Inorganic Chemistry
Lesson 7
Acidic oxides. Acids. Chemical calculations.

October 28, 2018

Mole

One of the most common operations any chemist is doing routinely is as follows: "How much of the substance A is needed to produce a substance B?", or "How much of the substance B is needed to react with the substance A?"

For example, consider the following reaction:

$$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_{2(g)} \tag{1}$$

In this reaction, zinc (atomic weight 65 Da) interacts with sulfuric acid (molecular weight 98 Da). Obviously, since one molecule of zinc[1] reacts with one molecule of sulfuric acid, we may replace Daltons with grams, and conclude 65 *grams* of zinc are needed to react with 98 *grams* of sulfuric acid. In other words, the amount of particles (molecules) in 65 grams of zinc is equal to the amount of particles in 98 grams of sulfuric acid. Generally speaking, from the chemist's point of view, the amount of matter in 65 grams of zinc and in 98 grams of H_2SO_4 is the same. Indeed, we chemists are more interested in looking at molecules, and we do not care too much about their weight, because it is the number of molecules that matters, not their weight. That is why for us it is much more convenient to measure matter not in grams, but in other units that take into account the number of molecules. This unit is called a *mole*.

One mole of any substance is the amount of this substance in grams that is numerically equal to the molecular weight of this substance in daltons. For example, the molecular weight of hydrogen (H_2) is 2 Da, and, accordingly, one mole of hydrogen weighs 2 grams. Accordingly, one mole of nitric acid (HNO_3, MW = 63) is 63 grams, one mole of calcium carbonate ($CaCO_3$, MW = 100 Da) is 100 grams, and so on.

The concept of mole is one of the most fundamental chemical concepts. It makes chemical calculations much easier, and we will be using this concept very frequently.

[1]Since metals do not form polyatomic molecules, for our purposes, zinc atom and zinc molecule is the same thing. This is true for all other metals.

Homework

1. Draw the structural formulas of the following compounds:

   HNO_3, H_3BO_3, Cr_2O_3, Cl_2O_7, C_2H_6, K_2SO_4.

   Based on these structural formulas, decide which compounds from this list are acids, and name these acids using the rules we discussed in the class (the rules are available in the previous class reading materials).

2. Draw structural formulas for the following acids:

   a) phosphoric acid, b) nitric acid, c) chloric acid[2], d) sulfurous acid, e) silicic acid.

3. Iodine is the element that can exist in four different valence states. Can you tell, what is the relationship between the term "periodic acid" and the term "periodicity"?

4. A 20 g sample of the mixture of quartz sand[3], iron shavings, and graphite was treated with dilute sulfuric acids, and the gas formed was collected. When evolution of the gas has ceased, more acid has been added to the sample, but no reaction was observed after that. The total volume of the gas was 4 L. What is the content of iron shavings (in percents) in the mixture[4]?

5. You have four pieces of different metals: calcium, magnesium, iron, and zinc. The mass of each piece is 40 g. Which piece contains the biggest and the smallest number of atoms? If you add an excess of dilute H_2SO_4 to each piece, what will be the volume of hydrogen that forms in each case?

1 Inorganic Chemistry Lesson 8

Salts and their reactions.

Reaction of active metals with water.

Bases, basic oxides, and their interaction with acids.

November 3, 2018

[2]Chlorine is pentavalent in chloric acid.
[3]Quartz is a crystalline silicon oxide.
[4]At room temperature and under atmospheric pressure, two grams of hydrogen occupy 22.4 L.

2 Nomenclature of salts

Before we started to discuss reactions of salts, and methods of their preparation, we need to know how to name them. Since salt are composed of some acidic residue[5] and a metal atom (or atoms), it would be logical to derive salt's name from the names of corresponding acids and metals. That is exactly what chemists do. The salt nomenclature (naming rules) are simple and straightforward. The rules are as follows.

Rule 1. (for non-oxygen acids):
The name of a salt formed by some metal and some non-oxygen acid is formed by combining the metal's name and the name of the acid. The prefix 'hydro' is removed, and the ending 'ic' is replaced with 'ide'
Examples Hydrochloric (*hydro*-chlor-*ic*) acid (HCl) and sodium form a salt named 'sodium chlor*ide* (NaCl).
Calcium and hydrochloric acid form calcium chloride $CaCl_2$.[6]
Rule 2. (for oxygen containing acids)
In salts formed by 'ic' acids, the ending 'ic' is replaced with 'ate'.
Examples Carbonic (carbon-*ic*) acid, H_2CO_3 and sodium form a salt named 'sodium carbon*ate* (Na_2CO_3).
Sulfur*ic* acid and calcium from a salt named 'calcium sulf*ate* ($CaSO_4$).
Rule 2a. (for 'ous' acids).
In salts formed by 'ous' acids, the ending 'ous' is replaced with 'ite'.
Examples. Sulfur-*ous* acid (H_2SO_3) and sodium from a salt named 'sodium sulf*ite* (Na_2SO_3).
Nitr*ous* acid (HNO_2) and potassium from a salt named potassium nitr*ite* (KNO_2).

Since the acids whose name starts with 'hypo' or 'per' also can form salts, a separate rule exists for that type acids. This rule is simple.

Rule 3.(for the acids whose names begin with 'per' or 'hypo'.)
If acid's name starts with the prefixes 'per' or 'hypo', such a prefix is preserved in the salt's name.
Examples. A salt formed by sodium and *hypo*chlor*ous* acid (HClO) acid is called 'sodium *hypo*chlor*ite*' (NaClO). A salt formed by sodium and *per*chlor*ic* acid ($HClO_4$ is called 'sodium *per*chlor*ate*' ($NaClO_4$).

We are almost finished with the rules. There is one more rule; it deals with a situation when a metal can exist in more than one valence state. For example, iron can be either di- or trivalent, and, accordingly, it can from two different salts with hydrochloric acid. Their formulas are $FeCl_2$ and $FeCl_3$. As we can see, both these salts are 'chlorides'. Two alternative

[5] Acidic residue is what is remaining when one or several hydrogens have been removed from the acid's molecule.

[6] In school, you may be requested to include numerals into the salt's name. For example, instead of 'calcium chloride' ($CaCl_2$) you should say 'calcium *di*chloride', instead of 'aluminum chloride' ($AlCl_3$) you should say 'aluminum *tri*chloride', etc. Although that is not incorrect, chemists prefer not to do that. During our lessons we will not use numerals unless that is absolutely necessary.

ways exist to create unique names for each of them. Firstly, we can show metal's valence using a Roman number.

> **Rule 4a.**
> *When more than one valence states is possible for some metal, its valence can be indicated with a Roman letter after the metal name.*
> **Examples.** The name of $FeCl_2$ is 'iron (II) chloride'. The name of $FeCl_3$ is 'iron (III) chloride'.

Another possibility is to add the ending 'ous' or 'ic' to the *Latin* name of the metal. The meaning of these prefixes is the same as for acids: lower valence is denoted by 'ous', whereas higher valence by 'ic'.

> **Rule 4b.**
> *When some metal is in a lower valence state, that fact can be indicated by adding the ending 'ous' to its Latin name. For metals in a higher valence state, the ending 'ic' is used.*
> **Examples.** A Latin name of iron is 'ferrum', therefore $FeCl_2$ is called 'ferr*ous* chloride', and $FeCl_3$ is called 'ferr*ic* chloride'. In Latin, copper's is called 'cuprum', therefore, their salts have names 'cuprous chloride' (CuCl), and 'cupric chloride' ($CuCl_2$).

This is an almost exhaustive set of rules. Most salts are named according to them. I neither expect nor want you to memorize all these rules, I presented them just to demonstrate that the rules are relatively simple. However, in future, you will use these rules frequently, and you know where can you find them: they will always be at our school's web site. The most frequently used rules are Rule 1 and Rule 2, sometimes, a Rule 4a. We will need them right now, during this lesson.

3 Reactions of salts with metals. More on the reactivity series.

Experiment 15a

Pour 5 mL of the solution of copper (II) sulfate ($CuSO_4$) into a test tube, and immerse an iron rod into it. Describe your observations.

After 5 minutes, the rod becomes reddish; the red film become more and more thick, and finally it peels off like a red sponge. It is easy to demonstrate that this is a copper metal. If we wait long enough we can see that a blue color of the copper sulfate solution gradually disappears, and the solution becomes pale greenish. This color belongs to another salt, iron (II) sulfate. Obviously, a chemical reaction occurs, and we can write the following equation for it:

$$Fe + CuSO_4 = FeSO_4 + Cu \tag{2}$$

As in the case of iron and sulfuric acid, a substitution reaction occurs, however, instead of elementary hydrogen, another simple substance, copper, is formed. Is such a reaction common for an arbitrary salt-metal pair? Let's try to think logically. Since a chemical reaction will hardly go into the opposite directions under the same conditions, swapping the sides in the equation 2 would lead to the equation describing the reaction that doesn't go normally. Actually, this consideration is totally correct: it is easy to demonstrate that reaction is not possible.

Experiment 15b

Pour 5 mL of the solution of iron (II) sulfate ($FeSO_4$) into a test tube, and immerse a piece of copper wire into it. Do you see any reaction?

As we expected, no reaction takes place.
Maybe, this reaction is specific to copper sulfate only? Let's check that.

Experiment 15b

Pour 5 mL of the solution of silver nitrate ($AgNO_3$), and immerse a piece of copper wire into it. What do you see?

We see that lustrous crystals quickly form on the copper surface, and that the colorless solution becomes green-blue. It is easy to demonstrate that the crystals we obtained are a silver metal. With regard to the color, it is characteristic for most copper salts, so we can conclude some copper salt, is formed. Indeed, a chemical analysis can demonstrate a new salt forms, a copper nitrate. The equation of this reaction is as follows:

$$\mathrm{Cu} + 2\,\mathrm{AgNO_3} = \mathrm{Cu(NO_3)_2} + 2\mathrm{Ag} \tag{3}$$

Again, similar to the of iron and copper sulfate case, a new metal and a new salt form. It is easy to demonstrate that the opposite reaction wouldn't go.

Do those reaction have anything in common? Yes. First of all, these reactions are *substitution reactions*. Secondly, in each of those reaction, one metal substitute another in its salt. Thirdly, there reactions go in one direction (copper sulfate reacts with iron), and do not go in another (iron sulfate does not react with copper). It is also easy to demonstrate that the acidic residue does not affect this reaction: for example, copper chloride and copper sulfate react similarly. All of that can be summarized as follows: copper *salts* react with iron to produce copper *metal*, silver *salts* react with copper to produce silver *metal*. It can be demonstrated that other metals, such as zinc, tin, etc, produce silver in the reaction with silver nitrate, but gold or platinum do not react with $AgNO_3$. Can we summarize all these facts in some simpler rule? We can try. To do that, let's look at the reactivity series again.

Reactivity series of metals
K, Na, Li, Ca, Mg, Al, Ti, Mn, Zn, Cr, **Fe**, Co, Ni, Sn, Pb (H) **Cu**, W, Hg, **Ag**, Au, Pt

As we can see, the metals we experimented with are arranged in the following order (in terms of their reactivity): iron is left of copper, and copper is left of silver. It can be easily demonstrated that rule is general: all metals left of tin are able to substitute it from tin salts, all metals left of gold can substitute it from gold salts, and so on. This is a general rule the reactivity series was built on. And it can be summarized as follows:

> **More active metals substitute less active metals from their salts. The opposite reaction does not go.**

4 Reactivity series and hydrogen

Let's look again at these two equations:

$$Fe + CuSO_4 = FeSO_4 + Cu \tag{4}$$

and

$$Fe + H_2SO_4 = FeSO_4 + H_2 \tag{5}$$

Clearly, they have much in common: both of them are substitution reactions, in both of them one element substitutes another element from its compound. The only difference is that in the first case iron reacts with salt, and in the second case it reacts with acid. This comparison explains why did we put hydrogen into the reactivity series: the metals left of hydrogen are more active than hydrogen, and they substitute hydrogen from acids (in the same manner they substitute, for example, copper or silver from their salts). In contrast, the metals left to hydrogen are less active, so they cannot substitute it from acids.
The reactivity series is a first example of an empiric law that allows us not only to describe chemical reactions, but also to predict their outcome. There are many similar law in chemistry that make it not just a random collection of facts, but a systematic science. We will learn many of them during this and the next year.

5 On the very left part of the reactivity series.

As we already know, all metals left of hydrogen are able to react with acids to produce hydrogen. The closer to the left end of the series they are, the more actively they react with acids. Thus, almost no reaction takes place between acetic acid and iron; zinc does react with acetic acid, although very slowly; magnesium reacts with acetic acid very actively. In other words, active metals are capable of substituting hydrogen even from the molecules that are not willing to easily donate hydrogen. What about more active metals, the metals left of magnesium? Those metals (shown in bold below) are so active that they react too violently even with acetic acid.

Reactivity series of metals
K, Na, Li, Ca, Mg, Al, Ti, Mn, Zn, Cr, Fe, Co, Ni, Sn, Pb (H) Cu, W, Hg, Ag, Au, Pt

Figure 1: Reaction of sodium with water. A liquid sodium ball in the left is partially covered with a water mist.

We know water contains hydrogen, but its hydrogen is not too active (at least, no hydrogen is formed when water is added to zinc or iron). We also know that common metals are not capable of substituting hydrogen from water. Let's see if active metals can do that.

Experiment 16

Pour 100 mL of water into a glass beaker. Take approximately 1/4 gram of sodium metal, carefully drop it into the beaker, and immediately cover the beaker with a glass funnel. Attach a test tube to the narrow end of the funnel as shown on the Fig. 1 . When the reaction is complete, remove the test tube (do not flip it) and bring a burning candle to the tube's neck. Describe your observations.

We can see sodium's behavior differs dramatically from what we expect from a metal. It reacts with ordinary water, a compound we usually consider inert (not active) in normal conditions, and some gas is formed during that reaction. The reaction is so violent, that the sodium melts and collapses into a lustrous ball on the water surface.[7] As we demonstrated, the gas formed during this reaction is combustible,[8] and it is lighter than air (it goes up, and it stays in the test tube when its neck is pointing down). We will see later that are the properties of hydrogen. We can conclude therefore that reaction of sodium with water produces the same gas we obtained during the reaction between zinc and hydrochloric acid, i.e. hydrogen. Had we tried to evaporate the remaining liquid in the beaker,[9] we would obtain a white soapy substance with a formula 'NaOH'. Therefore, the equation of this reaction can be written as follows:

$$2\mathrm{Na} + 2\,\mathrm{H_2O} = \mathrm{H_2} + 2\mathrm{NaOH} \tag{6}$$

In this equation, one compound (NaOH) has a formula we have never seen before. It is not an oxide, not a salt, and not an acid. We have never dealt with a compound of such a type before. Definitely, NaOH belongs to a new type of compounds.

6 Hydroxides, bases and alkali.

A compound with a formula NaOH can be represented as an analog of sodium oxide Na_2O, where one sodium atom has been replaced with a hydrogen atom:

Na—O—Na

Sodium oxide

Na—O—H

Sodium *hydr*oxide

[7]Density of sodium is smaller than the density of water, so sodium does not sink in water.
[8]Sometimes, sodium becomes so hot during this reaction that the gas ignites spontaneously.
[9]We will not do that for safety reasons.

It is intuitively clear why we call it “hydroxide”: in this substance, one oxygen’s valence is occupied by a hydrogen atom, and this diatomic particle, which is called a “hydroxy group”, forms a compound with the atom of metal (in this concrete case, sodium).

> **Hydroxides are the compounds with general formula $M(OH)_n$, where M denotes some element, and ‘n’ (a number of hydroxy groups) is equal to the element’s valence. Hydroxides, form another major class of inorganic compounds.**

Examples of hydroxides are calcium hydroxide $Ca(OH)_2$, magnesium hydroxide $Mg(OH)_2$, aluminum hydroxide $Al(OH)_3$.

6.1 Nomenclature of hydroxides

In contrast to acids, there is almost nothing you need to remember about names of hydroxides. The hydroxide’s name is created by combining the element’s name and the word “hydroxide”, in the same way we did in the end of the previous section. A situation is a little bit more complicated for the elements that can exist in more than one valence state. As a rule, such elements can form more than one hydroxide. In that case, you must denote the element’s valence with a Roman numeral. For example iron forms two hydroxides: iron (II) hydroxide ($Fe(OH)_2$), and iron (III) hydroxide ($Fe(OH)_3$).
That’s all what we need to know about hydroxides naming rules.

6.2 Preparation of hydroxides. Part I.

Our observations we made during the Experiment 16 can be generalized: it is natural to expect other metals in the left part of the reactivity series are able to react with water. This our hypothesis is correct, and it is easy to prove experimentally that potassium, lithium, calcium, as well as some other active metals not included in the reactivity series[10] produce hydrogen and hydroxides during their reaction with water according to the scheme:

$$\mathrm{Me} + \mathrm{H_2O} \longrightarrow \mathrm{H_2} + \mathrm{Me(OH)_n} \tag{7}$$

where Me denotes some active metal, and ‘n’ is the metal’s valence. **Reaction of active metals with water is the first method to obtain hydroxides.** Is it the only method? Apparently, no. Alternative ways to prepare of hydroxides exist.

Experiment 17

Place approximately 10-20 grams of calcium oxide[11] *into a glass beaker or a steel bowl. Add approximately 10 mL of water to it. What happens to the solid? Carefully touch an external surface of the beaker. What do you feel?*

[10] Remember, we are dealing with a short version the reactivity series: some other metals, besides potassium, sodium, lithium and calcium, are capable of reacting with water to produce hydrogen and hydroxides.

[11] Calcium oxide (CaO) is known under a name “quick lime”.

We can see that during this experiment a thin white powder of calcium oxide absorbs water and swells. The volume of the solid increases, and large amount of heat evolves. The reaction mixture becomes so hot that water we added starts to boil, and a cloud of steam forms above the beaker. The compound that forms during this reaction is calcium hydroxide ($Ca(OH)_2$). Since ancient times, it is being used to prepare a mortar, or a lime slurry. Until XIX century, when modern cement had been invented, slaked lime was vital and indispensable for construction. The equation of this reaction is:

$$CaO + H_2O = Ca(OH)_2 \tag{8}$$

Due to its practical importance, this reaction has its own name: "slaking",[12] and, accordingly, the technical name of calcium hydroxide is "slaked lime".

Ancient people started to use slaked lime long before a concrete had been discovered. They used it to prepare lime mortar, a paste to bind bricks or stone construction blocks together. During several months after the construction ended, the binding mixture was becoming harder and harder, and eventually it converted into some artificial stone. An astonishing longevity of ancient Roman aqueducts and bridges (for example, the aqueduct at the figure 2), which had been built more than two thousand years ago, and, nevertheless, remain virtually unchanged, may serve as a perfect demonstration of an excellent quality of the lime mortar cement. During this and the next lesson we will learn about the chemistry behind that phenomenon.

Calcium oxide is not the only oxide capable of formation of hydroxides. Many other oxides, such as sodium oxide or potassium oxide, react with water. The equation of the reaction of sodium oxide and water is as follows:

$$Na_2O + H_2O = 2NaOH \tag{9}$$

The reaction between metal oxides and water is the second way to prepare hydroxides.

7 Soluble hydroxides and their properties. Bases. Alkali.

Now it is a time to look at the properties of the compounds we prepared during the experiments 16 and 17.

[12] This term refers only to the reaction of calcium oxide and water. No special term exist for the reaction of other oxides.

7.1 Sodium hydroxide.

Sodium hydroxide (NaOH), also known as lye is a white highly hygroscopic solid with a slippery feeling upon contact.[13] It is highly soluble in water; its dissolution is a highly exothermic process. Accordingly, sodium hydroxide belongs to a family of compounds called "soluble hydroxides". Another common name for soluble hydroxides is "alkali".

Soluble metal hydroxides are called "alkali".

A solution of NaOH corrodes skin, paper, fabric, and many other materials changes the color of a standard indicator paper to deep blue, which corresponds to pH values above 13. Addition of few drops of the phenolphtalein[14] solution produces a purple color. This is indication that sodium hydroxide is *basic.* Basicity is a common property of soluble hydroxides, such as potassium hydroxide (KOH) and lithium hydroxide (LiOH).

7.2 Calcium hydroxide.

In contrast to sodium hydroxide, calcium hydroxide is poorly soluble in water. However, its water solution, a so called "lime water",[15] is also basic, because it produces a pink color when a colorless solution of phenolphtalein is added to it. Other moderately soluble hydroxides, such as silver hydroxide (AgOH) have similar properties.

7.3 Properties of soluble hydroxides. Reaction with acids ("Neutralization").

Thus we have learned that the alkali are "basic". We also know acids are "acidic". So far, we do not fully understand what does it mean, however, we know that a standard indicator paper becomes red in an acid media, and it becomes deep-blue in a basic media. We also know that an indicator dye, phenolphtalein, becomes pink in a presence of a base. In connection to that, it is interesting to see what happens when an acid and a base are mixed together.

Experiment 18.

Pour 100 mL of 4% solution of sodium hydroxide into a glass beaker and add few drop of phenolphtalein solution to it. Using a pipette, gradually add a 3.7 % dilute solution of hydrochloric acid to the beaker. When a pink color disappeared, record the volume of the HCl solution you added. Pour the solution obtained into a porcelain bowl and evaporate on open fire. What did you obtain?

Interestingly, during this experiment, exactly 100 mL of the HCl solution are needed for the pink color to disappear. What conclusion can be drawn from that fact? You have

[13] Actually, you should never touch it! It is very corrosive, so in a case of contact with your skin you must immediately rinse it with large amount of water until a slippery feeling disappears.

[14] An indicator. This substance is colorless, but it becomes purple when a common pH paper becomes deep-blue.

[15] We are already familiar with it. Do you remember what we used it for?

probably noticed that the concentration of both solutions was chosen in such a way that equal volumes of NaOH and HCl solutions contained equal number of NaOH and HCl molecules. Indeed, the molecular weight of NaOH in 40 Da (23 + 16 + 1 = 40), and the molecular weight of HCl is approximately 37 (35.5 + 1 = 36.5). That means, 100 mL of 4% NaOH solution contain 4 g of NaOH; the same volume of 3.7% HCl solution contains 3.7 g of HCl, and these amounts are proportional to the molecular masses of NaOH and HCl, accordingly. In other words, by the end of our experiment, one HCl molecule have been added per one NaOH molecule. What we obtained as a result of that addition? Clearly, the solution is not basic any more: a pink color of phenolphtalein had disappeared. Is it acidic? No. An indicator paper immersed into the solution does not become red.

It is easy to demonstrate that, when the order of addition changes (in other words, if 100 mL of a 4% NaOH solution will be added to 100 mL of 3.7% HCl solution), the result will be the same.

That means an acid and a base, when mixed together, “destroy”, or “eliminate” each other: an acid eliminates “basicity”, and a base eliminates “acidity”. Such a mutual elimination is called “neutralization”.

> **An acid and a base react with each other. Such a reaction is called “neutralization”. The resulting solution is neither acidic nor basic; it is “neutral”.**

What is a product of the neutralization reaction? Evaporation of the solution obtained in the Experiment 18 yields white crystals having a cubic shape. The shape of the crystals, their density, hardness, melting temperature, and other physical properties[16] are totally identical to the properties of common salt. Therefore, we can conclude the product of this reaction is sodium chloride (NaCl), and the reaction’s equation is as follows:

$$\mathrm{NaOH + HCl = NaCl + H_2O} \tag{10}$$

(The fact that the second product of this reaction is water also can be confirmed experimentally. However, we are not doing that because of the lack of time.)

Other hydroxides react with hydrochloric acid similarly. For example, calcium hydroxide produces calcium chloride ($CaCl_2$):

$$\mathrm{Ca(OH)_2 + 2HCl = CaCl_2 + 2H_2O} \tag{11}$$

Other acids are also react with the bases in the same way. Thus, potassium sulfate is formed in the reaction between potassium hydroxide and sulfuric acid:

$$\mathrm{2KOH + H_2SO_4 = K_2SO_4 + 2H_2O} \tag{12}$$

[16] Of course, we have neither an opportunity nor time to do all those measurement in the class, but, have we done that, we would obtain exactly the same results.

Numerous experiments demonstrated that every acid and every hydroxide can react with each other to produce salt and water, and this is a fundamental property of every base and every acid.[17] These observations had been summarized by a Swedish chemist Svante Arrhenius, who proposed a first definition of the term "bases".

> **Bases are the compounds that are capable of donating a hydroxy group in reaction with acids. Acids are the compounds donating hydrogen in a reaction with bases. The products of the reaction between an acid and a base (a neutralization reaction) are salt and water.**

Figure 2: Svante Arrhenius (1859-1927)
A men who proposed the first definition of "acids" and "bases".

Historically, this is a first definition of the terms "acid", "base" and "salt". Current definitions of the terms "acid" and "base" are somewhat broader. However, since these old definitions work perfectly for our purposes, we will stick with them during this school year.

7.4 Reaction of bases with acidic oxides.

If we pour transparent lime water in a glass beaker and blow bubbles through it, the water will become turbid in few minutes. What happens during this reaction? In this reaction, carbon dioxide you exhale react with calciun hydroxide according to the equation:

$$\mathrm{Ca(OH)_2 + CO_2 = CaCO_3 + H_2O} \tag{13}$$

The salt that forms during this reaction is calcium carbonate, aka calk, or limestone, of marble. Since this compound is insoluble in water, even small amount of CO_2 are sufficient to turn a clear and transparent lime water (i.e. $Ca(OH)_2$ solution into a turbid suspension. More importantly, a solid $Ca(OH)_2$ is also capable of reacting with atmospheric CO_2, which leads to a gradual conversion of soft, semi-soluble slaked lime ($Ca(OH)_2$) into a rock-solid limestone ($CaCO_3$).

As we can see, in this reaction, a salt, is formed not in a reaction between an acid and a base, but in the reaction between an *acidic oxide* and a *base*.
Again, that is a common property of all bases:

> **Bases are capable of reacting with both acids and acidic oxides to form salts. The same salt is formed in the reaction with an acid and a parent acidic oxide.**

A question. Do you understand now the chemical mechanism of the astonishing longevity of Antique Roman aqueducts, bridges and buildings?

[17] Of course, when the acid is too weak and the hydroxide is poorly soluble, such a reaction would be too slow to be detected.

8 Bases and basic oxides.

From the section 2.2, we know that some metal oxides are capable of reacting with water, and the metal hydroxide is a major product of such a reaction. In connection to that, it is interesting to compare that reaction with the reaction we studied during the Lesson 6 (section 2). As we already know, the product of the reaction between phosphorus (V) oxide and water is phosphoric acid:

$$P_2O_5 + 3\,H_2O = 2\,H_3PO_4 \tag{14}$$

Let's compare it with a reaction between calcium oxide and water (equation 8). Since phosphorus (V) oxide produces an acid, we call it, as well as all other oxides of that type, an "acidic oxide". Accordingly, it would be logical to introduce a term "basic oxide" to denote an oxide that produces a base in reaction with water.

Basic oxides are the oxides that react with water to produce a base.

8.1 Reaction of basic oxides with acids.

In the previous section, we found that acids and acidic oxides yield the same product in a reaction with acids. What about the bases and the basic oxides?

Experiment 19.

Put 1-2 grams of calcium oxide into a glass beaker. Add 10 mL of dilute acetic acid to it. When the reaction stopped, put the beaker on a how plate and gently evaporate to dryness.[18] *What did you obtain?*

The solid we obtained is a salt called "sodium acetate". It is the same salt you would obtain, had you taken calcium hydroxide instead of calcium oxide. Again, we can experiment with a various basic oxides and acids, and the result will be the same:

Acids are capable of reacting with both bases and basic oxides to form salts. The same salt is formed in the reaction with an base and a parent basic oxide.

You have probably noticed that the above statement mirrors the statement from the section 3.4: the only difference between them is that the words "acid" and "base" have been swapped.[19] Such a symmetry is not merely a coincidence. Let's talk about that during the next lesson.

Homework

1. A tin-led alloy or silver can be used as a solder to connect copper parts together. Imagine you have two copper vessels. One of them was made using a tin-led solder.

[18] Actually, we will not do this experiment, because it should be done either in the fume hood or on open air: although the vapors of acetic acid are not toxic, they have a very unpleasant odor.

[19] That is what I actually did: I used copy-past to save time.

Silver was used to solder the parts of another vessels. Can these vessels be used to store dilute hydrochloric acid?

2. Brass is a copper and zinc alloy. Depending on a zinc/copper ratio, it may have different properties. You have brass shavings with unknown zinc content. You took 5 grams of those shavings and added 200 mL of 20% HCl[20] to them. You used an apparatus (similar to that we used for preparation of oxygen) that allowed you to collect all gas that forms during that reaction. When the reaction was complete (evolution of the gas ceased) you measured the gas volume, and found that 0.4 L of some gas was formed. Can you determine a zinc content (in percents) in the brass using these data? For your calculations, you can use the fact that at room temperature and under atmospheric pressure, two grams of hydrogen occupy 22.4 L.[21]

3. It is a good time to start summarizing what we learned during previous lessons. Please, answer, how many major classes of inorganic compounds have we currently learned? Can you list them, and briefly describe their properties?

4. Since we are starting to discuss properties of various chemical compounds (we already know almost all major classes of inorganic compounds), we need to practice in naming them. Please, name the following compounds:
   a. $Al(OH)_3$
   b. $FeSO_3$
   c. H_3PO_4
   d. $MgCO_3$
   e. $CuOH$
   f. Al_2O_3
   g. $Sn_3(PO_4)_2$
   h. K_2SO_3

5. Write formulas and name the compounds formed during the reaction between:
   a. Silver hydroxide and nitric acid.
   b. Calcium and oxygen.
   c. Sodium hydroxide and sulfur (VI) oxide.
   d. Magnesium and hydrochloric acid.
   e. Iron (II) oxide and hydrochloric acid.
   f. Carbon and oxygen.
   g. Iron and dilute sulfuric acid.[22]
   h. Silicon oxide and potassium hydroxide.

6. Propose a reaction scheme (draw each equation separately) for the following transformation:

[20] '20%' means that 100 mL of solution contains 20 grams of HCl.

[21] Generally speaking, if a mass of one molecule of some gas is X Da, then X *grams* of this gas will occupy a volume of 22.4 L at room temperature and atmospheric pressure. This is a general law named 'Avogadro's' law (after its discoverer, Amedeo Avogadro).

[22] When polyvalent metals, such as iron, react with acids, a salt is formed where the metal has the lowest possible valence.

a.

$$Ca \longrightarrow CaO \longrightarrow Ca(OH)_2 \longrightarrow Ca_3(PO_4)_2 \tag{15}$$

b.

$$S \longrightarrow SO_2 \longrightarrow MgSO_3 \tag{16}$$

c.

$$C \longrightarrow CO_2 \longrightarrow Na_2CO_3 \tag{17}$$

d.

$$Na \longrightarrow NaOH \longrightarrow Na_3PO_4 \tag{18}$$

7. Propose three different reactions to prepare each of the following compounds:
   a. Calcium chloride.
   b. Iron (II) sulfate.
   c. Aluminum nitrate.

8. Propose four different reactions to prepare sodium phosphate Na_3PO_4.

9. You took 20 grams of calcium oxide, added 300 mL of 10% HCl, and evaporated the solution obtained to dryness. What is the formula of the solid you obtained? What is its mass?

10. A piece of zinc reacted with dilute hydrochloric acid in the apparatus that allowed you to collect all the gas formed. The zinc dissolved completely, and the volume of gas you collected was 35L. What is the amount of the second product formed during this reaction? What was the amount of zinc taken?[23]

11. Pont du Gard aqueduct was built 2000 years ago. It is still rock-stable. What chemical reaction is behind its outstanding stability? (A hint: we discussed this reaction in the class).

As usual, I would be grateful if you sent me your homework by evening of next Saturday. My e-mail is mark.lukin@gmail.com.

If you want to draw structural formulas using your computer, you may try to download a free program that does it. To install this progtam on your computer, go to the download page: `http://www.simulations-plus.com/software/medchem-designer/` and press a **Download** button.

> **This software is provided by a company that develops more sophisticated software for researchers and industry, so it is safe to download this program.**

[23] Just to remind you. In this problem, you should use the Avogadro's law: if a mass of one molecule of some gas is X Da, then X *grams* of this gas will occupy a volume of 22.4 L at room temperature and atmospheric pressure.

Figure 4: Janus, a two-faced Roman god.

To complete downloading procedure, ask the questions about you. I myself just typed my home address and answered all questions pretending I am a school student. It worked.

9

Inorganic Chemistry
Lesson 10
Water: a base or an acid?
Interrelation between bases and acids.
Classification of chemical reactions. Exchange reactions. Preparation of salts, acids, hydroxides. Genetic linkage between major classes of inorganic compounds. December 10, 2018

10 Water: a Janus molecule

In Roman mythology, Janus (aka Ianus Bifrons, i.e. "Janus the two-faced") was a god of time and transitions, of beginnings and endings, of doors and gates. He was usually depicted as having two faces, directed to the future and to the past. The first month of a year, "Ianuarium" (January) was named after him.

During the previous lesson, we learned about the Arrhenius' definition of acids and bases. It says:

> **Bases are the compounds capable of donating a hydroxy group in reaction with acids. Acids are the compounds donating hydrogen in a reaction with bases.**

In connection to that, it is interesting to look at water. Which class of inorganic compounds does it belong to? On the one hand, during the reaction with active metals it behaves as an acid: it forms a hydrogen gas and some metal-containing compound.

$$2Na + 2\,H_2O \longrightarrow H_2 + 2NaOH \tag{19}$$

On the another hand, this reaction leads to formation of a hydroxy containing compound, i.e. a base. In that sense, water can be considered a “Janus molecule”, a molecule with two faces. It can donate hydrogen, thereby demonstrating an acidic behavior, however, such a donation would inevitably lead to formation of a hydroxy group, which is a typical property of a base. In other words, water is simultaneously a base and an acid, and, therefore, it is neither the former nor the later. Water is *neutral*, and its formation is a final result of any reaction between an acid and a base.[24] As we have seen during the previous lesson, the basic and acidic oxides also participate in similar reactions.

To summarize, reactions between the following classes of compounds lead to formation of a salt and water:

1. **Reaction between acids and bases:**

$$H_2SO_4 + 2NaOH \longrightarrow Na_2SO_4 + 2H_2O \tag{20}$$

2. **Reaction between acidic oxides and bases:**

$$SO_3 + 2NaOH \longrightarrow Na_2SO_4 + H_2O \tag{21}$$

3. **Reaction between basic oxides and acids:**

$$Na_2O + H_2SO_4 \longrightarrow Na_2SO_4 + H_2O \tag{22}$$

As you can see, all three reactions yield the same products, sodium sulfate and water. Obviously, other acids, bases and oxides behave similarly. This is a fundamental property of most oxides, acids, bases.

11 Four major types of chemical reactions.

Before we continue to move further, let’s take a break and discuss reaction types. We have already learned about many chemical reactions, and we will learn about many more reactions in future. It would be senseless and useless to start to mechanically memorize each of them. Instead of memorizing, and to avoid possible confusion, it is desirable to introduce some general terminology to describe chemical reactions, and to separate them onto several classes.

Overwhelming majority of chemical reactions fit four *abstract basic types*. In our case, “abstract” means that the concrete nature of reactants or products does not matter for this classification: instead of formulas of concrete chemical compounds, we denote the reactants and products using Latin letters ‘A’, ‘B’, etc. Using such a notation, four generic chemical equations can be written, each of them defining some basic type of chemical reaction. All chemical reactions we are already familiar with, as well as most chemical reactions we will study in future belong to one of those four types. These types are listed below.

[24] Of course, I mean the acids and the bases that fit the Arrhenius definition.

11.1 Synthesis, or addition.

$$A + B \longrightarrow C \tag{23}$$

In this chemical reaction, two (or more) different molecules combine together to produce a single compound. Oxidation of elementary substances is the example of such a reaction. Concrete examples are:

1. Combustion of carbon:
$$C + O_2 \longrightarrow CO_2 \tag{24}$$

2. Combustion of magnesium:
$$Mg + O_2 \longrightarrow MgO \tag{25}$$

11.2 Decomposition.

$$A \longrightarrow B + C \tag{26}$$

In this reaction, some compound decomposes onto two or more substances (elementary substances or compounds). We already know many examples of that type reaction. Below are two of them:

1. Decomposition of mercury oxide:
$$HgO \longrightarrow O_2 + Hg \tag{27}$$

2. Decomposition of hydrogen peroxide:
$$H_2O_2 \longrightarrow H_2O + O_2 \tag{28}$$

11.3 Substitution, or replacement.

$$A + BC \longrightarrow AC + B \tag{29}$$

On this scheme, 'BC' and 'AC' denote some molecules composed of two parts: B and C, or A and C, accordingly. A, B, and C can be either a single atom, or a group of atoms. As we can see from the scheme, during this reaction, called a "substitution reaction", or "replacement reaction"[25] some atom or group of atoms substitutes an atom, or a group of atoms from another compound. Two new substances are formed as a result. During two previous lessons, we have learned about many examples of the substitution reaction. Two typical examples are shown below.

[25] The former term is being used by scientists, the latter term is popular in school textbooks.

1. Reaction of iron with sulfuric acid:

$$Fe + H_2SO_4 \longrightarrow FeSO_4 + H_2 \tag{30}$$

In this reaction, iron *replaces*, or *substitutes* hydrogen from the sulfuric acid molecule: 'A' is Fe, and 'B' is hydrogen, and 'C' is SO_4, a sulfuric acid residue (sulfate).

2. Substitution of silver from silver nitrate by a copper metal:

$$AgNO_3 + Cu \longrightarrow Cu(NO_3)_2 + Ag \tag{31}$$

In this reaction, a silver atom is being substituted by copper from a silver salt.

11.4 Exchange.

$$AB + CD \longrightarrow AC + BD \tag{32}$$

The exchange reaction[26] is a reaction between two *compounds*. In that reaction, the molecules 'AB' and 'BC' exchange their constituents, so two new 'hybrid' compounds AC and BD are formed as a result. The neutralization reaction we discussed in the previous section is a typical example of the exchange reaction.

$$NaOH + HCl \longrightarrow NaCl + H_2O \tag{33}$$

This type reaction (exchange, or "double replacement") is among the most common reactions salts are participating in. It is being widely used to prepare all types of inorganic compounds, including salts, bases and acids.

12 Exchange reactions between salts, bases, and acids.

After having defined major reaction types, we can continueour study of reactions of major types of inorganic compounds.

As we already know, bases and acids are capable of participating in exchange reactions. Are the exchange reactions specific only to these three classes of inorganic compounds? No.

During the Lesson 2, we made an experiment when calcium chloride and sodium carbonate reacted to produce two new salts. The equation of that reaction was as follows:

$$CaCl_2 + Na_2CO_3 \longrightarrow CaCO_3 + 2\,NaCl \tag{34}$$

The products of that reaction were calcium carbonate and sodium chloride. In other words, during that experiment, two salts, $CaCl_2$ and Na_2CO_3, reacted with each other to produce two new salts, calcium carbonate ($CaCO_3$) and sodium chloride (NaCl). Since both

[26] Again, for some unknown reason, school textbooks use a different name for this reaction: a "double replacement reaction". In scientific literature, this name is used rarely.

the reactants and the products of this reactions are salts, we can conclude not every pair of salts are capable of participating in the exchange reaction. Indeed, as far as calcium carbonate and sodium chloride are the *products* of the reaction **??**, they cannot serve as the *reactants* in the inverse reaction. In other words, if you take calcium carbonate and sodium chloride, you will never obtain calcium chloride and sodium carconate: the reaction **??** is not possible.

$$CaCO_3 + 2NaCl \neq CaCl_2 + Na_2CO_3 \tag{35}$$

That means, depending on the type of reactants and products, some exchange reactions proceed to completion, whereas others do not go at all. Why does it happen? Unfortunately, we cannot give a full and detailed answer right now: our theoretical background is insufficient so far. However, we can try to develop some empirical rules to predict an outcome of (at least) some exchange reactions.

Experiment 20.

Into four test tubes, pour 3 mL of the following dilute solutions: (i) silver nitrate; (ii) calcium chloride; (iii) copper sulfate; (iv) sodium carbonate. To these test tubes, add ca 3 mL of dilute solutions of: (i) sodium chloride; (ii) sodium phosphate; (iii) sodium hydroxide; (iv) sulfuric acid.

As we can see some reaction takes place in each of four test tubes: some sediments are formed in the first three test tubes, and some gas is formed in a fourth one. Let's discuss these reactions separately.

12.1 Reaction between two salts (test tubes 1 and 2).

Reactions in the first and second test tubes can be described by the equations (**??**) and (**??**).

$$AgNO_3 + NaCl \longrightarrow AgCl + NaNO_3 \tag{36}$$

$$3CaCl_2 + 2Na_3PO_4 \longrightarrow 2Ca_3(PO_4)_2 + 6NaCl \tag{37}$$

The sediments are poorly soluble salts, silver chloride and calcium phosphate, accordingly. These two reaction, as well as the reaction between $CaCl_2$ and Na_2SO_4 (equation **??**), proceed to full completion. Numerous experiments with various salts allowed chemists to propose the following empirical rule:

> **When at least one product of an exchange reaction between two salts is poorly soluble in water, such a reaction proceeds to completion, and a new insoluble salt is formed.**

Can we predict if a salt is soluble in water? Yes, we can. A solubility theory had been developed that explains why some salts are easily soluble, whereas others are not. This theory predicts a solubility of new salts quite well. We will discuss this theory in due time. Meanwhile, you can use the empirical table below to predict solubility of salts. This table summarizes some of experimental observations made by chemists during XIX century.

Solubility chart of salts formed by some metal (columns) and an acidic residues (rows).

	Li	Na	K	Ca	Mg	Al	Fe (II)	Fe (III)	Zn	Pb	Cu (I)	Cu (II)	Hg (II)	Ag
Cl	s	s	s	s	s	s	s	s	s	M	I	s	s	I
NO_3	s	s	s	s	s	s	s	s	s	s	s	s	s	s
ClO_4	s	s	s	s	s	s	s	s	s	s	s	s	s	s
S	s	s	s	D	s	D	s	s	I	I	I	I	I	I
SO_3	s	s	s	M	s	D	M	D	M	I	M	D	D	M
SO_4	s	s	s	I	s	s	s	s	s	I	M	s	s	M
PO_4	s	s	s	I	I	I	I	I	I	I	I	I	I	I
SiO_3	s	s	s	I	I	I	I	D	I	I	I	I	D	D
CO_3	s	s	s	I	D	I	I	D	I	I	I	I	I	I

In this table, 's' means the salt is soluble, 'M' means it is marginally soluble, 'I' means it is (virtually) insoluble. 'D' means such a salt decomposes in a presence of water. For example, from this table, we can conclude sodium chloride (NaCl) is soluble in water, whereas silver chloride (AgCl) is not, that sodium sulfide (Na_2S) is soluble, but silver sulfide (Ag_2S) is not, etc.

Interestingly, some salts (for example, nitrates NO_3 or perchlorates ClO_4) are soluble independently on the metal type, whereas other salts (for example, phosphates PO_4 or silicates SiO_3) are mostly insoluble. That is very important, because overwhelming majority of rocks and minerals Earth crust is composed of are phosphates, silicates, or carbonates of various metals.

12.2 Reaction between a salt and alkali (test tube 3).

In that test tube, a salt, copper (II) chloride, and a base, sodium hydroxide, had been mixed together, and that resulted in a formation of some new insoluble compound. This compound is copper (II) hydroxide ($Cu(OH)_2$, and the equation of this reaction is as follows:

$$CuCl_2 + 2\,NaOH \longrightarrow Cu(OH)_2 + 2\,NaCl \tag{38}$$

Copper (II) hydroxide belongs to the last class of inorganic compounds called *insoluble hydroxide*. Actually, hydroxides of most metals, including iron, zinc, aluminum, magnesium, tin, lead, etc, are insoluble, and the reaction between a salt of such a metal and an alkali represents a general method for preparation of insoluble hydroxides.

> **Salts and alkali can react with each other to produce a new salt and a new hydroxide if that hydroxide is insoluble.**

Below are other examples of such a reaction:

$$FeCl_3 + 3NaOH \longrightarrow Fe(OH)_{3(s)} + 3\,NaCl \tag{39}$$

$$MgCl_2 + 2\,NaOH \longrightarrow Mg(OH)_{2(s)} + 2\,NaCl \tag{40}$$

$$Al_2(SO_4)_3 + 6\,NaOH \longrightarrow 2\,Al(OH)_{3(s)} + 6\,NaCl \tag{41}$$

12.3 Reaction between a salt and an acid (test tube 4).

We observed no precipitate formation in the fourth test tube. Instead of that, we saw gas evolution, and the reaction's equation is as follows:

$$Na_2CO_3 + H_2SO_4 \longrightarrow Na_2SO_4 + CO_{2(gas)} + H_2O \tag{42}$$

At first glance, this reaction has little in common with the first three. However, it can be demonstrated that reaction is also an exchange reaction, and two, not three products are formed initially. Actually, this reaction is a two step reaction. These two steps are:

$$Na_2CO_3 + H_2SO_4 \longrightarrow Na_2SO_4 + H_2CO_3 \tag{43}$$

$$H_2CO_3 \longrightarrow CO_{2(gas)} + H_2O \tag{44}$$

In other words, during the first step (equation **??**), a new salt, sodium sulfate, and a new acid, carbonic acid, are formed, so this reaction is a typical exchange reaction. However, carbonic acid is very unstable, and it undergoes a decomposition reaction within few seconds (equation **??**). As in the case of hydroxides, this reaction is general.

> **Salts and acids can react with each other to produce a new salt and a new acid if that acid is unstable, volatile, or insoluble.**

Below are the examples.

$$2\,NaCl + H_2SO_4 \longrightarrow Na_2SO_4 + 2\,HCl_{(gas)} \tag{45}$$

Hydrochloric acid forms in a reaction between NaCl and H_2SO_4 because HCl is volatile, and escapes from the reaction mixture after formation. Some acids, such as a silicic acid (H_2SiO_3) are poorly soluble in water, therefore, they also can be prepared via an exchange reaction. A silicic acid forms a white loose precipitate.

$$Na_2SiO_3 + H_2SO_4 \longrightarrow Na_2SO_4 + H_2SiO_{3(s)} \tag{46}$$

13 Insoluble hydroxides: bases or acids? Amphoteric compounds.

Look at the formulas of copper or zinc hydroxides. They have much in common with $Ca(OH)_2$. Are they basic too? It is not easy to tell, because they are insoluble, so you cannot use an indicator (phenolphtalein or a pH-paper) to answer this question. However, as we already know, an intrinsic property of each base is its ability to form a salt with an acid, and, conversely, every acid is capable of reacting with a base to produce a salt. Let's test if insoluble hydroxides are bases or acids.

Experiment 21.

Add 3 mL of dilute solution of aluminium sulfate ($Al_2(SO_4)_3$) to each or two test tubes. To each test tube, gradually add 5% NaOH solution until a white loose precipitate is formed. After that, add 5 mL of the same NaOH solution, to the first test tube; to the second test tube, add 5 mL of 5% solution of HCl.

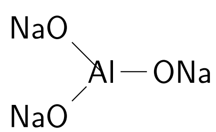
The reaction that takes place after initial addition of NaOH is quite understandable: like in the experiment 20, an insoluble hydroxide (in this case, aluminium hydroxide, $Al(OH)_3$, is formed, according to the equation **??**). However, what we observe after that is somewhat counter-intuitive: the loose precipitate that formed initially disappears after addition of both NaOH and HCl. In other words, a newly prepared compound, $Al(OH)_3$, reacts both with the base and with the acid. Does it mean this compound is a base and an acid simultaneously? No. Actually, aluminium hydroxide is a weak base in a presence of a strong acid (such as HCl), and it is a weak acid in a presence of a strong base (in our case, NaOH). These two reactions can be described by the equations:

$$2\,Al(OH)_3 + 6\,HCl \longrightarrow 2\,AlCl_3 + 3\,H_2O \tag{47}$$

and

$$2\,Al(OH)_3 + 6\,NaOH \longrightarrow 2\,Na_3AlO_3 + 3\,H_2O \tag{48}$$

A new compound with a formula Na_3AlO_3 has a name "sodium aluminate", and, based on the name and the equation, we can conclude it is a salt. Indeed, it is a salt. Its formula can be drawn as:



Sodium aluminate

and it possesses all properties of common salts. However, again, it would be incorrect to call aluminium hydroxide a base or an acid. This type compounds demonstrate acidic or basic behavior only in a presence of strong bases or acids, accordingly. These compounds are called *amphoteric*.

> **Amphoteric substances are the molecules that, depending on a situation, can act either as a weak acid or as a weak base.**

Many (although not all) insoluble hydroxides are amphoteric. As a rule, when a hydroxide of some metal is amphoteric, a corresponding metal and its oxide is also amphoteric. For example, aluminium metal reacts both with acids and alkali, and hydrogen gas is produced in both cases. We will discuss that in more details during a lesson devoted to aluminium.

13.1 Decomposition of insoluble hydroxides

A common property of insoluble hydroxides is their ability to decompose onto water and an oxide at high temperature. Thus, a blue cupric hydroxide ($Cu(OH)_2$) turns black when being heated:

$$Cu(OH)_2 \longrightarrow CuO + H_2O \tag{49}$$

14 Two classes of elements. Metals and non-metals.

All elements we have been dealing with can be subdivided onto two major types. The first type elements (we call them "metals"), such as sodium, zinc, iron or copper, form oxides, salts, hydroxides, but they do not like to form compounds with each other. Indeed, whereas zinc chloride, zinc oxide or zinc sulfide can be easily prepared, no "zinc sodiide", or "sodium zincide" (a putative zinc-sodium compound) is possible.

> **A common property of all metals is the ability to form at least one basic or amphoteric oxide or hydroxide.**

Another group pf elements demonstrate quite different properties. They form various binary compounds with metals and with each other. In addition, they are capable of forming more complex multiatomic molecules. These metals are called "nonmetals". The examples of nonmetals are oxygen, chlorine, carbon, hydrogen.

> **Most nonmetals form acidic oxides.**

Of course, there are some exception from this rule. For example, oxygen does not form acidic oxides, simply because it cannot oxidize itself. However, it is a typical nonmetal.

15 Genetic linkage between different classes of inorganic compounds.

Now we are ready to summarize the knowledge we obtained during this semester.

1. All elements can be subdivided onto two types, metals and nonmetals.
2. Metals are capable of forming compounds with nonmetals.
3. Nonmetals cam form binary compounds with each other and with metals; oxides are the most important binary compounds.
4. Most oxides react (directly or indirectly) with water to produce acids or bases. Accordingly, these oxides are called acidic or basic.
5. Acids and bases react with each other. The major product of such a reaction is called "salt".
6. Salts can also be formed in the reaction between a metal and an acid, between an acidic oxide and a base, and between an acid and a basic oxide.
7. Two salts can react with each other in solution, and two new salts can be produced, provided that at least one product of such a reaction is insoluble.
8. Some compounds can behave either as an acid or as a base. Such compounds are called "amphoteric".

9. Metals are the elements capable of forming at least one basic or amphoteric oxide. Oxides of nonmetals are always acidic.

That is a brief summary of what we know by now, and that is a core of inorganic chemistry.

It is easy to see that each type of inorganic compound is linked to other types: it begets compounds from other classes, and it can be begotten by a substance belonging to a progenitor class. That means a *genetic linkage* ("an ancestor - descendant linkage") exists between different classes of inorganic compounds. For example, some (not all) genetic linkages between different copper containing substances can be depicted as follows.

$$Cu \longrightarrow CuO \longrightarrow CuSO_4 \longrightarrow Cu(OH)_2 \longrightarrow CuO \tag{50}$$

It is possible to draw a general scheme (a graph) showing all genetic linkages between different classes of inorganic compounds, however, I would like you to do that by yourself. try to do that, and let's discuss it during the next Sunday.

Homework

1. Please, list all classes of inorganic compounds we currently know.

2. As we know, hydroxides can be prepared in a reaction between basic oxides and water. That means, a basic oxide is a parent substance for a corresponding hydroxide. In other words, a genetic linkage exists between basic oxides and hydroxides. List as many genetic linkages between different classes of inorganic compounds as you can (please, keep in mind that every compound can have several parent substances)? Can you draw a scheme summarizing all genetic linkages between each class?

3. Below, several compounds are listed. To which class of inorganic compound each of them belongs? Name each compound.
   a. $Ca(OH)_2$
   b. $FeSO_4$
   c. H_2SO_4
   d. Na_2SO_3
   e. $Zn(OH)_2$
   f. Fe_2O_3
   g. Na_2SO_4
   h. $MgSO_4$

4. You need to prepare the following salts: (i) NaCl, (ii) AgCl, (iii) HgS, (iv)$MgSO_4$, (v)$CaCO_3$, (vi)$Al_2(SiO_3)_3$, (vii)$NaClO_4$. Using the solubility chart, can you tell which of those salts can be prepared via the exchange reaction between two salts? Which salts should be taken as the reactants in each case? Write equations of each reaction.

5. Write equations of the reactions that would allow you to perform the following transformations:

(a)

$$AlCl_3 \longrightarrow Al(OH)_3 \longrightarrow Al_2O_3 \longrightarrow Al_2(SO_4)_3 \tag{51}$$

(b)

$$S \longrightarrow SO_2 \longrightarrow CaSO_3 \longrightarrow Ca(OH)_2 \tag{52}$$

(c)

$$AlCl_3 \longrightarrow Al(OH)_3 \longrightarrow Al_2O_3 \longrightarrow Al_2(SO_4)_3 \tag{53}$$

6. Look at the equations below:

   (a)

   $$Zn + H_2SO_4 \longrightarrow ZnSO_3 + H_2O \tag{54}$$

   (b)

   $$MgO + H_2 \longrightarrow Mg(OH)_2 \tag{55}$$

   (c)

   $$6\,NaOH + 2\,H_3PO_3 \longrightarrow 2\,Na_3PO_4 + 3\,H_2O \tag{56}$$

   (d)

   $$H_2 + KOH + PO_3 \longrightarrow K_3PO_4 + H_2O \tag{57}$$

   Some of those equations contain errors. Fix the errors and draw correct equations. Explain.

7. How can you prepare copper (II) chloride starting from copper metal? Draw equation(s).

8. Prepare potassium carbonate from sodium carbonate.

9. Starting from sodium chloride and sulfuric acid, prepare zinc chloride. You may use any zinc containing compound you want.

10. You have three test tubes, each of which contains one of the following solutions: (i) zinc chloride, (ii) sodium chloride, (iii) silver nitrate. The test tube labels have been wiped out by accident, and you need to restore them. To do that, you can use any glassware you want (test tubes, etc). You also can choose one additional chemical (any chemical on your choice). What chemical will you choose? How concretely will you do the analysis? Draw equations of each reaction.

As usual, I would be grateful if you sent me your homework by the evening of the next Saturday. My e-mail is mark.lukin@gmail.com.

Figure 3: Pont du Gard aqueduct in Southern France. Built about 2000 years ago, it is still almost functional.