Inorganic Chemistry
Lesson 2
Dalton's atomic theory. Composition of molecules. Valence.

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1 ...standing on the shoulders of giants

Dalton's ideas can be summarized as follows.

1. Matter is not infinitely divisible. It is composed of a large but finite number of extremely small ultimate particles (now we call them atoms and molecules).
2. Atoms of a given type are identical in size, mass, and other properties; atoms of different elements are different in some fundamental way (for example, they have different mass).
3. Substances that cannot be decomposed onto more simple substances are called elementary or simple substances. The atoms of a given elementary substance are identical.
4. Atoms combine in simple whole-number ratios to form composite substances, or chemical compounds.
5. Matter cannot be created or destroyed by chemical means; the only changes chemists can produce consist in separation, combination or rearrangement of atoms.

It would be correct to say that chemistry became a science only after these seemingly simple ideas had been formulated. Indeed, according to Dalton, small number of different atom (*elements*) combine with each other to form a huge variety of molecules of different kinds, and the rules that govern formation of these molecules depend of the types of the atoms involved in the interaction. To reveal these rules, and to show how the properties of molecules depend upon atomic composition is the main subject of chemistry, according to Dalton[1]. Yes, this theory was a major breakthrough, however, his work was based upon several major discoveries made by his great predecessors. Among these discoveries, two laws, which were initially derived experimentally, deserve a separate attention.

[1] Now, after two hundred years, it is still remaining the major goal of chemistry.

1.1 Law of conservation of mass

The idea that matter, which is composed of indestructible atoms, cannot be created or destroyed seems obvious to all present-days people, however, *does this idea follow from our every-days experience?* Of course, no.

Experiment 6

> *Weigh a candle and write down its weight. Light the candle and leave it for 20 minutes. Then put it out, and weigh the candle again. How did its weight change?*

From our everyday's experience, we may conclude the candle's weight decreases during combustion, and our experiment confirms that.

Experiment 7

> *Weigh a nail and record its weight. Leave it in a moist place. After one year, weigh it again. Can you see a difference?*

In that case, the mass of the nail *increases* when it rusts.

This, as well as many similar phenomena were interpreted by ordinary peoples and by scientists as an indication that *matter is not necessarily conserved during chemical reactions*, and this wrong belief was common among people until late XVIII century. The roots of this error were obvious: during their experiments, early scientists were unable to accurately measure all reactants (the substances participating in a chemical reaction) and all products (the substances that are formed during the reaction). Thus, during the Experiment **6** some gaseous products form, which have not been taken into account. As a result, we (as well as early scientists) observed a "disappearance" of matter. Similarly, in the Experiment **7** the increase of the nail's weight was due to its reaction with atmospheric moisture. Early scientists, who did not understand the processes of rust formation, interpreted that reaction as some spontaneous "creation" of matter from nothing. In early and mid-XVIII century, chemists proposed the idea that such a visible "disappearance" or "formation" of matter was a result of experimental errors. Nevertheless, the first comprehensive study of that issue was made only in late XVIII century by an outstanding French chemists Antoine-Laurent de Lavoisier. He made systematic studies of various chemical reactions in sealed vessels, when any possibility of loss of matter was eliminated. He found, for example, that, when a piece of wood was burned to ashes on open air, its mass decreased. However, when a similar piece was burned in a sealed vessel, the mass

Antoine-Laurent de Lavoisier (1743-1794),
a father of modern chemistry.

of the vessel remained unchanged. This, as well as a large number of others, meticulously planned and carefully performed experiments allowed Lavoisier to conclude that *"nothing is lost, nothing is created, everything is transformed"*.

> **During chemical reactions, matter cannot be created or destroyed.** This law is known as "Lavoisier's law".

This idea became one of the pillars of Dalton's theory. Indeed, we can speak about conservation of matter if, and only if its building blocks, atoms, cannot be created or destroyed.[2]

1.2 Law of definite proportions

The number of chemical reactions known to scientists is much greater that the number of chemical substances. That means that almost every chemical substance can be obtained *via* several different ways. Thus, you can obtain carbon dioxide (a gas used to produce soda water or coke) by burning charcoal, or by adding vinegar to baking soda, or by adding hydrochloric acid to limestone, or by dissolving baking powder in water, or by adding baking soda to boiling water, and so on. In all cases, carbon dioxide will be obtained, however, does it mean the chemical composition of this gas will be the same? Again, the answer on this question was not obvious to early chemists. To clarify that issue, another French chemist, Joseph Proust, performed a series of meticulous experiments, and convincingly demonstrated that each chemical compound always contains exactly the same proportion of elements *independently on the way it had been prepared*.

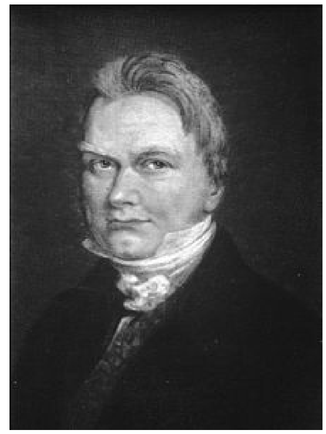
Joseph Proust (1754-1826),
a discoverer of the law of definite proportions.

2 Elements and molecular formulas

Elements are the atoms of a certain type. Simple substances (a term used by Dalton, which is currently widely used in non-English literature) are also called *"elements"*. One has to see a difference between two meanings of the word "element". Let me give just one example to demonstrate this idea. In late XVIII century, Lavoisier and his colleagues decided to determine a composition of diamond. They bought a diamond, put it under glass bell and heated it under sunlight using a big magnifying glass. To their big surprise, the diamond turned black, ignited and burned completely. The only product of combustion of diamond was carbon

[2]Of course, we speak about chemical reactions only. Discovery of atomic reactions demonstrated that atoms can be destroyed. Note, however, that Dalton made a very vise reservation: he never declared atoms are not possible to destroy, he said it is impossible *by chemical means*.

dioxide, the same gas that forms during combustion of ordinary charcoal. That experiment demonstrated that diamond, as well as ordinary charcoal or graphite is composed of the same *atom type* (carbon). However, does it mean charcoal, graphite and diamond are the same *substance*? Of course, no. These are *different substances composed of the same type of atoms.* Their properties are different because the same atoms (i.e carbon atoms) are organized differently in diamond, charcoal and graphite. Whereas the number of different molecules known to chemists exceeds many millions, the number of elements is very limited. Only 118 elements are currently known, and only 80 of them are stable (non-radioactive). The number of elements chemists can work with barely exceeds 90. However, we even don't need to memorize the names of each of them (at least, for now). To start learning Chemistry, we need no know the names of several essential elements. Below is the list of elements you need to remember (Table 1), because we will discuss them during this year. There are few things you need to know about them for the beginning: a name, an atomic symbol, and a mass. A mass of each element is (approximately) multiple of a mass of the lightest atom, hydrogen[3], so we will use hydrogen's mass as an atomic mass unit.[4]



Jons Jacob Berzelius
(1779-1848),
a developer of modern
chemical formula notation.

Table 1. Most common elements and their atomic masses

Element's name	Element's symbol	Atomic mass, Da
Aluminium	Al	27
Calcium	Ca	40
Carbon	C	12
Chlorine	Cl	35
Copper	Cu	64
Hydrogen	H	1
Iron	Fe	56
Nitrogen	N	14
Oxygen	O	16
Silver	Ag	108
Sodium	Na	23
Sulfur	S	32
Tin	Sn	119
Zinc	Zn	65

[3] It is not a coincidence, there is an important law behind that, and we will talk about that later.

[4] Currently, a little bit more precise mass unit is being used by chemists, namely, 1/12 of mass of a carbon atom. We will discuss the reason for that during the lesson devoted to isotopes.

2.1 Atomic mass unit, or Dalton

The atomic mass unit has its own specific name, **dalton**, or **Da**. This name had been chosen in a recognition of John Dalton's immense contributions into creation of modern chemistry. Initially, 1 Da was set to be equal to the mass of one hydrogen atom. Currently, a little bit different value is being used: one dalton is equal to 1/12 of mass of a carbon atom. The reason for that is purely technical. We will discuss that during the lesson devoted to isotopes.

2.2 Molecular formulas

Using the symbols from the Table 1, we can write *chemical formulas* instead of full name of substances. Not only that makes our life easier, it allows us to describe chemical substances more correctly. Thus, instead of writing *"a molecule of water is composed of one oxygen atom and two hydrogen atoms"* we can simply write: H_2O. The superscript symbols denote the number of each atom type is the molecule. Other examples of chemical formulas are: Al_2O_3, Na_2O, H_2CO_3, CuO etc. (These formulas are shown just to give you an impression on how chemical formulas look like. You do not need to memorize them.) Using such formulas, we can draw chemical equations to describe, for example, a chemical reaction we did during the Experiment **3** (1):

$$\mathrm{CaCl_2 + Na_2SO_4{=}CaSO_4 + 2\,NaCl} \tag{1}$$

Note, a number before a molecular formula indicates that more than onle molecule is formed. In this particular case, two molecules of sodium chloride are formed[5]

2.3 Molecular formula and molecular mass

Obviously, since there is nothing in molecules except the atoms they are composed of, the mass of some molecule is equal to the sum of masses of the atoms the molecule is built from. Although that is intuitively clear, it may probably be useful to give an explicit definition.

> **A mass of molecule, or its molecular mass, is a sum of masses of the atoms a molecule is composed of.**

For example, the mass of Al_2O_3 is equal to $27 \times 2 + 16 \times 3 = 102$ Da, mass of calcium chloride is $40 + 35 \times 2 = 110$, mass of sodium sulfate is $23 \times 2 + 32 + 16 \times 4 = 142$, mass of nitrogen is $14 \times 2 = 28$, etc.

3 Valence

As you probably have noticed, some molecules contain lower case indexes ("coefficients"). That means the number of atoms can be different in different molecules. For example, "H_2O"

[5] NaCl, table salt, is called "sodium chloride". We will not memorize the names of all compounds in advance. We will discuss the names for each class of chemical compounds when we will be studying each of them.

(i.e. a chemical formula of water) means there are two hydrogen atoms and one oxygen atom in each water molecule.

Is the composition of molecules arbitrary, or there is some law that defines it? If such a law does exists, then is it possible to predict composition of molecules?

Yes, it is possible to predict molecule's composition, and to derive chemical formula. That can be done based of some property of atoms called *valence*. To demonstrate the concept of valence, let's try to answer a following question using a common sense.

> *We know that a compound formed by hydrogen and chlorine has a formula HCl, a compound formed by hydrogen and oxygen has a formula H_2O, a compound formed by silver and oxygen has a formula Ag_2O. Using this information, can you predict a formula of a compound containing silver and chlorine?*

It is intuitively clear that, since oxygen binds to two atoms of hydrogen, valence of oxygen is as twice as big as valence of hydrogen. H_2O and Ag_2O formulas are similar, that means silver has the same valence as hydrogen. Since one atom of chlorine binds to one atom of hydrogen, their valences are the same. However, that means one atom of chlorine would add to one atom of silver,so the formula should be AgCl.

> **Ability of some atom to bind to a certain number of other atoms is called valence.**

It had been experimentally established that hydrogen has minimal possible value of valence. Therefore, its valence is assumed to be equal to one. Based on that, an alternative definition of valence can be proposed.

> **Valence is the ability of some atom to bind to a certain number of hydrogen atoms.**

Oxygen is capable of binding to two hydrogen atoms, nitrogen binds to three hydrogen atoms, and carbon binds to four hydrogen atoms. Therefore, valence of these elements is two, three, and four, accordingly. Using this information, we can predict, for example, that a compound formed by oxygen and carbon has a formula CO_2. It is necessary to note, however, that the same element may have different valence when it is bound to different atoms. Thus, sulfur is divalent when it is bound to hydrogen, but it may be either tetra- or even hexavalent when it is bound to oxygen. We will discuss that in details later.

Homework

1. Try to memorize symbols and names of the elements (and, if possible, their atomic masses) from the above table. They are being used very commonly, so it is very useful to know them. You will need to know them during subsequent lessons.

2. Calculate a molecular mass (in Daltons) of following compounds: CuO, SO_2, SO_3, NO_2, Na_2O.

3. Two substances have identical molecular masses. A first substance contains only nitrogen atoms, the second one contains oxygen and carbon[6]. Can you draw formulas of both of them?

4. A molecular mass of the product of combustion of sulfur is as twice as big as the atomic mass of sulfur. Can you draw the formula of this product?

5. A molecular formula of glucose is $C_6H_{12}O_6$. Is there more oxygen (by weight) in one gram of water than in one gram of glucose?

6. In all compounds listed below sulfur is divalent. Please, tell what is valence of a second element in each formula: Al_2S_3, ZnS, Na_2S, CS_2.

7. Copper forms two compounds with oxygen.[7] Their formulas are Cu_2O and CuO. What is the valence of copper in each of them?

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

[6] To solve this problem, you need to know that, whereas in most molecules carbon's valence is four, in some other molecules (rarely) it can be equal to two

[7] such compounds are called "oxides"