Foundational Concept 4

Content Category 4A: Translational motion, forces, work, energy, and equilibrium in living systems

Translational Motion (PHY)

- Units and dimensions
- Vectors, components
- Vector addition
- Speed, velocity (average and instantaneous)
- Acceleration

Force (PHY)

- Newton's First Law, inertia
- Newton's Second Law ($F = ma$)
- Newton's Third Law, forces equal and opposite
- Friction, static, and kinetic
- Center of mass

Equilibrium (PHY)

- Vector analysis of forces acting on a point object
- Torques, lever arms

Work (PHY)

- Work done by a constant force: $W = Fd\cos\theta$
- Mechanical advantage
- Work Kinetic Energy Theorem
- Conservative forces

Energy of Point Object Systems (PHY)

- Kinetic Energy: KE = 1⁄2 mv2; units
- Potential Energy
    - PE = mgh (gravitational, local)
    - PE = $1/2\ kx^2$ (spring)
- Conservation of energy
- Power, units

Periodic Motion (PHY)

- Amplitude, frequency, phase
- Transverse and longitudinal waves: wavelength and propagation speed

Content Category 4B: Importance of fluids for the circulation of blood, gas movement, and gas exchange

Fluids (PHY)

- Density, specific gravity
- Buoyancy, Archimedes' Principle
- Hydrostatic pressure
    - Pascal's Law
    - Hydrostatic pressure; $P = \rho gh$ (pressure vs. depth)
- Viscosity: Poiseuille Flow
- Continuity equation ($A \cdot v = constant$)
- Concept of turbulence at high velocities
- Surface tension
- Bernoulli's equation
- Venturi effect, pitot tube

Circulatory System (BIO)

- Arterial and venous systems; pressure and flow characteristics

Gas Phase (GC, PHY)

- Absolute temperature, (K) Kelvin Scale
- Pressure, simple mercury barometer
- Molar volume at 0°C and 1 atm = 22.4 L/mol
- Ideal gas
    - Definition
    - Ideal Gas Law: $PV = nRT$
    - Boyle's Law: PV = constant
    - Charles' Law: V/T = constant
    - Avogadro's Law: V/n = constant
- Kinetic Molecular Theory of Gases
    - Heat capacity at constant volume and at constant pressure (PHY)
    - Boltzmann's Constant (PHY)
- Deviation of real gas behavior from ideal gas law
    - Qualitative
    - Quantitative (Van der Waals' Equation)
- Partial Pressure, mole fraction
- Dalton's Law relating partial pressure to composition

Content Category 4C: Electrochemistry and electrical circuits and their elements

Electrostatics (PHY)

- Charge, conductors, charge conservation
- Insulators
- Coulomb's Law
- Electric Field **E**
    - Field lines
    - Field due to charge distribution
- Electrostatic energy, electric potential at a point in space

Circuit Elements (PHY)

- Current $I = \Delta Q/\Delta t$, sign conventions, units
- Electromotive force, voltage

- Resistance
    - Ohm's Law: $I = V/R$
    - Resistors in series
    - Resistors in parallel
    - Resistivity: $\rho = R \bullet A / L$
- Capacitance
    - Parallel plate capacitor
    - Energy of charged capacitor
    - Capacitors in series
    - Capacitors in parallel
    - Dielectrics
- Conductivity
    - Metallic
    - Electrolytic
- Meters

Magnetism (PHY)

- Definition of magnetic field **B**
- Motion of charged particles in magnetic fields; Lorentz Force

Electrochemistry (GC)

- Electrolytic Cell
    - Electrolysis
    - Anode, cathode
    - Electrolyte
    - Faraday's Law relating amount of elements deposited (or gas liberated) at an electrode to current
    - Electron flow; oxidation, and reduction at the electrodes
- Galvanic or Voltaic cells
    - Half-reactions
    - Reduction potentials; cell potential
    - Direction of electron flow
- Concentration Cell
- Batteries
    - Electromotive force, Voltage
    - Lead-storage batteries
    - Nickel-cadmium batteries

Specialized Cell – Nerve Cell (BIO)

- Myelin sheath, Schwann cells, insulation of axon
- Nodes of Ranvier: propagation of nerve impulse along axon

Content Category 4D: How light and sound interact with matter

Sound (PHY)

- Production of sound
- Relative speed of sound in solids, liquids, and gases
- Intensity of sound, decibel units, log scale
- Attenuation (Damping)

- Doppler Effect: moving sound source or observer, reflection of sound from a moving object
- Pitch
- Resonance in pipes and strings
- Ultrasound
- Shock waves

Light, Electromagnetic Radiation (PHY)

- Concept of Interference; Young Double-slit Experiment
- Thin films, diffraction grating, single-slit diffraction
- Other diffraction phenomena, X-ray diffraction
- Polarization of light: linear and circular
- Properties of electromagnetic radiation
    - Velocity equals constant c, *in vacuo*
    - Electromagnetic radiation consists of perpendicularly oscillating electric and magnetic fields; direction of propagation is perpendicular to both
- Classification of electromagnetic spectrum, photon energy $E = hf$
- Visual spectrum, color

Molecular Structure and Absorption Spectra (OC)

- Infrared Region
    - Intramolecular vibrations and rotations
    - Recognizing common characteristic group absorptions, fingerprint region
- Visible Region
    - Absorption in visible region gives complementary color (e.g., carotene)
    - Effect of structural changes on absorption (e.g., indicators)
- Ultraviolet Region
    - π-Electron and non-bonding electron transitions
    - Conjugated systems
- NMR Spectroscopy
    - Protons in a magnetic field; equivalent protons
    - Spin-spin splitting

Geometrical Optics (PHY)

- Reflection from plane surface: angle of incidence equals angle of reflection
- Refraction, refractive index n; Snell's law: $n1 \sin \theta 1 = n2 \sin \theta 2$
- Dispersion, change of index of refraction with wavelength
- Conditions for total internal reflection
- Spherical mirrors
    - Center of curvature
    - Focal length
    - Real and virtual images
- Thin lenses
    - Converging and diverging lenses
    - Use of formula $1/p + 1/q = 1/f$, with sign conventions
    - Lens strength, diopters
- Combination of lenses
- Lens aberration
- Optical Instruments, including the human eye

Content Category 4E: Atoms, nuclear decay, electronic structure, and atomic chemical behavior

Atomic Nucleus (PHY, GC)

- Atomic number, atomic weight
- Neutrons, protons, isotopes
- Nuclear forces, binding energy
- Radioactive decay
    - α, β, γ decay
    - Half-life, exponential decay, semi-log plots
- Mass spectrometer

Electronic Structure (PHY, GC)

- Orbital structure of hydrogen atom, principal quantum number n, number of electrons per orbital (GC)
- Ground state, excited states
- Absorption and emission line spectra
- Use of Pauli Exclusion Principle
- Paramagnetism and diamagnetism
- Conventional notation for electronic structure (GC)
- Bohr atom
- Heisenberg Uncertainty Principle
- Effective nuclear charge (GC)
- Photoelectric effect

The Periodic Table – Classification of Elements into Groups by Electronic Structure (GC)

- Alkali metals
- Alkaline earth metals: their chemical characteristics
- Halogens: their chemical characteristics
- Noble gases: their physical and chemical characteristics
- Transition metals
- Representative elements
- Metals and non-metals
- Oxygen group

The Periodic Table – Variations of Chemical Properties with Group and Row (GC)

- Valence electrons
- First and second ionization energy
    - Definition
    - Prediction from electronic structure for elements in different groups or rows
- Electron affinity
    - Definition
    - Variation with group and row
- Electronegativity
    - Definition
    - Comparative values for some representative elements and important groups
- Electron shells and the sizes of atoms
- Electron shells and the sizes of ions

Stoichiometry (GC)

- Molecular weight
- Empirical versus molecular formula
- Metric units commonly used in the context of chemistry
- Description of composition by percent mass
- Mole concept, Avogadro's number NA
- Definition of density
- Oxidation number
    - Common oxidizing and reducing agents
    - Disproportionation reactions
- Description of reactions by chemical equations
    - Conventions for writing chemical equations
    - Balancing equations, including redox equations
    - Limiting reactants
    - Theoretical yields

Foundational Concept 5

Content Category 5A: Unique nature of water and its solutions

Acid/Base Equilibria (GC, BC)

- Brønsted–Lowry definition of acid, base
- Ionization of water
    - Kw, its approximate value (Kw = [H+][OH–] = 10^(–14) at 25°C, 1 atm)
    - Definition of pH: pH of pure water
- Conjugate acids and bases (e.g., NH4+ and NH3)
- Strong acids and bases (e.g., nitric, sulfuric)
- Weak acids and bases (e.g., acetic, benzoic)
    - Dissociation of weak acids and bases with or without added salt
    - Hydrolysis of salts of weak acids or bases
    - Calculation of pH of solutions of salts of weak acids or bases
- Equilibrium Constants Ka and Kb: pKa, pKb
- Buffers
    - Definition and concepts (common buffer systems)
    - Influence on titration curves

Ions in Solutions (GC, BC)

- Anion, cation: common names, formulas and charges for familiar ions (e.g., NH4+ ammonium, PO4 3– phosphate, SO4 2– sulfate)
- Hydration, the hydronium ion

Solubility (GC)

- Units of concentration (e.g., molarity)
- Solubility product constant; the equilibrium expression Ksp
- Common ion effect, its use in laboratory separations
    - Complex ion formation
    - Complex ions and solubility
    - Solubility and pH

Titration (GC)

- Indicators
- Neutralization
- Interpretation of the titration curves
- Redox titration

Content Category 5B: Nature of molecules and intermolecular interactions

Covalent Bond (GC)

- Lewis Electron Dot formulas
    - Resonance structures
    - Formal charge
    - Lewis acids and bases
- Partial ionic character
    - Role of electronegativity in determining charge distribution
    - Dipole Moment
- Sigma and Pi bonds
    - Hybrid orbitals: sp3 , sp2 , sp and respective geometries
    - Valence shell electron pair repulsion and the prediction of shapes of molecules (e.g., NH3, H2O, CO2)
    - Structural formulas for molecules involving H, C, N, O, F, S, P, Si, Cl
    - Delocalized electrons and resonance in ions and molecules
- Multiple bonding
    - Effect on bond length and bond energies
    - Rigidity in molecular structure
- Stereochemistry of covalently bonded molecules (OC)
    - Isomers
        - Structural isomers
        - Stereoisomers (e.g., diastereomers, enantiomers, cis/trans isomers)
        - Conformational isomers
    - Polarization of light, specific rotation
    - Absolute and relative configuration
        - Conventions for writing R and S forms
        - Conventions for writing E and Z forms

Liquid Phase – Intermolecular Forces (GC)

- Hydrogen bonding
- Dipole Interactions
- Van der Waals' Forces (London dispersion forces)

Content Category 5C: Separation and purification methods

Separations and Purifications (OC, BC)

- Extraction: distribution of solute between two immiscible solvents
- Distillation
- Chromatography: Basic principles involved in separation process
    - Column chromatography
        - Gas-liquid chromatography

        - High pressure liquid chromatography
    - Paper chromatography
    - Thin-layer chromatography
- Separation and purification of peptides and proteins (BC)
    - Electrophoresis
    - Quantitative analysis
    - Chromatography
        - Size-exclusion
        - Ion-exchange
        - Affinity
- Racemic mixtures, separation of enantiomers (OC)

Content Category 5D: Structure, function, and reactivity of biologically-relevant molecules

Nucleotides and Nucleic Acids (BC, BIO)

- Nucleotides and nucleosides: composition
    - Sugar phosphate backbone
    - Pyrimidine, purine residues
- Deoxyribonucleic acid: DNA; double helix
- Chemistry (BC)
- Other functions (BC)

Amino Acids, Peptides, Proteins (OC, BC)

- Amino acids: description
    - Absolute configuration at the α position
    - Dipolar ions
    - Classification
        - Acidic or basic
        - Hydrophilic or hydrophobic
    - Synthesis of α-amino acids (OC)
        - Strecker Synthesis
        - Gabriel Synthesis
- Peptides and proteins: reactions
    - Sulfur linkage for cysteine and cystine
    - Peptide linkage: polypeptides and proteins
    - Hydrolysis (BC)
- General Principles
    - Primary structure of proteins
    - Secondary structure of proteins
    - Tertiary structure of proteins
    - Isoelectric point

The Three-Dimensional Protein Structure (BC)

- Conformational Stability
    - Hydrophobic interactions
    - Solvation layer (entropy)
- Quaternary structure
- Denaturing and Folding

Non-Enzymatic Protein Function (BC)

- Binding
- Immune system
- Motor

Lipids (BC, OC)

- Description, Types
    - Storage
        - Triacyl glycerols
        - Free fatty acids: saponification
    - Structural
        - Phospholipids and phosphatids
        - Sphingolipids (BC)
        - Waxes
    - Signals/cofactors
        - Fat-soluble vitamins
        - Steroids
        - Prostaglandins (BC)

Carbohydrates (OC)

- Description
    - Nomenclature and classification, common names
    - Absolute configuration
    - Cyclic structure and conformations of hexoses
    - Epimers and anomers
- Hydrolysis of the glycoside linkage
- Keto-enol tautomerism of monosaccharides
- Disaccharides (BC)
- Polysaccharides (BC)

Aldehydes and Ketones (OC)

- Description
    - Nomenclature
    - Physical properties
- Important reactions
    - Nucleophilic addition reactions at C=O bond
        - Acetal, hemiacetal
        - Imine, enamine
        - Hydride reagents
        - Cyanohydrin
    - Oxidation of aldehydes
    - Reactions at adjacent positions: enolate chemistry
        - Keto-enol tautomerism (α-racemization)
        - Aldol condensation, retro-aldol
        - Kinetic versus thermodynamic enolate
- General principles
    - Effect of substituents on reactivity of C=O; steric hindrance
    - Acidity of α-H; carbanions

Alcohols (OC)

- Description
  - Nomenclature
  - Physical properties (acidity, hydrogen bonding)
- Important Reactions
  - Oxidation
  - Substitution reactions: SN1 or SN2
  - Protection of alcohols
  - Preparation of mesylates and tosylates

Carboxylic Acids (OC)

- Description
  - Nomenclature
  - Physical properties
- Important reactions
  - Carboxyl group reactions
    - Amides (and lactam), esters (and lactone), anhydride formation
    - Reduction
    - Decarboxylation
  - Reactions at 2-position, substitution

Acid Derivatives (Anhydrides, Amides, Esters) (OC)

- Description
  - Nomenclature
  - Physical properties
- Important Reactions
  - Nucleophilic substitution
  - Transesterification
  - Hydrolysis of amides
- General Principles
  - Relative reactivity of acid derivatives
  - Steric effects
  - Electronic effects
  - Strain (e.g., β-lactams)

Phenols (OC, BC)

- Oxidation and reduction (hydroquinones, ubiquinones): biological 2e- redox centers

Polycyclic and Heterocyclic Aromatic Compounds (OC, BC)

- Biological aromatic heterocycles

Content Category 5E: Principles of chemical thermodynamics and kinetics

Enzymes (BC, BIO)

- Classification by reaction type
- Mechanism

    - Substrates and enzyme specificity
    - Active site model
    - Induced-fit model
    - Cofactors, coenzymes, and vitamins
- Kinetics
    - General (catalysis)
    - Michaelis–Menten
    - Cooperativity
    - Effects of local conditions on enzyme activity
- Inhibition
- Regulatory enzymes
    - Allosteric
    - Covalently modified

Principles of Bioenergetics (BC)

- Bioenergetics/thermodynamics
    - Free energy/Keq
    - Concentration
- Phosphorylation/ATP
    - ATP hydrolysis $\Delta G << 0$
    - ATP group transfers
- Biological oxidation–reduction
    - Half-reactions
    - Soluble electron carriers
    - Flavoproteins

Energy Changes in Chemical Reactions – Thermochemistry, Thermodynamics (GC, PHY)

- Thermodynamic system – state functions
- Zeroth Law – concept of temperature
- First Law – conservation of energy in thermodynamic processes
- *PV* Diagram: work done = area under or enclosed by curve (PHY)
- Second Law – concept of entropy
    - Entropy as a measure of "disorder"
    - Relative entropy for gas, liquid, and crystal states
- Measurement of heat changes (calorimetry), heat capacity, specific heat
- Heat transfer – conduction, convection, radiation (GC)
- Endothermic/exothermic reactions (GC)
    - Enthalpy, H, and standard heats of reaction and formation
    - Hess' Law of Heat Summation
- Bond dissociation energy as related to heats of formation (GC)
- Free Energy: *G* (GC)
- Spontaneous reactions and $\Delta G°$ (GC)
- Coefficient of expansion (PHY)
- Heat of fusion, heat of vaporization
- Phase diagram: pressure and temperature

Rate Processes in Chemical Reactions – Kinetics and Equilibrium (GC)

- Reaction rate
- Dependence of reaction rate on concentration of reactants

    - Rate law, rate constant
    - Reaction order
- Rate-determining step
- Dependence of reaction rate upon temperature
    - Activation energy
        - Activated complex or transition state
        - Interpretation of energy profiles showing energies of reactants, products, activation energy, and ΔH for the reaction
    - Use of the Arrhenius Equation
- Kinetic control versus thermodynamic control of a reaction
- Catalysts
- Equilibrium in reversible chemical reactions
    - Law of Mass Action
    - Equilibrium Constant
    - Application of Le Châtelier's Principle
- Relationship of the equilibrium constant and $\Delta G°$