can see that the copper will replace silver, resulting in:

$$Cu + AgNO_3 \rightarrow Ag + CuNO_3$$

Before you get too comfortable with this type of reaction, you need to consider a couple of things:

- The reaction has to produce a product that actually exists in the real world. For example, if you have predicted that Na_2Cl will be formed, you won't be correct because the real formula of sodium chloride is NaCl. This may require you to balance the equation, but since you already know how to do this, that shouldn't be a problem.

- The pure metal on the left side of the element has to be higher on the activity series than the pure metal on the right if the reaction's going to take place.[12] What does this mean? All it means is that, for this type of reaction to occur, the metal that's doing the replacing (the one on the left) has to be more reactive than the one being replaced (the one on the right). If it's not, there won't be any reaction and nothing will happen. The term "activity series" is just a relative list of how reactive the metals are with relation to one another.[13]

Activity series (greater = more reactive)

Li > K > Ca > Na > Mg > Al > Mn > Zn > Fe > Ni > Sn > Pb > Cu > Ag > Pt > Au

more reactive less reactive

As a result, the reaction we mentioned above will occur (because Cu is higher on the activity series than Ag), but the reaction $Fe + Al(NO_3)_3$ will not take place because iron is lower on the activity series than aluminum.

[12] In a single displacement reaction, the elements that are doing the displacing are sometimes halogens. Everything I say here for metals is also true for halogens, and the activity series for halogens is F > Cl > Br > I.

[13] This is also in Appendix 2, along with the activity series for halogens.

Double Displacement Reactions

Double displacement reactions are pretty easy to identify because the two reactants are both ionic compounds. Since the general formula of these reactions is AB + CD → AD + CB, just switch the cations around and write the appropriate formulas to figure out what will be formed:

$$Pb(NO_3)_2 + 2\ KI \rightarrow PbI_2 + 2\ KNO_3$$

Now, there's something important to keep in mind: Double displacement reactions only take place under the following conditions:

- Both of the reactants must be soluble in water.
- Only one of the products can be soluble in water. The other will be a solid.

To figure out if a compound is soluble in water, use the table below (also in Appendix 3):

	$C_2H_3O_2^{-1}$	Br^{-1}	CO_3^{-2}	Cl^{-1}	OH^{-1}	I^{-1}	NO_3^{-1}	O^{-2}	PO_4^{-3}	SO_4^{-2}	S^{-2}
NH_4^+, H^+, alkali metals	S	S	S	S	S	S	S	S	S	S	S
Al^{+3}	S	S	X	S	I	S	S	I	I	S	D
Ba^{+2}	S	S	P	S	S	S	S	S	I	I	D
Ca^{+2}	S	S	P	S	P	S	S	P	P	P	P
Cu^{+2}	S	S	X	S	S	X	S	I	I	S	I
Fe^{+2}	X	S	P	S	I	S	S	I	I	S	I
Fe^{+3}	X	S	X	S	I	S	S	I	P	P	D
Pb^{+2}	S	S	X	I	P	P	S	P	I	P	I
Mg^{+2}	S	S	P	S	I	S	S	I	P	S	D
Mn^{+2}	S	S	P	S	I	S	S	I	P	S	I
Ag^{+1}	P	I	I	I	X	I	S	P	I	P	I
Sr^{+2}	S	S	P	S	S	S	S	S	I	P	S
Sn^{+2}	D	S	X	S	X	S	D	I	I	S	I
Sn^{+4}	S	S	X	S	I	D	X	I	X	S	I
Zn^{+2}	S	S	P	S	P	S	S	P	I	S	I

S = soluble in water (it dissolves)
P = partially soluble in water (some, but not all, of it dissolves)
I = insoluble in water (it doesn't dissolve)
D = decomposes in water (the compound breaks apart in water)
X = unknown (something bad happens to bust up the compound)

Given this table and the criteria, we find that the equation for the reaction of lead (II) nitrate and potassium iodide looks like this:

$$Pb(NO_3)_{2(aq)} + 2\ KI_{(aq)} \rightarrow PbI_{2(s)} + 2\ KNO_{3(aq)}$$

Because both reagents are soluble in water and only one product is soluble,[14] this double displacement reaction occurs in water.

Different Equation Types That Are Often Used With Double Displacement Reactions:

The equation for the reaction above is called the "chemical equation" and it shows just the formulas of the compounds that are forming. However, there are other ways to describe the action in a chemical reaction:

- **Complete ionic equations** show what happens to all of the ions when you put them in water. To write one, write the formulas of each dissolved ionic compound in the form of its separated ions, rather than as a chemical compound. The complete ionic equation for the reaction of lead (II) nitrate with potassium iodide is:

$$Pb^{+2}{}_{(aq)} + 2\ NO_3^{-1}{}_{(aq)} + 2\ K^{+1}{}_{(aq)} + 2\ I^{-1}{}_{(aq)} \rightarrow PbI_{2(s)} + 2\ K^{+1}{}_{(aq)} + 2\ NO_3^{-1}{}_{(aq)}$$

- **Net ionic equations** show you only the ions that actually take part in any chemical reaction. For example, if we look at the complete ionic equation for the reaction above, we see that the nitrate and potassium ions remain unchanged during the reaction. As a result, we can ignore them as "spectator ions" and write the following net ionic equation:

$$Pb^{+2}{}_{(aq)} + 2\ I^{-1}{}_{(aq)} \rightarrow PbI_{2(s)}$$

Acid-Base Reactions

If you see something that starts with H and another compound that ends with OH, you're looking at an acid-base reaction. The products of these reactions will be an ionic compound and water:

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

Unlike double displacement reactions, there are no particular limitations on the states of the reactants or products of these reactions.

[14] The insoluble product is a solid called a "precipitate" and in the reaction will appear as the formation of either a milky liquid or chunky solid.