Some basic chemistry

Living organisms and chemistry

Biology is about living things - organisms. All living organisms are made of chemicals. To understand biological substances and the changes that take place in living organisms you need a good knowledge of the underlying chemistry. We will build up a picture of the chemicals that make up living organisms by starting small and getting bigger.

The starting point is atoms - the building blocks of all matter. We will then look at how these come together to make elements and compounds.

Atoms

Atoms are the building blocks of all matter. They consist of three sub-atomic particles: **protons**, **neutrons** and **electrons**. Protons and neutrons are found in the nucleus of an atom. Electrons are found in energy levels around the nucleus as shown in the diagram representing a carbon atom with 6 protons, 6 neutrons and 6 electrons.

Sub-atomic particles

Particle	Whereabouts in atom	Relative mass	Charge
Proton	Nucleus	1	+1
Neutron	Nucleus	1	0
Electron	Outside the nucleus	$^{1}/_{1840}$	-1

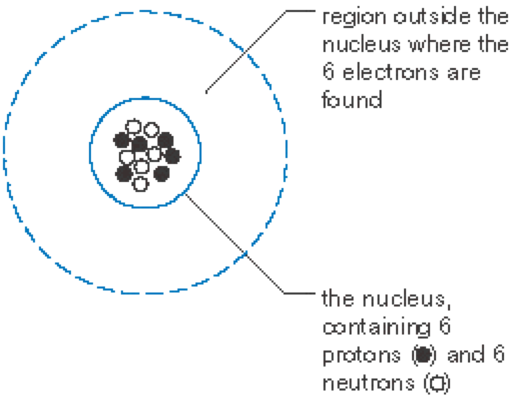
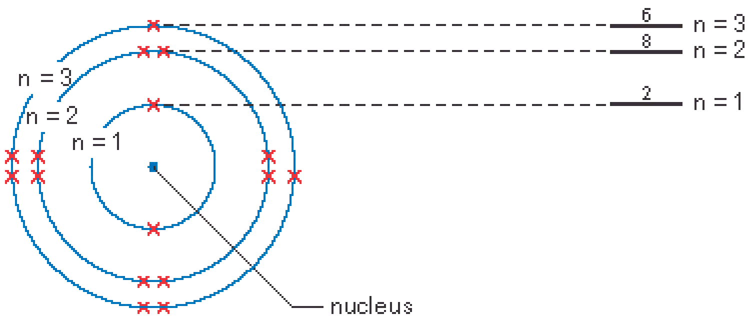


Diagram of carbon atom - nucleus with electrons orbiting

In chemistry we are particularly interested in electrons. As you will see later, this is because chemical reactions involve the rearrangement of electrons. Nuclei of atoms (protons and neutrons) usually remain unchanged (except in radioactive decay).

Electrons are arranged in atoms according to their energies. This is called the **electronic structure**or **electronic configuration** of the atom. A crude but still useful model says the electrons can be in different energy levels. Electrons in a particular energy level all have the same energy as one another. The lowest energy level can accommodate up to 2 electrons. The second level can accommodate up to 8 electrons. The third level can accommodate up to 18 electrons. The diagram shows the situation for a sulfur atom.



Importantly it's only electrons in the outermost energy level of an atom that are involved in chemical bonding.

Elements

An **element** is a substance made up of atoms with the same number of protons. Elements are the simplest substances known. They can be metals (e.g. iron, copper, sodium magnesium) or non-metals (e.g. carbon, hydrogen, oxygen, nitrogen). There are just over 100 of them.

Each element has its own:

- name and chemical symbol
- characteristic physical properties, e.g. density, electrical conductivity, melting point and boiling point
- characteristic chemical properties, e.g. reactions with water, oxygen, acids and other chemicals

These physical and chemical properties do not change. They can be used to identify an element. Elements are listed in the Periodic table.

Many elements have different **isotopes**. Although the numbers of protons and electrons are the same in all atoms of a given element, the number of neutrons may differ. For example, in a typical sample of carbon:

- 98.9% of the carbon atoms have 6 protons, 6 electrons and 6 neutrons
- 1.1% of the carbon atoms have 6 protons, 6 electrons and 7 neutrons
- a small trace have 6 protons, 6 electrons and 8 neutrons - carbon-14

This fact is made good use of in radiocarbon dating. The proportion of carbon-14 in living systems is constant because they absorb and re-emit carbon-containing compounds continuously. However, once an animal or plant dies the proportion of carbon-14 in its structure decreases because carbon-14 atoms undergo β-decay to give nitrogen:

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathbf{e}$$

In dead material the carbon-14 atoms are not being replaced and therefore, the older the remains of living things are, the lower the level of radioactivity they show.

This table shows a comparison of the composition of the Earth's crust with that of the human body:

Elements in the Earth's crust (% by mass)		Elements in the human body (% by mass)	
Oxygen	46.4	Oxygen	65
Silicon	28.0	Carbon	18
Aluminium	8.1	Hydrogen	10
Iron	5.1	Nitrogen	3
Sodium	2.8	Calcium	1.5
Potassium	2.5	Phosphorus	1
Magnesium	2.0	Potassium	0.35
Titanium	0.58	Sulfur	0.25

Note: none of these elements exists freely; all are found chemically combined with other elements in compounds.

Although there are over 100 elements, only 12 or so are used to make biological materials. Living organisms are built predominantly from non-metal elements. However, trace amounts of many metal elements are essential for healthy growth. The most abundant elements in living organisms are:

Element	Symbol	No. of protons in atom (atomic number)	No. of electrons in atom	Electron arrangement
Carbon	C	6	6	2,4
Hydrogen	H	1	1	1
Oxygen	O	8	8	2,6
Nitrogen	N	7	7	2,5
Sulfur	S	16	16	2,8,6
Phosphorus	P	15	15	2,8,5

Compounds

Elements form **compounds**. But simply mixing elements together does not make a compound. A chemical reaction is needed.

Atoms of elements combine, but only in certain fixed ratios. The ratios are determined by the **combining power** of atoms. For example:

- carbon has a combining power of 4, which means each carbon atom can form 4 bonds
- hydrogen has a combining power of 1, which means each hydrogen atom can form 1 bond
- oxygen has a combining power of 2, which means each oxygen atom can form 2 bonds
- nitrogen has a combining power of 3, which means each nitrogen atom can form 3 bonds

Where does this number come from? The combining power is the number of electrons in an atom that can be used to form chemical bonds. When one atom bonds to another it is these available electrons which are involved, i.e. those in the outermost electron-containing energy level. Their arrangement is always changed by a chemical reaction unlike the electrons in the inner shells. Usually, when atoms react, they achieve a more stable electronic structure.

We use the **empirical formula** to show the ratio of atoms in a compound. For example:

Compound	Molecular formula	Empirical formula	Ratio of atoms in compound
Carbon dioxide	CO_2	CO_2	1 carbon atom : 2 oxygen atoms
Methane	CH_4	CH_4	1 carbon atom : 4 hydrogen atoms
Sulfuric acid	H_2SO_4	H_2SO_4	2 hydrogen atoms : 1 sulfur atom: 4 oxygen atoms
Ethane	C_2H_6	CH_3	1 carbon atom : 3 hydrogen atoms

The empirical formula is the simplest ratio in which atoms combine to form a compound.
The **molecular formula** tells us how many of each type of atom there are in each molecule of the compound - see below.

Each compound has its own:

- name and formula (there are different types: empirical formula, **molecular formula**, **structural formula** and **displayed formula**)
- characteristic physical properties and chemical properties - these can be used to identify a compound.

Atoms are held together in compounds by **chemical bonds**. However, when atoms bond to one another there is a rearrangement of electrons and the particles present in compounds are no longer atoms. They are **ions** or **molecules**.

The compounds that make up living organisms fall into two types:

- **Inorganic** compounds, e.g. water (which exists as molecules) and salts (which contain ions such as potassium, calcium and chloride).
- **Organic** compounds, e.g. carbohydrates, lipids and proteins, all of which exist as molecules. These may be classified as (a) small biological molecules and (b) large biological molecules and polymers.

Organic compounds can be recognised from their formulae - they all contain the element carbon. The only inorganic compounds that contain carbon are carbon dioxide (CO_2), carbon monoxide (CO), salts containing the carbonate ion (CO_3^{2-}) or the hydrogencarbonate ion (HCO_3^-) and inorganic carbonyl compounds e.g. $Co(CO)_6$.

Find out more by looking at the sections on:

> Water
> Carbohydrates
> Lipids
> Proteins
> Nucleotides and nucleic acids

Mixtures

All the materials we come across in our lives are mixtures. Pure elements or compounds do not exist! Even substances labelled 'pure' contain trace amounts of impurities.

Mixtures contain different compounds (and occasionally elements) mixed together. The substances are not chemically combined and may be separated relatively easily. The characteristics of a mixture are:

- there is no fixed proportion for the substances present
- its properties are the same as those of the substances that make it up
- the substances that make it up can be separated by physical means, e.g. filtration, evaporation and distillation

Living organisms need to be able to separate mixtures.

> See the topic about In and out of cells

Chemical bonds

Ionic bonding

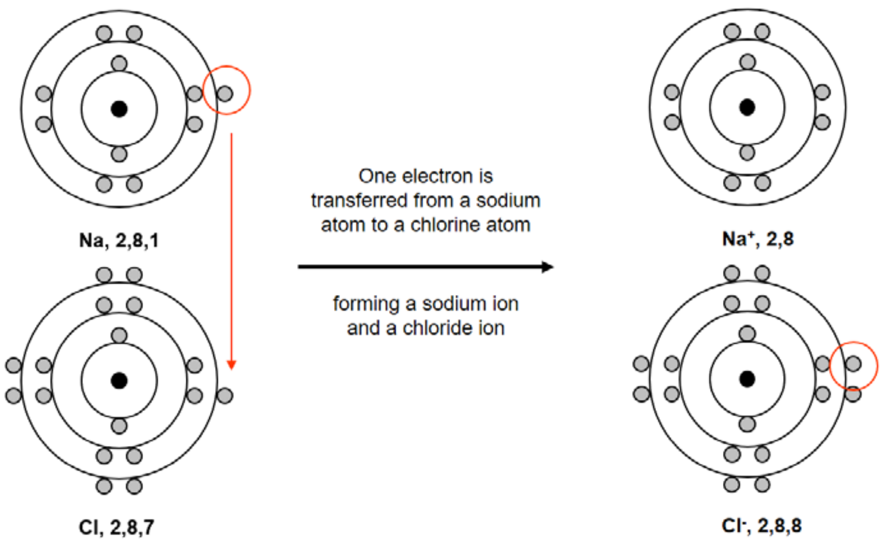
In the formation of an **ionic bond** electrons are transferred between atoms, leaving some with fewer electrons and others with more electrons. These are **ions**. Positively charged ions are called cations and negatively charged ions are called anions.

For example, an electron is transferred from a sodium atom (Na) to a chlorine atom (Cl) to form a sodium ion (Na^+) and a chloride ion (Cl^-):

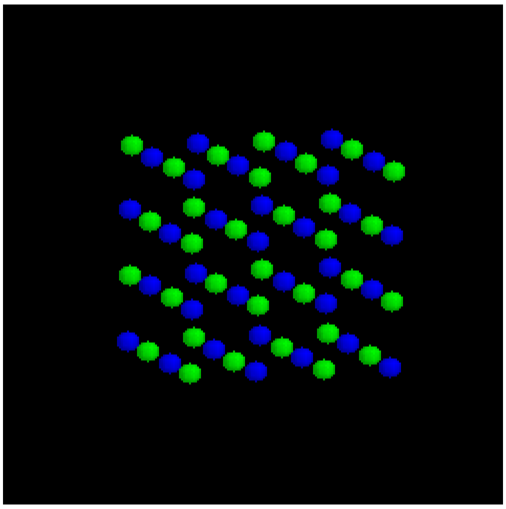
Na (2,8,1) and Cl (2,8,7) combine to form Na^+ (2,8) and Cl^- (2,8,8)

where the numbers in brackets show the electron arrangements in the atoms and ions.

Formation of sodium chloride



Cations and anions are attracted to one other because of their opposite charges. They are held together in a giant three-dimensional lattice.



NaCl

Salts are examples. Like other ionic compounds, many salts are soluble in water. In water, the giant 3-D lattice breaks up into ions which move around relatively freely in solution. Each ion is surrounded by a cluster of water molecules (we say they are **hydrated**). This can be shown by an equation:

$NaCl$ (s) + aq $\rightarrow$ Na^+ (aq) and Cl^- (aq)

where (s) shows a substance is a solid, aq represents water, and (aq) shows an ion is in solution and hydrated.

To understand why this happens you need to know about water. You need to understand the structure of water molecules and bonding, both within a water molecule (polar covalent bonds) and between water molecules (hydrogen bonding).

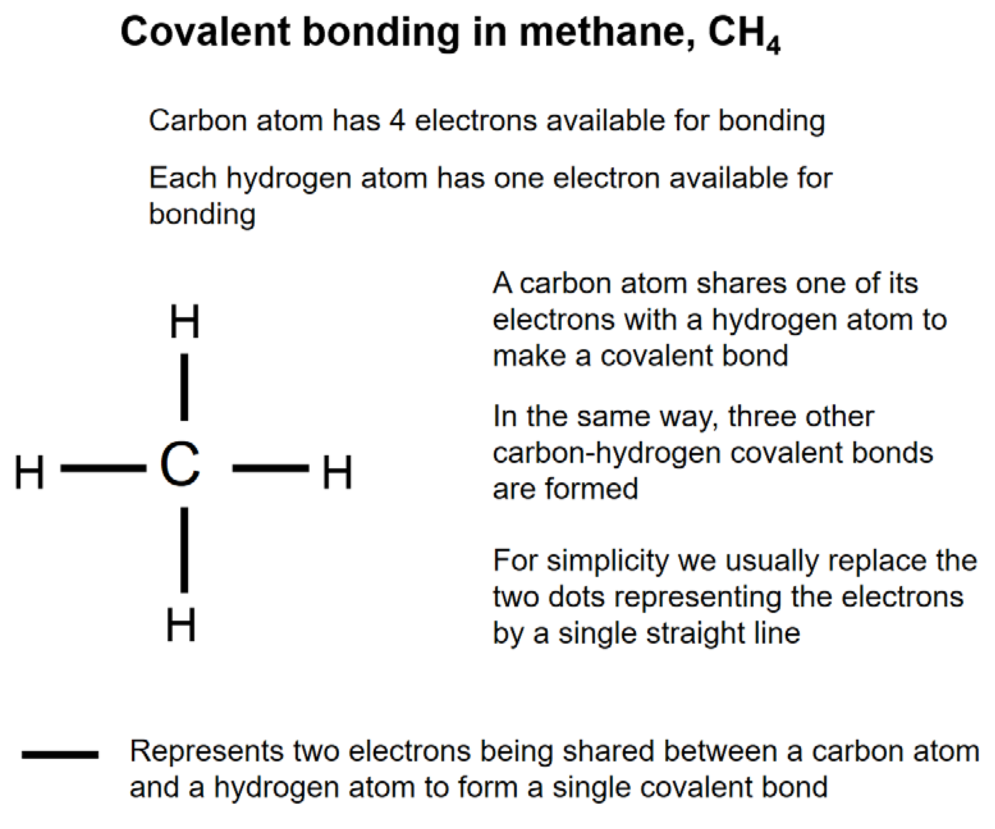
> See the topic about Water

Hydration is important. It's the diameter of a hydrated ion that determines how quickly the ion passes through a cell membrane.

Covalent bonding

In the formation of a **covalent bond** electrons are shared between atoms. They are always shared in pairs, so a covalent bond may consist of two, four or six electrons being shared. These are called single, double and triple covalent bonds respectively. It is the mutual attraction of the atoms' nuclei (which are positively charged) for the shared electrons (negatively charged) that hold the bond together.

For example, carbon and hydrogen atoms share electrons to form covalent bonds in methane, CH_4.



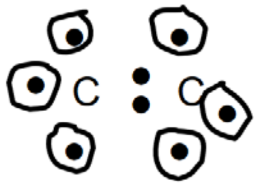
Rules about combining power are still obeyed when carbon and hydrogen atoms combine to form ethane, C_2H_6.

Covalent bonding in ethane, C_2H_6

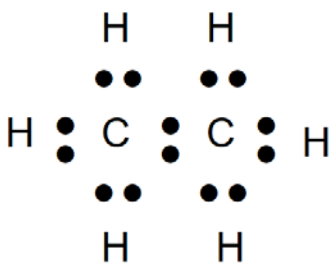
There are other ways that carbon and hydrogen atoms can combine – and still obey the combination rules

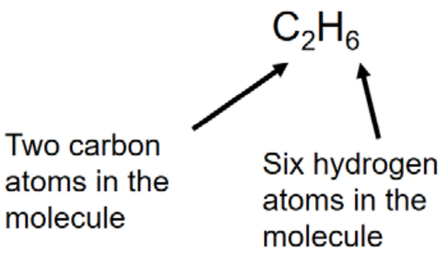
Remember: electrons available for bonding: Carbon: 4 Hydrogen: 1

Suppose a carbon atom forms a single bond with another carbon atom



This leaves enough electrons to bond 6 hydrogen atoms





Molecules

Clusters of atoms held together by covalent bonds are called **molecules**. Compounds that exist as molecules are often called **molecular compounds**. Notice that the formula of ethane is given as C_2H_6, not CH_3 (its empirical formula). C_2H_6 is the **molecular formula** of ethane. It shows the actual number of atoms present in the molecule.

But a molecular formula does not show what bonds are present in a molecule. This is done using a **structural formula**. A simple example to illustrate the idea:

Carbon dioxide is a molecular compound with:

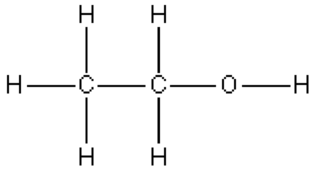
- Molecular formula CO_2
  which shows that one molecule consists of one carbon and two oxygen atoms

- Structural formula O=C=O
  which shows that four electrons are shared between the carbon atom and each of the oxygen atoms (in other words, two double covalent bonds)

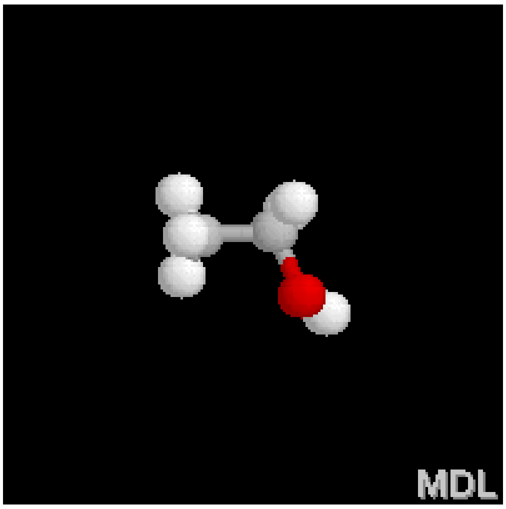
Ethanol is also a molecular compound with:

- Molecular formula C_2H_6O
  which shows that one molecule consists of two carbon, six hydrogen and one oxygen atom

- Structural formula



which shows that two electrons are shared between the two carbon atoms, two are shared between the carbon and oxygen atoms, two are shared in each carbon-hydrogen bond and in the oxygen-hydrogen bond.



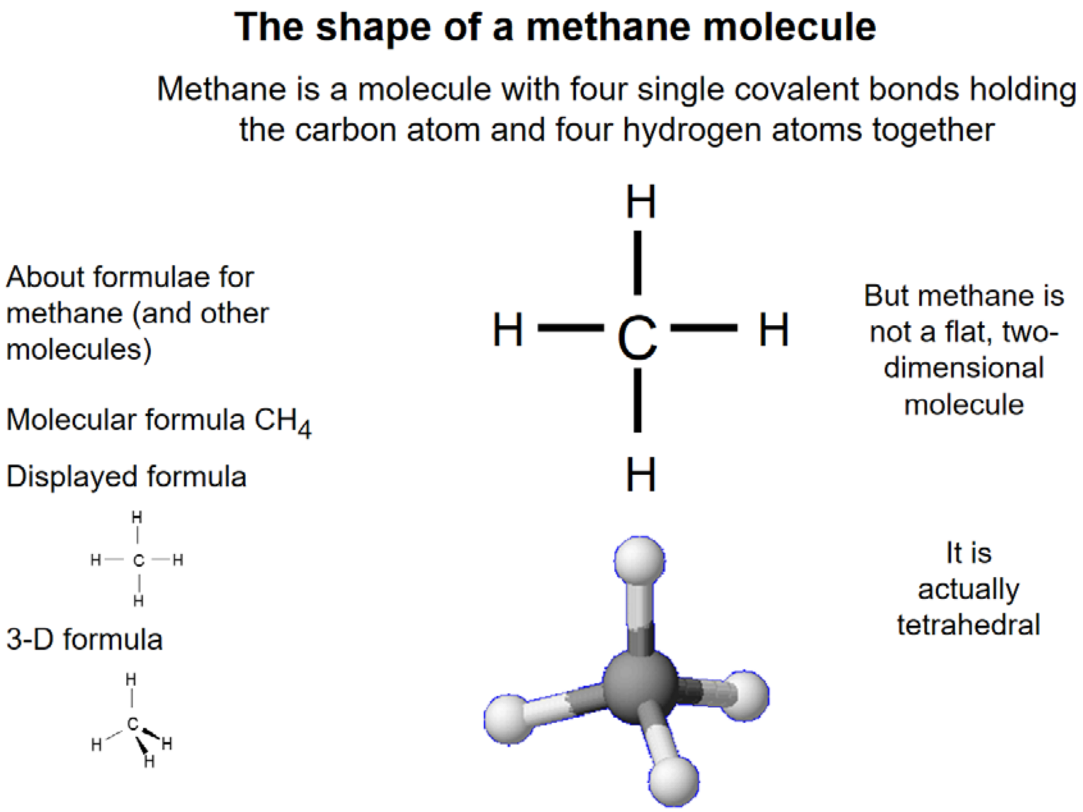
Ethanol

Molecules have three-dimensional shapes. Two atoms held by single covalent bonds are free to rotate relative to one another. This means that molecules can twist, flex and bend. The properties of a molecular compound are determined by:

- the arrangement of its atoms (which ones are bonded to one another)
- the strength of the bonding between atoms in a molecule
- the shape of the molecule (including its ability to adopt different **conformations**)
- the bonding between one molecule and another (much weaker than the covalent bonds within a molecule)

Knowledge of structure, bonding and shape is invaluable when it comes to understanding how biological molecules behave.

Molecular models are a really useful tool for 'looking' at molecules. The structure of DNA was derived from a combination of experimental work and model-building. The models used by Crick and Watson were homemade. Nowadays commercial molecular model kits can be bought. But these are being surpassed by software packages that enable 3-D images to be manipulated on screen. You will use molecular modelling throughout much of this guide.

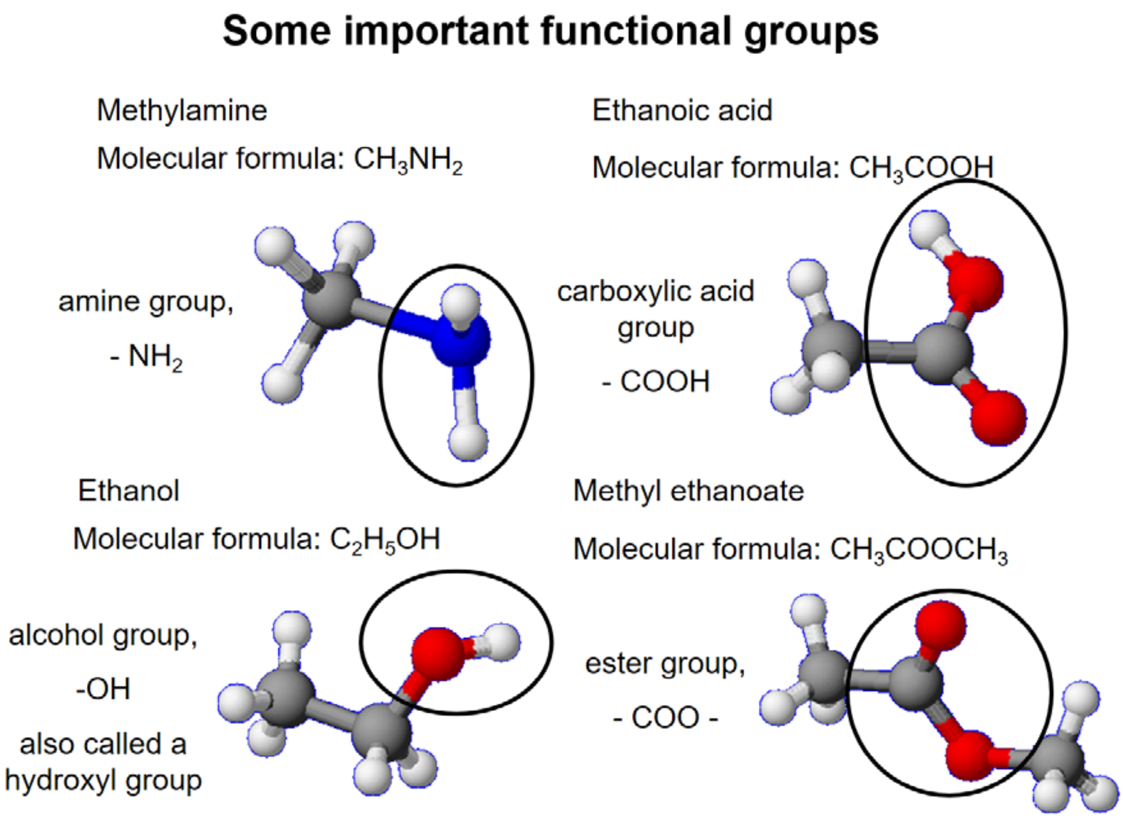


A reminder about chemical formulae:

- The simplest ratio in which atoms combine to form a chemical is shown by its **empirical formula**. For example, ethane's empirical formula is CH_3.
- The number of atoms in a molecule is shown by its **molecular formula**.
- The arrangement of its atoms is shown by its **structural formula**.
- The arrangement of its atoms in space is shown by its **displayed formula**.

Some groupings of atoms in a molecule have characteristic reactions no matter what the rest of the molecule looks like. These groupings are called **functional groups**. Here are some important ones that you will find in biological molecules:

C=C	alkene	
-OH	hydroxyl (alcohol)	
-COOH	carboxylic acid	
-COOR	ester	'R' stands for any alkyl group
$-NH_2$	amine	



Test your knowledge

[Take quiz on *Some Basic Chemistry*]