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Chapter 2: The Chemical Foundation of Life

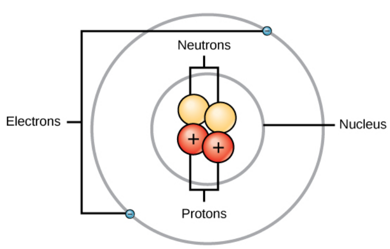
Introduction

- Various chemical combinations comprise all matter
    - Living things are primarily composed of carbon (C), hydrogen (H), nitrogen (N), oxygen (O), sulfur (S), and phosphorus
        - Used to form nucleic acids, proteins, carbohydrates, and lipids
    - Scientists seek to understand these building blocks to understand how biological systems

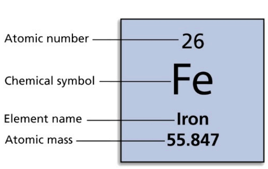
Atoms, Isotopes, Ions, and Molecules: The Building Blocks

- Introduction
    - Matter - anything that has mass and occupies space
    - Elements - one of 118 unique substances that cannot be broken down into smaller substances; each element has unique properties and a specified number of protons
        - Each element has its own chemical symbol
            - Composed of one or two letters (two if the first letter is already being used)
        - Four most common in life are oxygen, carbon, hydrogen, and nitrogen
- 2.1a: The Structure of an Atom

Approximate Percentage of Elements in Living Organisms (Humans) Compared to the Non-living World			
Element	**Life (Humans)**	**Atmosphere**	**Earth's Crust**
Oxygen (O)	65%	21%	46%
Carbon (C)	18%	trace	trace
Hydrogen (H)	10%	trace	0.1%
Nitrogen (N)	3%	78%	trace



- Atom - the smallest unit of matter that retains all of the chemical properties of an element
    - Composed of several smaller elements
    - Measured in atomic units or amus (1.67 × 10 $^{-24}$ grams or one Dalton)
        - Nucleus - core of an atom; contains protons and neutrons; contains protons and neutrons, and the outermost region of the atom which holds its electrons in orbit around the nucleus
            - One exception: hydrogen is made of one proton and one electron; no nucleus
        - Proton - a positively charged particle that resides in the nucleus of an atom; has a mass of one amu and a charge of +1
        - Neutron - uncharged particle that resides in the nucleus of an atom; has a mass of one amu
        - Electrons - negatively charged subatomic particle that resides outside of the nucleus in the electron orbital; lacks functional mass and has a negative charge of -1 unit; much smaller in mass than protons, weighing only 9.11 × 10 $^{-28}$ grams, or about 1/1800 of an atomic mass unit
            - Because of their small size, electrons are ignored in mass calculations
    - Most of an atom's mass is empty space
    - Every stable atom has an equal amount of protons and electrons
- 2.1b: Atomic Number and Mass
    - Atomic Number - determined number of protons; distinguishes one element from another
        - The number of neutrons is variable, resulting in isotopes
            - Isotope - different forms of the same atom that vary only in the number of neutrons they possess
                - Different number of neutrons affects stability



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- ◆ Example: carbon (C) has two isotopes: ^{13}C and ^{14}C; ^{14}C ejects electrons from the nucleus, leaving behind a new proton to counter the instability; degreades into nitrogen over time

➢ Mass Number - determined by the number of protons and the number of neutrons

➢ Atomic Mass - the calculated mean of the mass number for its naturally occurring isotopes

❖ 2.1c: Isotopes

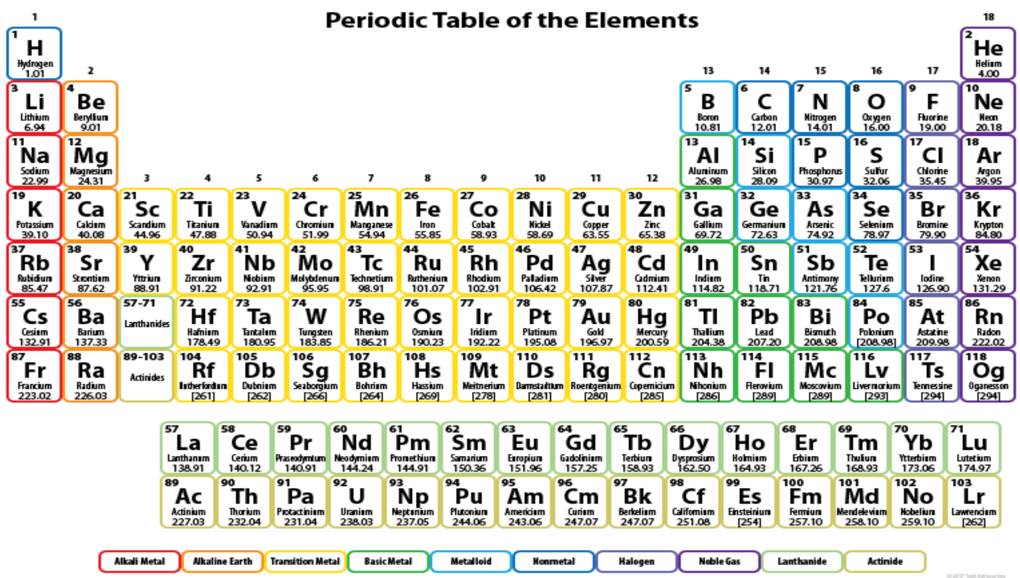
➢ Isotope -a different form of an element that have the same number of protons but a different number of neutrons

➢ Radioisotopes - isotopes that emit neutrons, protons, and electrons, and attain a more stable atomic configuration (lower level of potential energy)

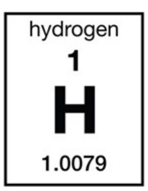
- ■ Radioactive Decay - the energy loss that occurs when an unstable atom's nucleus releases radiation

❖ 2.1d: The Periodic Table

➢ Periodic table: organizational chart of elements indicating the atomic number and atomic mass of each element; provides key information about the properties of the elements



- ■ Groups elements according to chemical properties
- ■ Differences in chemical reactivity between elements are based on the number and spatial distribution of an atom's electrons
- ■ Molecules - atoms that chemically react and bond
  - ● Compound - molecule composed of different elements; not every molecule is a compound, but every compound is a molecule



➢ Hydrogen (H)

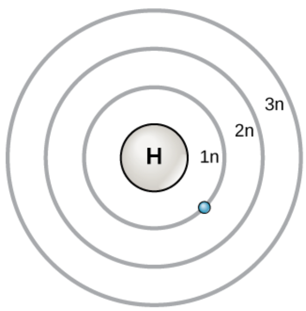
- ■ Has one proton and no neutrons
- ■ Has one electron
- ■ Without an electron, hydrogen's charge changes from zero to positive one (H^+)
  - ● All that is left is a single proton which is why H^+ can be used as the symbol for proton

❖ 2.1e: Electron Shells and the Bohr Model

➢ There is a connection between the number of protons in an element: the atomic number that distinguishes one element from another, and the number of electrons it has

➢ Niels Bohr (1885-1962)

- ■ Developed early model of an atom
  - ● Shows the atom as a central nucleus containing protons and neutrons with electrons in circular orbitals at specific distances from the nucleus



- ◆ <u>Orbital</u> - region surrounding the nucleus; contains electrons
  - ➢ Orbits form electron shells/energy levels
  - ➢ Designated by "n"
  - ➢ Orbital Capacity
    - ■ 1n: 2
    - ■ 2n: 8
    - ■ 3n: 18 (can be satisfied with 8)
- ■ Electrons and Orbitals
  - ● Electrons fill orbitals in a particular manner: fill orbitals from the nucleus out
    - ◆ <u>Octet Rule</u> - states, with the exception of the innermost shell, that atoms are more stable energetically when they have eight electrons in their valence shell
      - ➢ <u>Valence Shell</u> - outermost electron shell
    - ◆ Group 18 elements have filled shells and therefore do not need to bond to be stable
      - ➢ <u>Inert</u>/<u>Noble Gases</u> - element with filled outer electron shell that is unreactive with other atoms; includes helium (H), neon (Ne), and argon (Ar)
    - ◆ Group 1 elements have one electron in their outermost shell
      - ➢ Includes hydrogen (H), lithium (Li), and sodium (Na)
      - ➢ Means they can achieve a stable configuration and a filled outer shell by "donating" one electron to another atom or molecule
        - ■ Become positively charged ions
          - ● <u>Ion</u> - atom or chemical group that does not contain an equal number of protons and electrons
            - ◆ <u>Cation</u> - positive ion
            - ◆ <u>Anion</u> - negative ion
            - ◆ Changing the number of protons would change the element
    - ◆ Group 17 elements have 7 electrons
      - ➢ Includes fluorine (F) and chlorine (Cl)
      - ➢ Tend to fill the shell with an electron from another atom or molecule
        - ■ Gives them a negative charge and makes them a negative ion
    - ◆ Group 14 elements have four electrons
      - ➢ Includes carbon (C)
        - ■ Allows for several covalent bonds with other atoms

- ❖ 2.1f: Chemical Reactions and Molecules
  - ➢ Elements are most stable when all shells are full
    - ■ Elements without naturally full shields seek electrons to fill them
    - ■ Results in chemical bonds
  - ➢ <u>Chemical Bond</u> - interactions between two or more of the same or different atoms that results in the formation of molecules
  - ➢ <u>Chemical Reactions</u> - occur when two or more atoms bond together to form molecules or when bonded atoms are broken apart
    - ■ Chemical reactions break (release energy), make (store energy), or break *and* make bonds
    - ■ <u>Reactant</u> - substances used in the beginning of a chemical reaction; usually found on the left side of a chemical equation
    - ■ <u>Product</u> - substances found at the end of the reaction; usually found on the right side of a chemical equation
  - ➢ <u>Reversible Chemical Reaction</u> - chemical reaction that functions bi-directionally, where products may turn into reactants if their concentration is great enough

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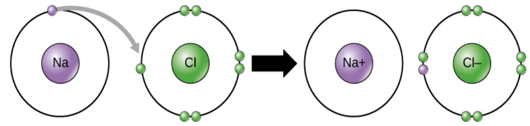
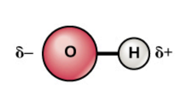
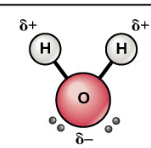
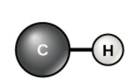
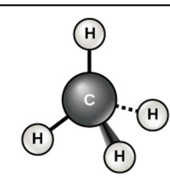
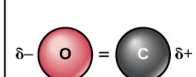
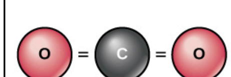
- Example: $2H + O \rightarrow H_2O$ (hydrogen +oxygen → water)
- Balanced Chemical Equation - wherein the number of atoms of each element is the same on each side of the equation
  - Example: $2H_2O \rightarrow 2H_2O + O_2$ (hydrogen peroxide → water + oxygen)
    - Hydrogen peroxide and water are examples of a subclass of molecules : compounds



- 2.1g: Ions and Ionic Bonds
  - Some atoms become more stable when they gain or lose an electron
    - Because the number of electrons is not equal to number of protons, ions have a net charge
    - Electron Transfer - movement of electrons from one element to another
      - For some atoms, it may take more or less energy to donate electrons rather than to accept them
        - Example: it is easier for sodium (Na) to donate an electron rather than accept 7
    - Ionic Bonds - formed between ions with opposite charges
      - Magnet-like in nature of opposites attract
      - Example: positively charged sodium ions and negatively charged chloride ions bond together; makes crystals of sodium chloride, or table salt, creating a crystalline molecule with zero net charge
- 2.1h: Covalent Bonds and Other Bonds and Interactions
  - δ + - slightly positive charge
  - δ – - slightly negative charge
  - Covalent Bonds - type of strong bond formed between two of the same or different elements; forms when electrons are shared between atoms
    - Commonly found in carbon-based organic molecules like DNA
    - Holds together molecules
    - The more bonds, the stronger
      - Sharing one is single, two is a double bond, and three is triple
    - Water is bound by covalent bonds
  - Polar Covalent Bonds - the electrons are unequally shared by the atoms and are attracted more to one nucleus than the other; because of the unequal distribution of electrons between the atoms of different elements, a slightly positive or slightly negative charge develops
    - Example: water is a polar molecule; the hydrogen atoms acquiring a partial positive charge and the oxygen a partial negative charge; occurs because the nucleus of the oxygen atom is more attractive to the electrons of the hydrogen atoms than the hydrogen nucleus is to the oxygen's electrons; oxygen has a higher electronegativity
      - Electronegativity - ability of some elements to attract electrons (often of hydrogen atoms), acquiring partial negative charges in molecules and creating partial positive charges on the hydrogen atoms
  - Nonpolar Covalent Bonds - form between two atoms of the same element or between different elements that share electrons equally
    - Example: methane; carbon has 4 electrons in its outermost shell—needs 4 more to fill which it gets from hydrogen atoms
  - Ionic and covalent bonds require energy to break
    - Ionic are weaker than covalent bonds
  - Hydrogen Bonds
    - Not technically a bond
    - Hydrogen Bonds - very weak bonds between slightly positively charged

	Bond type	Molecular shape	Molecular type
Water	 Polar covalent	 Bent	Polar
Methane	 Nonpolar covalent	 Tetrahedral	Nonpolar
Carbon dioxide	 Polar covalent	 Linear	Nonpolar

hydrogen atoms to slightly negatively charged atoms in other molecules
- Common and occurs regularly between water molecules
- Individual hydrogen bonds are weak and easily broken
- Responsible for zipping DNA together into a double helix

Water

- 2.2a: Water's Polarity
  - Polarity - a separation of electric charge leading to a molecule or its chemical groups having an electric dipole moment, with a negatively charged end and a positively charged end
  - Hydrogen and oxygen in the molecules form polar covalent bonds
    - While there is no net charge to a water molecule, the polarity gives the hydrogen (H) a slightly positive and the oxygen (O) a slightly negative charge
    - Water's charges are generated because oxygen is more electronegative than hydrogen, making it more likely that a shared electron would be found near the oxygen nucleus than the hydrogen nucleus, thus generating the partial negative charge near the oxygen
  - Water molecules attract each other and other pola rmolecu;les and ions
    - Hydrophilic - a polar substance that interacts readily with or dissolves in water
      - *Hydro* - water
      - *Philic* - loving
    - Hydrophobic - describes uncharged non-polar molecules that do not interact well with polar molecules such as water
      - *Phobic* - fearing
      - Hydrophobic substances cannot form hydrogen bonds with water
        - Held together by nonpolar covalent bonds
        - Have no charge; slides past each other
          - Example: olive oil
- 2.2b: Water's States: Gas, Liquid, and Solid
  - In liquid water, hydrogen bonds are constantly formed and broken as the water molecules slide past each other
    - Breaking of these bonds makes kinetic energy (motion) due to heat in the system
  - Heating water breaks the bonds and allows the molecules to float freely in steam or vapor
  - When the temperature of water is reduced and water freezes, the water molecules form a crystalline structure maintained by hydrogen bonding
    - Not enough energy to break the hydrogen bonds
    - Ice is less dense than liquid water
      - Why ice floats in your drinks
      - Due to the way hydrogen bonds are oriented as it freezes: the water molecules are pushed farther apart compared to liquid water
- 2.2c: Water's High Heat Capacity
  - Water has the highest specific heat capacity
    - Specific Heat Capacity - the amount of heat one gram of a substance must absorb or lose to change its temperature by one degree Celsius
      - For water, this is amount is one calorie
        - Calorie - the amount of heat required to change the temperature of one gram of water by one degree Celsius
- 2.2d: Water's Heat of Vaporization
  - Heat of Vaporization - high amount of energy required for liquid to turn into gas
    - Water needs a considerable amount of heat energy (586 cal) to do this
    - Takes place on the surface of water
    - Evaporation - separation of individual molecules from the surface of a body of water, the leaves of a plant, or the skin of an organism
      - As water reaches its boiling point of 100° Celsius (212° Fahrenheit), the heat is able to break the hydrogen bonds between the water molecules, and the kinetic energy (motion) between the water molecules allows them to escape from the liquid as a gas
- 2.2e: Water's Solvent Properties

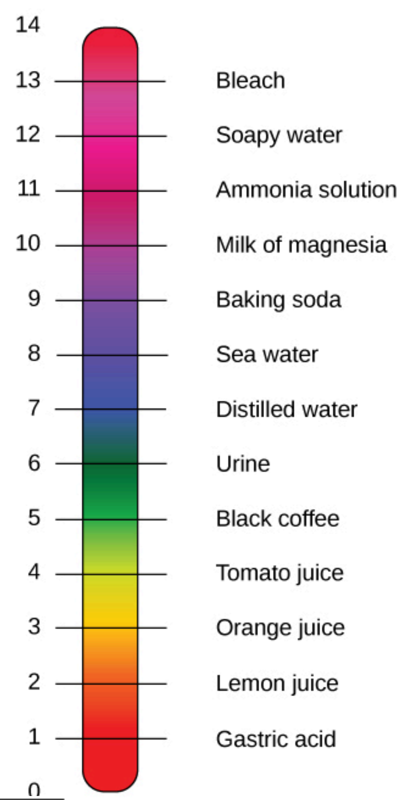
- ➢ Because of water's polarity and charges, many ions and polar molecules will dissolve in it; water is a solvent
    - ■ Solvent - a substance capable of dissolving other polar molecules and ionic compounds
    - ■ Sphere of Hydration - when a polar water molecule surrounds charged or polar molecules thus keeping them dissolved and in solution
    - ■ Disassociation - release of an ion from a molecule such that the original molecule now consists of an ion and the charged remains of the original, such as when water dissociates into H^+ and OH^-
- ➢ Water can also trigger hydrolysis reactions
    - ■ Hydrolysis Reactions - large molecules are broken down into smaller ones, due to the presence of water

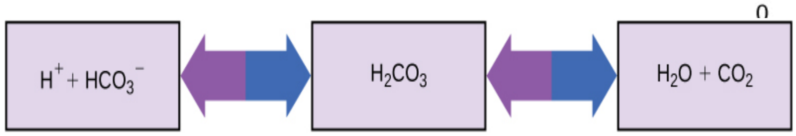
❖ 2.2f: Water's Cohesive and Adhesive Properties

- ➢ Cohesion - intermolecular forces between water molecules caused by the polar nature of water; responsible for surface tension
    - ■ Allows for the development of surface tension
        - ● Surface Tension - tension at the surface of a body of liquid that prevents the molecules from separating; created by the attractive cohesive forces between the molecules of the liquid
    - ■ Why water stays in droplet form
- ➢ Adhesion - attraction between water molecules and other molecules
    - ■ Observed when water "climbs" up a tube known as capillary action
        - ● Capillary action - occurs because water molecules are attracted to charges on the inner surfaces of narrow tubular structures such as glass tubes, drawing the water molecules to the sides of the tubes
- ➢ Both are important for life

❖ 2.2g: pH, Buffers, Acids, and Bases

- ➢ pH/litmus paper - filter paper that has been treated with a natural water-soluble dye that changes its color as the pH of the environment changes so it can be used as a pH indicator
    - ■ Tests acidity or alkalinity that exists in a solution
- ➢ pH Scale
    - ■ Goes from 0 to 14
        - ● 0.0 to 6.9 is acidic
            - ◆ Solution with more H^+ ions than OH^- ions
            - ◆ *More protons*; can release protons
        - ● 7.1 to 14.0 is alkaline/basic
            - ◆ solution with more OH^- ions than H^+ ions
            - ◆ *Fewer protons*; can gain protons
        - ● 7.0 in neutral
- ➢ Buffer - a substance that prevents a change in pH by absorbing or releasing hydrogen or hydroxide ions; how the body maintains equilibrium in terms of pH
    - ■ Readily absorb excess H^+ or OH^-, keeping the pH of the body carefully maintained in the narrow range required for survival
    - ■ Maintaining a constant blood pH is critical to a person's well-being
    - ■ Normal pH for human blood: 7.35-7.45





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- This diagram shows the body's buffering of blood pH levels. The blue arrows show the process of raising pH as more CO_2 is made. The purple arrows indicate the reverse process: the lowering of pH as more bicarbonate is created.

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Ocean Acidity

- Harmfulness of the Acidity
  - Could devastate coral communities within the next decade
  - Acidity is exacerbated by other water issues like agriculture and urban runoff
- Latest Research
  - Focused on better understanding of which organisms will be most vulnerable without considering economic role
    - Makes explicit link with shellfish
      - $1 billion industry in the United States
    - New work is "exactly what we have been missing." (Jeremy Mathis, director of the Ocean Environmental Research Division at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory in Seattle, Washington (not involved in study)
  - Acidity has increased 30% over the past several decades
    - Driven primarily by the burning of fossil fuels
      - Carbon dioxide levels rise in atmosphere
      - About ¼ dissolves in the top layer of the ocean
      - Reacts with water, forming carbonic acid which lowers the pH of the water
        - Lowers availability of carbonate ions
          - Used by oysters and shellfish to build their shells
        - Drop in carbonate ions reduces aragonite saturation state
          - Refers to the level of mineral form of calcium carbonate called aragonite that oyster larvae need to form growing shells
          - When the aragonite saturation state falls below 1.5, the larvae die
    - Some increases in acidity are normal
      - Cold water from the deep ocean upwells along West Coast
      - Cold water dissolves more carbon dioxide
    - Conventional wisdom instructed that shellfish farmers not farm in cold water
- A Broader Look
  - By Julia Ekstrom, social scientist who studies coastal communities at UC and colleagues
  - They added factors that can impact acidity levels on a regional basis
    - One example being discharge of water from large rivers and eutrophication in estuaries
      - <u>Eutrophication</u> - excessive richness of nutrients in a lake or other body of water, frequently due to runoff from the land, which causes a dense growth of plant life and death of animal life from lack of oxygen
        - Occurs when agricultural and urban runoff boosts nitrogen and phosphorus levels
        - Triggers algal bloom
      - Large rivers can reduce or increase acidity if they carry budders versus holding few such minerals
  - Analyzed economic dependence of coastal communities (shellfish farming)
    - Determined that the threat only impacted shellfish farmers
    - Produced a map to display risks
      - Found 16 of 23 coastal bioregions around the United States are highly vulnerable
        - Massachusetts topped the list
        - Pacific Northwest
        - Mid-atlantic
        - Several regions along the Gulf Coast
- Threats Against Eastern Seaboard and Gulf Coast
  - Issue wasn't immediate threat of acidification due to CO_2
  - Rather the added effects of nutrient runoff and rovers were what increased regional acidity levels
    - Could be fixed regionally and locally as opposed to nationally
      - Won't be easy to change policies

- ❖ Annual Dead Zone
  - ➢ Annual occurrence of an extensive dead zone in the Gulf of Mexico is due to agricultural runoff throughout the midwest
    - ■ Already been linked to modern farming practices that haven't been changed yet
- ❖ Consequences
  - ➢ If change does not happen, oysters, clams, and other shellfish could disappear from the United States
  - ➢ Would take jobs and way of life with them