STEM
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CHEMISTRY

What is chemistry?

Chemistry is the **natural and experimental science that studies matter**, its structure, properties, and composition. It also **analyzes the transformation** that matter undergoes through reactions, as well as its relationship with energy. Chemistry is considered **one of the major contemporary sciences.**

According to Jean-Marie Lehn, a supramolecular chemist and winner of the 1987 Nobel Prize in Chemistry, chemistry **"**is a science that aims not only to discover but also, and above all, to create, since it is the art of making matter complex."

Chemistry's evolution, as well as our understanding of it and its denomination as a science, has changed over time, and these are a few milestones in its history:

- **Prehistoric period**, when the first humans were interested in materials, making them, handling them, and using them for survival. What we today know as combustion responds to **homo erectus's** need to generate fire and heat.

- **Greek antiquity,** when the first philosophers presented hypotheses regarding matter **based on observation and experimentation**. The most valuable contribution from this era is in philosopher Abdera Democritus's approach: he established that **matter was composed of small particles called atoms.**

- **Eastern chemistry,** which precedes what we know as modern chemistry. Around the year 1330, alchemists held mystical beliefs about the philosopher's stone for **transforming materials into gold** while **developing techniques, materials, and instruments** now used in chemical laboratories.

- In 1661, Irishman **Robert Boyle** published **The Skeptical Chemist.** With this work, chemistry was unfettered from any subjective claims advanced by alchemists.
- From the eighteenth century on, **chemistry began to be called a modern experimental science** due to the development of more precise, verifiable techniques for measurement that gave way to the discovery of various phenomena. This was consecrated with the postulation of **John Dalton's atomic theory** in 1983.

- 2011 was declared the **International Year of Chemistry** by the United Nations (UN).

What are the essential concepts associated with chemistry?

There are several basic concepts that are essential not only to study chemistry but to understand its complexity:

- **Matter:** everything that has mass and volume and is composed of particles, whether pure substances or mixtures.
- **Atom**: the basic, smallest unit of matter chemistry considers. Atoms have weight, volume, and electric charge. They are made up of an atomic nucleus surrounded by a set of electrons revolving around it.
- **Subatomic particles**: the particles that make up atoms and give them properties. There are three types: protons (positively charged), electrons (negatively charged), and neutrons (uncharged).
- **Molecules**: the union of two or more atoms with unique properties, which form compounds.
- **Chemical element**: a substance made up of a set of atoms that have the same number of protons in their nucleus. There are 118 chemical elements in the periodic table.
- **Chemical compounds:** substances consisting of more than one chemical element in the periodic table. Their main characteristic is that they have a chemical formula, such as water, for example, which is composed of hydrogen and oxygen.

What are the branches or disciplines of chemistry?

Chemistry is organized according to the type of material at hand. These include:

1. **Organic chemistry.**
2. **Inorganic chemistry.**
3. **Biochemistry,** which studies the substances present in biological organisms.
4. **Physiochemistry,** which studies the structure and energy load in chemical systems at the macroscopic, molecular, and atomic levels.
5. **Analytical chemistry,** which analyzes samples of materials to understand their structure and composition through reactions.

How is chemistry applied to sustainability?

As we have seen, chemistry has played a significant role in the lives of human beings since the distant past, **influencing our lifestyle and transforming our environment.**

In sustainable industrial production, both for producing materials and for their processing and sale, the following are important:

- It makes **producing fuels other than hydrocarbons** possible, thus aiming to reduce environmental impact.
- It makes it possible to **create new techniques for recycling materials.**
- It makes it easier **to manufacture much more resistant, economical, and ecological building materials.**
- **It helps develop compounds to eliminate pests in crops.**

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ATOMS

What are atoms?

Atoms are the **smallest stable units of matter. They maintain all the properties of a chemical element.** They are organized and classified according to their atomic numbers, chemical properties, and electronic charge in the periodic table.

Atoms are made up of **smaller parts called subatomic particles**, which include **protons, neutrons, and electrons.** These micro-units combine and form molecules that interact with each other.

Atoms of the same element are identical; what differentiates them is the way they combine to form chemical compounds. This means that hydrogen atoms all over the Universe are identical to those in the human body, food, or materials used in industry.

What characteristics does an atom have?

In addition to their basic characteristic of being the smallest particle of matter, atoms also:

- **They are very light particles**, weighing very little.
- **They retain their original properties when a chemical reaction** takes place. This means that they are neither created nor destroyed; they are just organized in different ways to create new bonds between different atoms.
- **They are organized or grouped to form molecules,** and these can consist of the same or different chemical elements. When grouped together, they reach a state of minimum energy and maximum stability, gaining, losing, or sharing electrons. Eventually, the stored energy is released as heat or light.
- Atoms obey **Lewis's octet rule,** proposed by chemical physicist Gilbert Newton Lewis. This rule states that chemical bonds acquire the electronic configuration of noble gases, with eight electrons located at their last energy level, which makes them very stable and unreactive.

What are the parts of an atom?

Every atom consists of a complex structure divided into:

1. **Nucleus:** the part of the atom that contains the **protons** (positively charge) and **neutrons** (neutral charge). **99% of the mass of an atom is concentrated in the nucleus**.

2. **Electron cloud:** the part that **surrounds the nucleus where electrons are located** (negatively charged particles); represented by the shape of the atomic orbitals.

Though it is believed that atoms are indivisible particles, they contain the following **subatomic particles**:

- **Protons:** subatomic particles with a positive electric charge that determine the atomic number of the element.
- **Neutrons:** subatomic particles with a neutral electric charge – that is, equal to zero – which makes them easy to penetrate and difficult to manipulate.
- **Electrons**: subatomic particles with a negative electric charge; they represent less than 0.06% of the total mass of the atom and orbit around the nucleus.

How do atoms behave according to their parts?

Protons and electrons are attracted by the electromagnetic interaction, while **protons and neutrons are attracted to each other by the nuclear force,** the exclusive force of the particles that make up the atom's nucleus.

Normally, **an atom's charge is neutral** since it has as many protons as electrons, allowing the positive charges to cancel out the negative charges.

What are the properties of the atom?

- **Every atom has mass** which mainly comes from the protons and neutrons of the nucleus. In chemistry, the unit used to denote mass is the **mol,** which weighs as many grams as the atomic mass of an element.

- **Every atom has a size**, though it is not delimited, and it is determined by the electron cloud. **Its dimensions are so small** that they cannot be observed by optical measuring instruments.

- **Every atom has energy levels.** An electron in an atom has potential energy that is inversely proportional to its distance from the nucleus, which means that **it increases in energy according to that distance.** The unit for expressing atomic energy is the **electron volt.**

- **Every atom establishes electrical interactions between protons and electrons** in its nucleus.

What atomic theories have there been over time?

Interest in and study of the atom dates back to Ancient Greece, but it was not until the nineteenth century that the first theories began to develop. The main ones are:

- **The theory by English chemist John Dalton,** which established that matter was made up of indivisible, equal elementary particles.

- **The atomic model** by English scientist **J.J. Thomson,** where he suggests the existence of electrons and refutes the theory of his predecessor regarding the indivisibility of the atom. His model is known as **the plum pudding model**, and it explains that atoms are masses with positive and negative charges.

- **The theory of the nuclear atom** developed by New Zealand scientist **Ernest Rutherford,** who discovered that most of the mass of an atom is located in its nucleus, with negative charges orbiting around it.

- **The atomic model** by Danish physicist **Niels Henrik David Bohr**, proposing that an atom's electrons are in orbit at some distance from the nucleus and that they can jump from one orbit to another with just the right amount of energy.

- **Quantum mechanical model of the atom**, developed by physicists **Werner Heisenberg, Louis de Broglie, and Erwin Schrödinger.** It states that electrons behave like standing waves orbiting in an electron cloud.

- Finally, in 1932, scientist **James Chadwick discovered the neutron,** thus completing the model of the atom known today.

CHEMICAL BONDS

What are chemical bonds?

A chemical bond involves **atoms combining to form chemical compounds** and **bring stability to the resulting product.** In this process, atoms can share or give up electrons from their outermost shell to bond and **create a new homogeneous substance.**

When a chemical bond is formed, **the structure and characteristics of atoms don't change;** there is only electron sharing. This means that when the chemical bond for water (H_2O) is formed, for example, its elements (oxygen and hydrogen) remain the same.

The environment around us is the result of multiple chemical bonds that **give matter properties, both physical and chemical.** This is a product of the **force generated by atoms when they combine and form bonds,** given that these small particles are much more stable together than by themselves.

How does a chemical bond occur?

Every atom is composed of a **core** with **positively charged protons** and **neutral neutrons**, and it is surrounded by an **outer layer** called the **electron cloud**, which has a **negative charge.**

Opposite charges attract both within the same atom and between atoms. This attraction forms chemical bonds between different elements.

Atoms round out their electric charges by **electron exchanges**: they can give up, accept, or share these particles to **achieve a stable electronic configuration**, meaning a lower energy consumption.

What is the Lewis octet rule, and what is its relationship to chemical bonds?

American chemical physicist Gilbert Lewis devised the octet rule in 1917; **it explains how atoms of different chemical elements combine to form bonds.**

This theory **proposes that the ions of elements on the periodic table fill their last energy levels with 8 electrons**. This way, the molecules achieve stability at the level of their electronic structure**.**

Thus, **elements with high electronegative charges gain electrons** until reaching the octet, while **those with low electronegativity usually lose them** to achieve the same goal.

What types of chemical bonds are there?

Depending on the type of bonded atoms, which have their own characteristics and mechanisms, a chemical bond can be:

1. **Covalent:** occurs when **non-metallic atoms share electrons**. In this type of bond, **electrons move between atoms**, producing **polar covalent bonds** (sharing electrons unequally) and **non-polar ones** (when the number of electrons is evenly distributed).
   Example: water (H_2O) is composed of two hydrogen atoms and one oxygen atom, and in its bond, each hydrogen atom shares an oxygen atom.

2. **Ionic:** this occurs when **metallic and non-metallic atoms bond and an electron charge is given from one to the other.** As a result, both negatively charged ions (**anions**) and positive ones (**cations**) are produced, and there is an attraction between their opposite charges.
   Example: in sodium chloride (NaCl), which combines a chlorine atom and a sodium atom, the former has seven electrons, and the latter has one. When forming the ionic bond, sodium gives up its electron to chlorine, thus fulfilling the octet law.

3. **Metallic:** these **are formed between atoms of metals,** whose atomic nuclei gather and are surrounded by their electrons like a cloud. This is a strong kind of bond that **is spread out like a network.**
   All pure metallic elements consist of metal bonds, for example, gold (Au), iron (Fe), aluminum (Al), etc.

What are some characteristics of chemical bonds?

- They hold **atoms together** inside the chemical molecules.
- The strength of a chemical bond is determined by the **difference in electronegativity** (the higher it is, the greater the strength of the electrons attracted between atoms.)
- Generally, **the numbers of electrons are even.**
- **Covalent bonds** can exist as a **gas**, **solid**, or **liquid**.

- Some **covalent bonds** are **soluble in water**, while others are in **organic solvents**.

- **Acid covalent bonds conduct electricity** in the presence of an aqueous solution (other covalent bonds are not good conductors), and **ionic bonds** do so when dissolved in water or melted.

- **Ionic bonds** have **high melting** and **boiling points.**

- **Metal bonds** are good **conductors of heat** and **electricity**, they're typically in a **solid state**, and they are **highly malleable**.

CHEMICAL REACTIONS

What are chemical reactions?

Chemical reactions are **thermodynamic processes that transform matter**. Inthis process, two or more **chemical substances, also called reactive substances, change their molecular structure** and chemical bonds to consume or release energy. This way, they manage to generate **new chemical structures other than the initial ones; these are called products.**

These processes **can occur naturally and spontaneously** in nature, and **they can be generated through human intervention** in a controlled environment, such as a laboratory.

Chemical reactions are expressed through **chemical equations**, which are formulas describing the reagents involved, as well as the result or product obtained. These equations also **usually describe the conditions under which the chemical reaction occurs** – that is, if they are in the presence of heat, light, etc.

What concepts are associated with chemical reactions?

- **Matter:** everything that takes up space and has mass, shape, weight, and volume and is therefore perceptible.
- **Atoms:** the smallest unit of matter that has the characteristics of a chemical element.
- **Chemical element:** a type of matter made up of atoms of the same kind.
- **Molecule:** a group of atoms that are the same or different that are held together. When they are separated, this affects or destroys the properties of the substance.
- **Bond:** what establishes interactions between atoms and molecules.
- **Chemical compound:** a substance that is made up of the combination of two or more elements from the periodic table.
- **Chemical substance:** matter with a defined chemical composition; the result of the combination of two chemical elements that is made up of molecules and atoms. Its elements cannot be separated by any physical means.

- **Products:** substances that result from the chemical reaction and which fulfill a certain function. They are made up of one or more chemical compounds.

What are the characteristics of chemical reactions?

- In a chemical reaction, **atoms do not change**; what changes are the bonds between them.
- Most chemical reactions **occur in aqueous solutions.**
- They can be **reversible** if the products become reactants again, or **irreversible** when the products do not go back to being the reactants that gave rise to them.
- Reactions **can be simple** when they require a single step for the reactants to be converted into products, **or complex** when there are several steps between the reactants and the product; intermediate compounds may also be formed in the latter case.

How does a chemical reaction occur?

A chemical reaction **occurs when moving molecules hit each other, breaking their bonds and producing an exchange of atoms** that form new products. Another way a chemical reaction can occur is through the **vibration of substances**; when they do so with sufficient energy, they can be broken down into smaller molecules.

What explains the law of conservation of matter?

The law of the **conservation of matter** is fundamental in all natural sciences, but especially in chemistry. It states that, **in any chemical reaction, mass is conserved. This means that the matter consumed in the process is equal to the mass resulting from the products formed.**

> The approach states the following:
> **in an isolated system, during every ordinary chemical reaction, the total mass in the system remains constant - that is, the mass of the reactants consumed is equal to the mass of the products obtained.**

This law was originally proposed by Russian scientist **Mikhail Lomonosov** in 1748. It wasn't until 40 years later that it was really developed by French chemist **Antoine-Laurent de Lavoisier**. That's why the law is also called the **Lomonosov-Lavoisier Law**. In short, while mass cannot be created or destroyed, it can be transformed, just as the entities associated with it can change form.

What types of chemical reactions are there?

1. **Synthesis reaction (combination):** when two or more reagents combine to form a more complex product.

2. **Displacement, substitution, or exchange reaction:** in this type of reaction, elements of the compounds are replaced to create new ones. They can be simple when one element displaces another, or double when elements are exchanged.

3. **Decomposition reactions:** when a chemical compound is divided into simpler substances. These types of reactions are the opposite of synthesis reactions.

4. **Oxidation-reduction reactions:** when an electron transfer or exchange occurs. While one compound loses electrons (oxidizes), the other gains them (reduces).

5. **Acid-base reactions:** in this type of reaction, a basic substance is neutralized with an acidic one, and the result is a neutral compound and water.

6. **Combustion reactions:** these are similar oxidation-reduction reactions, though they differ in that oxidation occurs quickly in combustion. For it to happen, a combustible material combines with oxygen and gives off energy.

7. **Exothermic and endothermic reactions:** the former give off heat from the reactive process, and the latter require it.

8. **Endoluminous and exoluminous reactions**: the former need light to occur; the latter emit light.

9. **Exo-electric and endo-electric reactions**: the former transfer electrical energy out, and the latter require it.

STATES OF MATTER

What is matter?

Matter is anything that has mass and takes up space. Both physics and chemistry study matter from different points of view. Everything around us is composed of matter, which can occur in various states.

What are the states of matter?

Matter occurs in three states, also called **phases of matter:**

1. **Solid:** the atoms of solid matter are very close together, so they have a **fixed shape and volume**. Solids cannot be compressed; however, high temperatures increase the vibration of their particles, causing them to dilate slightly. Solids have **shape memory**, so if they are deformed, they tend to return to their original shape.

2. **Liquid:** they have a **fixed volume**, but their atoms are less cohesive than those of solids, so their **shape varies** accordingly; they take the shape of the surface or container where they are located.

3. **Gas:** their particles are not cohesive and tend to spread out, so **they have no fixed shape or volume**. Like liquids, their shape will depend on the container, but unlike them, gases occupy absolutely all the space available in their container. The volume of gases changes according to temperature and pressure conditions, so **they can be compressed** to accommodate a greater quantity in smaller containers.

These are the **classical states of matter**, as well as those that can most easily be observed in everyday conditions. However, as science has advanced, new states of matter have been observed in extreme or extraterrestrial conditions.

What are the new states of matter?

- **Plasma:** basically a gas, but **ionized**; that is, it is composed of atoms that have separated from some of their electrons.
  While it might seem that this characteristic is insufficient to consider it a distinct state of matter, in practice, plasma happens to be **capable of conducting electricity**, and under the influence of a magnetic field, it can form rays and filaments (example: plasma screens).
  The sun and much of the universe are made of plasma.

- **Bose-Einstein Condensate:**
  It is a state of matter that can occur in certain materials at **temperatures close to absolute zero**. The condensate has no classical analogue and is considered the **fifth state** of matter. It is **cold and dense** (300 times colder than atoms had been cooled before), and scientists are sure that their atoms become immobile (known as **absolute zero**).
  This state was predicted by Albert Einstein and Satyendra Nath Bose in 1927. It remained a **theoretical state of matter** for almost half a century, until physicists E. A. Cornell, W. Ketterle, and C. E. Wieman managed to develop it in the laboratory, which earned them the Nobel Prize in Physics in 2001.

How does matter change state?

Matter changes state under variations in temperature and pressure. Each of these changes is given a name:

SOLID	– fusion →	LIQUID
SOLID	– sublimation →	GAS
LIQUID	– evaporation →	GAS
LIQUID	– solidification →	SOLID
GAS	– deposition* →	SOLID
GAS	– condensation →	LIQUID
GAS	– liquefaction* →	LIQUID
GAS	– ionization →	PLASMA
PLASMA	– deionization →	GAS

* **Deposition** may also be called **reverse sublimation.**

* The difference between **condensation** and **liquefaction** is that condensation is the **reverse evaporation process**, while in liquefaction, the change of state occurs due to **an increase in pressure and decrease in temperature** (as in the production of liquid nitrogen).

Each element changes its state under different conditions and circumstances, but water (and its cycle) is a good example to see and understand changes in the state of matter more easily:

Water occurs naturally in a **liquid state**, but you simply have to cool it enough (reaching the **freezing point**, 0 °C) for it to go to a **solid state** (known as **ice**), or heat it sufficiently (reaching the **boiling point**, around 100 °C) for it to become **water vapor** (**gaseous state**). Finally, **condensation** returns water vapor (the gaseous state) to the **liquid state** - water (for example, **rain**).

The process of **sublimation** (direct passage from a **solid to a gas**, bypassing the liquid state) is generally rarer to see in natural circumstances, but in the case of water, this can be observed as **dry ice**. Another rare process is that of **deposition,** or **reverse sublimation**; again, in the case of water, we can see the atmospheric phenomenon of **hail**.

Are there other states of matter?

There are many other states of matter. Most of them are only possible in **very extreme or controlled circumstances** (in a laboratory, under very specific conditions in the outside world, etc.), or have even only appeared **theoretically** (there are models and theories according to which such a state should exist, but its observation and study is not currently possible). Other states are considered near **variations** of the major states. Some of these are:

- Supersolid
- Liquid crystal
- Strongly or weakly symmetric matter
- Quark matter (also known as strange matter)
- Degenerate matter
- Polariton superfluid
- Quantum spin liquid

ORGANIC CHEMISTRY

What is organic chemistry?

Organic chemistry is the field of chemistry over **the study of organic substances and compounds** - that is, those that **contain carbon** in their molecular structure, combined with other elements such as hydrogen, nitrogen, oxygen, and sulfur.

This type of chemistry focuses mainly on **analyzing the structure, properties, behaviors, and uses of chemical compounds** that help answer how life works in our environment. This, in turn, allows us to understand how chemical processes occur in living organisms, as well as how they operate at the molecular level.

Nucleic acids, enzymes, and proteins are organic substances since these are living compounds. By **understanding their structure and molecular transformation, we can harness their full potential**. This is only possible thanks to organic chemistry.

What is the origin of organic chemistry?

The term "organic chemistry" was first used in about 1807, when Swedish chemist Jöns Jacob Berzelius introduced it to explain the study of **compounds derived from the living resources available in nature.**

However, it was not until 1828 that German scientist Friedrich Wöhler experimented in laboratories with ammonium cyanate (an inorganic substance) and discovered that it could be converted into urea, an organic substance, through chemical processes. Through these experiments, **he proved that organic matter could be synthesized in a laboratory** without being linked to life, thus refuting Berzelius's theory.

Later, in the year 1861, German chemist Friedrich August Kekulé von Stradonitz **defined organic chemistry as the branch of chemistry dealing with carbon compounds**; this was a pioneering move in putting carbon at the heart of this field.

Today, organic chemistry can be applied to almost any field, **from transportation to food, the pharmaceutical industry, and genetics**.

How are organic compounds classified?

There may be **more than 50 million** organic compounds, so classifying them is necessary to study them. They can be categorized by:

1. **Their origin:**
   - **Natural compounds:** these originate from living beings or their waste.
   - **Artificial or synthetic compounds:** these can originate in a synthesized form in laboratories.

2. **Their structure:**
   - **Aliphatic compounds:** these bond and form chains.
   - **Aromatic compounds:** these form rings with interspersed double bonds.
   - **Organometallic compounds:** these are made up of carbon atoms covalently bonded to one or more atoms of a metallic element.
   - **Heterocyclic compounds:** these form rings with other non-organic elements.

3. **Functional groups:**
   - **Alkanes, alkenes, and alkynes:** their chemical structure is based on carbon and hydrogen, forming hydrocarbons. Alkanes are formed by single chemical bonds, alkenes by double bonds, and alkynes by triple bonds.
   - **Alcohols:** these are hydrocarbons where one hydrogen is replaced with a hydroxyl group. If there are several groups, these form polyalcohols.
   - **Ketones:** these compounds have a carbonyl group bonded to two carbon atoms.
   - **Aldehydes:** these are compounds whose structure includes a carbonyl group bonded to a hydrogen atom and another carbon atom.
   - **Carboxylic acids:** compounds with a carboxyl group.
   - **Amines:** compounds whose structure is based on the substitution of one or several hydrogens of the ammonia molecule.

4. **Their molecular weight or size:**
   - **Monomers:** molecular units that are formed through chemical bonds and form macromolecules.
   - **Polymers:** macromolecules composed of monomers.

What is the difference between organic chemistry and inorganic chemistry?

While both chemistries study chemical and molecular bonds, **the difference lies in the elements they study.** While organic chemistry studies compounds based on carbon and hydrogen, **inorganic chemistry looks at all other chemical**

elements. There are inorganic compounds containing carbon and hydrogen; however, **organic compounds are not possible without carbon.**

Furthermore, **inorganic chemistry studies compounds created synthetically with bonds involving electrostatic interactions,** which are good conductors of heat and electricity; **organic chemistry focuses on compounds formed by covalent bonds,** meaning they share electrons in their atoms' last energy levels.