Structure of Matter Course

(First semester)

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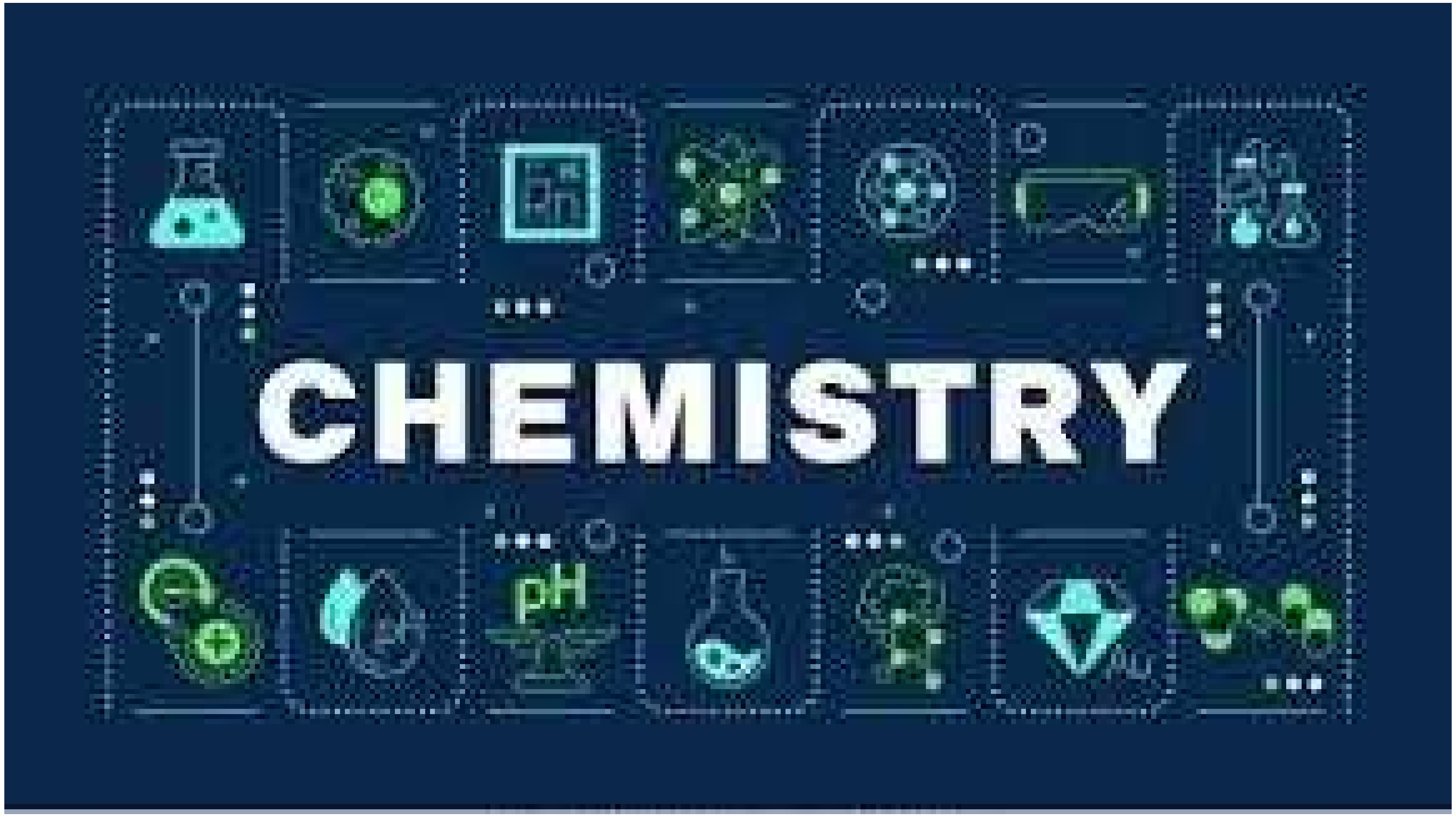
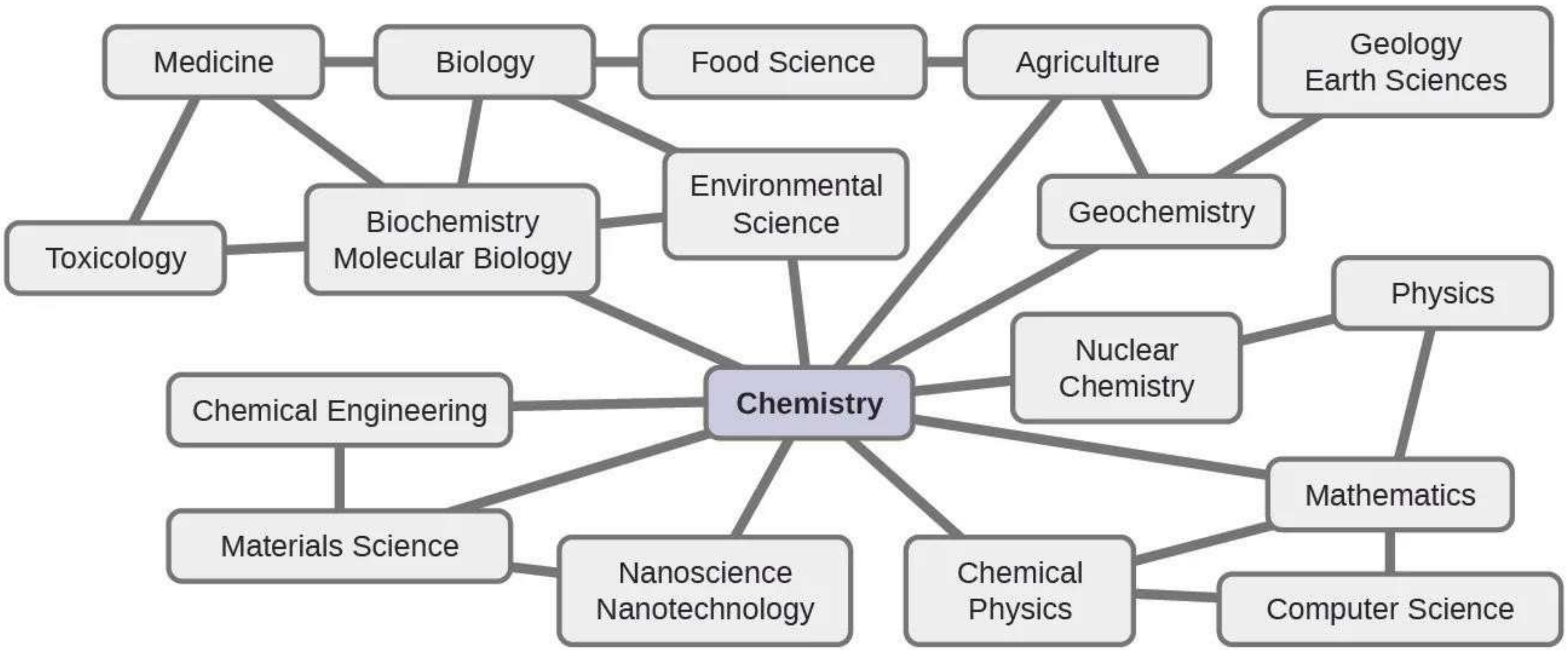


Definition of Chemistry

- "Chemistry is the study of the **composition**, **properties**, and **interactions** of matter."

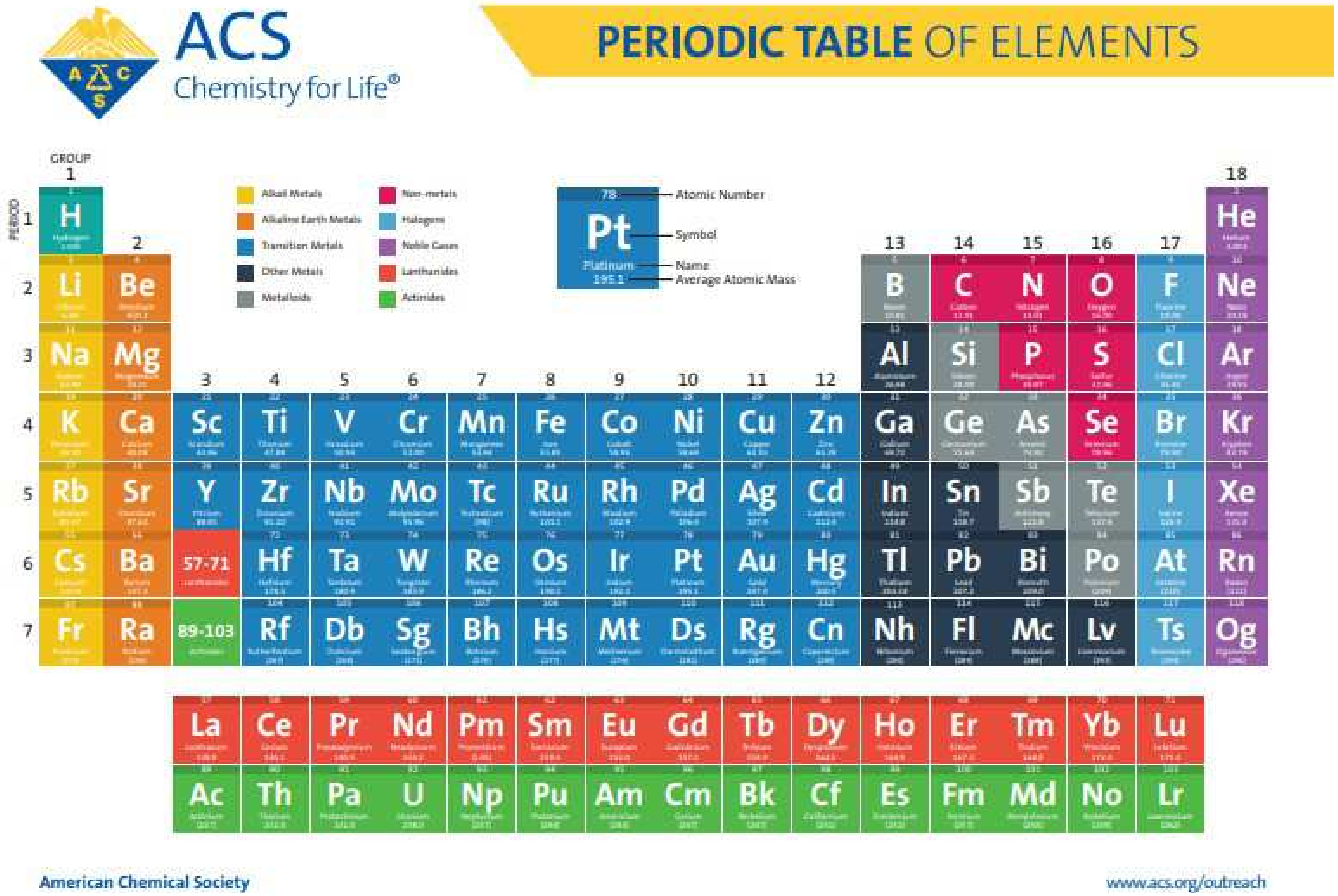
- "Chemistry is the branch of science that deals with the composition, structure, properties, and **transformations** of matter, as well as the **energy changes** associated with these processes."

interrelationships between chemistry and other fields

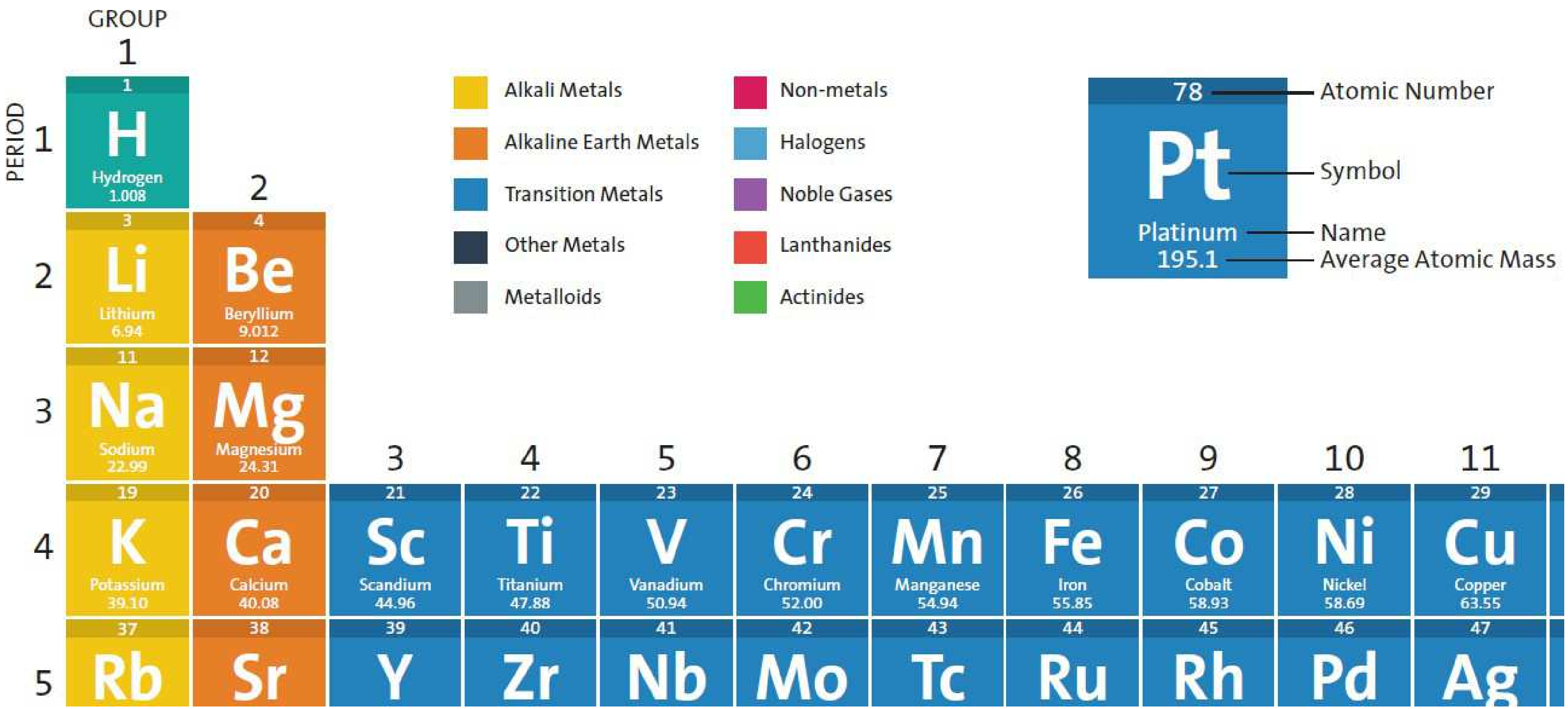


Knowledge of chemistry is central to understanding a wide range of scientific disciplines.

Periodic Table of elements



Legend (Color code key)



Organisation

- **Mendeleev's Table (1869) :**

Arranged by increasing atomic mass.

- En français, on écrit **Mendeleïev.**

- **The Modern Periodic Table:**

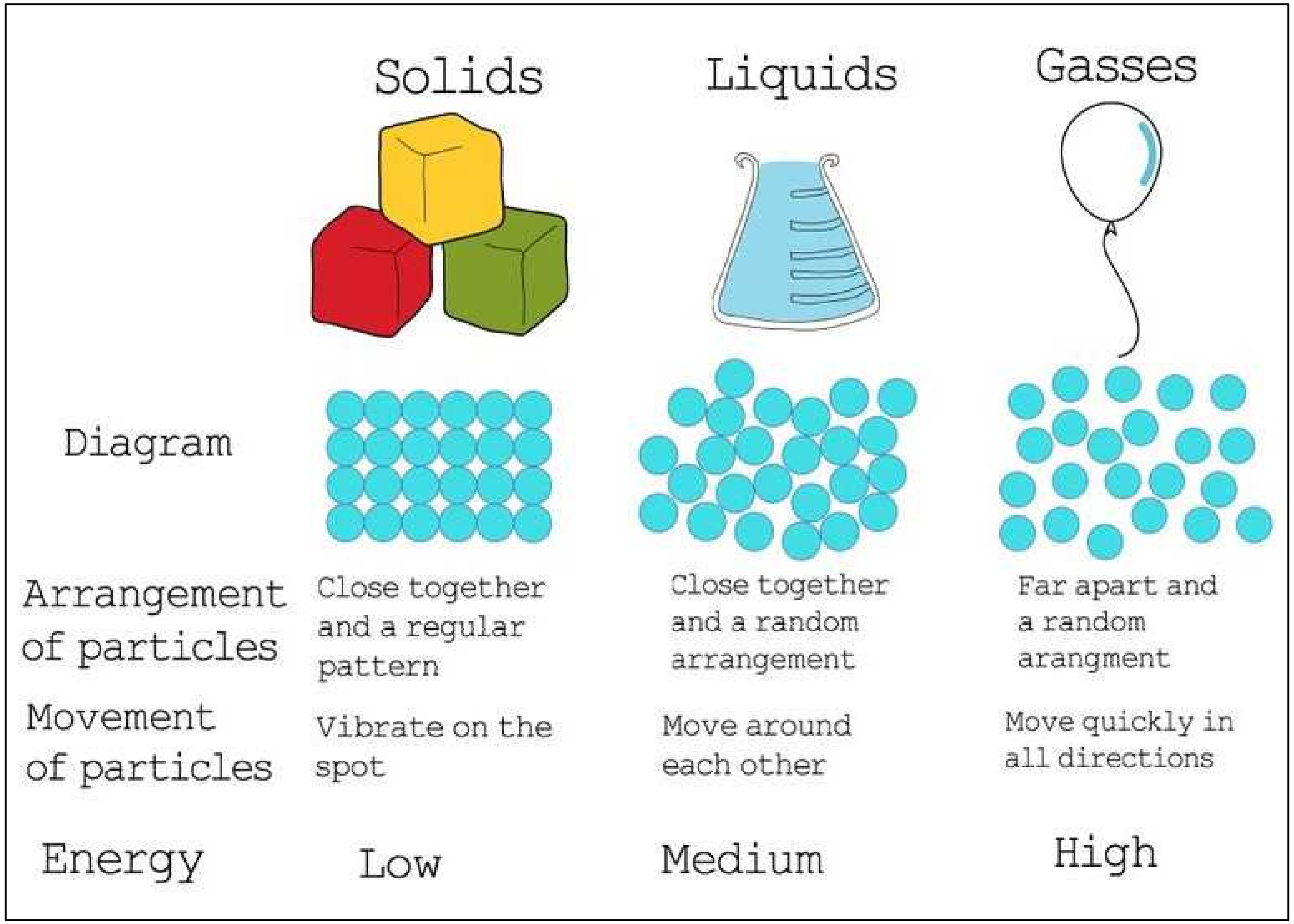
Arranged by increasing atomic number

(atomic number = number of protons).

- **Current structure**:
- 7 periods (horizontal rows).
- 18 groups (vertical columns).
- Organized by electronic configuration and chemical properties.

I. Matter

- Matter is anything that has mass and occupies space.

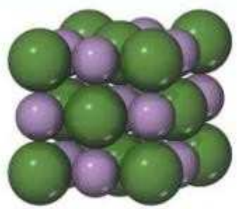


States of Matter: Solid

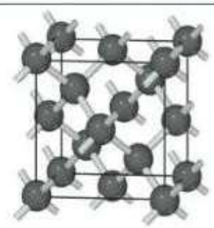
- Solids have fixed shape and volume; particles vibrate in place.

Type of Solid	Form of Unit Particles	Forces Between Particles	Properties	Examples
Molecular	Atoms or molecules	London dispersion, dipole-dipole forces, hydrogen bonds	Fairly soft, low to moderately high melting point, poor thermal and electrical conduction	Argon, Ar; methane, CH_4; sucrose, $C_{12}H_{22}O_{11}$; Dry Ice™, CO_2
Covalent-network	Atoms connected in a network of covalent bonds	Covalent bonds	Very hard, very high melting point, often poor thermal and electrical conduction	Diamond, C; quartz, SiO_2
Ionic	Positive and negative ions	Electrostatic attractions	Hard and brittle, high melting point, poor thermal and electrical conduction	Typical salts—for example, NaCl, $Ca(NO_3)_2$
Metallic	Atoms	Metallic bonds	Soft to very hard, low to very high melting point, excellent thermal and electrical conduction, malleable and ductile	All metallic elements—for example, Cu, Fe, Al, Pt

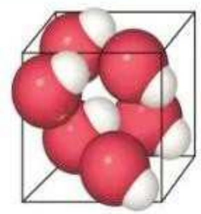
Metallic solids
Extended networks of atoms held together by metallic bonding (Cu, Fe)



Ionic solids
Extended networks of ions held together by ion–ion interactions (NaCl, MgO)



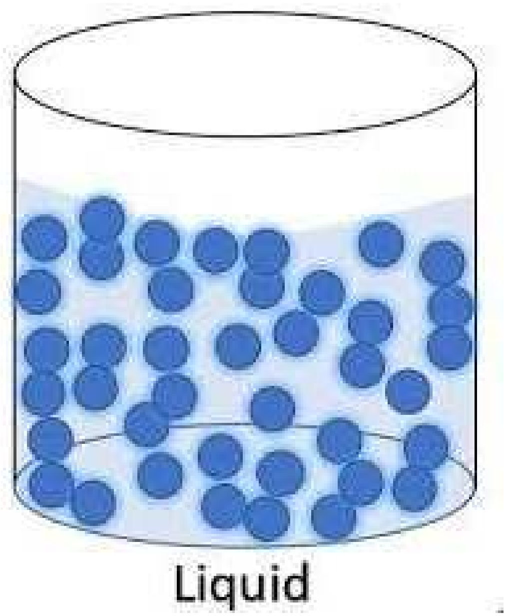
Covalent-network solids
Extended networks of atoms held together by covalent bonds (C, Si)



Molecular solids
Discrete molecules held together by intermolecular forces (HBr, H_2O)

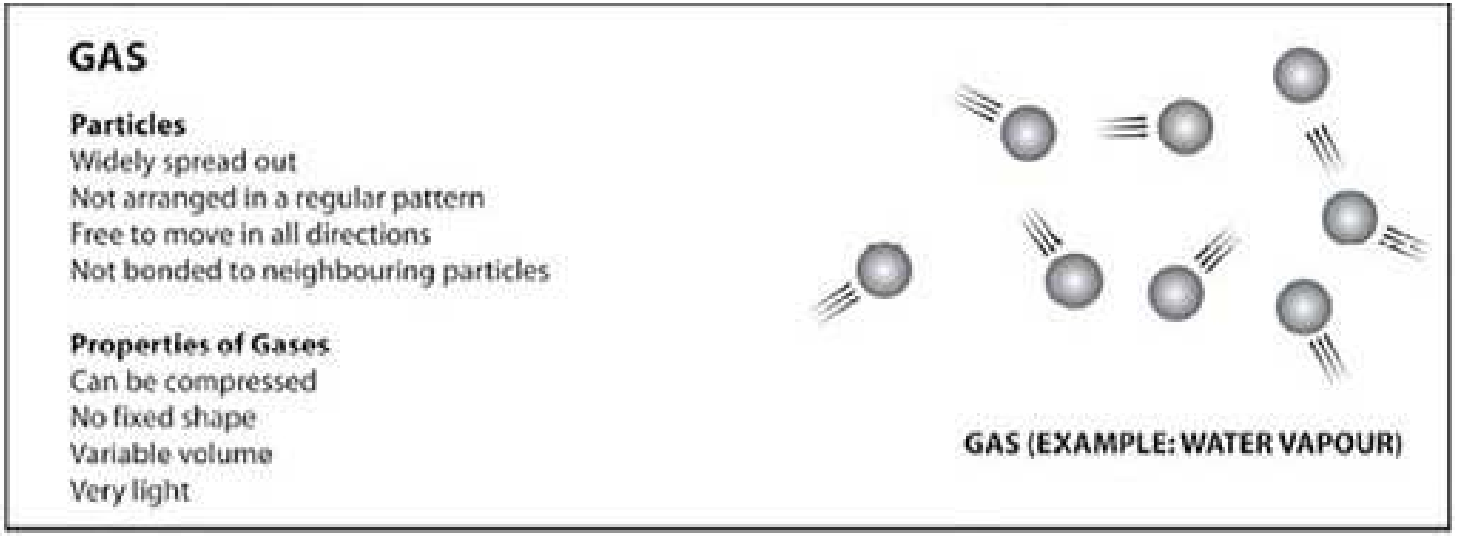
States of Matter: Liquid

- Liquids have fixed volume but no fixed shape; particles slide past each other.

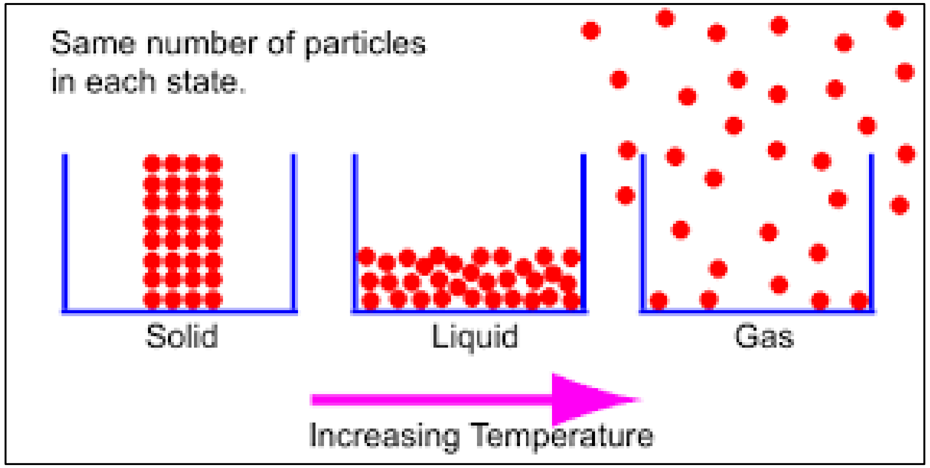


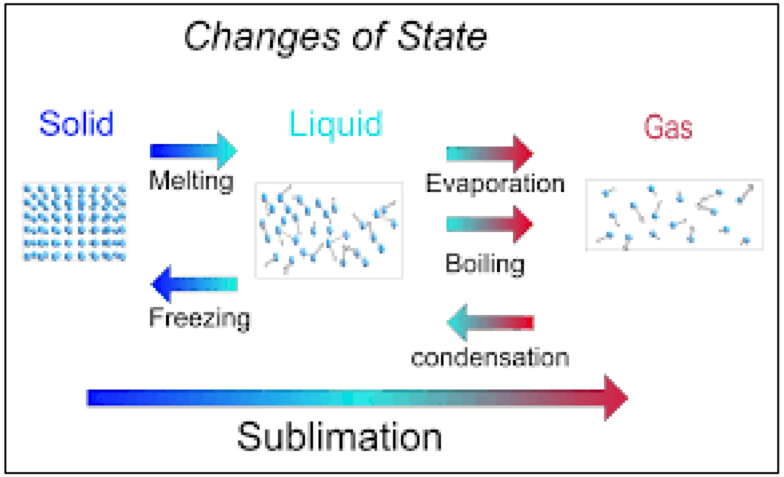
States of Matter: Gas

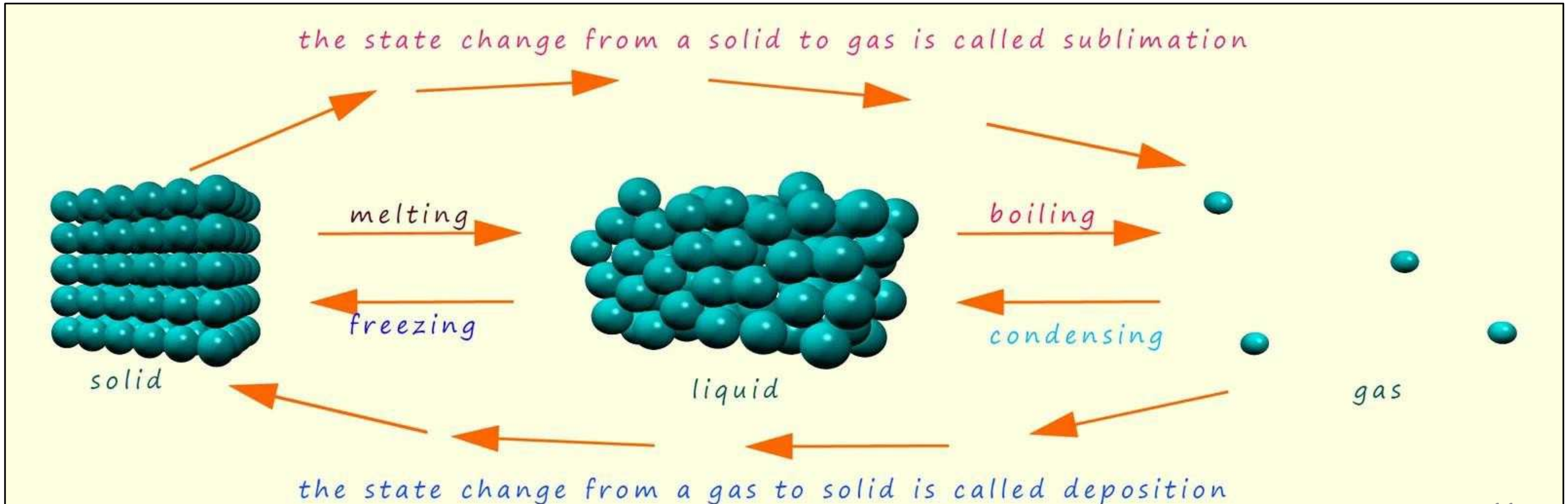
- Gases have no fixed shape or volume; particles are far apart and move freely.



Changes of State







Simple substance

- Definition**:** A **simple substance** is a chemical substance made of **only one type of chemical element**, either as single atoms or molecules composed solely of that element.

- Examples:
- O_2 (molecular oxygen)
- N_2 (molecular nitrogen)
- Fe (metallic iron)
- He (rare gas or noble gas)

Compound

- Definition**:** A **compound** is a chemical substance made of **two or more different chemical elements**, combined in a **fixed proportion** and bonded chemically.

- Examples:
- H_2O (water: hydrogen + oxygen)
- CO_2 (carbon dioxide: carbon + oxygen)
- NaCl (sodium chloride: sodium + chlorine)

Pure substance

- Definition: A **pure substance** is a material that has a **uniform and fixed chemical composition**, made of **either a simple substance or a compound.**

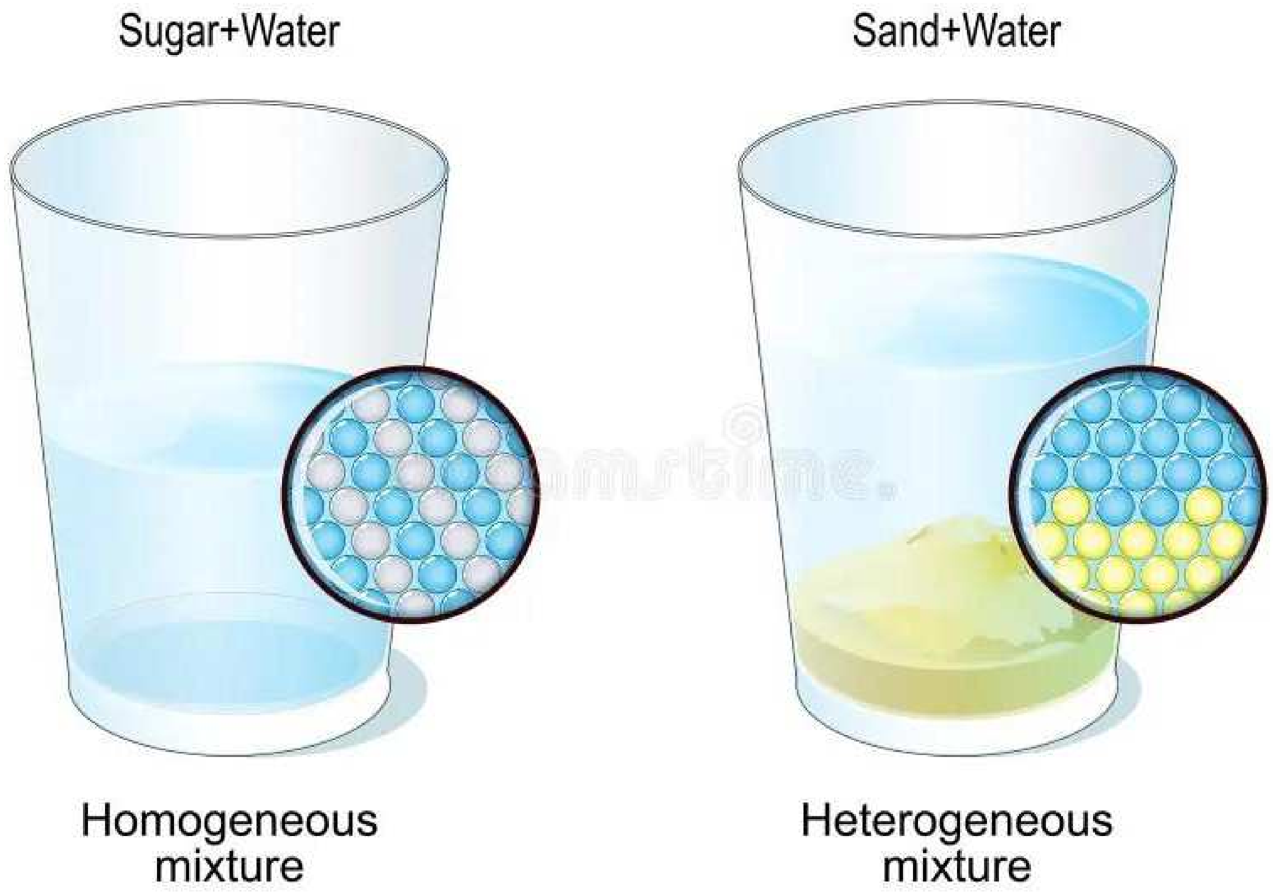
- Examples:
- O_2 (oxygen) – simple substance
- H_2O (water) – compound
- NaCl (sodium chloride) – compound

Mixture

- Definition: A **mixture** is a material composed of two or more substances, **physically combined without a chemical reaction**, and whose composition can vary.

- Examples:
- Air (mixture of gases)
- Sugar water (water + sugar)
- Metal alloys (like bronze: copper + tin)

Mixture



Sugar+Water
Sand+Water
Homogeneous mixture
Heterogeneous mixture

heterogeneous mixture

- **heterogeneous mixture:** combination of substances with a composition that varies from point to point.
- Non-uniform composition with visible phases.

homogeneous mixture

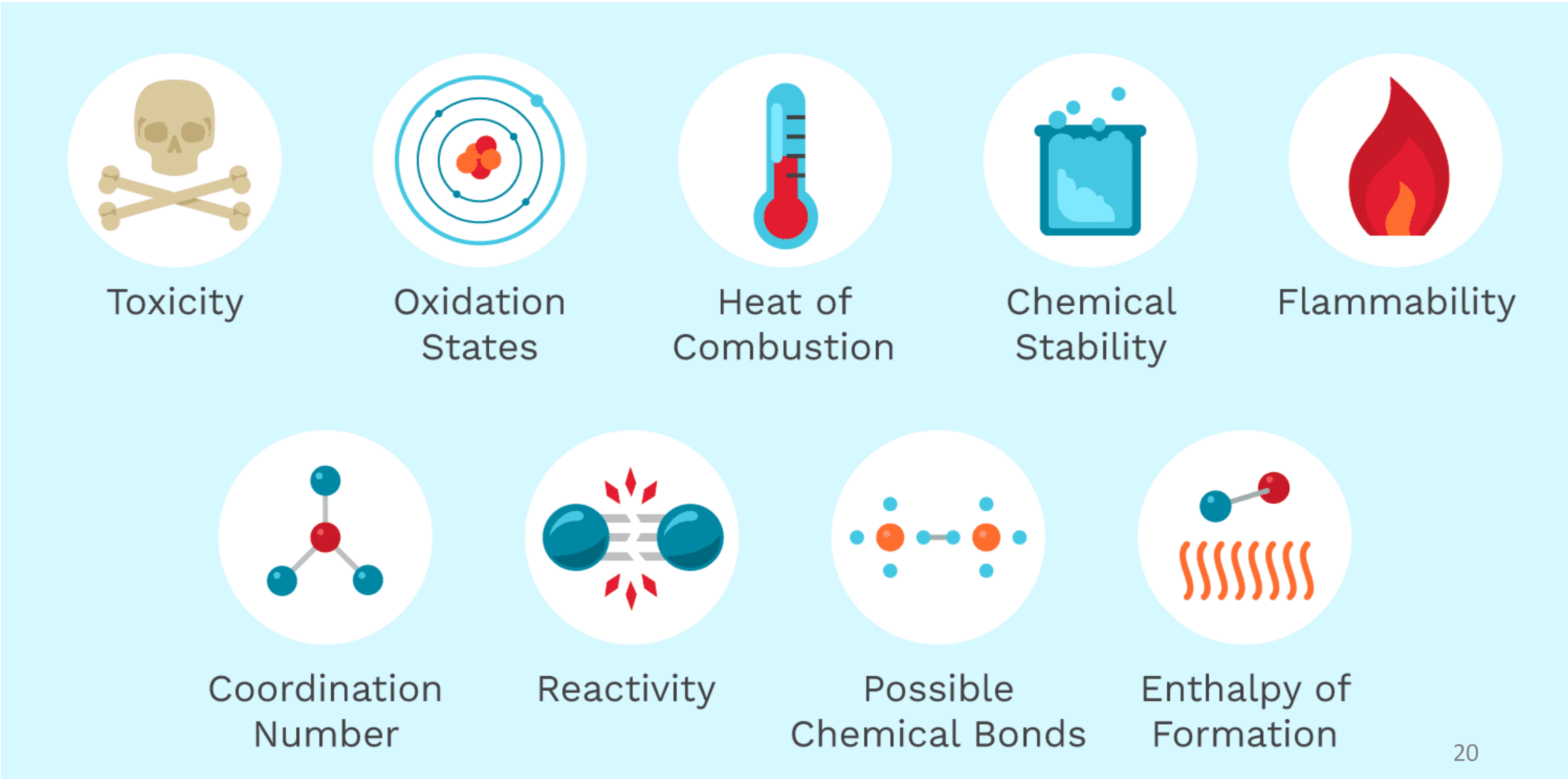
- **homogeneous mixture**(also, solution): combination of substances with a composition that is uniform throughout.

Physical Properties

- Properties measurable without changing composition.

Chemical Properties

- Properties observable during chemical changes.



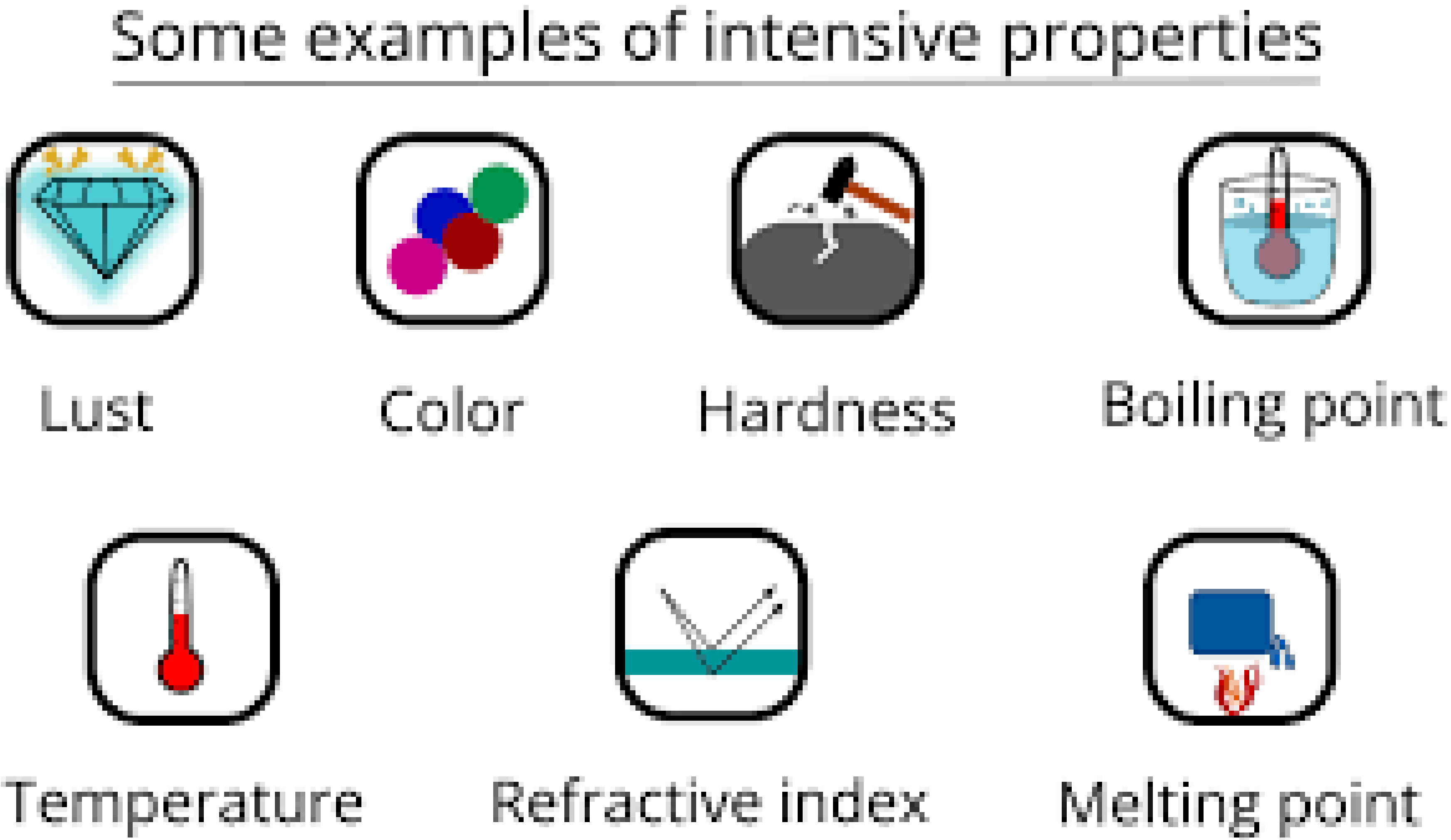
Intensive Properties

- Do not depend on the amount of substance:

these are properties **independent of the amount of matter**.

Examples: temperature, density, color, melting point, conductivity.

Intensive Properties

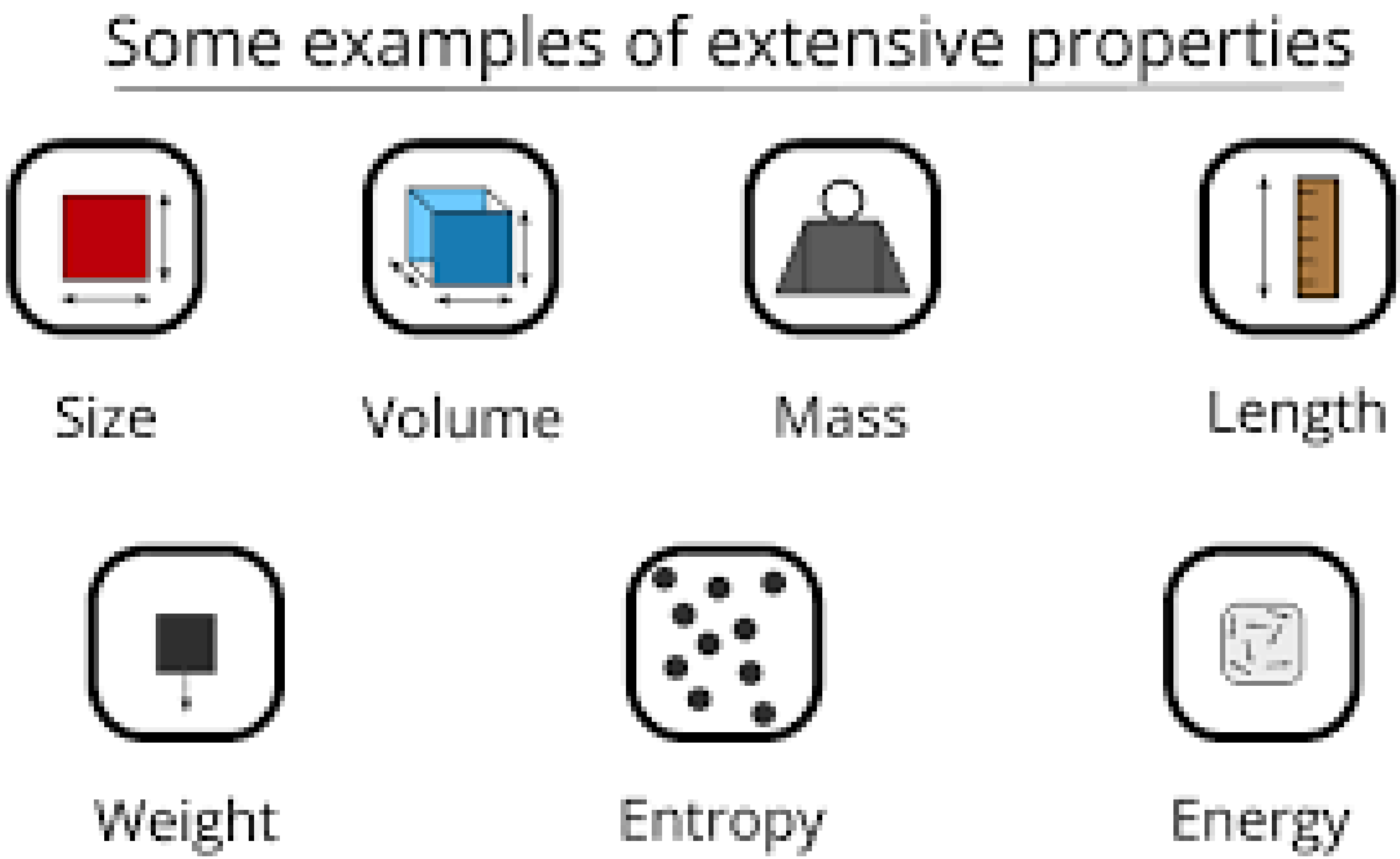


Extensive Properties

- Depend on the amount of substance:

these are properties **dependent on the amount of matter**. They increase or decrease if the quantity of substance changes.
Examples: mass, volume, energy, heat quantity.

Extensive Properties



chemical element

- A **chemical element** is a distinctive chemical entity consisting of atoms that all have the **same atomic number**, or number of **protons**.
- The chemical elements are organized into a tabular array known as the periodic table, which is arranged by ascending atomic number and reflects a periodic law that certain properties reoccur when elements are sorted in particular ways.

Atom

- An **atom** is the smallest particle of a chemical element that retains the element's properties, consisting of a central nucleus (made of positively charged protons and neutral neutrons) surrounded by negatively charged electrons.
- Atoms are the fundamental building blocks of all matter, and when they bond together, they form molecules and compounds.

molecule

- A **molecule** is a group of two or more atoms that form the smallest identifiable unit into which a pure substance can be divided and still retain the composition and chemical properties of that substance.
- Example: H_2O

Ion

- An **ion** is a positively or negatively **charged** atom or group of atoms bonded together.
- A **positively** charged ion is a "**cation**" Ex: Na^+
- A **negatively** charged ion is an "**anion**" Ex: Cl^-

molecular formula

- The **molecular formula** of a compound represents its composition in the form of chemical symbols.
- The subscripts indicate the number of atoms of each element present in the smallest representative unit of the compound.

- For molecular compounds, it is a chemical formula that shows how many atoms of each element are contained in a single molecule of the compound. Example: H_2O, each water molecule contains two H atoms and one O atom.

- Simple gaseous substances at ordinary temperature exist in the form of diatomic molecules (molecules consisting of two atoms), e.g., O_2, N_2, H_2, Cl_2, except for noble gases (single atom).

The mole

- In chemistry, a **mole** (**symbol: mol**) is the SI unit for amount of substance, representing a fixed number of elementary entities (atoms, molecules, ions, etc.) equal to **Avogadro's number.**
- This number is precisely $6.022\ 140\ 76 \times 10^{23}$ particles per mole. This allows chemists to measure large quantities of microscopic particles in a practical way.

Molar mass

- The molar mass of an element is the mass in grams of 6.023×10^{23} atoms of that element. It is the mass shown in the periodic table.
- Example: nitrogen (N), M = 14 g/mol (one mole weighs 14 g).
- The molar mass of a compound is the mass of N molecules of that compound.
- Example: H_2O; $M = 2 \times 1 + 16 = 18$ g/mol (1 mol of H_2O molecules weighs 18 g).

Molar concentration or molarity (c)

- Molar concentration or molarity is most commonly expressed in units of moles of **solute** per litre of **solution**.
- Unit: (M) or (mol/L)
- The amount of substance of solute per unit volume of solution.
- **C = n/V**
- “n” is the amount of the solute in moles
- “V” the volume of the solution

mass concentration

- the **mass of solute (in grams) per unit volume of solution (in liters)**.
- Unit : (**g / L**)
- $C = m_{solute} / V_{solution}$
- m_{solute}: mass of solute (g)
- $V_{solution}$: volume of solution (L)

Normality (symbole : **N**)

- **Normality (N):** Normality is defined as the number of gram equivalents of solute present in one liter of solution.
- **Unit:** equivalents per liter (eq/L) or simply **N**.
- The relationship between **Molarity (M)** and **Normality (N): N = Z . C**
- Acid–Base reactions:
- n_{eq} = number of **H^+ ions** an acid can donate or number of **OH^- ions** a base can provide.
- $H_2SO_4 \rightarrow 2\ H^+ \rightarrow N = 2.M$

Dilution

- **Dilution** is an operation that consists of **reducing the concentration of a solution** by adding solvent, without changing the amount of solute.
- $C_1 \ V_1 = C_2 \ V_2$ $(n_1 = n_2)$
- C_1: initial concentration (Stock solution)
- V_1: volume taken from the initial solution
- C_2: final concentration (after dilution)
- V_2: final volume of the solution

Dilution factor

- **Dilution factor (DF):** The dilution factor is the ratio of the **final volume of the solution** (Vf) to the **initial volume of the solution taken** (Vi) before dilution.
- DF=Vf/Vi
- ☞ It indicates how many times the initial solution has been diluted.

Chemical equation

- $CH_4(g)+2O_2(g) \rightarrow CO_2(g)+2H_2O(l)$
- **A chemical reaction** is a process in which one or more substances (called reactants) are transformed into one or more new substances (called products), through the breaking and formation of chemical bonds.
- It is represented by a **chemical equation** showing the reactants, products, and their states.

Stoichiometry

- **Stoichiometry in a chemical reaction** is the quantitative relationship between the amounts of reactants and products, based on the balanced chemical equation.
- $2H_2(g)+O_2(g)\rightarrow 2H_2O(l)$
- Stoichiometry shows that **2 moles of hydrogen** react with **1 mole of oxygen** to produce **2 moles of water**.

Reaction yield

- **Reaction yield** is a measure of the efficiency of a chemical reaction. It compares the **amount of product actually obtained** to the **amount of product theoretically expected** based on stoichiometry.
- Yield (%)=(Actual amount of product/Theoretical amount of product)*100

Limiting reactant

- **Limiting reactant** (or limiting reagent) is the substance in a chemical reaction that is **completely consumed first**, limiting the amount of product that can be formed.
- Once the limiting reactant is used up, the reaction **stops**, even if other reactants are still available.
- The other reactants are called **excess reactants**.

Base Units of the SI system

The measurement units for seven fundamental properties ("base units") are listed in Table 1.2. The standards for these units are fixed by international agreement, and they are called the **International System of Units** or **SI Units** (from the French, *Le Système International d'Unités*). SI units have been used by the United States National Institute of Standards and Technology (NIST) since 1964. Units for other properties may be derived from these seven base units.

Base Units of the SI System

Property Measured	Name of Unit	Symbol of Unit
length	meter	m
mass	kilogram	kg
time	second	s
temperature	kelvin	K
electric current	ampere	A
amount of substance	mole	mol
luminous intensity	candela	cd

Particles of the atom

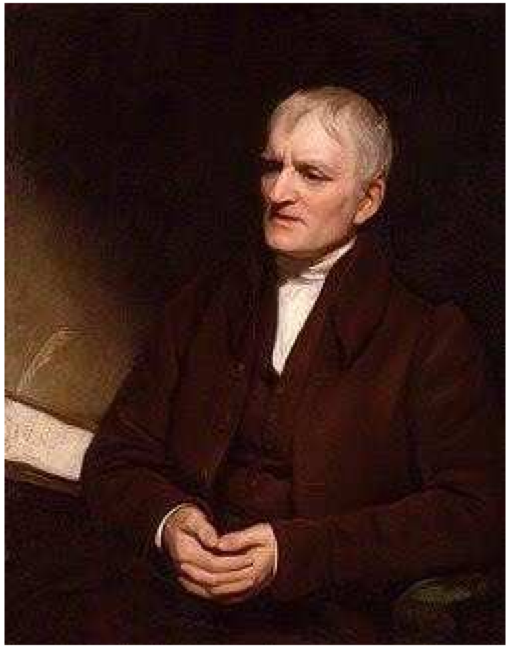
- **LEARNING OBJECTIVES**

By the end of this section, you will be able to:

- Outline milestones in the development of modern atomic theory
- Summarize and interpret the results of the experiments of Thomson, Millikan, and Rutherford
- Describe the three subatomic particles that compose atoms
- Define isotopes and give examples for several elements

Dalton's atomic theory

Dalton described the atom as a tiny, solid, indivisible sphere, like a billiard ball, that is the fundamental building block of matter.



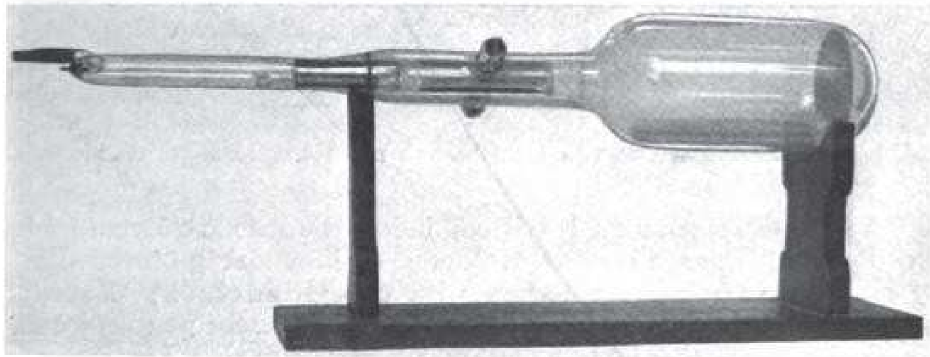
John **Dalton**, at the beginning of the **19th century (around 1808)**, proposed the **first modern atomic theory**.

First experiments in characterizing atoms

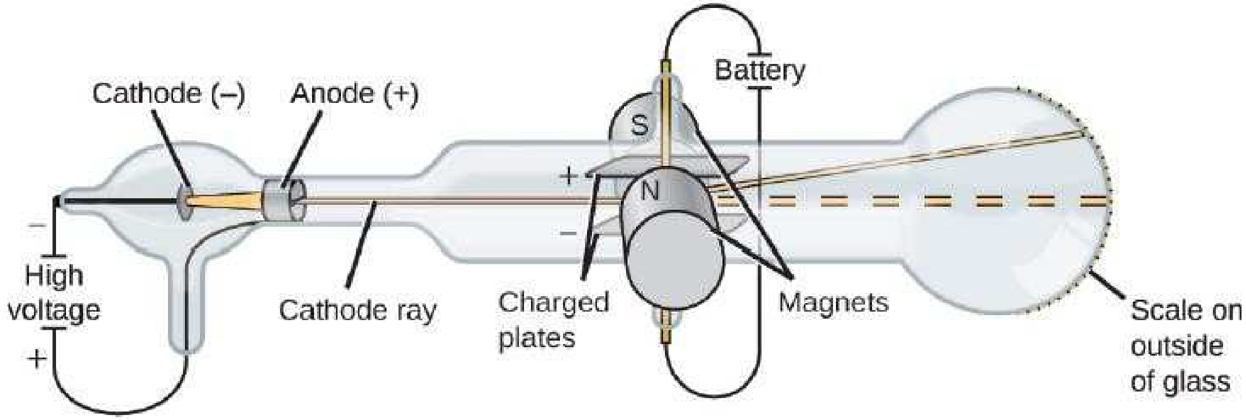
- a/ Electron:

J. J. Thomson's Experiment (1897)

(a)



(b)



(c)

J. J. Thomson's Experiment

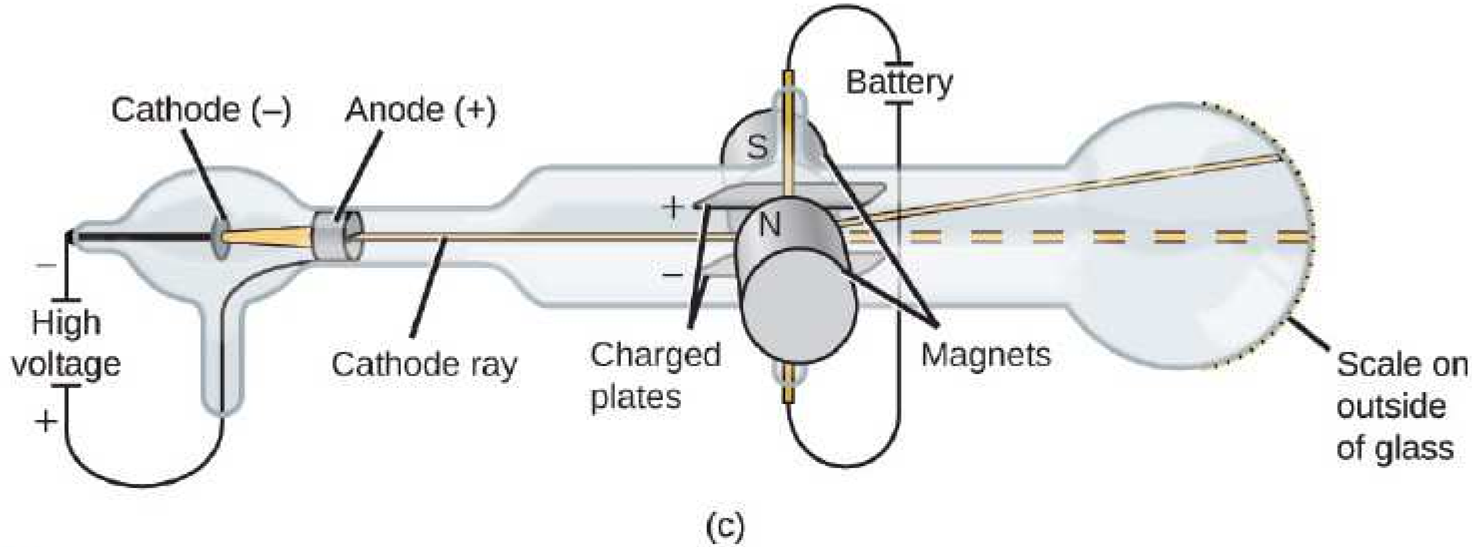
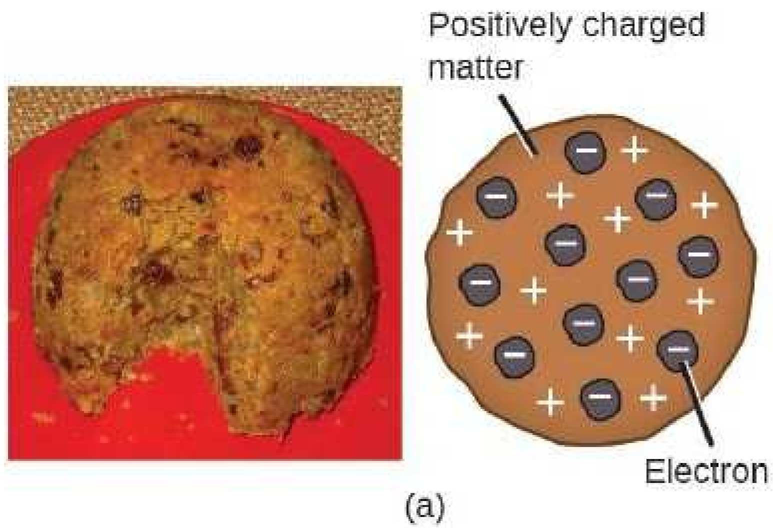


FIGURE 2.6 (a) J. J. Thomson produced a visible beam in a cathode ray tube. (b) This is an early cathode ray tube, invented in 1897 by Ferdinand Braun. (c) In the cathode ray, the beam (shown in yellow) comes from the cathode and is accelerated past the anode toward a fluorescent scale at the end of the tube. Simultaneous deflections by applied electric and magnetic fields permitted Thomson to calculate the mass-to-charge ratio of the particles composing the cathode ray. (credit a: modification of work by Nobel Foundation; credit b: modification of work by Eugen Nesper; credit c: modification of work by "Kurzon"/Wikimedia Commons)

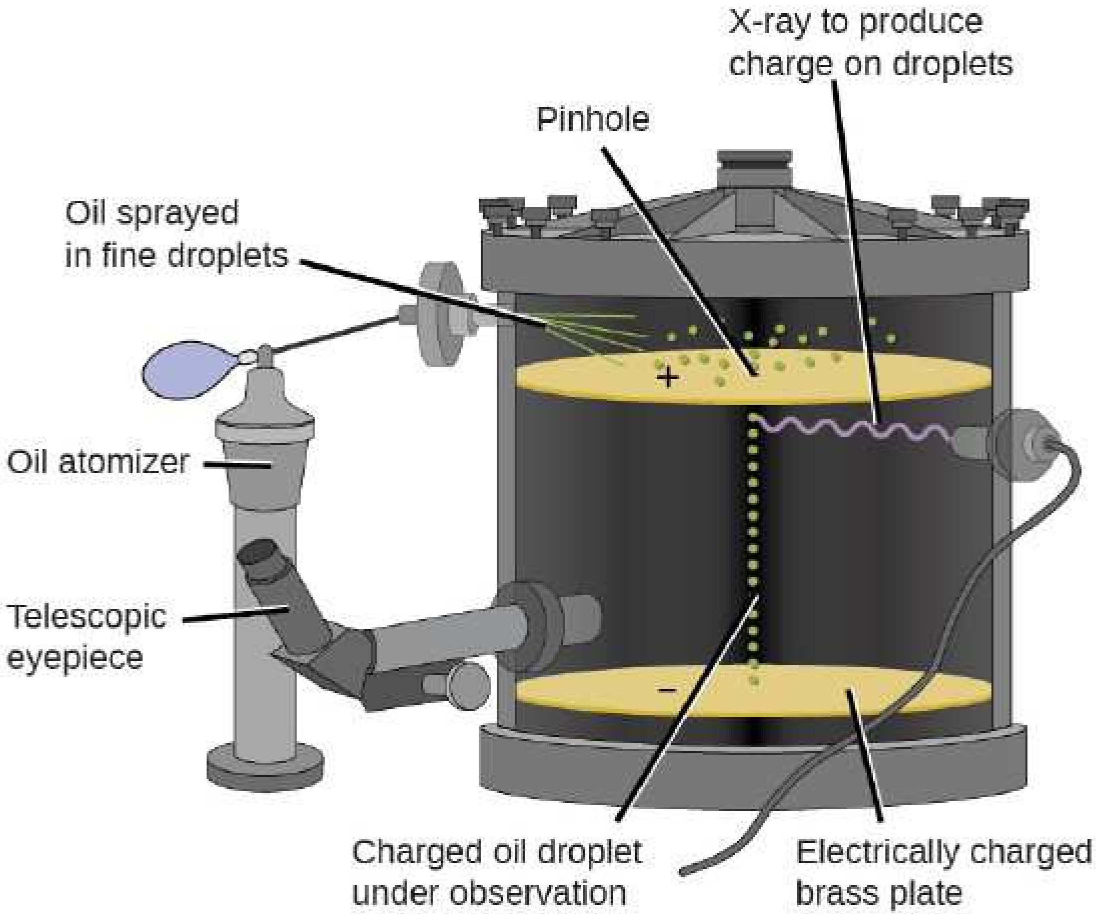
- Mass to charge ratio: e/m = $1{,}76\times10^{11}$ C/kg

Thomson model of atom

- The Thomson model, also known as the plum pudding model, proposed that an atom is a sphere of uniformly distributed positive charge, with negatively charged electrons embedded within it, like raisins in a plum pudding.



Millikan’s Oil Drop Experiment (1909)



Oil drop	Charge in coulombs (C)
A	4.8×10^{-19} C
B	3.2×10^{-19} C
C	6.4×10^{-19} C
D	1.6×10^{-19} C
E	4.8×10^{-19} C

FIGURE 2.7 Millikan’s experiment measured the charge of individual oil drops. The tabulated data are examples of a few possible values.

Millikan's Oil Drop Experiment

- Determination of the value of the elementary charge and deduction of the mass of the electron
- e = 1,602 176 634 × 10^{-19} C

$$
\begin{aligned}
\text{mass of an electron} &= \frac{\text{charge}}{\text{charge/mass}} \\
&= \frac{-1.6022 \times 10^{-19}\ \text{C}}{-1.76 \times 10^{8}\ \text{C/g}} \\
&= 9.10 \times 10^{-28}\ \text{g}
\end{aligned}
$$

Rutherford’s Gold Foil Experiment (1911)

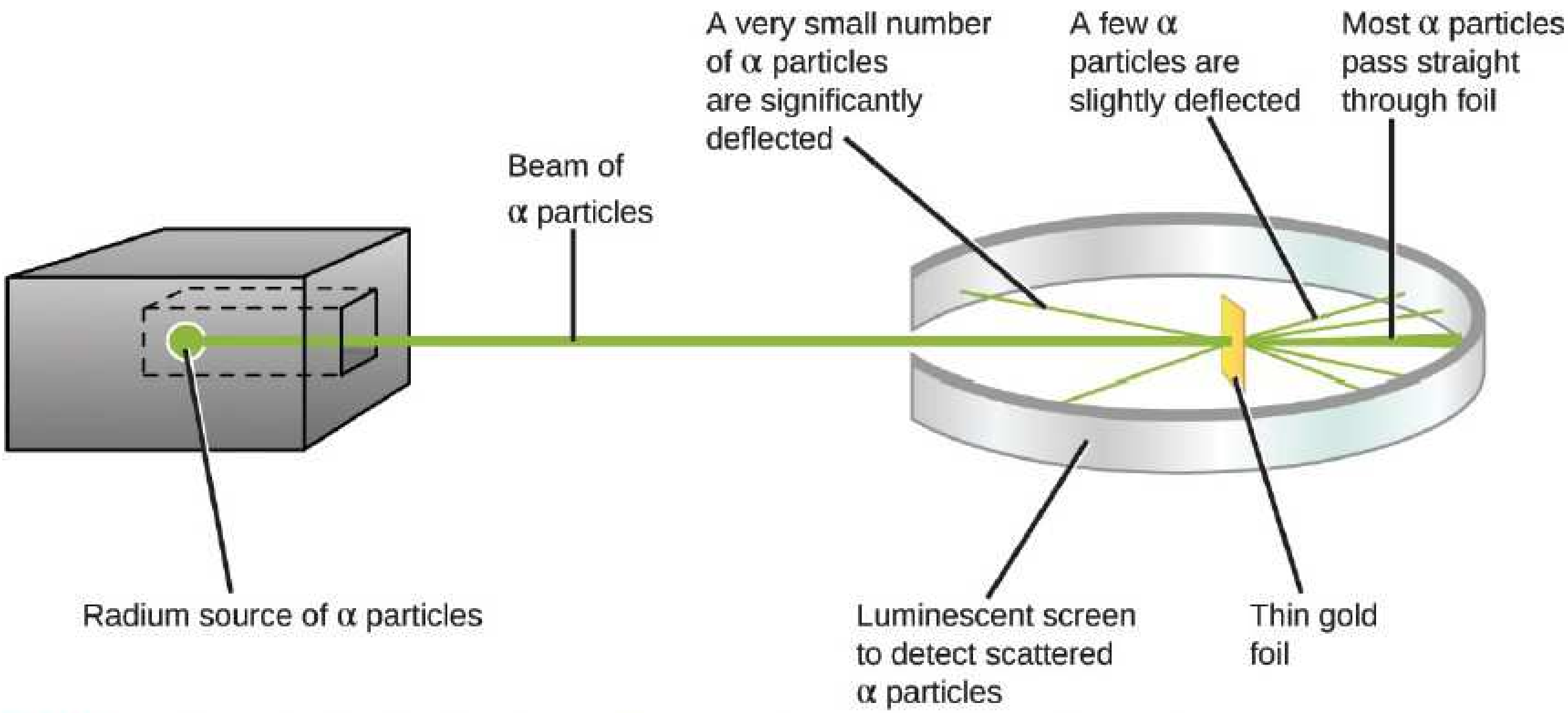
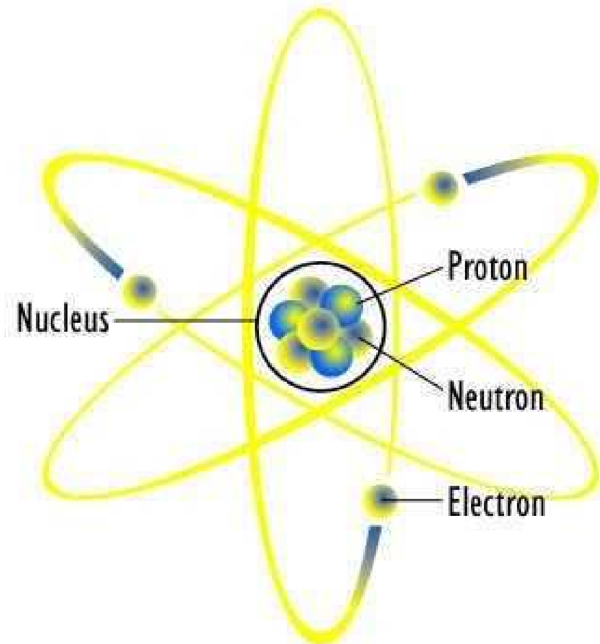


FIGURE 2.9 Geiger and Rutherford fired α particles at a piece of gold foil and detected where those particles went, as shown in this schematic diagram of their experiment. Most of the particles passed straight through the foil, but a few were deflected slightly and a very small number were significantly deflected.

Rutherford’s Gold Foil Experiment

- **Rutherford's Planetary model:** Rutherford's model introduced the concept of a nucleus, a dense, positively charged center where most of the atom's mass is concentrated.



b/ Discovery of the proton

- In 1919, Rutherford proved that the nucleus of the hydrogen atom is present within other nucleus. He noticed that when alpha particles were fired into nitrogen gas, his scintillation detectors indicated the signature of hydrogen nucleus. He then determined that this nucleus could only have come from nitrogen. This hydrogen nucleus was therefore present within another nucleus. Rutherford named the corresponding particle a "proton."

c/ Discovery of the neutron

- The neutron was discovered in 1932 by the English physicist James Chadwick. While studying certain nuclear reactions, he observed radiation from neutral particles. He named these particles "neutrons."

Subatomic Particles

- Protons (+), Neutrons (0), Electrons (-).

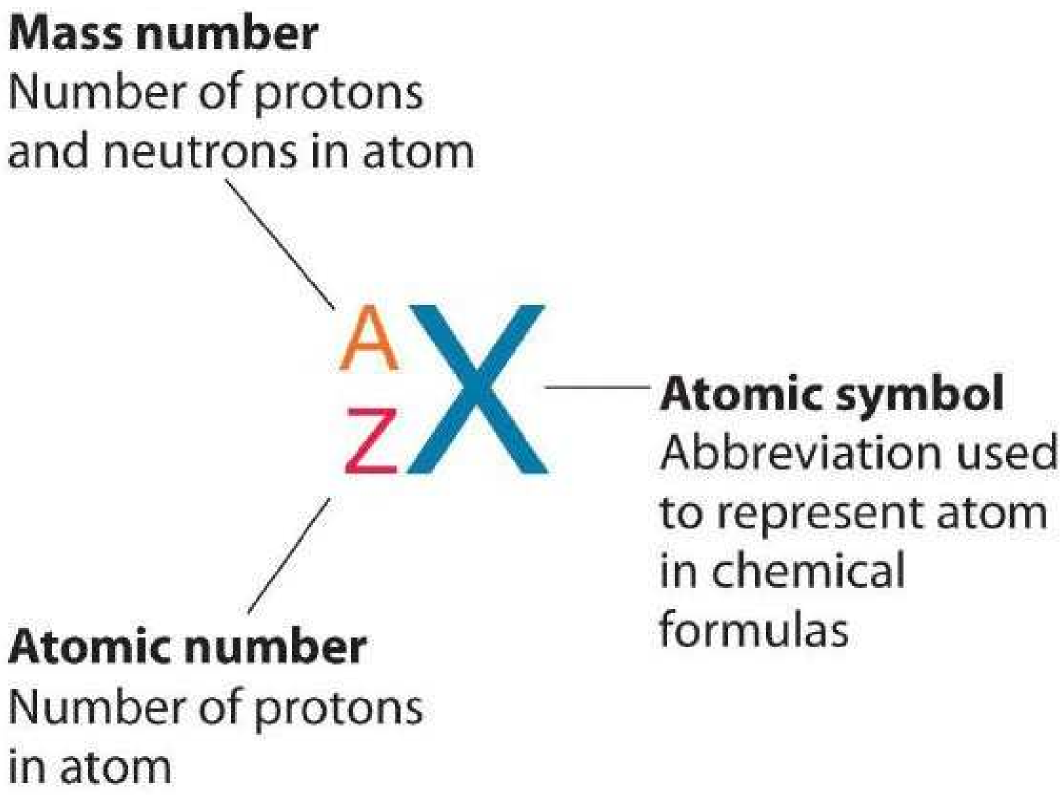
*The **mass** of an **electron** is about **9.109 x 10^{-31} kg**, while the mass of a **proton** is about **1.673 x 10^{-27} kg** and that of a **neutron** is slightly larger, about **1.675 x 10^{-27} kg**.*

***Protons and neutrons** (**nucleons**) therefore have very similar masses, much larger than that of the electron.*

Characteristics of Subatomic Particles

Particule	Masse (kg)	Charge (C)
Électron	$9{,}109.10^{-31}$	$-1{,}602\times10^{-19}$
Proton	$1{,}673\times10^{-27}$	$1{,}602\times10^{-19}$
Neutron	$1{,}675\times10^{-27}$	0

Representation of a neutral atom



Atomic Number (Z), Mass Number (A)

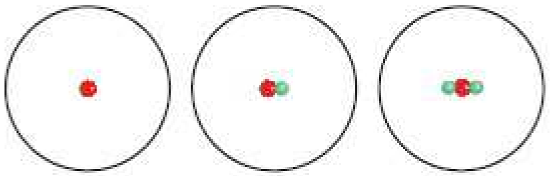
The number of protons in the nucleus of an atom is its **atomic number (Z)**. This is the defining trait of an element: Its value determines the identity of the atom. For example, any atom that contains six protons is the element carbon and has the atomic number 6, regardless of how many neutrons or electrons it may have. A neutral atom must contain the same number of positive and negative charges, so the number of protons equals the number of electrons. Therefore, the atomic number also indicates the number of electrons in an atom. The total number of protons and neutrons in an atom is called its **mass number (A)**. The number of neutrons is therefore the difference between the mass number and the atomic number: A – Z = number of neutrons.

$$\begin{aligned} \text{atomic number (Z)} &= \text{number of protons} \\ \text{atomic mass (A)} &= \text{number of protons + number of neutrons} \\ A - Z &= \text{number of neutrons} \end{aligned}$$

Isotopes

In most cases atoms of a given element do not all have the same mass. *Atoms that have the same atomic number but different mass numbers* are called ***isotopes.*** For example, there are three isotopes of hydrogen. One, simply known as hydrogen, has one proton and no neutrons. The deuterium isotope has one proton and one neutron, and tritium has one proton and two neutrons. The accepted way to denote the atomic number and mass number of an atom of element X is as follows:

mass number → $^{A}_{Z}X$ ← atomic number



$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$

Thus, for the isotopes of hydrogen, we write

$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$
hydrogen	deuterium	tritium

Isotopes

- Average molar mass:

$$M = (a/100) \times M1 + (b/100) \times M2 + (c/100) \times M3 + \ldots$$

Isotopes

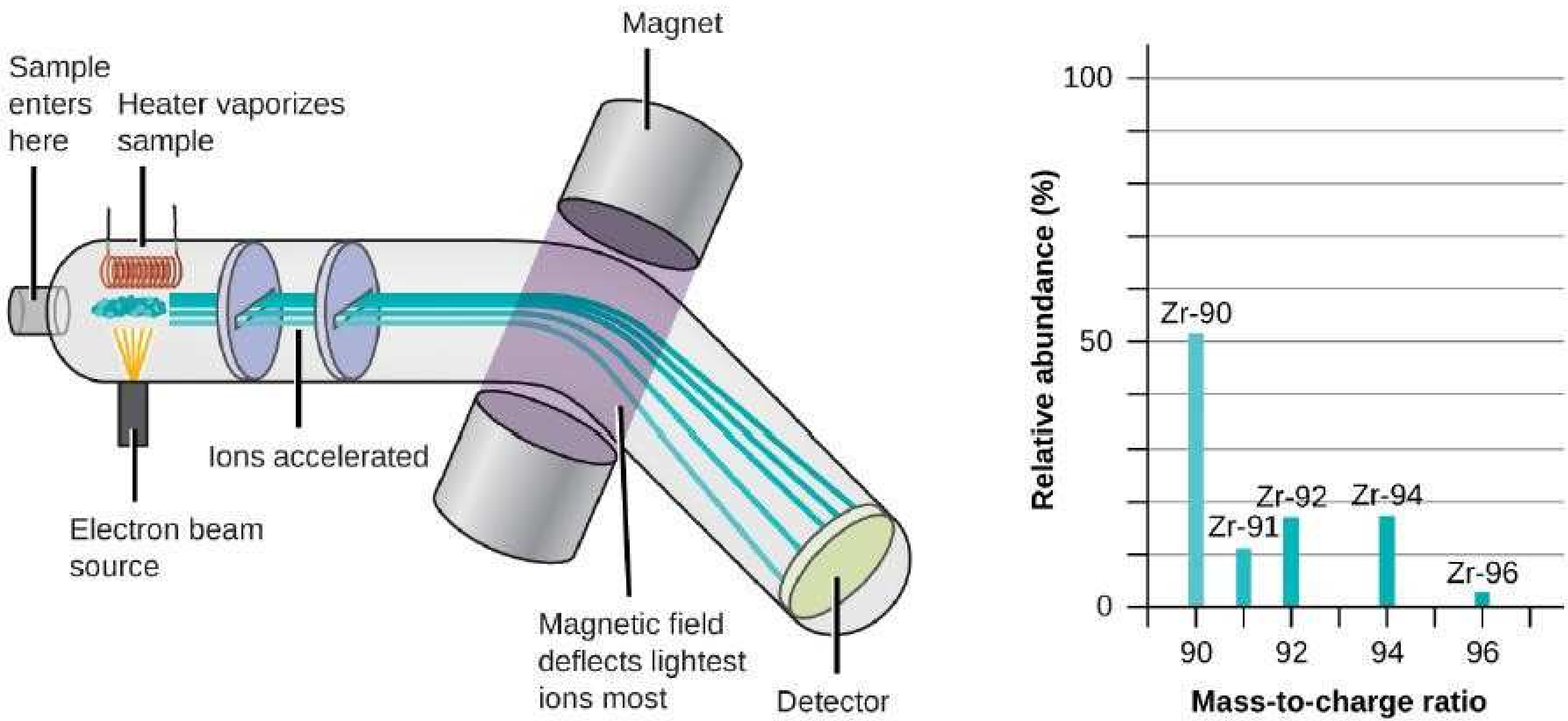


FIGURE 2.15 Analysis of zirconium in a mass spectrometer produces a mass spectrum with peaks showing the different isotopes of Zr.

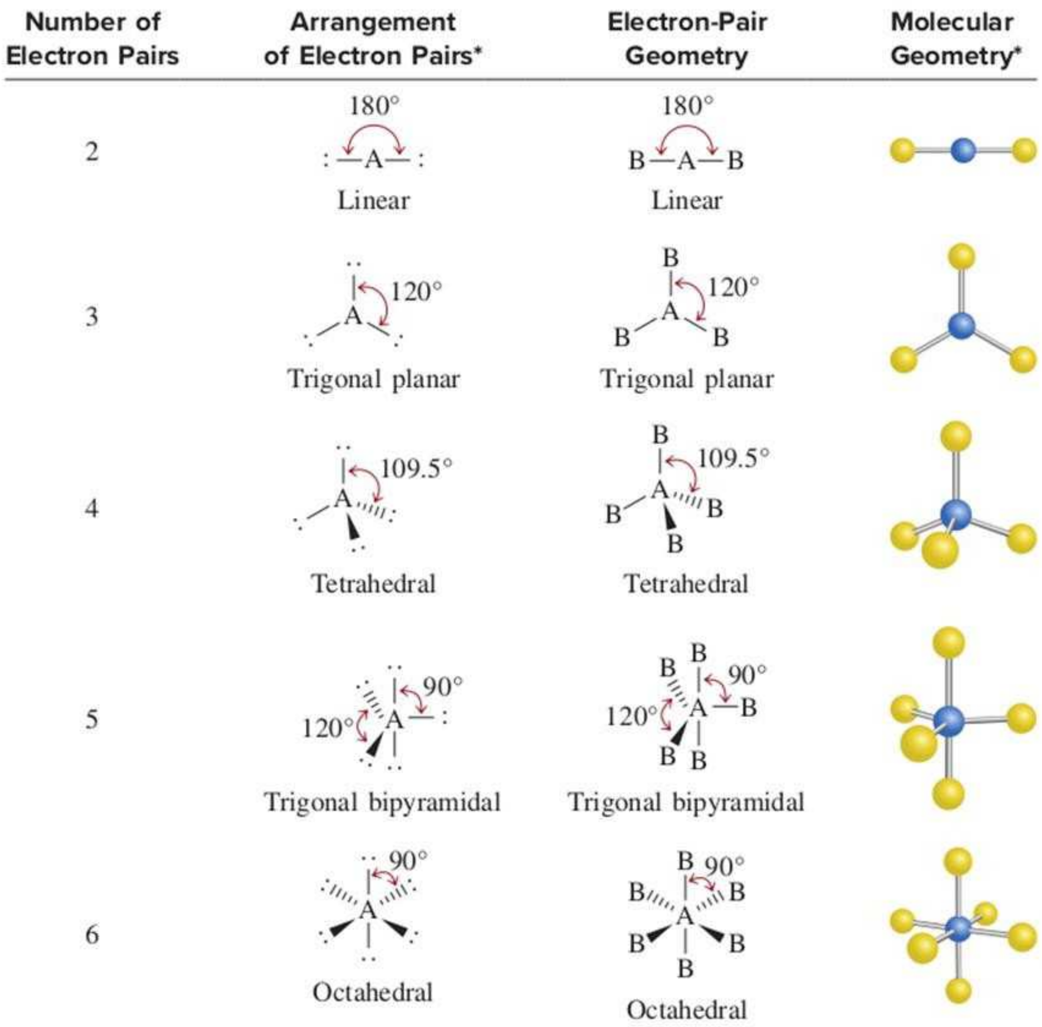
Chemical Bonding and Molecular Geometry

- Chemical bonding is the attractive force holding atoms or ions together to form stable compounds, driven by the interaction of their valence electrons (outermost electrons) to reach a lower, more stable energy state, primarily through sharing (covalent), transferring (ionic), or pooling (metallic) electrons, creating the diverse matter and structures around us, from water to salt.

Molecular Geometry

- Molecular geometry is the three-dimensional arrangement of atoms in a molecule.
- A molecule's geometry affects its physical and chemical properties, such as melting point, boiling point, density, and the types of reactions it undergoes.

Electron-Pair Geometry



*Bonds coming out of the page are represented as solid wedges. Bonds going into the page are represented as dashed wedges. Bonds in the plane of the page are represented as solid lines.

Guidelines for Applying the VSEPR Model

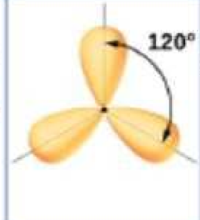
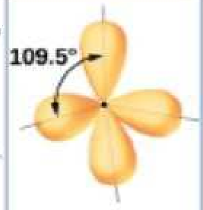
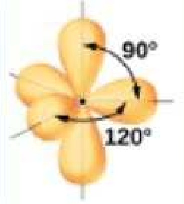
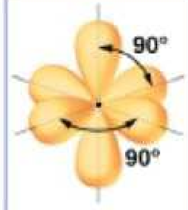
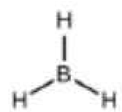
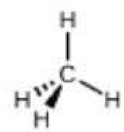
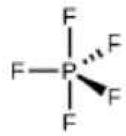
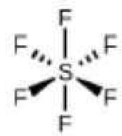
1. Write the Lewis structure of the molecule, considering only the electron pairs around the central atom (that is, the atom that is bonded to more than one other atom).

2. Count the number of electron pairs around the central atom (bonding pairs and lone pairs). Treat double and triple bonds as though they were single bonds.

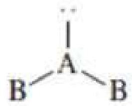
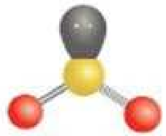
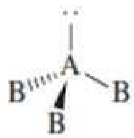
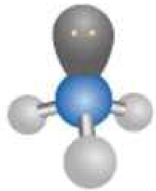
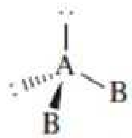
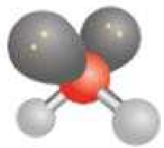
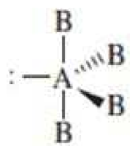
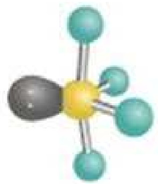
3. Predict the geometry of the molecule.

4. In predicting bond angles, note that a lone pair repels another lone pair or a bonding pair more strongly than a bonding pair repels another bonding pair. Remember that in general there is no easy way to predict bond angles accurately when the central atom possesses one or more lone pairs.

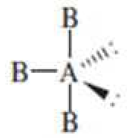
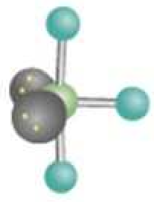
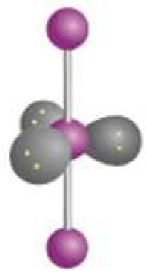
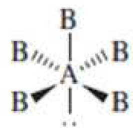
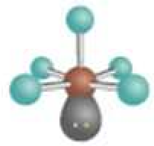
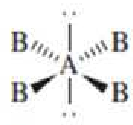
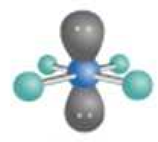
VSEPR theory

Number of regions	Two regions of high electron density (bonds and/or unshared pairs)	Three regions of high electron density (bonds and/or unshared pairs)	Four regions of high electron density (bonds and/or unshared pairs)	Five regions of high electron density (bonds and/or unshared pairs)	Six regions of high electron density (bonds and/or unshared pairs)
Spatial arrangement					
Line-dash-wedge notation					
Electron region geometry	Linear; 180° angle	Trigonal planar; all angles 120°	Tetrahedral; all angles 109.5°	Trigonal bipyramidal; angles of 90° or 120° An attached atom may be equatorial (in the plane of the triangle) or axial (above or below the plane of the triangle).	Octahedral; all angles 90° or 180°

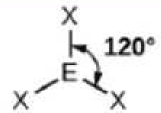
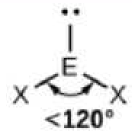
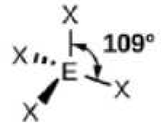
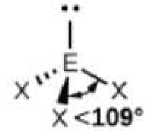
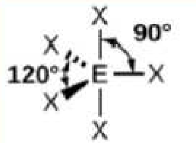
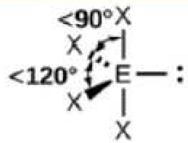
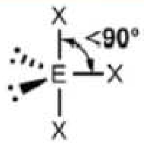
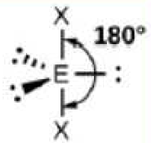
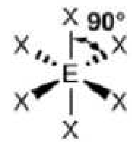
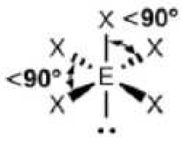
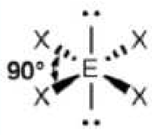
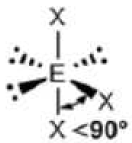
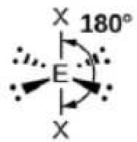
Electron-Pair Geometry and Molecular Geometry of Molecules and Ions

Class of Molecule	Total Number of Electron Pairs	Number of Bonding Pairs	Number of Lone Pairs	Arrangement of Electron Pairs	Geometry of Molecule or Ion	Examples
AB_2E	3	2	1	 Trigonal Planar	Bent (or V-shaped)	 SO_2
AB_3E	4	3	1	 Tetrahedral	Trigonal pyramidal	 NH_3
AB_2E_2	4	2	2	 Tetrahedral	Bent (or V-shaped)	 H_2O
AB_4E	5	4	1	 Trigonal bipyramidal	Seesaw (or distorted tetrahedron)	 SF_4

Electron-Pair Geometry and Molecular Geometry of Molecules and Ions

AB_3E_2	5	3	2	 Trigonal bipyramidal	T-shaped	 ClF_3
AB_2E_3	5	2	3	 Trigonal bipyramidal	Linear	 I_3^-
AB_5E	6	5	1	 Octahedral	Square pyramidal	 BrF_5
AB_4E_2	6	4	2	 Octahedral	Square planar	 XeF_4

Electron-pair geometries

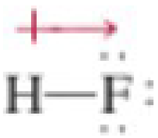
Number of electron regions	Electron region geometries: 0 lone pair	1 lone pair	2 lone pairs	3 lone pairs	4 lone pairs
2	 Linear				
3	 Trigonal planar	 Bent or angular			
4	 Tetrahedral	 Trigonal pyramid	 Bent or angular		
5	 Trigonal bipyramid	 Sawhorse or seesaw	 T-shape	 Linear	
6	 Octahedral	 Square pyramid	 Square planar	 T-shape	 Linear

Chemical Polarity

- Dipole moment is a measure of the charge separation in molecules containing atoms of different electronegativities.
- The dipole moment of a molecule is the resultant of whatever bond moments are present. Information about molecular geometry can be obtained from dipole moment measurements.

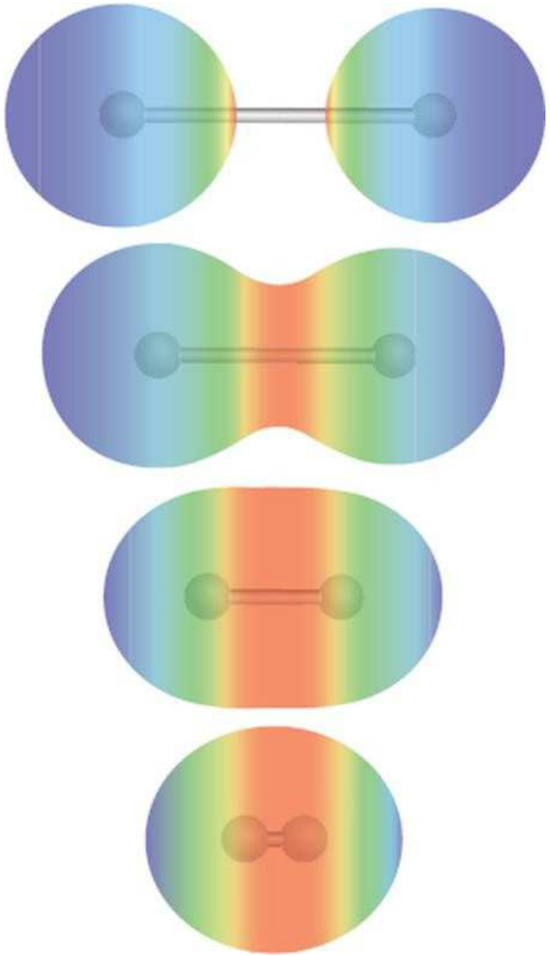
Chemical Polarity

The shift of electron density is symbolized by placing a crossed arrow above the Lewis structure to indicate the direction of the shift. For example,



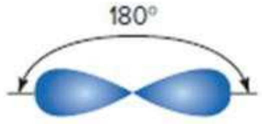
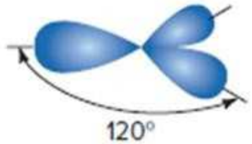
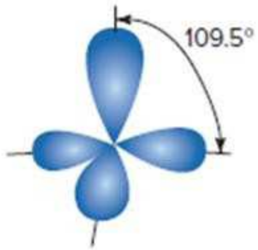
The consequent charge separation can be represented as

Valence Bond Theory

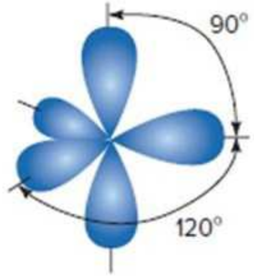
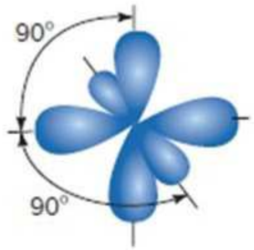


Top to bottom: As two H atoms approach each other, their 1s orbitals begin to interact and each electron begins to feel the attraction of the other proton. Gradually, the electron density builds up in the region between the two nuclei (red color). Eventually, a stable H_2 *molecule is formed with an internuclear distance of 74 pm.*

Hybridization of Atomic Orbitals

Pure Atomic Orbitals of the Central Atom	Hybridization of the Central Atom	Number of Hybrid Orbitals	Shape of Hybrid Orbitals	Examples
s, p	*sp*	2	 Linear	$BeCl_2$
s, p, p	sp^2	3	 Trigonal planar	BF_3
s, p, p, p	sp^3	4	 Tetrahedral	CH_4, NH_4^+

Hybridization of Atomic Orbitals

s, p, p, p, d	sp^3d	5	 Trigonal bipyramidal	PCl_5
s, p, p, p, d, d	sp^3d^2	6	 Octahedral	SF_6

Important Hybrid Orbitals and Their Shapes

Procedure for Hybridizing Atomic Orbitals

- In essence, hybridization simply extends Lewis theory and the VSEPR model. To assign a suitable state of hybridization to the central atom in a molecule, we must have some idea about the geometry of the molecule. The steps are as follows:

1. Draw the Lewis structure of the molecule.

2. Predict the overall arrangement of the electron pairs (both bonding pairs and lone pairs) using the VSEPR model.

3. Deduce the hybridization of the central atom by matching the arrangement of the electron pairs with those of the hybrid orbitals.