Structure of Matter

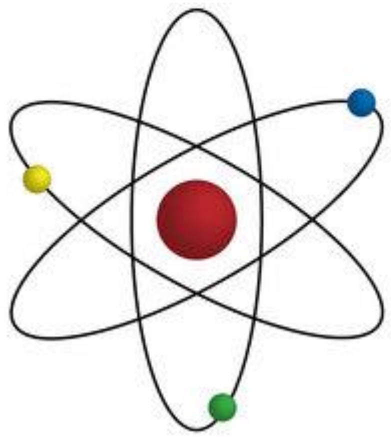
Key Words

matter
atom(-s)
atomic model
theory / theories
proton
neutron
electron
nucleus / nuclei
valance
electronic shells
cation
anion
metal
nonmetal
compounds
binary
ternary
mole

Introduction

In this unit we will continue to build on your knowledge of Matter from the previous section. You know that matter is "anything that has mass and occupies space" (Chemicool.com, 2015), and you know how to measure it and what units to use. The building blocks of matter are known as "atoms", from the Greek word meaning "un-cuttable" (Skorucak, 2015).

You have probably seen a picture like this before, which is one way to draw, model, an atom:



(Headberg, 2015)

But, how do we know what something looks like, if it is **far too small** to see?

Humankind has been thinking about what their world is made of for a long time. The first recorded discussions that matter is made of particles were over 2000 years ago when a Greek named Democritus suggested that matter is made of atoms, different materials contained different types of atoms and atoms could be "re-arranged" to make different substances. However, Aristotle did not agree with Democritus, so people rejected the idea until Robert Boyle came along in 1661 (Splung.com, 2015).

Boyle gave us the modern definition of an element:

"**An element** is a substance that cannot be broken down into simpler substances but can form compounds with other elements" (Splung.com, 2015).

Let's look at some history to try to understand how the knowledge and understanding of the atom evolved over the years.

THE ATOM

An atom is the smallest building block of matter. In Ancient Greece the word **atom** was used to define the smallest indivisible particle that could be conceived (a- without, tomos- division). The atom was thought of as indestructible. However, we know today that the atom can be broken down into sub-atomic particles.

Knowledge about the size and makeup (composition) of the atom grew very slowly as scientific theory progressed. Three scientists who have greatly contributed to the knowledge on the atomic structure are, among others, **John Dalton, J.J. Thomson, and Ernest Rutherford**.

Today we know that atoms are made up of three fundamental sub-atomic particles: protons, neutrons, and electrons.

DALTON'S ATOMIC THEORY

In 1803 the British physicist-chemist John Dalton (1766-1844) presented a theory on the constitution of matter known as the **atomic theory**. J. Dalton developed its atomic theory based not only on his own experiences, but also on the experiences carried out by earlier scientists such as Boyle (1627-1691) and Proust (1754-1826).

Dalton's theory besides explaining the laws of chemical reactions, it allows us to understand why there are two main types of chemical substances: compounds and elements. **Compounds** can be broken down into simpler substances, and **elements** cannot be broken down.

In this theory, he proposed the following:

- All matter is made up of indivisible particles called atoms.
- All atoms of any given element are identical.
- The atoms of a given element are different from those of any other element.
- Atoms of one element can combine with atoms of other elements to form compounds. A given compound always has the same types of atoms and in the same proportion.
- Atoms cannot be created, divided into smaller particles, nor destroyed in the chemical process. A chemical reaction simply changes the way atoms are grouped together.

Dalton was right in many respects. However, as you will see, his idea about atoms being indivisible would prove wrong with time.

SUB-ATOMIC PARTICLES

The **electron** (e-) was discovered in 1897 by the physicist J.J. Thomson when studying cathodic rays. He also calculated the mass of the electron and found that it was very small compared to the total mass of the atom. Therefore, a revision of Dalton's indivisible atom was necessary.

If the atom was not indivisible; how did it really look like?

More experiments were carried out and, in 1911, Rutherford discovered the positive particle that makes the atom. It was called a proton. Its mass was about 2 000 times greater than that of the electron, and its charge was exactly the same as the electron's but with a positive sign.

So far, we can conclude that all matter is made of atoms, and atoms are made of electrons and protons. Additionally, atoms must have the same number of protons and electrons, since they are neutral.

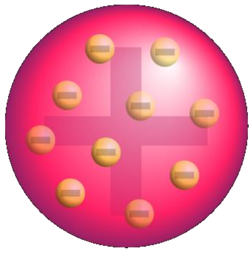
The neutron still had to be discovered but this was not until 1932, by Chadwick, pupil of Rutherford. Its mass is similar to that of the proton, and it is not charged.

Once the different sub-atomic particles had been discovered, the big question was how were they arranged inside the atom?

ATOMIC MODELS

THOMSON'S 'PLUM-PUDDING' MODEL OF THE ATOM

J.J. Thomson (1856 – 1940) was one of the next most recognized people involved in the progression of atomic theory. As a result of his experiments with cathode rays Thomson discovered the nature of the electron and theorized that, although the atom was made of small particles, it was not the same indestructible model proposed by Dalton. Thomson stated that protons and electrons were evenly distributed throughout the atom. Thomson described the atom as a mass of positively charged particles (protons) with electrons embedded in it, like raisins in a 'plum pudding'.


Schematic representation of Thomson's "plum pudding" atomic model.

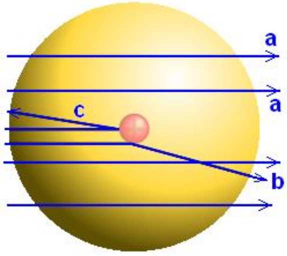
RUTHERFORD’S EXPERIMENT AND ATOMIC MODEL

Ernest Rutherford (1871-1937), a major contributor to the atomic model, run the following experiment.

He took a sheet of gold foil (gold foil is extremely thin, you need to handle it with tweezers, and if you use your fingers it would get stuck to them) and bombarded it with positive particles (known as alpha particles). Behind the sheet he placed a camera so he could follow and study the pathway of particles as they passed through or bounced off.

Rutherford found that:

a) The majority of the alpha particles passed through the gold foil un-deflected (without deviation).
b) A small portion of the particles were strongly deflected from their path as they passed through the gold foil.
c) One out of 10 000 particles bounced off the gold foil.



From his results Rutherford drew the following conclusions:

- The majority of the atom is empty space
- The atom’s positive charge is found in a small and dense nucleus.
- The electrons orbit around the nucleus.

With his experiment he proved that although Dalton and Thomson were partially correct there was still a flaw in both of their models of the atom. Rutherford also proved that the atom consisted mostly of empty space. At the center of this space is a very small core, called the nucleus. Rutherford established that the mass of the atom is concentrated in its nucleus. He found that an electron is 1/1836 the mass of a proton and he also proposed that electrons travel orbiting around the nucleus.

Atoms are made of protons, neutrons and electrons

- The protons are particles which carry a positive electrical charge. The mass of a proton is very similar to the mass of a hydrogen atom.
- The neutrons have a mass which is similar to the mass of a proton. However, neutrons are not electrically charged.
- The electrons carry a negative electrical charge and their mass is around 1836 times smaller than the mass of a proton.

As you have seen above, there have been several theories to explain the distribution of the subatomic particles in the atom. Nowadays, the most accepted theory suggests that the atom is formed by two parts; the **nucleus** and the **electron cloud** around it, but this will be studied in upper courses.

The nucleus of an atom is extremely small in comparison to the atom. If an atom was the size of a football stadium, then its nucleus would be the size of a pea.

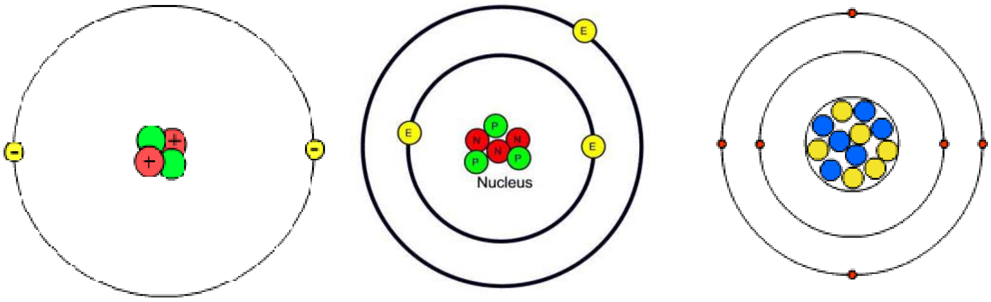
ATOMIC NUMBER, Z

The number of protons varies from one element to another, but **all atoms of the same element always have the same number of protons**.

So, the **atomic number (Z),** is the fixed number of protons of an element, which is characteristic for each element.

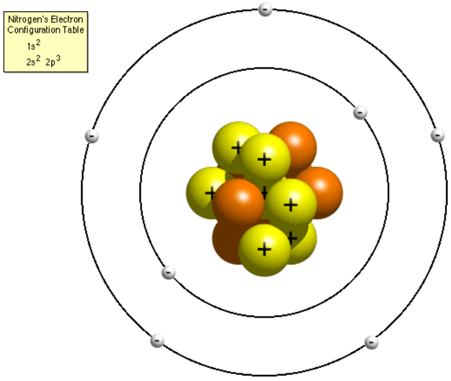
Example: Each atom of helium has two protons, the lithium atoms have three protons each, and every carbon atom presents six protons. In their natural state, atoms do not carry any electrical charge; they are **neutral**. This means that they have the same number of positively charged protons and negatively charged electrons. Therefore, a helium atom, in its natural state, has two electrons; a lithium atom three and a carbon atom six. So in a neutral atom the atomic number also indicates the number of electrons.

Z = atomic number = number of protons = number of electrons in neutral atoms.



Helium (He), Z = 2 Z = 3 Carbon (C), Z = 6

Three different representations of the atoms dealt with in the example on the previous page.



A simplified atom model of a nitrogen atom (with 7 protons, 7 electrons and 7 neutrons). Please remember that the enormous dimensions of an atom's electronic shells are impossible to represent on a sheet of paper. In the drawing above, you see nice circles showing where the electrons go around the atom. In reality, scientists cannot tell exactly where an electron is at a given moment or where it is going. That is why we talk about an "electron cloud" or probability region.

ISOTOPES

The number of protons and electrons is always the same in all neutral atoms of a chemical element, but the number of neutrons can vary. Atoms which present this circumstance are called **isotopes**.

Example: The most abundant isotope of hydrogen (Z = 1) is protium (a single proton, no neutrons) followed by deuterium (a proton and a neutron) and the least abundant tritium (a proton and two neutrons). Another example is oxygen, which atomic number is 8 but it can have 8, 9, or 10 neutrons.

MASS NUMBER, A

The protons and neutrons are situated in the nucleus of the atom. The **mass number** of an atom is the sum of the number of protons and the number of neutrons. It is represented with the letter **A**.

A = mass number = number of protons + number of neutrons

If we call the number of neutrons n, we conclude that

$$A = Z + n$$

Consequently, we can know the number of all the fundamental particles which form an atom if we know Z (the atomic number) and A (the mass number).

Example: symbol = C name = carbon atomic nº (Z) = 6
atomic mass number (A) = 12 (→ atomic mass = 12 u)

Relative atomic masses

The majority of the elements have isotopic forms (isotopes), and therefore, the atomic mass number is estimated as an average of the atomic mass numbers of the isotopes found in nature, weighed by isotopic abundance. In the Periodic Table, you will find that the atomic mass number of carbon is 12.01 and the one of hydrogen is 1.008.

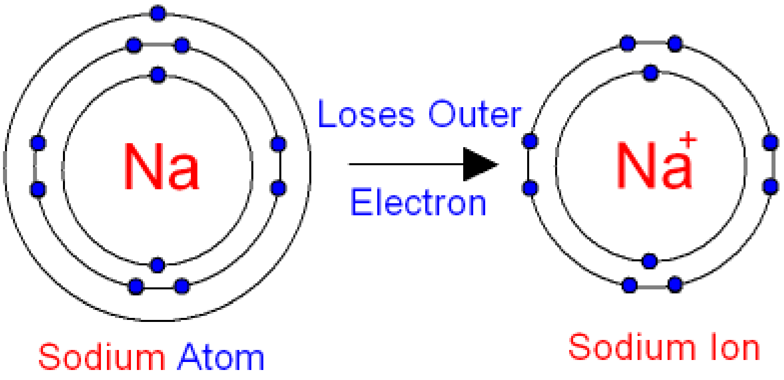
IONS

Atoms have the same number of protons and electrons, and therefore are electrically neutral. However, if an atom *loses* or *gains* electrons, the overall charge will change and will be *unbalanced*.

If the charge is not neutral, the atom has become an **ion.**
A positive ion is called a **cation**, and a negative ion is known as an **anion**.

Atoms form ions in order to get a full outer shell of electrons. All atoms "want" to have a full outer shell to be like the Nobel gasses, as that gives them stability. To do this they will either fill a nearly full shell or empty a shell that has only a few electrons in it. Whichever involves moving the least number of electrons.

For example sodium (Na) has 1 electron in its outer shell. It could try and get 7 more electrons to fill the shell, but it is easier to lose 1 electron and have the full 2nd shell become the outer shell. All the elements in group 1 will do as sodium.



OXIDATION NUMBERS

Oxidation numbers **do not** have anything to do with oxygen. Chemists use oxidation numbers to keep track of **the number of electrons** an ion has.
A positive number means that the atom has fewer electrons than protons.
A negative number means that the atom has more electrons than protons.

Calcium has a 2+ charge, which means it lost two electrons.
Oxygen has a 2- charge, which means it gained two electrons.

The oxidation numbers relate to the groups of the periodic table because they depend on the usual number of electrons in the outer shell that an atom has. Elements in the same group will usually have the same oxidation numbers. Some elements, especially the transition metals can have many different oxidation numbers. We will talk some more about this when doing chemical formulation.

THE PERIODIC TABLE

An element is a substance formed by a single type of atoms. Nowadays, 118 different chemical elements are known. Very early on, scientists saw the need of arranging them in some type of order. They realized that there were groups of elements which had similar characteristics. **Elements that resemble each other are on the same group.**

There were a few scientists involved in the evolution of the periodic table. However, it was the periodic table of the Russian scientist Mendeleev that served as a prototype (precursor) of today's periodic table. He ordered the chemical elements by their atomic mass and into groups with similar behaviour, arranging them in rows and columns. All the elements in a given column had similar properties. When Mendeleiev arranged the elements into his periodic table, he left 'spaces in the table' where none of the known elements fit the pattern. He left the gap and predicted the properties of the still undiscovered element that had to go in that particular place. As new elements were discovered they would fill up those gaps showing the predictions were extremely accurate. This made of Mendeleev's version of the periodic table a very powerful description of matter.

The periodic table is a chart which categorizes elements by 18 "groups" (the vertical columns) and 7 "periods" (the horizontal rows). In an atom with a neutral charge, the number of electrons equals the number of protons; **the periodic table represents neutral atoms.** The atomic number is typically located above the element symbol. The **atomic mass number** is typically found beneath the element symbol. Below is a diagram of a typical cell on the periodic table.

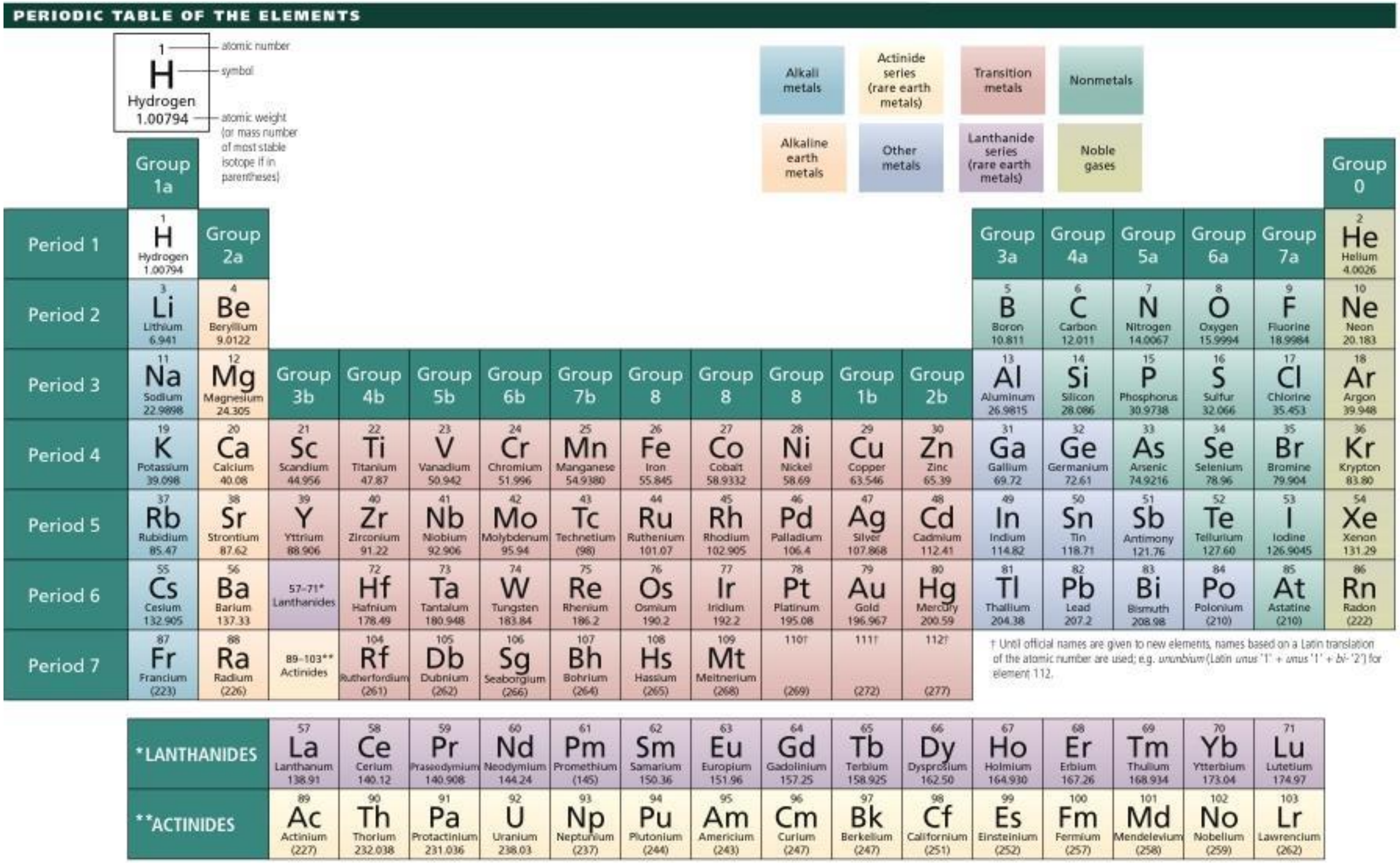
Going from left to right on the periodic table, you will find metals, then metalloids, and finally non-metals. The 4th, 5th, and 6th periods are called the transition metals. The transition metals include two periods known as the lanthanides and the actinides which are located at the very bottom of the periodic table.

Some of the groups have special names:

- Group 1 is also called **the alkali metals.**
- Group 2 is also called **the alkaline earth metals.**
- Group 13 is **the earth metals.**
- Group 17 is **the halogens.**
- Group 18 is **the noble gases.**

► Review the name and the symbol of the 35 elements of the periodic table you have to know this year and try to remember their position. Draw them in your notebook.

►How are the elements ordered in the Periodic Table?



PERIODIC TABLE OF THE ELEMENTS

1 — atomic number
H — symbol
Hydrogen
1.00794 — atomic weight (or mass number of most stable isotope if in parentheses)

Alkali metals
Actinide series (rare earth metals)
Transition metals
Nonmetals
Alkaline earth metals
Other metals
Lanthanide series (rare earth metals)
Noble gases

	Group 1a	Group 2a	Group 3b	Group 4b	Group 5b	Group 6b	Group 7b	Group 8	Group 8	Group 8	Group 1b	Group 2b	Group 3a	Group 4a	Group 5a	Group 6a	Group 7a	Group 0
Period 1	1 H Hydrogen 1.00794																	2 He Helium 4.0026
Period 2	3 Li Lithium 6.941	4 Be Beryllium 9.0122											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984	10 Ne Neon 20.183
Period 3	11 Na Sodium 22.9898	12 Mg Magnesium 24.305											13 Al Aluminum 26.9815	14 Si Silicon 28.086	15 P Phosphorus 30.9738	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
Period 4	19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.87	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.9380	26 Fe Iron 55.845	27 Co Cobalt 58.9332	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.61	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
Period 5	37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.22	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.4	47 Ag Silver 107.868	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.9045	54 Xe Xenon 131.29
Period 6	55 Cs Cesium 132.905	56 Ba Barium 137.33	57-71* Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (210)	85 At Astatine (210)	86 Rn Radon (222)
Period 7	87 Fr Francium (223)	88 Ra Radium (226)	89-103** Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (268)	110† (269)	111† (272)	112† (277)						

† Until official names are given to new elements, names based on a Latin translation of the atomic number are used; e.g. *ununbium* (Latin *unus* '1' + *unus* '1' + *bi-* '2') for element 112.

*LANTHANIDES	57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97
**ACTINIDES	89 Ac Actinium (227)	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

SIMPLE SUBSTANCES AND COMPOUNDS

Simple substances

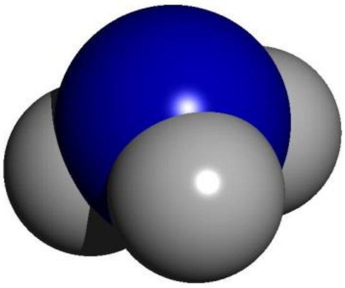
The atoms of the metals cluster together forming networks of numerous atoms. They are represented by the symbol of the element. Thus, Cu indicates the name of the element copper and it also represents the chemical formula the substance: copper metal.

However, simple substances of non-metals have a tendency to unite through a simple and fixed bond, forming groups called **molecules**. The most frequent are the **diatomic molecules**, formed by two atoms. Oxygen, (O_2), nitrogen (N_2) and chlorine (Cl_2) form diatomic molecules. There are also **monoatomic** molecules, formed by one single atom (Example: the noble gases, He, Kr, Xe, Rn) as well as **triatomic** (ozone, O_3) and **tetra-atomic** molecules (phosphorous, P_4), etc.

Compound substances

Compound substances are formed by two or more different types of atoms, which unite forming molecules or big networks. Example: One atom of nitrogen joins with three atoms of hydrogen, forming a molecule of a new substance, ammonia (NH_3).

Compounds formed in the union of two different elements are called **binary compounds**, if three elements unite, the compound is a **ternary compound**, **quaternary** if the constituting elements are four, etc.



Ammonia (NH_3) is a binary compound.

All molecules in a pure substance are identical. They are formed by atoms belonging to one single element if the substance is simple and different atoms if the substance is a compound.

► Order the following molecules of pure substances into the following table:
water (H_2O), neon (Ne), fluorine (F_2), nitric acid (HNO_3).

Molecules			
Simple substances		**Compound substances**	
Monoatomic	**Diatomic**	**Binary**	**Ternary**

Chemical symbols and formulas

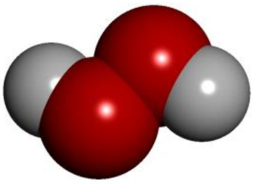
Molecules are represented with chemical formulas.

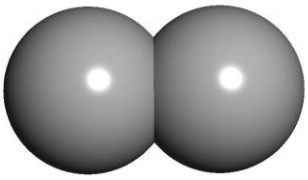
The chemical formula of a substance indicates the elements it contains and the proportions of the constituting elements.

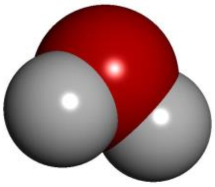
Since long ago scientists have been used to representing the names of the atoms of different elements in abbreviated form through **symbols**.

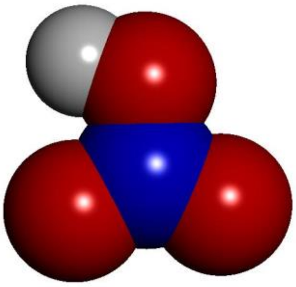
We **represent the elements with one capital letter. If we use two letters, then the 2nd letter is always written in lower case. E.g.: Lithium (Li), Potassium (K).**

Chemical formulas represent in an abbreviated way the composition of molecules.


Hydrogen peroxide (H_20_2)


Bromine (Br_2)


Water (H_2O)


Nitric Acid (HNO_3)

► Indicate the constituting atoms and their quantity in the molecules of the following substances:

a) sulfuric acid b) sodium hydroxide c) methane d) copper sulfate

Molecular mass (gram formula mass)

As molecules are formed by atoms, the mass of a molecule is equal to the sum of the masses of the constituting atoms. For example, the molecular mass of oxygen gas (O_2) is calculated with the atomic mass of oxygen, 16 u:

2 atoms of oxygen (O) = $2 \times 16 = 32$ u

The molecular masses of substances are expressed in atomic mass units (amu or u). However, these units are extremely small:

$u = 1.66 \times 10^{-24}$ g, in other words 0.00000000000000000000000166 g.

These quantities are impossible to measure in a laboratory. In order to work in the laboratories, we need to use bigger units like the gram, which is measurable on a balance. How have scientists solved the problem with the tiny molecular masses? Answer: With the unit **mole.**

MOLE AS A UNIT OF QUANTITY OF MATTER

We have already seen that it is impossible to work in the lab with just a few molecules, because their mass is not visible. Therefore, it is necessary to use a much bigger number of molecules. Experimentally it has been proven that a mass of whatever substance equal to the molecular mass in *u* but expressed in grams contains a constant number of molecules. This number is as large as 6.023×10^{23} and it is called **Avogadro's number (N_A)**.

Mole is a unit of quantity of matter and it is defined as the quantity of matter which contains 6.023×10^{23} particles (atoms, molecules, ions, electrons…).

Exercises Unit 4. Structure of Matter

1- Outline if these statements are true or false. If they are false, explain why.

a) Aluminium atom has 13 protons and 15 electrons.

b) The atomic number is the same as the number of protons, and also the same as the number of neutrons.

c) The atomic number is the same as the number of protons, and also the same as the number of electrons.

2.- State the number of protons and electrons of the atoms with the following characteristics: a) $Z = 30$ b) $Z = 15$ c) atomic number = 25

3.- Chlorine has 18 neutrons and $Z = 17$. Explain the following questions:

a) How many electrons does it have and what is its mass number?

b) How many electrons, protons and neutrons would a chlorine isotope have if $A = 37$?

4.- Calcium has $A = 40$ and $Z = 20$. Explain the following questions:

a) How many electrons, protons and neutrons make up the calcium atom?

b) How many electrons, protons and neutrons would an isotope have if $A = 41$?

5.- Determine the gram formula mass (or molecular mass) of the following compounds:

a) Carbon dioxide b) ammonia c) water d) sodium chloride

Atomic masses: C = 12; O = 16; Na = 23; Cl = 35,5; N = 14; H = 1

6.- Determine the gram formula mass (or molecular mass) of the following compounds:

a) $KMnO_4$ b) KCl c) $Al_2(SO_4)_3$ d) H_2CO_3 e) $Ba(ClO_3)_2$

Atomic masses: K=39; Mn =55; O =16; Cl =35.5; Al =27; S =32; H =1; C =12; Ba =137

7.- How many molecules are there in five moles of magnesium hydroxide, $Mg(OH)_2$? Data: Atomic masses: H = 1; O = 16; Mg = 24

8.- How many molecules are there in 36 grams of water?

Data: Atomic masses: H = 1; O = 16

9.- Determine the number of grams in each of the quantities below:

a) 1 mole of nitrogen atoms b) 0.5 moles of calcium nitrate- $Ca(NO_2)_2$

c) 2.5 moles of sodium chloride d) 1.7 moles of potassium chloride - KCl

10.- How many atoms of iron are there in 200g of iron?

Atomic mass: Fe = 56

11.- Calculate the mass (in g) of $48x10^{23}$ atoms of silver.
Atomic mass: Ag = 108.

12.- Determine the mass (in g) of one mole of sulfuric acid. (H_2SO_4)
Atomic masses: S=32; O=16; H=1.

13.- How many moles are there in 45g of water? Atomic masses: H=1; O=16

14.- Calculate the mass (in g) of one mole of sodium carbonate. (Na_2CO_3)
Atomic masses: C=12; Na=23; O=16.

15.- How many moles are there in 30.115 x 10^{23} molecules of iron(III) nitrate? $Fe(NO_2)_3$
Atomic masses: O=16; Fe=56; N=14.

16.- Calculate the number of moles there are in 50 grams of marble (calcium carbonate) $CaCO_3$
Atomic masses: C=12; Ca=40; O=16.

17.- Determine the mass of one molecule of hydrochloric acid. HCl
Atomic masses: Cl = 35.5; H = 1.

18.- How many moles and how many molecules are there in 504g of sodium sulfite? Na_2SO_3
Atomic masses: S = 32; O = 16; Na = 23.

19.- How many molecules are there in 2 moles of calcium hypoiodite? $Ca(IO)_2$
Atomic masses: I = 137; Ca = 40; O = 16.

20.- Which of the two samples will have more molecules: a) 684g of aluminium sulfate ($Al_2(SO_4)_3$) ; or b) 2 moles of mercury(I) chloride (HgCl).
Atomic masses: S = 32; O = 16; Al = 27; Cl = 35.5; Hg = 200.

21.- How many atoms are there in 202g of potassium nitrate (KNO_2)?
Atomic masses: N = 14; K = 39; O = 16.

22.- Determine the number of moles and molecules there are in 136g of magnesium hydroxide. $Mg(OH)_2$
Atomic masses: Mg = 24.5; H = 1; O = 16.