Credits to:

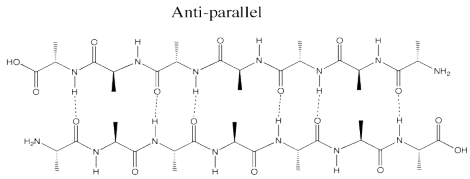
mcat-review.org
Khan Academy
Examkrackers
Kaplan
r/MCAT
A redditor, whose name we cannot find, who posted a similar guide long ago

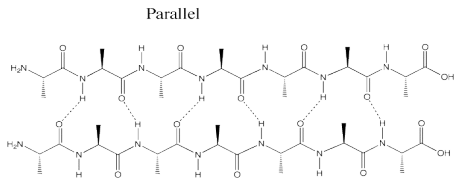
Content Category 1A: Structure and function of proteins and their constituent amino acids

Amino Acids (BC, OC)

- Description
  - Absolute configuration at the α position
    - The alpha carbon IN EVERY amino acid is a chiral center EXCEPT in **glycine** (it is achiral, since the R group is an H)
    - EVERY AA has S configuration EXCEPT FOR **cysteine** (R configuration)
  - Amino acids as dipolar ions
    - At low pH, amino acid = cationic
    - At high pH, amino acid = anionic
    - At pH = pI, amino acid = zwitterionic (neutral)
  - Classifications
    - Acidic or Basic
      - ACIDIC: Aspartic Acid (Asp, D) ; Glutamic Acid (Glu, E)
      - BASIC: Lysine (Lys, K) ; Arginine (Arg, K) ; Histidine (His, H)
    - Hydrophobic or Hydrophilic
      - HYDROPHILIC: If the R group contains acids, bases, amines or alcohols
        - Arginine (Arg, R), Lysine (Lys, K), Aspartic Acid (Asp, D), Glutamic Acid (Glu, E), Glutamine (Gln, Q), Asparagine (Asn, N), Histidine (His, H), Serine (Ser, S), Threonine (Thr, T), Tyrosine (Tyr, Y), Cysteine (Cys, C), Tryptophan (Trp, W)
      - HYDROPHOBIC: If the R group DOES NOT contain what is listed above ^^
        - Alanine (Ala, A), Isoleucine (Ile, I), Leucine (Leu, L), Methionine (Met, M), Phenylalanine (Phe, F), Valine (Val, V), Proline (Pro, P), Glycine (Gly, G)
- Reactions
  - Sulfur linkage for cysteine and cystine
    - Cysteine = amino acid with the thiol R group
    - Cystine = 2 cysteines that have formed a **disulfide bond**
  - Peptide linkage: polypeptides and proteins
    - Peptide bonds link amino acid chains together
    - Peptide bonds are formed by the *nucleophilic addition-elimination* (*condensation, dehydration rxn)* reaction **between the carboxyl group of one amino acid and the amino group of another amino acid**
    - The nucleophilic amino group attacking an electrophilic carbonyl
    - The bond when formed has a lot of resonance delocalization (partial double bond character all over the place!)
      - Makes the bond very rigid/planar
      - However, this is still free rotation around the ALPHA CARBON
  - Hydrolysis
    - The process of breaking the peptide bond
      - Done by either acid/base hydrolysis (nonspecific) or with the help of proteolytic enzymes (specific)

Protein Structure (BIO, BC, OC)





- Structure
  - 1° structure of proteins
    - Linear sequence of amino acids
    - Determined by the peptide bond linking each amino acid
    - Covalent (Peptide) bonds
  - 2° structure of proteins
    - Local structure, stabilized by hydrogen bonding
      - **α-helices** – hydrogen bonds run up and down, stabilizing the structure
      - **β-pleated sheets** – stabilized by hydrogen bonds connecting the sheets
        - Antiparallel vs. Parallel configurations
    - The way the linear sequence folds on itself
    - Determined by the backbone interactions (primarily **hydrogen bonds**)
    - Hydrogen bonds between backbone atoms
  - 3° structure of proteins
    - 3-D structure stabilized by hydrophobic interactions, acid-base interactions (salt bridges), hydrogen bonding, and disulfide bonds
    - Depends on distant group interaction
      - Stabilized by hydrogen bonds, van der Waals, hydrophobic packing, disulfide bridge formation
    - Disulfide bond formation happens on the exterior of the cell (covalent bond of two cysteines)
      - Extracellular space prefers the formation of disulfide bonds (the oxidizing environment)
    - Hydrophobic interactions and polar interactions between side chains
  - 4° structure of proteins
    - Interactions between subunits (multiple polypeptides)
    - Hydrophobic interactions and ionic bonds between side chains (i.e. cysteine side chains making disulfide bonds)
- Conformational stability
  - Denaturing and Folding
    - Primary Structure = determined by peptide bonds
    - Secondary Structure = determined by backbone interactions (hydrogen bonds)
    - Tertiary Structure = determined by distant interactions between groups (van der Waals, hydrophobic packing, disulfide, hydrogen bonding)
    - Quaternary Structure = determined by same bonds from tertiary structure
    - Protein is ONLY FUNCTIONAL when in the proper conformation
      - A force that helps stabilize the protein is the solvation shell
        - **Solvation shell** = layer of solvent surrounding the protein (can be the water solvent interaction with polar AAs, etc.)
    - **Denaturation** = when a protein loses active conformation and becomes inactive
      - Occurs by changing pH, temp, chemicals or even enzymes
    - If you denature by heating, you destroy all the structures of the protein **except the primary structure** (primary structure is conserved)
  - Hydrophobic Interactions/Solvation Layer (entropy) (BC)
    - The hydrophobic regions of the protein aggregate, which releases the water from cages → This increases the entropy of water, which is the major thermodynamically favorable component of protein folding

- Separation techniques
    - Isoelectric point
        - pI is determined by averaging the pKa values that refer to the protonation and deprotonation of the zwitterion
        - **Isoelectric focusing** = gel electrophoresis method that separates proteins on basis of their relative contents of acidic and basic residues (gel with pH gradient is used)
    - Electrophoresis
        - Positively charged anode at bottom, negatively charged cathode at top
        - Larger molecules will have harder time moving, thus separation created by size with the smallest molecules towards the bottom
        - Native Page = retains structure of protein ; SDS-Page = break into subunits

Non-Enzymatic Protein Function (BIO, BC)

- Binding (BC)
    - Bind various biomolecules – bind specifically and tightly
    - Receptors/Ion channels in the membrane:
        - Receptors bind or receive signaling molecules (ligand) which makes a chemical response (i.e. insulin receptor)
        - Ion channels can allow ions to enter/exit the cell
- Immune System
    - **Antibodies** = protein components of the adaptive immune system whose main function is to find foreign antigens and target them for destruction
    - **Antigen = the ligand for antibodies**
        - Antigens can be thought of as little red flags for the immune system letting us know, "Hey, that's not supposed to be there!"
- Motors
    - Transport: e.g. Hemoglobin (at high concentration of ligand, have high affinity, at low concentration of ligand, have low affinity)
    - Myosin/Kinesin/Dynein
        - Myosin = responsible for forces exerted by contracting muscles
        - Kinesin/Dynein = motor proteins responsible for intracellular transport
            - Dynein = plays a role in the motility of cilia

Enzyme Structure and Function (BIO, BC)

- Function of enzymes in catalyzing biological reactions
    - Enzymes function to lower the activation energy of reactions (do not get used up!)
    - Structure determines function → change in structure = change in function
- Enzyme classification by reaction type
    - 6 Types of Enzymes:
        - **Transferase**
            - Move a functional group from one molecule to another
            - A + BX → AX + B
        - **Ligase**
            - Join two large biomolecules, often of the same type
            - A + B → AB
        - **Oxidoreductase**
            - Catalyze oxidation-reduction reactions that involve the transfer of electrons
            - Oxidase = oxidizing or taking away electrons from a molecule
            - Reductase = reducing or giving electrons to a molecule
            - A + B: ←→ A: + B
        - **Isomerase**

        - Interconversion of isomers, including both constitutional and stereoisomers
        - A → B
    - **Hydrolase**
        - Cleavage with the addition of water
        - $A + H_2O \rightarrow B + C$
    - **Lyase**
        - Cleave without the addition of water and without the transfer of electrons (reverse reaction, synthesis, is usually more biologically important)
        - A → B + C (does not use water, or oxidation/reduction)
        - Lyases generate either a double bond or a ring structure
- Reduction of activation energy
    - <u>Acid/Base catalysis</u> = enzymes use acidic/basic properties to make rxns go faster by proton transfer
    - <u>Covalent catalysis</u> = enzymes covalently bind to help with electron transfer
    - <u>Electrostatic catalysis</u> = charged molecules or metal ions used to stabilize big positive or negative charges
    - <u>Proximity/Orientation effects</u> = enzymes make collisions between reacting molecules happen more often
    - Transition state = highest energy point from path A to B (in A→ B)
        - Where you also find **most instability** (high energy = more unstable)
    - Enzymes lower the activation energy of the reaction (making it easier for the reactants to transition to form products)
- Substrates and Enzyme Specificity
    - Enzyme-substrate specificity derives from structural interactions
    - Enzymes can be specific enough to determine between stereoisomers
- Active Site Model
    - Location on the enzyme where it reacts with its substrate
    - Shape/characteristics (functional groups) of an active site are responsible for the specificity of the enzyme
- Induced-fit Model
    - Initial Binding = when the substrate first binds to the enzyme (not perfect)
        - Forces holding the two together are strong, but not at the maximum strength yet
    - Enzyme and substrate thus mold their shape to bind together super tightly
        - Called the **induced fit** because both the enzyme and substrate have changed their shape a little so they bind together really tightly (catalyzing reaction at full force)
    - Binding between reactant and enzyme STRONGEST at the **transition state**
- Mechanism of catalysis
    - Cofactors
        - <u>Directly involved in the enzyme's catalytic mechanism</u> (might be stabilizing the substrates, or helping the reaction to convert substrates from one form to another) (e.g. Mg^{2+})
    - Coenzymes
        - <u>Organic carrier molecules</u> (i.e. NADH, CoA)
    - Water-soluble vitamins
        - Need to obtain from the diet
        - Vitamins → organic cofactors and coenzymes
        - e.g. Vitamin B3 is precursor for NAD
        - e.g. Vitamin B5 is precursor for CoA
- Effects of local conditions on enzyme activity
    - Enzymes work best in specific environments
    - Effects of pH changes:

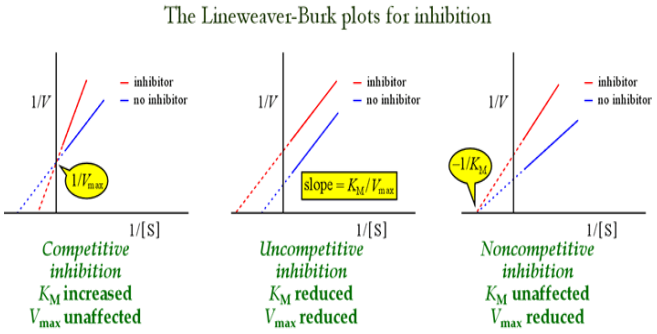
        - e.g. DNA → Negatively charged → DNA Polymerase binds Mg^{2+} cofactor to stabilize negative charge on DNA
            - In normal conditions, DNA Pol holds onto Mg ion through electrostatic interaction between magnesium and one of its aspartate residues, which would be deprotonated and thus negatively charged at neutral pH values
            - If you took DNA Pol and put it in environment with reduced pH, the aspartate residue would become protonated since pH has dropped so much, and protonated form has no negative charge, so can't bind Mg ion cofactor
            - DNA Pol cannot do job properly in low pH environment
    - Effects of temperature changes:
        - Proteins fold from primary → secondary → tertiary → quaternary structures to function properly
        - Significant changes in temp cause protein to lose its functionality (loses its shape)
            - e.g. when we get sick and our body temperature goes up, our digestive enzymes cannot work properly and consequently we cannot eat food as well

Control of Enzyme Activity (BIO, BC)

- Kinetics
    - General (catalysis)
        - Enzymes lower the activation energy of a reaction, or the ΔG of the transition state (NOT OF THE RXN!)
        - E + S ←→ ES ←→ E + P
        - At really high [S] the enzymes will be <u>saturated</u>
            - Even if you increase concentration of [S] from this point, there will still be a V_{max}
    - **Michaelis-Menten**
        - V_{max} is defined for a specific enzyme concentration (adding more enzyme will increase the V_{max})
        - Michaelis-Menten equation calculates the rate of reaction using V_{max}, the substrate concentration [S], and the Michaelis constant K_m. K_m = the [S] required to reach $1/2V_{max}$.
        - K_m does not fluctuate with changes in [enzyme] and is indicative of enzyme-substrate affinity
        - Enzymes with high enzyme-substrate affinity will reach $1/2V_{max}$ at a lower substrate concentration (**Lower K_m)**
        - Lower enzyme-substrate affinities will result in needing a higher substrate concentration to reach $1/2V_{max}$ **(Higher K_m)**
        - $V = \frac{vmax\,[S]}{Km+[S]}$
            - As substrate concentration increases, the reaction rate also increases until a maximum value is reached
            - At ½ Vmax, [S] = Km
        - **$k_{cat} = V_{max} / [E]_T$**
            - = Enzyme's "Turnover Number"
            - How many substrates can this enzyme turn into product in one second at its maximum speed
        - **Catalytic Efficiency = k_{cat} / K_m**
    - Cooperativity
        - Some proteins can bind more than 1 substrate
        - Cooperativity = substrate binding changes substrate affinity
        - <u>Positive</u> Cooperative Binding = Substrate binding <u>increases</u> affinity for subsequent substrate

- Negative Cooperative Binding = Substrate binding decreases affinity for subsequent substrate
- Non-Cooperative Binding = Substrate binding does not affect affinity for subsequent substrate
- **TOW RIGH (Hemoglobin affinity for O_2)**
  - T state = Low affinity
  - R state = High affinity

- Feedback Regulation
  - When product of reaction binds allosteric site of the enzyme, affecting the catalytic activity
    - Can be positive = increases enzyme-substrate affinity
    - Can be inhibitory = reducing activity at the active site or inactivating it completely
- Inhibition – Types
  - Competitive
    - E (inhibitor binds to E here to make EI) + S ←→ ES ←→ E + P
    - Blocks the enzyme and makes it unable to react with substrate to form product
    - Inhibitor competes with substrate for space on the enzyme
    - **Binds: Active Site**
    - **Impact on Km: Increases**
    - **Impact on Vmax: No Change**
  - Uncompetitive
    - E + S ←→ ES (inhibitor binds to the ES here to make ESI) ←→ E + P
    - Molecule that binds only to the enzyme-substrate complex, rendering it catalytically inactive
    - **Binds: Allosteric Site**
    - **Impact on Km: Decreases**
    - **Impact on Vmax: Decreases**
  - Non-competitive
    - Prevents the enzyme from turning substrate into product
    - Binds to an allosteric site on the enzyme, causing a conformational change that decreases catalytic activity at the active site regardless of whether a substrate is already bound
    - **Binds: Allosteric Site**
    - **Impact on Km: No Change**
    - **Impact on Vmax: Decreases**
  - Mixed
    - Molecule that binds to an allosteric site on the enzyme, causing a conformational change that decreases catalytic activity at the active site
    - Generally, have preference towards binding either the enzyme-substrate complex, or binding the enzyme alone
    - **Binds: Allosteric Site**
    - **Impact on Km: Increase** (if prefer enzyme w/o substrate) **or Decrease** (if prefer enzyme with substrate bound)
    - **Impact on Vmax: Decreases**



- Regulatory Enzymes
  - Allosteric Enzymes
    - Allosteric site present, molecule binds it, can either upregulate or downregulate the enzyme function
  - Covalently-modified enzymes
    - Not all enzymes are proteins (i.e. Inorganic metals, small organic molecules like Flavin)
    - **Small Posttranslational Modifications:**
      - Translation → synthesis of AA polymer
      - "Post-translation" → after initial synthesis
      - "Small" → adding or removing small functional groups
    - **Methylation**
      - Modification of a protein that involves addition of methyl group (CH_3)
    - **Acetylation**
      - Modification of a protein that involves addition of an acetyl group
    - **Glycosylation**
      - Addition of a sugar to a protein
    - I.e. Acetylation of lysine residue on a protein
      - **Electron withdrawing impact of the acetyl group** will prevent nitrogen from carrying positive charge and modify the behavior of the amino acid
    - **Suicide Inhibition**
      - Suicide inhibitors covalently bind the enzyme and prevent it from catalyzing reactions
      - Rarely unbind – why it's called suicide (enzyme won't work anymore)
  - **Zymogens**
    - Inactive form of an enzyme that requires covalent modification to become active
    - I.e. Digestive enzymes of the pancreas
      - Pancreas releases trypsinogen (a zymogen)
      - Once in the intestine, it is covalently modified by an enzyme called enterokinase to the active form Trypsin
      - This makes sure trypsin does not break down proteins that we need in the pancreas

Content Category 1B: Transmission of genetic information from the gene to the protein

Nucleic Acid Structure and Function (BIO, BC)

- Description
  - Nucleic acids can be DNA or RNA, single-stranded or double-stranded
  - Protein coat covers the nucleic acid
  - The 2 single-strands are anti-parallel to each other. Going from 5' to 3' of one strand means going 3' to 5' of other strand.
- Nucleotides and nucleosides
  - **Nucleotide** = base (Adenine, Guanine, Thymine, Cytosine) + sugar + phosphate
  - **Nucleosides** = base + sugar = Adenosine, Guanosine, Thymidine, Cytidine
  - Sugar phosphate backbone
    - Important structural component of DNA which consists of the pentose sugar and phosphate groups
    - Sugars linked together by a phosphodiester bond
  - **Pyrimidine**, **purine** residues
    - Adenine and Guanine are purines (2 rings)
    - Cytosine, Threonine, and Uracil are pyrimidines (1 ring)
- Base pairing specificity: A with T, G with C
  - A forms 2 hydrogen bonds with T
  - G forms 3 hydrogen bonds with C
  - GC bonds are stronger. DNA with high GC content harder to break apart.
  - Complementary strands of DNA hydrogen bond with each other.
- Function in transmission of genetic information
  - Because of the complementary nature of base pairing, DNA can transmit genetic information through replication
- DNA denaturation, reannealing, hybridization
  - Disruption of the hydrogen bonds, such as with high temperature, can cause the unwinding of the two strands (denaturation), which can then also be brought back together when proper conditions return (reannealing)
  - A single strand of DNA will readily bind another single strand DNA in process of hybridization where there is significant amount of base pair matching between their sequences

DNA Replication (BIO)

- Mechanism of replication: separation of strands, specific coupling of free nucleic acids
  - 1. Double-stranded DNA must separate or unwind. To do this:
    - **DNA gyrase** (class II topoisomerase) responsible for uncoiling the DNA ahead of the replication fork
    - **Helicase** responsible for unwinding DNA at replication fork
    - **Single-strand binding protein** (SSB) responsible for keeping DNA unwound after helicase. SSBs stabilize ssDNA by binding to it.
  - 2. You start making DNA that is complementary to the unwound/separated DNA. Note, all biological DNA synthesis occurs from 5' to 3' end.

        - **Primase** lays down short RNA primer on unwound DNA. Primer made of RNA but is complementary to DNA sequence. Later, this RNA is replaced with DNA.
        - **DNA polymerase** takes over and makes DNA that is complementary to unwound DNA.
        - DNA synthesis occurs on both strands of unwound DNA. Synthesis that proceeds in direction of replication fork is leading strand. Synthesis that proceeds in opposite direction to replication fork is lagging strand. Lagging strand contains Okazaki fragments.
    - 3. RNA primers replaced with DNA by a special DNA polymerase. Okazaki fragments in lagging strands are stitched together by DNA ligase.
    - DNA synthesis is **bidirectional**: 2 replication forks form and proceeds in opposite directions.
    - Biological DNA synthesis always proceeds from 5' to 3' end.
    - DNA polymerase has **proofreading activity**, corrects any mistakes (mutations) it makes
    - Replication occurs once every cell generation, during the S phase. (Cell division may occur twice in meiosis, but replication still only occurs once)
- Semi-conservative nature of replication
    - Newly synthesized DNA contains one old strand and one new strand
    - Meselson and Stahl proved this by experiment: used **heavy** (**^{15}N**) DNA as old (pre-replication) DNA and used **light** (**^{14}N**) nucleotides for synthesis of new DNA. They can tell difference between heavy and light DNA by centrifugation. They found that when heavy DNA undergoes one round of replication in light nucleotides, the DNA is made of intermediate weight. After second round of replication, DNA is split between intermediate and light weight.
    - If DNA replication were completely **conservative**, only heavy and light DNA would be seen, nothing in between.
    - If DNA replication were **dispersive**, everything would be of intermediate weight. This was not the case because after second round of replication, light DNA was seen.
- Specific enzymes involved in replication
    - **Helicase** = uses hydrolysis of ATP to "unzip" or unwind DNA helix at replication fork to allow resulting single strands to be copied
    - **Primase** = polymerizes nucleotide triphosphates in a 5' to 3' direction. Synthesizes RNA primers to act as a template for future Okazaki fragments to build on to.
    - **DNA Polymerase III** = synthesizes nucleotides onto leading end in classic 5' to 3' direction.
    - **DNA Polymerase I** = synthesizes nucleotides onto primers on lagging strand, forming Okazaki fragments. This enzyme cannot completely synthesize all the nucleotides.
    - **Ligase** = glues together Okazaki fragments, an area DNA Pol I unable to synthesize
    - **Telomerase** = catalyzes lengthening of telomeres; enzyme includes molecule of RNA that serves as template for new telomere segments
    - **Nuclease** = excises or cuts out unwanted or defective segments of nucleotides in DNA sequence
    - **Topoisomerase** = introduced single-strand nick in the DNA, enabling it to swivel and thereby relieve the accumulated winding strain generated during unwinding of double helix
    - **Single Strand Binding Proteins** = holds the replication fork of DNA open while polymerases read the templates and prepare for synthesis
- Origins of replication, multiple origins in eukaryotes
    - Process of DNA replication begins at origin of replication, where molecule's two strands are separated, producing a replication bubble with two replication forks unzipping the DNA bidirectionally away from the origin.
    - **Prokaryotes** have single origin of replication for their single, circular DNA
    - **Eukaryotes** have multiple origins of replication across their numerous linear chromosomes
- Replicating the ends of DNA molecules
    - Linear chromosomes arrive at issue with replication at ends of their lagging strands by which a portion of the strand at the very end (located in telomere, a region of repetitive sequences at the

end of the chromosome) is unable to by synthesized due to lack of 3' end of a nucleotide to extend from
    - This results in shortening of telomeres in linear chromosomes after numerous rounds of replication
    - Issue resolved in presence of telomerase which lengthens telomeres with repetitive sequences, thus protecting them from loss during replication

Repair of DNA (BIO)

- Repair during replication
    - DNA polymerase has proofreading activity (also called 3' → 5' exonuclease activity). If a wrong nucleotide gets incorporated, polymerase will "back-up" and replace it with correct one
    - Special polymerase that replaces the RNA primers with DNA also have 5' → 3' activity. This allows polymerase to clear away short stretches of incorrect nucleotides (RNA or incorrect DNA) and replace it with the right ones (DNA).
- Repair of mutations
    - **Mismatch repair**: enzymes recognize incorrectly paired base-pairs and cuts out stretch of DNA containing the mismatch. Then polymerase re-adds the correct nucleotides in.
        - During mismatch repair, repair enzyme must decide what strand of DNA to cut since DNA contains 2 strands. To do this, the enzyme cuts DNA strand that does not have methylations. The original (old) DNA has methylations but newly synthesized DNA does not have them until shortly after replication. Thus, there is a short period when mismatch repair enzymes can find out what strand to cut if mismatch is encountered.
    - **Base-excision repair**: a damaged base gets cut out. Then the base's sugar phosphate backbone gets cut out. Several more nucleotides next to base get cut out. Finally, polymerase remakes the cut-out nucleotides.
    - **Nucleotide-excision repair**: damaged nucleotide(s) get cut out then polymerase replaces it. This is like mismatch-repair, but not for mismatch. It's for damages like thymine dimers, and other damages that changes normal nucleotides into abnormal nucleotides.
    - **Nick translation**: basically 5' → 3' exonuclease activity coupled to polymerase activity. The polymerase chugs along, chews off bad nucleotides and replaces them with new nucleotides. This is what happens when RNA primers are replaced with DNA.
    - **SOS response in E. Coli**: during replication, when there's too much DNA damage for normal repair to handle, the SOS repair system comes along. Instead of correcting any DNA damages during replication, polymerase replicates over the damaged DNA as if it were normal. By using damaged DNA as template error rates are high, but still better than not replicated at all.

Genetic Code (BIO)

- Central Dogma: DNA → RNA → protein
    - **DNA**: Resides in nucleus. Codes information in genes.
    - **Transcription**: Inside the nucleus, the DNA genes get transcribed into RNA (messenger RNAs or mRNAs)
    - **RNA**: The mRNAs get transported out of nucleus into cytoplasm. mRNAs are working copies of the gene.
    - **Translation**: Ribosomes read off mRNAs to make proteins.
    - **Protein**: Synthesized by ribosomes. End product of what's encoded in the genes and they perform all functions in the cell.
- The triplet code
    - **Codon**: The mRNA is a sequence of nucleotides, but it codes for a sequence of amino acids. To do this, every 3 nucleotide codes for an amino acid. These triplets of nucleotides are called codons. A single mRNA contains many codons.

        - Codons are continuous, non-overlapping and degenerate.
        - Continuous because one codon follows right after another. There are no nucleotides in between.
        - Non-overlapping because the 3 nucleotides that consist one codon never serve as part of another codon
        - Degenerate (see below)
    - **Anticodon**: the 3 bases on the "tip" of the tRNA. A single tRNA contains a single anticodon at the "tip" and the corresponding amino acid at the "tail." Anticodons are complementary to their corresponding codon.
- Codon-anticodon relationship
    - During translation, codons pair with anticodons so that the correct amino acids can be linked to a given codon.
- Degenerate code, wobble pairing
    - Genetic code is degenerate because more than one codon codes for a given amino acid
    - We refer to variable third base in the codon as the wobble position. Wobble is an evolutionary development designed to protect against mutations in the coding regions of our DNA. Mutations in the wobble position tend to be called silent or degenerate, which means no effect on the expression of the amino acid and therefore no adverse effects on the polypeptide sequence
- Missense, nonsense codons
    - **Missense** codon: mutated codon that results in a different amino acid
    - **Nonsense** codon: mutated codon that results in a stop codon
- Initiation, termination codons
    - **Initiation codon** (AUG): signals the start of translation. Lies just downstream of the Shine Dalgarno sequence (Kozak sequence for eukaryotes)
    - **Termination codon** (UAG, UGA, UAA): signals the end of translation. Unlike other codons, tRNA are not involved. A protein called "release factor" comes along and terminates translation.
- Messenger RNA (mRNA)
    - mRNA stands for messenger RNA. It's the product of transcription and the template for translation
    - The 5' cap is a modified nucleotide linked in a special way to mRNA. This protects 5' end from exonuclease degradation.
    - The poly-A tail protects 3' end of mRNA from exonuclease degradation
    - Eukaryotic mRNA: 5' cap - nucleotides - 3' poly-A tail
    - Prokaryotic mRNAs don't have 5' cap or poly-A tail

Transcription (BIO)

- **Transfer RNA** (tRNA); **ribosomal RNA** (rRNA)
    - Both tRNA and rRNA are products of transcription. However, they do not serve as template for translation. tRNA responsible for bringing in correct amino acid during translation. rRNA makes up ribosome, enzyme responsible for translation.
    - tRNA made of nucleotides, many of which are modified for structural and functional reasons. At the 3' end, the amino acid is attached to the 3'OH via an ester linkage.
    - tRNA structure: clover leaf structure with anticodon at tip, and amino acid at 3' tail.
    - rRNA made of nucleotides, many modified for structural and functional reasons
    - rRNA highly structured because it contains active site for catalysis. The rRNA of large ribosomal subunit is responsible for catalyzing peptide bond formation and can do this even without ribosomal proteins.
- Mechanism of transcription (RNA polymerase, promoters, primer not required)
    - 1. **Chain Initiation**: RNA polymerase binds to promoter (TATA box) of dsDNA (closed complex). Double stranded DNA template opens up (open complex)

    - 2. **Chain Elongation**: nucleoside triphosphates (AUGCs) adds corresponding to the DNA template. No primer is required. RNA elongates as RNA polymerase moves down DNA template. RNA made from 5' to 3' direction.
    - 3. **Chain Termination**: 2 ways that transcription can terminate:
        - 1. Intrinsic termination: specific sequences called a termination site creates a stem-loop structure on RNA that causes RNA to slip off template.
        - 2. Rho (ρ) dependent termination: a protein called the ρ factor travels along the synthesized RNA and bumps off the polymerase
- Ribozymes, spliceosomes, small nuclear ribonucleoproteins (snRNPs), small nuclear RNAs (snRNAs)
    - **Ribozyme** = RNA molecule that is capable of catalyzing specific chemical reactions
    - **snRNPs** = RNA-protein complexes that combine with unmodified pre-mRNA and various other proteins to form a spliceosome, a large RNA-protein molecular complex upon which splicing of pre-mRNA occurs
    - **snRNAs** = complexed with proteins to form snRNPs to splice primary RNA transcripts.
- Functional and evolutionary importance of introns
    - Introns and alternative splicing allow different mRNA sequences and ultimately a greater variety of proteins through translation. Without introns or alternative splicing, less protein variability.
    - Efficient way to generate wide variety of proteins through use of mRNA compared to modifying preexisting proteins.
    - Splicing of introns = using snRNA/snRNP to form a spliceosome complex to excise intron lariat loop
- Post-transcriptional modification
    - Post-transcriptional modifications include addition of the 5' cap, polyA tail and splicing
    - In prokaryotes, mRNAs with better Shine-Dalgarno sequence are translated more
    - In eukaryotes, post-transcription regulation can involve adding more polyAs to mRNA (longer mRNA life time), modulation of the translation machinery (phosphorylation of initiation factors), or storing mRNAs to be translated at a later time (mRNA masking)
    - The cap and polyA tail are added co-transcriptionally, but still considered post transcriptional
    - Splicing gives rise to isoforms. Depending on how you arrange the introns/exons, you get different proteins by alternative splicing.

Translation (BIO)

- Role of mRNA, tRNA, rRNA
    - **mRNA**: contains codons that code for the peptide sequence
    - **tRNA**: contains the anticodon on the "tip" and the corresponding amino acid on the "tail." Link correct amino acid to its corresponding mRNA codon through codon-anticodon interaction.
    - **rRNA**: forms the ribosome. Catalyzes the formation of the peptide bond.
- Role and structure of ribosomes
    - Ribosome is the enzyme that catalyzes protein synthesis
    - Ribosome has 2 subunits - the large and the small
    - Large subunit responsible for peptidyl transfer reaction
    - Small subunit responsible for recognizing mRNA and binds to Shine-Dalgarno sequence on mRNA (Kozak sequence for eukaryotes)
    - Both subunits needed for translation to occur and they come together in a hamburger fashion that sandwiches the mRNA and tRNAs in between
- Mechanism of translation
    - 1. **Chain Initiation**: To begin, you need to form initiation complex, basically an assembly of everything. This includes mRNA, initiator tRNA (fmet), and ribosome (initiation factors, and GTP aids in formation of initiation complex). The initiation complex forms around initiation codon (AUG), which is just downstream of the Shine-Dalgarno sequence. The Shine-Dalgarno

sequence is the "promoter" equivalent of translation for prokaryotes (Kozak sequence for eukaryotes).
    - 2. **Chain Elongation**: protein made from N terminus to C terminus. mRNA codons read from 5' to 3' end. Elongation consists of:
        - 1. **Binding**: new tRNA with its amino acid (tRNA + amino acid is called aminoacyl-tRNA) enters the A site. GTP and elongation factor required.
        - 2. **Peptidyl transfer**: attachment of the new amino acid to existing chain in P site. The already existing chain in P site migrates and attaches to the aminoacyl-tRNA in the A site.
        - 3. **Translocation**: the lone tRNA in the P site gets kicked off (E site), and the tRNA in the A site, along with peptide attached to it, moves into the P site. The mRNA gets dragged along also - the codon that was in the A site is now in P site after translocation. A site is now empty and ready for the binding of a new aminoacyl-tRNA to a new codon. Elongation factor and GTP required.
    - 3. **Chain Termination**: When a stop codon is encountered, proteins called release factors, bound to GTP, come in and block the A site. Peptide chain gets cleaved from tRNA in the P site. Peptide chain falls off and the whole translation complex falls apart.
    - Amino acid activation: enzymes called aminoacyl-tRNA synthetases attach the correct amino acids to their corresponding tRNAs. ATP required.
- Post-translational modifications to protein
    - Modifications of the protein through addition of groups to the protein through covalent bonds or cleavage of the protein
    - Deals with activation/inactivation or enhancing the protein's function
    - Examples include phosphorylation, glycosylation, and ubiquitination (inactivation by tagging protein for proteasome degradation)

Eukaryotic Chromosome Organization (BIO)

- Chromosomal proteins
    - **Histones**: responsible for compact packing and winding of chromosomal DNA. DNA winds itself around histone octamers.
    - **Non-histone** chromosomal proteins: all the other proteins are lumped together in this group. Responsible for roles such as regulatory and enzymatic.
- Single copy vs. repetitive DNA
    - **Single copy** = DNA sequence that does not repeat (ex. ATCCGTAG)
    - Single copy holds most of the organism's important genetic information. It is transcribed and translated and has a low mutation rate.
    - **Repetitive DNA** = DNA sequence that does repeat (ex. ATCCATCC)
    - Repetitive DNA found near the centromeres. They may contain genes that are transcribed/translated; however, there may be parts that are not transcribed/translated. They have higher mutation rate.
    - Highly repetitive DNA contains no genes so not transcribed/translated and very high mutation rate (ex. telomeres)
- Supercoiling
    - **Supercoiling** is a wrapping of DNA on itself as its helical structure is pushed even further toward the telomeres during replication. To alleviate the torsional stress and reduce risk of strand breakage, DNA gyrase (DNA topoisomerase II) introduces negative supercoils.
- Heterochromatin vs. euchromatin
    - **Euchromatin** is structured as loose beads on a string. The beads represent nucleosomes. The majority of DNA is in euchromatin form, as it's generally under active transcription all the time. Note: Prokaryotes only have euchromatin as heterochromatin has a more complex structure.

    - **Heterochromatin** is densely packed, so like coiled beads on a string. It was thought that the genes here were inaccessible for transcription, but recent research says otherwise. Additionally, if some euchromatin is not being transcribed, it may be converted into heterochromatin, and vice-versa.
- Telomeres, centromeres
    - Telomere: the 2 ends of the chromosome
    - Centromere: a region on the chromosome, can be at the center or close to one of the ends. After replication, sister chromatids are attached at the centromere. During mitosis, spindle fibers are attached at the centromere and pulls the sister chromatids apart.

Control of Gene Expression in Prokaryotes (BIO)

- Operon Concept, Jacob-Monod Model
    - **Operon** = a cluster of genes transcribed as a single mRNA. The numerous genes share a single common promoter region on the DNA sequence and are transcribed as a group. Two types of operons: inducible and repressible systems.
    - Jacob-Monod Model:
        - 1. Structural gene: codes for protein of interest
        - 2. Operator site: nontranscribable region of DNA capable of binding a repressor protein
        - 3. Promoter site: provides a place for RNA polymerase to bind
        - 4. Regulator gene: codes for the repressor protein
- Gene repression in bacteria
    - Operons have a binding site for regulatory proteins that turn expression of the operon "up" or "down"
    - Some regulatory proteins are repressors that bind to pieces of DNA called operators. When bound to its operator, a repressor reduces transcription (e.g., by blocking RNA polymerase from moving forward on DNA)
- Positive control in bacteria
    - Some regulatory proteins are activators. When an activator is bound to its DNA binding site, it increases transcription of the operon (e.g., by helping RNA polymerase bind to the promoter)

Control of Gene Expression in Eukaryotes (BIO)

- Transcriptional regulation
    - Transcription factors (protein) bind to enhancers or silencers (DNA) to affect transcription. **Enhancers** increase transcription when bound, while **silencers** decrease it. The main difference in eukaryotes from prokaryotes is that enhancers/silencers can be very far away from actual promoter and can be upstream or downstream. The DNA must loop back on itself so that the transcription factor bound to enhancer/silencer can make contact with promoter. Intermediate proteins are involved in the process.
    - Eukaryotes lack bacterial transcription regulation mechanisms such as the operon and attenuation
- DNA binding proteins, transcription factors
    - DNA-binding proteins and transcription factors bind to DNA. TFs have a DNA-binding domain.
    - DNA-binding domains interact with the grooves in the double helix (major and minor grooves)
- Gene amplification and duplication
    - Once the transcription complex is formed, basal (or low-level) transcription can begin and maintain moderate, but adequate, levels of the protein encoded by this gene in the cell. There are times, however, when the expression must be increased, or amplified, in response to specific signals such as hormones, growth factors, and other intracellular conditions. Eukaryotic cells accomplish this through enhancers and gene duplication.
    - Gene duplication can also increase expression of a gene product by duplicating the relevant gene. Genes can be duplicated in series on the same chromosome, yielding many copies in a row of the same genetic information. Genes can also be duplicated in parallel by opening the gene with

helicases and permitting DNA replication only of that gene; cells can continue replicating the gene until hundreds of copies of the gene exist in parallel on the same chromosome.

- Post-transcriptional control, basic concept of splicing (introns, exons)
    - tRNA and rRNA modifications: some normal nucleotides are modified to control the structure of these RNAs
    - mRNA modifications
        - RNA splicing: sequences called introns cut out, sequences called exons are kept and spliced (joined) together
        - Alternate splicing: different ways of cutting up the RNA and rejoining the exons pieces makes different final RNA products
        - 5' capping and 3' poly-A tail: these help to protect the RNA from degradation, so they can last longer
    - After the correct modifications, RNA is transported out of nucleus where they can function in translation
    - After some time, RNA is degraded. The rate and timing of RNA degradation can be controlled by the cell.
- Cancer as a failure of normal cellular controls, oncogenes, tumor suppressor genes
    - Failure of normal cellular controls:
        - Cancer cells continue to grow and divide in situations normal cells would not
        - Cancer cells fail to respond to cellular controls and signals that would halt this growth in normal cells
        - Cancer cells **avoid apoptosis** (self-destruction) that normal cells undergo when extensive DNA damage is present
        - Cancer cells stimulate **angiogenesis** (cause new blood vessels to grow to nourish the cancer cell)
        - Cancer cells are immortal while normal cells die after a number of divisions
        - Cancer cells can **metastasize** - break off and grow in another location
    - **Oncogenes**: genes that cause cancer when activated. The product of many oncogenes is involved in speeding up cell division. Before an oncogene is activated, it is a harmless proto-oncogene. Something occurs that changes proto-oncogene to an oncogene. Classic example is src.
    - **Tumor suppressors**: if the oncogene is the "bad" gene, tumor suppressors are the "good" genes. The product of many tumor suppressors is involved in slowing down or controlling cell division. If something happens that cause tumor suppressor to no longer function, then the cell becomes cancerous. Classic example is p53.
- Regulation of chromatin structure
    - Chromatin made up of DNA, histone proteins, and non-histone proteins. There are repeating units of chromatin, called nucleosomes, which are made up of double helical DNA wrapped around a core of eight histones.
    - DNA comes in two flavors: densely packed, and transcriptionally inactive DNA called heterochromatin, and the less dense, transcriptionally active DNA called euchromatin
    - Methylated DNA may be bound to methyl cpg-binding domain proteins that recruit additional proteins to the locus certain genes and other chromatin remodeling proteins, and this modifies the histones, forming condensed inactive heterochromatin that is basically transcriptionally silent.
    - Acetylation promotes open DNA (aka active chromatin or euchromatin)
- DNA methylation
    - Involved in chromatin remodeling and regulation of gene expression levels in the cell. Methylation often linked with <u>silencing of gene expression</u>. During development, methylation plays an important role in silencing genes that no longer need to be activated.
    - Heterochromatin regions of the DNA are more heavily methylated, hindering access of the transcriptional machinery to the DNA.

- Role of non-coding RNAs
    - **Non-coding RNA** is a functional RNA transcribed from DNA but not translated into proteins. They function to regulate gene expression at the transcriptional and post-transcriptional level.
    - Three major classes are microRNAs (miRNAs), short interfering RNAs (siRNAs), and piwi-interacting RNAs (piRNAs)

Recombinant DNA and Biotechnology (BIO)

- Gene cloning
    - Retrieve gene of interest and plasmid that has one area with similar sequence. Cut both with the same Restriction Enzyme. Hybridize, then seal with DNA ligase. This produces a Recombinant Plasmid. Insert plasmid into bacteria and allow for replication inside bacteria.
    - Plasmid must have a restriction site because you need to open it up for the insertion of your gene.
    - Plasmid must have an origin of replication because you want to clone your gene, which is inside your plasmid.
    - Plasmid must have antibiotic resistant gene because this lets you kill competing, useless bacteria that don't have your plasmid. when you add an antibiotic, only the bacteria with antibiotic resistant plasmid will live.
    - Plasmids replicate independently of the genomic DNA of the bacteria.
- Restriction enzymes
    - **Restriction enzymes** cut double stranded DNA at palindrome sequences. The resulting fragments are called restriction fragments.
    - If you read from 5' → 3' of one strand, then read from 5' → 3' of the other strand, and they are the same, then the section of the double stranded DNA that you read is palindrome sequence.
    - Some restriction enzymes cut to make sticky ends, which can hybridize.
    - Some restriction enzymes cut to make blunt ends, which cannot hybridize.
- DNA libraries
    - DNA library is a collection of DNA fragments that have been cloned into vectors so that researchers can identify and isolate the DNA fragments that interest them for further study. There are two kinds of libraries: genomic and cDNA libraries.
    - **Genomic libraries** contain large fragments of DNA in either bacteriophages or bacterial or P1-derived artificial chromosomes (BACs and PACs).
    - **cDNA libraries** are made with cloned, reverse-transcribed mRNA, and therefore lack DNA sequences corresponding to genomic regions that are not expressed, such as introns and 5' and 3' noncoding regions. cDNA libraries generally contain much smaller fragments than genomic DNA libraries and are usually cloned into plasmid vectors.
- Generation of cDNA
    - Once mRNA is purified, *oligo-DT* (a short sequence of deoxy-thymidine nucleotides) is tagged as a complementary primer which binds to the poly-A tail providing a free 3'-OH end that can be extended by reverse transcriptase to create the complementary DNA strand. Now, the mRNA is removed by using RNAse enzyme leaving a single stranded cDNA (sscDNA). This sscDNA is converted into double stranded DNA with the help of DNA polymerase.
    - However, for DNA polymerase to synthesize a complementary strand a free 3'-OH end is needed. This is provided by sscDNA itself by generating a hairpin loop at the 3' end by coiling on itself. The polymerase extends the 3'-OH end and later the loop at 3' end is opened by the scissoring action of S_1 *nuclease*. Restriction endonucleases and DNA ligase are then used to clone the sequences into bacterial plasmids.
    - The cloned bacteria are then selected, commonly through the use of antibiotic selection. Once selected, stocks of the bacteria are created which can later be grown and sequenced to compile the cDNA library.
- Hybridization
    - **Hybridization**, also called annealing, is where DNA strands base pair with each other.

    - In Southern blotting, DNA probes are used to hybridize onto DNA fragments containing a target sequence.
    - In gene cloning, hybridization refers to the process where sticky ends from a restriction fragment of a gene base pairs with the same sticky ends on a plasmid.
- Expressing cloned genes
    - cDNA transformed into plasmid, then add antibiotic resistant gene.
    - Infect bacteria with plasmid and add antibiotics. This allowed only the successfully infected bacteria to survive which contain our gene of interest.
    - The bacteria replicates creating many copies of our gene of interest.
- Polymerase chain reaction
    - 1. **Denaturation**: heat (90˚C) to separate double stranded DNA template
    - 2. **Annealing**: cool reaction in order for primers to anneal to the now single stranded DNA template
        - Excess amount of primers, so they outcompete re-annealing of the template strands
    - 3. **Elongation**: use heat stable polymerase to extend the primers
    - 4. Repeat steps 1 to 3 for n cycles. The resulting amplification of the original DNA template after n cycles is 2^n
- Gel electrophoresis and Southern blotting
    - **Gel electrophoresis**: separation of proteins, DNA, or RNA based on size and/or charge. For proteins and small molecules of DNA and RNA, the gel will be **polyacrylamide**. For larger molecules of DNA (> 500bp), the gel will be **agarose**. An electrical charge is placed across the gel. At the bottom is the **positively charged anode** and the top is the **negatively charged cathode**.
        - Keep in mind, since a voltage source is applied to gel electrophoresis, it follows the same principles as an electrolytic cell. Negatively charged molecules will travel toward the anode. Because of resistance of the gel, larger molecules will have a harder time moving and thus, the molecules will be separated by size with the smallest molecules toward the bottom. The gel can be stained for visualization, typically using Coomassie Blue dye. A lane will be loaded with a collection of molecules of a known size, called a ladder, which can be used to determine the size of the molecules being ran.
    - Southern blotting:
        - 1. DNA strand of interest is exposed to restriction enzymes that cut the DNA strand into smaller fragments.
        - 2. The newly cleaved strands of DNA are denatured using a solution of NaOH to create ssDNA strands
        - 3. The single stranded cleaved strands of DNA undergo gel electrophoresis, separating them by size. Smaller fragments will be found at the bottom of the gel. Polyacrylamide is used if the stands are less than 500 base pairs. Agarose is used if the strands are over 500 base pairs.
        - 4. The DNA from the gel is transferred to a sheet of nitrocellulose paper and then exposed to a ^{32}P radiolabeled DNA probe that is complementary to DNA of interest.
        - 5. Nitrocellulose paper is then viewed using autoradiography to identify the strand of interest.
- DNA (Sanger) sequencing
    - Used to determine the sequence of nucleotides in a strand of DNA
    - Modified nucleotides, known as “dideoxynucleotides” (ddNTPs), are used in this method. ddNTPs are missing the OH group on the 3’ carbon, thus unable to create a new 5’→3’ phosphodiester bond. This allows us to control termination of replication.
    - 1. DNA strand of interest is denatured using an NaOH solution to create a ssDNA strand that we can use for replication
    - 2. ssDNA strand of interest is added to a solution containing:

        - 1. A radiolabeled DNA primer that is complementary to the gene of interest
        - 2. DNA polymerase
        - 3. All four dNTPs (dATP, dTTP, dCTP, dGTP)
        - 4. A very small quantity of a single ddNTP (e.g., ddATP)
        - This is done once for each of the four nucleotides in separate solutions
    - 3. Each solution containing a specific dNTP and ddNTP are placed in their own lane of a gel and ran under gel electrophoresis. The gel is transferred to a polymer sheet and autoradiography is used to identify the strands in the gel.
    - For each respective nucleotide, the insertion of a ddNTP will terminate replication and create various strands of different length that correspond to that specific nucleotide. Therefore, the gel can be read from bottom-to-top to determine the nucleotide sequence. The smaller the fragment, the further it travels in the gel.
- Analyzing gene expression
    - **Northern blotting**: Similar steps to Southern except Northern uses RNA so steps 1 and 2 are not done.
    - **Western blotting**: Detection of a specific protein in a sample.
        - 1. Proteins from a sample are loaded into an SDS-PAGE gel and separated based on size.
        - 2. Proteins from gel are transferred to a polymer sheet and exposed to a radiolabeled antibody (sometimes using two antibodies; one specific to protein of interest and another radiolabeled antibody that binds to first antibody) that is specific to protein of interest
        - 3. The polymer sheet is viewed using autoradiography. The protein of interest that is bound to the radiolabeled antibody will be visible.
    - **RT-qPCR**: used when starting material is RNA. In this method, RNA is first transcribed into complementary DNA (cDNA) by reverse transcriptase from total RNA or messenger RNA (mRNA). cDNA then used as template for qPCR reaction. RT-qPCR is used in a variety of applications including gene expression analysis, RNAi validation, microarray validation, pathogen detection, genetic testing, and disease research.
        - RT-qPCR can be performed in a one-step or a two-step assay. One-step assays combine reverse transcription and PCR in a single tube and buffer, using a reverse transcriptase along with a DNA polymerase. One-step RT-qPCR only utilizes sequence-specific primers. In two-step assays, the reverse transcription and PCR steps are performed in separate tubes, with different optimized buffers, reaction conditions, and priming strategies.
- Determining gene function
    - Knocking out the gene allows us to observe what functions the gene are responsible for.
- Stem cells
    - **Totipotent**: can differentiate into any cell of an organism, including the placenta, the amnion and chorion
    - **Pluripotent**: can give rise to all cell types, excluding the placenta, the amnion and chorion. They arise from Totipotent cells, and are more specialized
    - **Multipotent**: can develop into more than one cell type, but are more limited than pluripotent cells; adult stem cells and cord blood stem cells are considered multipotent
    - **Embryonic**: within first couple of cell divisions after fertilization are the only cells that are totipotent
- Practical applications of DNA technology: medical applications, human gene therapy, pharmaceuticals, forensic evidence, environmental cleanup, agriculture
    - Medical applications: some vaccines we use recombinant DNA technology including hep B virus and the herpes virus and malaria.
    - **Gene therapy**: intended for diseases in which a given gene is mutated or inactive, giving rise to pathology. By transferring a normal copy of the gene into the affected tissues, the pathology should be fixed.

        - Efficient gene delivery vectors must be used to transfer the cloned gene into the target cells' DNA. Because viruses naturally infect cells to insert their own genetic material, most gene delivery vectors in use are modified viruses. A portion of the viral genome is replaced with cloned gene such that the virus can infect but not complete its replication cycle.
    - Forensics: There are parts of the genome known as non-coding regions of the genome. These regions can help forensic scientists identify specific individuals by looking at things like **short tandem repeats**, STRs, which are short sequences of DNA, two to six base pairs long. They are found in high amounts and to varying degrees between individuals. Thus, if they sequence these STRs, they could identify specific individuals given a DNA sample.
    - Agriculture: scientists can now create crops resistant to insects and resistant to herbicides. Some can delay ripening of crops, so you can transport crop from farm to store.
- Safety and ethics of DNA technology
    - Safety concerns such as increased resistance in viruses and bacteria can impact both humans the environment in which we live. Ethical dilemmas arise such as testing for life-threatening genetic diseases and potentially terminate a pregnancy based on results. How much should we meddle with our own genetic makeup becomes an issue.

Content Category 1C: Transmission of heritable information from generation to generation and the processes that increase genetic diversity

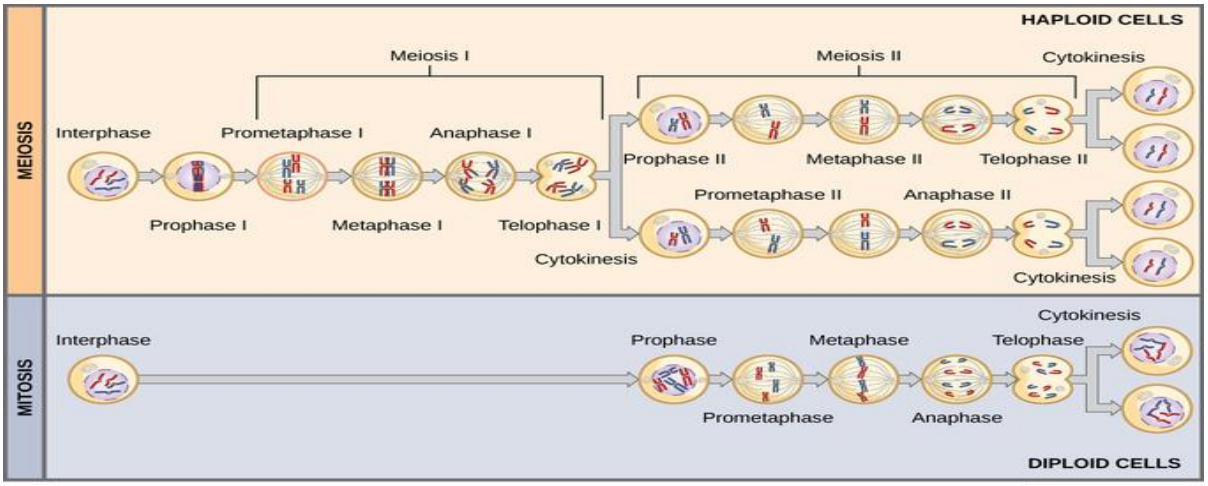
Mendelian Concepts (BIO)

- Phenotype and genotype
    - **Phenotype** = what you observe (i.e. height, color, whether organism exhibits trait)
    - **Genotype** = the genetic makeup (i.e. homozygous dominant, heterozygous, homozygous recessive)
- Gene
    - Stretch of DNA that codes for a trait (in molecular bio, a gene codes for a protein, which acts to bring about a trait)
- Locus
    - Location of a gene on a chromosome
- Allele: single and multiple
    - Allele is a variant of a gene (gene may have a number of alleles, all alleles of the same gene exist at the same locus)
    - Cell holds two alleles for each gene, one from mom and one from dad
    - 2 alleles = simple case (i.e. TT, Tt, tt)
    - When gene has more than 2 alleles, it is called MULTIPLE ALLELES
        - e.g. Blood type (have I^A, I^B, i)
- Homozygosity and heterozygosity
    - **Homozygous** = when two alleles that an individual carry are the same (i.e. AA, aa)

    - **Heterozygous** = when two alleles that an individual carry are different (i.e. Aa)
- Wild-type
    - The "normal" allele or phenotype for an organism (usually most prevalent, but not always)
- Recessiveness
    - The "weak" allele
    - Only expressed if both copies are present (aa)
- Complete Dominance
    - Normal way of assigning alleles
        - I.e. AA = dominant; Aa = dominant; aa = recessive
- Co-dominance
    - When the heterozygous conveys both traits
        - I.e. Blood type: AA = expresses A; AB = expresses A and B; BB = expresses B
- Incomplete dominance, leakage, penetrance, expressivity
    - Incomplete Dominance:
        - When the heterozygous conveys a mixture of the two alleles
            - I.e. AA = expresses A; AB = expresses a MIX of A and B; BB = expresses B
            - I.e. When crossing black and white chickens, you make blueish gray chickens
    - Leakage
        - Gene flow from one species to another (through hybrid offspring)
    - Penetrance
        - Frequency that a genotype will result in a phenotype
        - e.g., 100% penetrance means that if you have the genes for being smart, you will 100% be smart
            - Less than 100% means that you could have the genes for being smart, but that doesn't mean 100% that you'll be smart
    - Expressivity
        - The degree to which a penetrant gene is expressed
        - Constant Expressivity = if gene for being smart manages to penetrate (show up as a trait), then IQ is 120
        - Variable Expressivity = your IQ does not have to be 120, it could be somewhat lower or higher
- Hybridization: Viability
    - Process of two complementary, single-stranded DNA or RNA combining together, producing a double-stranded molecule through base pairing
    - Technique is used for interbreeding between individuals of genetically distinct populations
- Gene Pool
    - All the alleles in a population
    - The sum of all genes/alleles in a population at a given time
    - High ratings have more genetic diversity and more fitness

Meiosis and Other Factors Affecting Genetic Variability (BIO)

- Significance of meiosis
    - Genetic division process of creating haploid sex cells
    - Occurs in two separate mitosis events
    - Final result = 4 cells with n number of singular chromosomes
    - Introduces genetic variability by genetic recombination
        - Genetic recombination = product of independent assortment and crossing over, which introduces genetic variability
- Important differences between meiosis and mitosis



						OUTCOME
PROCESS	DNA synthesis	Synapsis of homologous chromosomes	Crossover	Homologous chromosomes line up at metaphase plate	Sister chromatids line up at metaphase plate	Number and genetic composition of daughter cells
MEIOSIS	Occurs in S phase of interphase	During prophase I	During prophase I	During metaphase I	During metaphase II	Four haploid cells at the end of meiosis II
MITOSIS	Occurs in S phase of interphase	Does not occur in mitosis	Does not occur in mitosis	Does not occur in mitosis	During metaphase	Two diploid cells at the end of mitosis

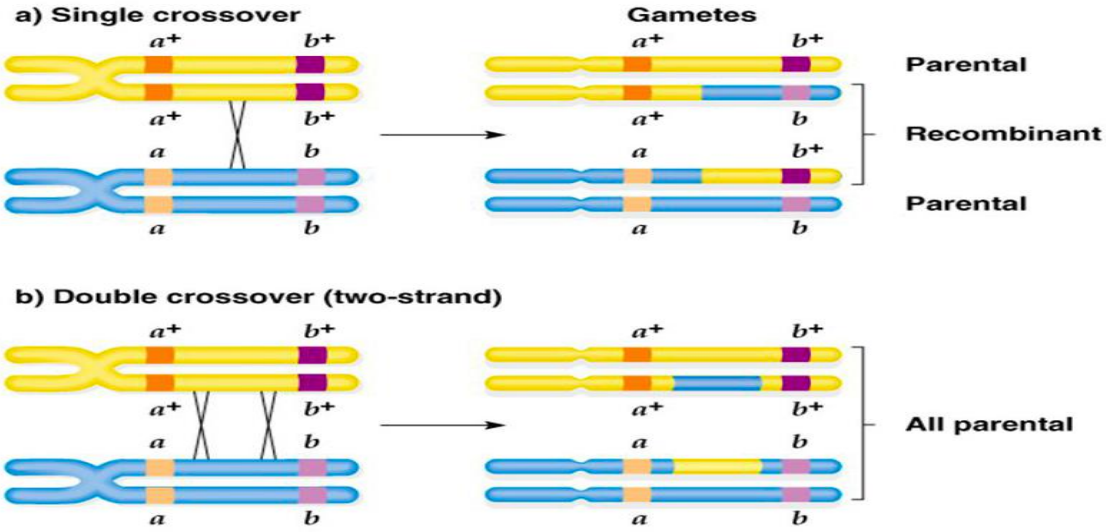
Mitosis	Meiosis
No tetrad	Tetrad formation (pairing of homologous chromosomes) and crossing over
Daughter cells identical to parent cells	Daughter cells different from parent cells
Diploid (2n) daughter cells	Haploid (n) daughter cells
1 division involved	2 divisions involved
2 daughter cells	4 sperm cells or 1 egg (with polar bodies)

***A human cell has 46 total or 23 pairs of chromosomes. Following mitosis, the daughter cells would each have a total of 46 chromosomes. After meiosis I, the two daughter cells would have 23 chromosomes**

- Segregation of genes
    - Independent Assortment
        - Generates genetic variation
        - Cell has 2 copies of each somatic chromosome – one from mom/dad
            - Independent assortment shuffles the chromosomes, and then places only one copy of each into the gamete
            - e.g., AaBb - A and B alleles assort independent of each other
        - **Mechanism:**
            - During metaphase I of meiosis, homologous chromosome pair up along the metaphase line in random orientation – sometimes the mom chromosome is on the right, or sometimes on the left
            - During anaphase I of meiosis, the homologous chromosomes are pulled apart
                - Those on the left will go into one daughter cell, the one on the right will go into another daughter cell
    - Linkage
        - Because of independent assortment, genes on different chromosomes can be randomized (HOWEVER, genes on same chromosome cannot be randomized by this mechanism)
        - Genes on same chromosome are linked to a certain extent
            - Basically, genes located near one-another on the same chromosome **are likely to be inherited together**

- **Crossing Over** = mechanism that reduces linkage
    - Only efficient when the genes are physically apart from each other on the chromosome
- When genes are further apart on a chromosome, crossing over makes them less linked
- The physically closer the genes are, the more linked they are

- Recombination (made up by independent assortment and crossing over, increase genetic diversity)
    - Single Crossovers
        - Occurs during prophase I and suggests that chromatids exchange alleles at a locus (results in genetic recombination)
        - When homologous chromosomes are aligned and chromatids from two different chromosomes can exchange segments resulting in genetic recombination
        - **Only affect the ends of a chromosome's arms**
    - Double Crossovers
        - An event that has 3 outcomes:
            - Chromatids exchange alleles, then exchange back (no R)
            - Chromatids exchange alleles, then exchange with different chromatids (R)
            - Chromatids exchange alleles, then two different chromatids on the same chromosome exchange again
        - Chromatids from two homologous chromosomes come in contact at two points
        - **Can affect segments of the chromosome closer to the middle of the chromosome**



- Synaptonemal Complex
    - Complex of proteins that are located between pairs of homologous chromosomes
    - Protein structure that mediates synapsis (the pairing of homologous chromosomes in Prophase I)
        - Consists of SYCP2 and SYCP3 which attach laterally to homologous chromatin structures and are attached via a central region (SYCP1 and other proteins) – interdependent with recombination
- Tetrad
    - A chiasma (point at which paired chromosomes remain in contact during the first metaphase of meiosis, and at which crossing over and exchange of genetic material occur between the strands) between a pair of homologous chromosomes resulting in the formation of 4 chromatids

- Sex-linked characteristics
  - Gene for characteristic is on the X chromosome
  - Mom always donates X chromosome
- Very few genes on Y chromosome
  - Y chromosome is very small and carries few genes of importance
  - All the sex-linked alleles are carried on the X chromosome
- Sex determination
  - XX = female
  - XY = male
- Cytoplasmic/extra-nuclear inheritance
  - Cytoplasmic inheritance = inheritance of things other than genomic DNA
  - All cellular organelles, such as mitochondria, is inherited from the mother
  - Extra-nuclear inheritance = situations where genes are inherited outside of the nucleus
    - Includes receiving all the information about the mitochondria from the mother's egg

- Mutation
  - General concept of mutation – error in DNA sequence
    - Mutation = change in DNA by means other than recombination
  - Types of mutations: random, translation error, transcription error, base substitution, inversion, addition, deletion, translocation, mispairing
    - **Random:**
      - Random changes in the DNA sequence (could be due to radiation, chemicals, replication error, etc.)
    - **Translation Error:**
      - Even if the DNA for a gene is perfect, errors during translation can cause expression of a mutant phenotype
    - **Transcription Error:**
      - Even if the DNA for a gene is perfect, errors during transcription can cause expression of a mutant phenotype
    - **Base Substitution:**
      - Mutation involving a base (A, T, G, C) changing to a different base
    - **Inversion:**
      - A stretch of DNA (segment of chromosome) breaks off, then reattaches in the opposite orientation
        - Chromosome rearrangement in which a segment of the chromosome is reversed end to end (i.e. when a chromosome breaks and rearranges within itself)
    - **Addition:**
      - Also called insertion → an extra base is added/inserted into the DNA sequence (can cause frameshift mutation)
    - **Deletion:**
      - A base is taken out of the DNA sequence (can cause frameshift mutation)
    - **Translocation:**
      - A stretch of DNA (segment of chromosome) breaks off, and then reattaches somewhere else
    - **Mispairing:**
      - A not pairing with T, or G not pairing with C
  - Advantageous vs. deleterious mutation
    - Advantageous = results in a benefit in the fitness of an organism
    - Deleterious = results in harmful effects on the fitness of an organism
  - Inborn errors of metabolism

        - Genetic diseases resulting in faulty metabolism
        - Considered congenital (present since birth) metabolic diseases & inherited metabolic diseases
    - Relationship of mutagens to carcinogens
        - **Mutagen** = something that causes a mutation
        - **Carcinogen** = something that causes a mutation that causes cancer
        - Carcinogens are almost always mutations (EXCEPTION: some are direct mitogens = increase mitosis)
        - Not all mutagens are carcinogens
- Genetic Drift
    - Random changes in a population (random changes in allele frequencies)
    - Effect of genetic drift increases as the population size decreases
- Synapsis or crossing-over mechanism for increasing genetic diversity
    - Synapsis and crossing over help increase genetic diversity (genes recombine and create larger diversity in number of recombinants)

Analytic Methods (BIO)

- Hardy-Weinberg Principle
    - $p + q = 1$
    - $(p + q)^2 = 1 \rightarrow p^2 + 2pq + q^2 = 1$
    - 5 Assumptions of Hardy-Weinberg:
        - Infinitely large population
        - No mutation
        - No migration
        - Random mating (no sexual selection)
        - No natural selection
- Testcross (Backcross; concepts of parental, F1, and F2 generations)
    - **Test Cross**
        - So, you have something with dominant phenotype. It could either be Aa or AA. To find out, you cross it with the homozygous recessive aa. If Aa, half of the offspring will express the recessive phenotype. If AA, no offspring will express the recessive phenotype
    - **Back Cross**
        - Matting between the offspring and the parent = preserve parental genotype
    - **Parental Generation = P**
        - Generation of the parent. On a pedigree, this is the row that represents the parents
    - **F1 Generation = Filial 1 = children**
        - On a pedigree, this is the row below the parents, and represents the children of the parents
    - **F2 Generation = Filial 2 = grandchildren**
        - On a pedigree, this is the row below the F1, and represents the children of the F1 and the grandchildren of the parents
- Gene mapping: crossover frequencies
    - Genetic recombination occurs between maternal and paternal sister chromatids
        - Can also occur with the identical chromatid within one chromosome, but that will not have any consequence
    - More likely for recombination to occur over a larger distance (can exchange genetic information anywhere along the long stretch of chromatid)
        - **Further apart that two genes are, the more likely it is that they recombine**
    - Less likely for recombination to occur over a smaller distance (not that much space)
    - Centimorgen = unit of measurement we use to measure distance on a chromosome (or genetic map unit)
        - Distance between genes for which one product of meiosis in 100 is recombinant

        - e.g., 1 distance is 25 m.u. ; another is 6 m.u.
            - For 25 m.u., 25% of the time that meiosis happens, recombination will occur with respect for the two genes within the map unit distance
            - For 6 m.u., 6% of the time that meiosis happens, recombination will occur
- Biometry: statistical methods
    - Use of statistical methods to understand biological data
    - ID genes in the population that are bad

Evolution (BIO)

- Natural selection
    - Fitness concept
        - Fitness is defined as the ability to pass your genes on (reproductive success)
    - Selection by differential reproduction
        - Individuals who produce more VIABLE offspring are selected for
        - Individuals who reproduce LESS VIABLE offspring are selected against
    - Concepts of natural and group selection
        - **Natural Selection**: Survival and reproduction of the fittest
        - **Directional Selection:** selects for a trait of one extreme (e.g., selection for tall canopy tree in rainforest because the taller tree can reach the sun)
        - **Stabilizing Selection:** selects for a trait that is moderate, and selects against the extremes (e.g., just the right birth weight when a baby is born)
        - **Disruptive Selection:** selects for the extremes (e.g., birds occupying habitat with 2 different niches, one bird with small beak, the other with big beak)
        - **Group Selection:** natural selection acting on the group, not the individual (altruism = sacrifice the fitness of the individual to benefit the group or family, which shares similar genes with the individual)
            - When benefit outweighs the cost, altruistic behavior is selected for
    - Evolutionary success as increase in percent representation in the gene pool of the next generation
        - If the frequency of an allele is increased, then that's evolutionary success for that allele
        - If the frequency of alleles increased in a population, then that's evolutionary success for that individual
- Speciation
    - **Polymorphism**
        - Different forms for alleles or traits (i.e. a yellow jaguar and a black jaguar)
    - Adaptation and specialization
        - **Adaptation** = genetic change in a population caused by natural selection
        - **Specialization** = adaption of traits to better fill a niche
    - **Inbreeding**
        - Mating between relatives
        - Increases the frequency of homozygotes, decreases heterozygotes, and decreases genetic diversity
        - Inbreeding depression occurs because of the increase in frequency of homozygous recessive detrimental alleles
    - **Outbreeding**
        - Mating with non-relatives, which is just the opposite of inbreeding
        - Increases heterozygosity
    - **Bottleneck**
        - Severe reduction in population size (e.g., can be caused by natural disaster that wipes out majority of the population)
        - Genetic drift = random changes in allele frequencies
        - Effect of genetic drift increases as population size decreases

        - Bottlenecks increase the effect of genetic drift
- Evolutionary Time
    - Random genetic mutations (drift) that are not acted on by natural selection (neutral) occur at a constant rate
    - By measuring the amount of these neutral mutations, you can find out how much time has passed
    - You can compare genome differences between two species to find out how long ago they diverged
    - "Molecular Clock"

Content Category 1D: Principles of bioenergetics and fuel molecule metabolism

Principles of Bioenergetics (BC, GC)

- Bioenergetics/thermodynamics
    - **Free energy/K_{eq}:**
        - Free energy is the energy available that can be converted to do work
        - $\Delta G = \Delta H - T\Delta S$
        - T is temperature in Kelvin
    - Equilibrium constant (2 ways of getting K_{eq})
        - From an equation, K_{eq} = products/reactants = $[C]^c[D]^d/[A]^a[B]^b$
        - From thermodynamics, $\mathbf{\Delta G^\circ = -RT \ln (K_{eq})}$
            - Derivation: $\Delta G = 0$ at equilibrium
            - $\Delta G = \Delta G^\circ + RT \ln Q$
            - $0 = \Delta G^\circ + RT \ln Q_{at\ equilibrium}$
            - $\Delta G^\circ = -RT \ln Q_{at\ equilibrium}$
        - At equilibrium:
            - $\Delta G = 0$
            - $r_{forward} = r_{backward}$
            - $Q = K_{eq}$
        - K_{eq} is ratio of $k_{forward}$ over $k_{backward}$
            - If $K_{eq} > 1$, then position of equilibrium is to the right, more products present at equilibrium
            - If $K_{eq} = 1$, then position of equilibrium in center, number of products roughly equal to number of reactants
            - If $K_{eq} < 1$, then position of equilibrium is to the left, more reactants are present at equilibrium

        - Relationship of the equilibrium constant and ΔG°
            - $\Delta G = \Delta G^\circ + RT \ln Q$
                - Set $\Delta G = 0$ at equilibrium
                - Q becomes K_{eq} at equilibrium
            - $0 = \Delta G^\circ + RT \ln (K_{eq})$
            - $\Delta G^\circ = -RT \ln (K_{eq})$
    - Concentration
        - **Le Châtlier's Principle**: if you knock a system off its equilibrium, it will readjust itself to reachieve equilibrium
        - A reaction at equilibrium doesn't move forward or backward, but the application of Le Châtlier's principle means that it will proceed forward or backward in order to restore equilibrium

Reaction at equilibrium	What will induce the reaction to move forward	What will induce the reaction to move backward
A (aq) + B (aq) <--> C (aq) + D (aq)	Add A or B. Remove C or D.	Remove A or B. Add C or D.
A (s) + B (aq) <--> C (l) + D (aq)	Add B. Remove D. Adding or removing solids or liquids to a reaction at equilibrium doesn't do anything that will knock the system off its equilibrium. So, altering A and C won't make a difference.	Remove B. Add D.
A (s) + B (aq) <--> C (l) + D (g)	Add B. Remove D. Remove (decrease) pressure.	Remove B. Add D. Add (increase) pressure.
A (s) + B (g) <--> C (l) + D (g)	Add B. Remove D. Since both side of the balanced equation contains the same mols of gas products, modifying pressure is of no use.	Remove B. Add D.
A (s) + B (aq) <--> C (l) + D (aq) ΔH < 0	Add B. Remove D. Removing heat by cooling the reaction.	Remove B. Add D. Add heat by heating the reaction.

- Endothermic/exothermic reactions
  - **Endothermic** = energy taken up by reaction in form of heat. ΔH is positive
  - **Exothermic** = energy released by reaction in form of heat. ΔH is negative
  - Enthalpy, H, and standard heats of reaction and formation
    - Enthalpy, H, is heat content of a reaction.

- ΔH is change in heat content of a reaction. + means heat is taken up, - means heat is released
- **Standard heat of reaction**, ΔH_{rxn}, is change in heat content for any reaction
- **Standard heat of formation**, ΔH_f, is change in heat content of a formation reaction
- Formation reaction is where a compound or molecule in its standard state is formed from its elemental components in their standard states. Standard state is where things are in their natural, lowest energy, state. e.g. oxygen is O_2 (diatomic gas) and carbon is C (solid graphite)
- Unit for enthalpy is energy (J), or can be expressed as energy per mol (J/mol)

  - Free Energy: G
    - Free energy is energy available that can be converted to do work
    - $\Delta G = \Delta H - T\Delta S$
  - Spontaneous reactions and ΔG°
    - Spontaneous reactions occur by themselves.
    - They have negative ΔG.
    - Do not assume that an exothermic reaction is spontaneous, because a large, negative ΔS can cause it to become nonspontaneous
    - Do not assume that an endothermic reaction is nonspontaneous, because a large, positive ΔS can make it spontaneous
    - Do not assume that spontaneous reactions will occur quickly, because it depends on kinetics

- Phosphoryl group transfers and ATP
  - ATP hydrolysis $\Delta G << 0$
    - Adenosine 5'-triphosphate (ATP) serves as main source of free energy in living cells. Energy stored by ATP can be liberated through direct hydrolysis or group transfer.
    - Direct hydrolysis of ATP consists of nucleophilic attack by H_2O at γ phosphate position of ATP and cleavage of the γ - β phosphoanhydride bond.
    - $ATP + H_2O \rightarrow ADP + P_i$
    - **$\Delta G^{\circ\prime} = -30.5$ kJ/mol**
  - ATP group transfers
    - Group transfer reactions involve the covalent transfer of a portion of the ATP molecule to a substrate (e.g. an enzyme active site), which in turn makes subsequent metabolic reactions involving this substrate more thermodynamically favorable.
- Biological oxidation-reduction
  - Half-reactions
    - Oxidation half reaction describes the species that loses electrons (increases in charge). e.g. $Cu \rightarrow Cu^{2+} + 2e^-$
    - Reduction half reaction describes the species that gains electrons (decreases in charge). e.g. $Ag^{2+} + 2e^- \rightarrow Ag$
  - Soluble electron carriers
    - Think about electron-carrier molecules a bit like a molecular shuttle.
    - It is the job of electron carriers to harness the electrons that are lost at each step of the breakdown process. They carry the electrons lost from the oxidation process, eventually to the final electron acceptor in the body, which is oxygen.
    - Flow of electrons in the electron transport chain that allows production of energy to produce ATP.
    - Water-soluble carriers are free-floating in the cytosol (e.g. NADH, $FADH_2$, cytochrome c, etc.)
    - Lipid-soluble carriers are embedded in membrane (e.g. CoQ, FMN, etc.)
  - Flavoproteins

        - Flavoproteins are proteins that contain a nucleic acid derivative of riboflavin: the Flavin adenine dinucleotide (FAD) or flavin mononucleotide (FMN)
        - They are located on the matrix face of the inner mitochondrial membrane and functions as a specific electron acceptor for primary dehydrogenases, transferring the electrons to the ubiquinone pool in the inner mitochondrial matrix

Carbohydrates (BC, OC)

- Description
    - Nomenclature and classification, common names
        - Nomenclature:
            - Carbohydrate = sugars, monosaccharides, disaccharides, polysaccharides
            - Prefix:
                - Deoxy = has an -H in place of an -OH at a certain position
                - D/L = absolute configuration = assigned based on the chirality of the carbon atom furthest from the carbonyl group
                - α/β = anomeric configuration
            - Suffix: all sugars end in -ose
        - Classification
            - **Aldose** = sugars with an aldehyde group
            - **Ketose** = sugars with a ketone group
            - **Pyranose** = sugars in a 6-membered ring structure = hexagonal shaped
            - **Furanose** = sugars in a 5-membered ring structure = pentagonal shaped
            - # ose = sugar with # carbon atoms. e.g. Hexose = sugar with 6 carbons
            - In order to be classified as a carbohydrate, a molecule must have:
                - at least a 3-carbon backbone
                - an aldehyde or ketone group
                - at least 2 hydroxyl groups
        - Common Names
            - The simplest, smallest carbohydrates are **glyceraldehyde** and **dihydroxyacetone**
            - The 3 common monosaccharides are glucose, fructose, and galactose. Glucose is our blood sugar and the product of photosynthesis. Fructose is the sugar in fruits, and it is sweeter than glucose. Galactose is one of the monomers that make up lactose, which is the sugar in milk; it is less sweet than glucose.
            - The sugars that make up RNA is ribose and for DNA it is deoxyribose (more precisely 2'-deoxyribose because the difference is at the 2 carbon)
            - **Sucrose** is a disaccharide made from α-glucose and β-fructose joined at the hydroxyl groups on the anomeric carbons (making acetals). Sucrose is table sugar, the sugar we buy in stores.
            - **Lactose** is a disaccharide made from β-galactose and α/β-glucose joined by a 1-4 linkage
            - **Starch** = glucose molecules joined by α 1-4 linkage (amylose = unbranched; amylopectin = branched)
            - **Glycogen** = same as starch, but with additional α 1-6 linkages for branching
    - Absolute configuration
        - The chiral carbon furthest from carbonyl group determines the absolute configuration L or D of the sugar
        - If in the Fischer projection, the OH group on the chiral carbon furthest from the carbonyl is pointing left, then it's L. If it's pointing right, then it's D.
        - Note: L and D are enantiomers, not epimers. So, every chiral carbon center inverts. It's just that you assign L and D based on the chiral carbon furthest from the carbonyl.
    - Cyclic structure and conformation of hexoses

        - Fructose forms a furanose when carbon 5 attacks the carbonyl carbon
        - Glucose forms a pyranose when carbon 5 attacks the carbonyl carbon
        - Convert a Fischer projection to Haworth (cyclic) form
            - -OH groups that point Left on Fischer become Up on Haworth
            - -OH groups that point Right on Fischer become Down on Haworth
            - -OH group on anomeric carbon (Fischer carbonyl) can be either Up (beta) or Down (alpha)
            - The CH_2OH group on absolute configuration carbon (carbon 5) points up for D, and down for L
        - In the planar conformation, everything is eclipsed
        - In the chair conformation, everything is staggered
        - All the conformations in between are partially eclipsed
        - The Boat conformation has Flagpole interactions because axial groups attached to the head and tail of the boat clash
        - The Twist-boat conformation lessens these Flagpole interactions in addition to reducing the number of eclipsed interactions
    - Epimers and anomers
        - **Epimers** = different configuration in just one chiral carbon
        - **Anomers** = different configuration in the chiral, anomeric carbon when the molecule is in the cyclic form
        - Anomers are simply special types of epimers
        - Epimers are simply special types of Diastereomers
        - Don't confuse with enantiomers (D/L configuration), in which everything changes configuration
- Hydrolysis of the glycoside linkage
    - **Glycoside linkage** = acetal linkage = linkage involving the hydroxyl group of the anomeric carbon
    - Glycoside linkage can also mean linkage between sugar and base in nucleotides
    - Examples of glycosidic linkages = starch, glycogen, nucleotide
    - Hydrolysis of the glycosidic bond has the same mechanism as hydrolysis of the acetal bond
    - Glycoside + H_2O + catalyst → hydrolysis
    - Catalysts include: Amylase for starch and glycosylase for nucleotide
- Monosaccharides
    - Simple sugars, the most common of which is glucose. Have a formula $(CH_2O)_n$, and typically contain three to seven carbon atoms.
    - Most oxygens in monosaccharides are found in hydroxyl (OH) groups, but one of them is part of a carbonyl (C=O) group. The position of the carbonyl (C=O) group can be used to categorize the sugars:
        - If sugar has an aldehyde group, meaning that carbonyl C is last one in chain, it is known as an aldose.
        - If carbonyl C is internal to the chain, so there are other carbons on both sides of it, it forms a ketone group and the sugar is called a ketose.
    - Sugars are named according to their number of carbons: some of the most common types are trioses (three carbons), pentoses (five carbons), and hexoses (six carbons)
- Disaccharides
    - Form when two monosaccharides join together via a **dehydration reaction**, also known as a condensation reaction or dehydration synthesis. In this process, the hydroxyl group of one monosaccharide combines with the hydrogen of another, releasing a molecule of water and forming a covalent bond known as **glycosidic linkage**.
    - Common disaccharides include lactose, maltose, and sucrose. Lactose consists of glucose and galactose and found naturally in milk. Many people can't digest lactose as adults, resulting in

lactose intolerance. Maltose, or malt sugar, is made of two glucose molecules. Most common disaccharide is sucrose (table sugar), made of glucose and fructose.

- Polysaccharides
  - Long chain of monosaccharides linked by glyosidic bonds. The chain may be branched or unbranched and may contain different types of monosaccharides.
  - Common examples in living organisms include starch, glycogen, cellulose, and chitin.
  - Starch is the stored form of sugars in plants and made up of a mixture of two polysaccharides, amylose and amylopectin (both polymers of glucose). Plants able to synthesize glucose using light energy gathered in photosynthesis, and excess glucose, beyond the plant's immediate energy needs, is stored as starch in different plant parts.
  - Cellulose is major component of plant cell walls, rigid structures that enclose the cells.

Glycolysis, Gluconeogenesis, and the Pentose Phosphate Pathway (BIO, BC)

- **Glycolysis** (aerobic), substrates and products
  - Glycolysis = convert glucose (6 carbons) to 2 molecules of pyruvate (3 carbons)
    - **Key enzymes: Hexokinase, Phosphofructokinase, Pyruvate Kinase**
    - Location: cytosol
    - 2 net ATP made for every glucose (2 input ATP, 4 output ATP)
    - 2 NADH made for every glucose
    - Occurs under both aerobic and anaerobic conditions
    - Glycolysis inhibited by ATP
  - **Aerobic decarboxylation** (mitochondrial matrix) = convert pyruvate (3 carbons) to an acetyl group (2 carbons)
    - **Key enzyme: Pyruvate dehydrogenase**
    - 1 NADH made for every pyruvate
    - Only occurs in the presence of oxygen
    - Acetyl group attaches to Coenzyme A to make acetyl CoA
  - Feeder pathways: glycogen, starch metabolism
- **Fermentation** (anaerobic glycolysis)
  - **Key enzyme: Lactate dehydrogenase**
  - 1 NAD+ made for every pyruvate
  - Alcohol fermentation = pyruvate reduced to ethanol
  - Lactic acid fermentation = pyruvate reduced to lactate
  - Purpose: to regenerate NAD+, which is needed for glycolysis
- **Gluconeogenesis** (BC)
  - Reversal of glycolysis. Instead of using carbohydrates to produce glucose, our body converts non-carbohydrate sources (like amino acids) in our liver into glucose.
  - Step 1 (first irreversible step): We start with two pyruvate molecules that came from a non-carbohydrate source. Pyruvate (3 carbons) is combined with bicarbonate to create oxaloacetate (4 carbons) through **pyruvate carboxylase**. This reaction requires ATP. Another GTP is then used to transform oxaloacetate into phosphoenolpyruvate, a 3-carbon molecule with a phosphate group attached through **phosphoenolpyruvate carboxykinase**.
  - Step 2: Hydroxyl group is used to change the 3-carbon molecule, preparing for a phosphate group to be transferred to another carbon in the molecule.
  - Step 3: ATP is used to add another phosphate group to the 3-carbon molecule.
  - Step 4: The high energy electrons carried by NADH are used to remove one of the phosphate groups. Once NADH has lost its high energy electrons (oxidation) it's called NAD+.
  - Steps 1-4 occur twice, each time with a pyruvate molecule. We need enough carbons to eventually get a 6-carbon molecule.
  - Step 5: The two 3-carbon molecules are attached back together, forming one 6-carbon molecule with two phosphate groups.

    - Step 6 (second irreversible step): Enzyme is used with water to create the single phosphorylated 6-carbon molecule through **Fructose-1,6-bisphosphatase**. The molecule is then rearranged before the final step.
    - Step 7 (third irreversible step): Another enzyme uses water to remove the phosphate group to produce glucose through **Glucose-6-phosphatase**!
- **Pentose phosphate pathway** (BC)
    - **Key enzyme: Glucose-6-phosphate dehydrogenase**
    - Can use any available molecules of glucose-6-phosphate, whether they are produced by glycolysis or other methods.
    - Takes place in the cytosol of the cell, same location as glycolysis. Two most important products are ribose-5-P sugar used to make DNA and RNA, and the NADPH molecules which help with building other molecules.
    - The **oxidative phase**: made up of 2 irreversible steps
        - 1. G6P oxidized to form lactone. NADPH produces as a byproduct of this reaction as NADP+ is reduced as G6P is oxidized. Another reaction, catalyzed by different enzyme, uses water to form 6-phosphogluconate, the linear product. NADPH often used in reactions that build molecules and occurs in a high concentration in the cell.
        - 2. A carbon is cleaved, and CO_2 is released. Once again, the electrons released from this cleavage is used to reduce NADP+ to NADPH. This new 5-carbon molecule is called ribulose-5-phosphate.
    - **Non-oxidative phase**: reactions are reversible. Allows different molecules to enter the PPP in different areas of the non-oxidative phase and be transformed up until the first molecule of the non-oxidative phase (ribulose-5-P). Ribulose-5-P is the precursor to the sugar that makes up DNA and RNA, and is also a product of oxidative stage
        - 3. Ribulose-5-P can be converted into two different 5-carbon molecules. One is the sugar used to make up DNA and RNA called, ribose-5-phosphate. Ribulose-5-P isn't being divided because the carbon count is the same in the next step.
        - 4. Rest of the cycle depends on the cell's needs. Ribose-5-P is combined with another molecule of ribose-5-P to make one, 10-carbon atom. Excess ribose-5-P, which may not be needed for nucleotide biosynthesis, is converted into other sugars that can be used by cell for metabolism.
        - 5. The 3-carbon molecule and 7-carbon molecule, from interconversion in step 4, interconvert again to make a new 4-carbon and 6-carbon molecule. The 4-carbon is a precursor for amino acids, while the 6-carbon molecule can be used in glycolysis. The same reversal of steps in option 4 can happen here as well.
    - Summary:
        - Oxidative phase:
            - -1 H2O
            - +2 NADPH
            - +1 CO2
        - Non-oxidative phase:
            - Ribose-5-P for DNA/RNA building
- Net molecular and energetic results of respiration processes
    - Glycolysis:
        - Net yield of 2 ATP per glucose molecule (4 total made but 2 used)
        - Net yield of 2 NADH per glucose

Principles of Metabolic Regulation (BC)

- Regulation of metabolic pathways (BIO, BC)
    - Maintenance of a dynamic steady state

        - The body continually degrades and synthesizes proteins in order to keep the organism functioning properly at a steady level.
        - e.g. Hemoglobin: body continually and simultaneously degrades older hemoglobin and synthesizes new hemoglobin.
        - This keeps metabolic enzymes fresh and new so there will be very few issues, if any, with aging and degrading enzymes in the pathway
- Regulation of glycolysis and gluconeogenesis
    - Think about Le Châtlier's Principle: if there's any change to something in equilibrium, the equilibrium will adjust to counter that change and return the system back to equilibrium
    - e.g. if we have large influx of glucose, this promotes glycolysis
    - e.g. if we have large influx of oxaloacetate, the equilibria will be pushed towards the opposite direction towards the production of glucose
    - Allosteric regulation: if we have lots of ATP in the cell, gluconeogenesis would be favored, and glycolysis would be inhibited.
    - These are fast-acting forms of regulation.
    - Slow-acting forms of regulation: often take advantage of transcriptional changes within the cell. Imagine an organism is in a long-term fasting state. It will want to up-regulate the transcription of enzymes that promote things like gluconeogenesis to dump glucose into the blood. It's implied that the process of going from DNA to mRNA to enzymes will take much longer than simple Le Châtlier or allosteric regulation. This is more of an adaptive process that allows the organism to adapt to more long-term changes that it experiences in its environment.
    - Hormonal regulation: **insulin and glucagon**
        - If blood glucose level rises, it stimulates the body to release the hormone insulin, and if the blood glucose levels decrease, it stimulates the body to release the hormone glucagon.
        - Thus, **insulin** promotes **glycolysis** and **glucagon** promotes **gluconeogenesis**.
- Metabolism of glycogen
    - **Glycogenolysis**: degradation of stored glycogen occurs through action of glycogen phosphorylase and glycogen debranching enzyme. Rate limiting enzyme is **glycogen phosphorylase**, which converts the glucose 1-phosphate to glucose 6-phosphate.
        - Glycogen phosphorylase breaks α-1,4 glycosidic bonds, releasing glucose 1-phosphate from periphery of granule. Cannot break α-1,6 bonds and thus stops when it nears outermost branch points.
        - Enzyme is activated by glucagon in liver, so glucose can be provided for rest of the body. In skeletal muscle, it is activated by AMP and epinephrine, which signal that muscle is active and requires more glucose. It is inhibited by ATP.
        - **Debranching enzyme** is a two-enzyme complex that deconstructs the branches in glycogen that have been exposed by glycogen phosphorylase.
        - Breaks an α-1,4 bond adjacent to branch point and moves the small oligoglucose chain that is released to the exposed end of the other chain. Forms a new α-1,4 bond. Hydrolyzes the α-1,6 bond, releasing the single residue at the branch point as free glucose. This represents the only free glucose produced directly in glycogenolysis.
    - **Glycogenesis**: synthesis of glycogen granules.
        - **Glycogen synthase** is the rate-limiting enzyme of glycogen synthesis and forms the α-1,4 glycosidic bond found in the linear glucose chains of the granule. It is stimulated by glucose 6-phosphate and insulin. It is inhibited by epinephrine and glucagon through a protein kinase cascade that phosphorylates and inactivates the enzyme.
        - **Branching enzyme** is responsible for introducing α-1,6 linked branches into the granule as it grows. Hydrolyzes one of the α-1,4 bonds to release a block of oligoglucose (few glucose molecules bound together in a chain), which is then moved and added in a slightly different location
        - 1. Glycogen synthase makes a linear α-1,4 linked polyglucose chain. 2. Branching enzyme hydrolyzes an α-1,4 bond. 3. Branching enzyme transfers oligoglucose unit and

attaches it with an α-1,6 bond to create a branch. 4. Glycogen synthase extends both branches.

- Regulation of glycogen synthesis and breakdown
    - Glycogen phosphorylase in glycogenolysis activated by glucagon in liver. In skeletal muscle, it is activated by AMP and epinephrine. Inhibited by ATP.
    - Glycogen synthase in glycogenesis activated by glucose 6-phosphate and insulin. Inhibited by epinephrine and glucagon through a protein kinase cascade that phosphorylates and inactivates the enzyme.
- Analysis of metabolic control

Citric Acid Cycle (BIO, BC)

- Acetyl-CoA production (BC)
    - Glycolysis
        - Pyruvate, the product from glycolysis, is transformed into acetyl CoA in the mitochondria. Through the enzyme, **pyruvate dehydrogenase**, which is a multi-enzyme complex, pyruvate loses a carbon to produce a new, 2-carbon molecule called acetyl-CoA. The carbon that is removed takes two oxygens from pyruvate with it and exits the body as carbon dioxide (CO_2). CO_2 is the waste product that you release when you exhale.
    - Aerobic decarboxylation (mitochondrial matrix) = convert pyruvate (3 carbons) to an acetyl group (2 carbons)
        - 1 NADH made for every pyruvate. Only occurs in the presence of oxygen. Acetyl group attaches to Coenzyme A to make acetyl-CoA.
    - Fat metabolism
        - A process called **beta-oxidation** breaks down the fatty-CoA, 2 carbons at a time, to make acetyl-CoA. β-oxidation produces acetyl-CoA and also $FADH_2$ and NADH. The acetyl-CoA feeds into the Krebs cycle, and the $FADH_2$ and NADH feed into the ETC.
    - Protein metabolism
        - The carbon in the amino acid is converted to pyruvate or acetyl-CoA, (or other metabolic intermediates such as oxaloacetate), depending on what amino acid it is
- Reactions of the cycle, substrates and products
    - Location: matrix of mitochondria
    - Acetyl-CoA and oxaloacetate are substrates for citrate synthase. Acetyl-CoA is the main substrate. Oxaloacetate can be produced by pyruvate carboxylase that converts pyruvate to oxaloacetate, however this is not as energy efficient.
    - Major product of this cycle is oxaloacetate, NADH, $FADH_2$, ATP.
- Regulation of the cycle
    - No hormonal control
    - Major form of regulation is through allosteric regulation.
        - Acetyl-CoA is major substrate so if the body doesn't have a lot of Acetyl-CoA the speed that NADH and $FADH_2$ is produced will slow down.
        - Citrate, under conditions of high ATP, generally shuttles lots of acetyl-CoA into cytoplasm for fatty acid synthesis.
        - When our body breaks down amino acids and enter the TCA cycle, such as conversion to α-ketoglutarate. This occurs when body is starving so it wants to be able to produce more NADH and $FADH_2$ to produce more ATP.
        - The main important enzymes are citrate synthase, isocitrate dehydrogenase, and α-ketoglutarate dehydrogenase.
        - NADH allosterically inhibits all three of these enzymes because it is a product of the overall TCA cycle. Another inhibitor is ATP, since this indicates that our body has produced enough energy.

        - Products can also inhibit, such as citrate which performs negatively feedback on citrate synthase and succinyl-CoA which negatively feedbacks onto α-ketoglutarate dehydrogenase, citrate synthase as well.
        - First allosteric activator is ADP since this indicates need for energy. NAD+ for a similar reason. Another is calcium. Remember that muscle cells require an influx of calcium to contract. This is a way for the body, especially in skeletal muscles, to essentially couple muscle contraction with producing more ATP to meet the needs of those contracting muscles. It has been shown to activate isocitrate and α-ketoglutarate dehydrogenase.
- Net molecular and energetic results of respiration processes
    - Citric Acid or TCA Cycle
        - Net yield of 2 ATP per glucose molecule (per 2 acetyl CoA)
        - Net yield of 6 NADH and 2 FADH2
        - Net yield of 4 CO2 molecules

Metabolism of Fatty Acids and Proteins (BIO, BC)

- Description of fatty acids (BC)
    - Fatty acids are amphipathic molecules possessing a polar carboxylate-head group and nonpolar hydrocarbon tail.
    - Exist in body in 3 common forms:
        - 1. **Triglycerides** (or triaglycerols)
            - 3 fatty acids esterified to glycerol
            - Nonpolar tails - used for energy storage
            - Digested by lipase
            - With low food intake, broken down by liver to form ketone bodies
        - 2. **Phospholipids**
            - Fatty acids bound to glycerol, phosphate, and other groups
            - Amphipathic (hydrophilic + hydrophobic components) - used for cell membranes
        - 3. **Cholesterol**
            - Fatty acids in ring form
            - Cholesterol is amphipathic. The ring is nonpolar and the -OH head group is polar
            - Used for steroid hormones, bile, membrane fluidity
- Digestion, mobilization, and transport of fats
    - The small intestine is lined with specialized epithelial cells, which are special cells that absorb nutrients that line the inside of this tube.
    - **Lipases** are enzymes that break down fat molecules into smaller pieces for the cells to absorb. Some are secreted by the pancreas, others are found naturally along the border of the cells.
    - Fatty acids are nonpolar so they group together and want to bind to each other instead of dissolving into the aqueous environment. So, they form fatty droplets. Our body secretes **bile** from the liver once food enters the small intestine and breaks up the fat molecules into smaller pieces, increasing the surface area for which the lipase enzymes can act upon them. Specifically, they bind to the ester linkages by adding a water molecule. The end result is a free glycerol backbone which contains a hydroxyl group, which it accepts from water, forming a carboxylic acid group.
    - These molecules are small enough to diffuse into the intestinal cell. First step is to get the molecules into the small intestine to turn them back into triglycerides because you want to pack them in a compact unit, so we can send them to various tissues. A carrier molecule, called a **lipoprotein**, essentially packages all of the triglycerides along with any other hydrophobic substances that the body absorbs, such as cholesterol, into the core of a protein molecule. These proteins have polar heads, meaning they interact with the aqueous environment inside the blood stream. The specific name this particular lipoprotein that's produced within the intestinal cell from absorbed fats, is called **chylomicron**.

- Recall that all of these cells are surrounded by capillaries, so they have a source of oxygen and nutrients, but also surrounded by specialized lymphatic capillaries called **lacteals** (a lymphatic capillary). The capillaries have very tiny fenestrations, or gaps, to allow molecules to be absorbed. They allow proteins and carbs to pass through, but not chylomicrons. Instead, they are taken up by lacteals, which have much larger pores relative to the capillary and thus allows chylomicrons to travel within them.
- Where do they drain? Anything that goes into the lymphatic vessels will drain into veins in the left side, called the **left thoracic duct** (near our shoulder). Some lymph is also drained into the **right thoracic duct**. Veins enter the heart and the heart pumps it to the lungs, which reoxygenate the blood, and eventually the chylomicrons reach the arteries which drain into capillary beds, which is the site of absorption of fats by other tissues in the body.
- There are enzymes in the capillary bed called **lipoprotein lipase**. They take the triglycerides contained in the chylomicron and break them up into individual fatty acids. This enzyme is also activated by insulin, which is present in your body in response to an influx of glucose right after a meal.
- Perhaps the biggest absorber of the fatty acids in the capillary are **adipose cells**. They are specialized cells for storing fat and have small nuclei and a lot of room in their cytoplasm to store fat. They take up the fatty acids floating around and compact them down for storage, turn them back into triglycerides and store them as big, fatty droplets inside of their cells.
- At the end of capillary bed, we have **chylomicron remnants**, or CR. The liver contains receptors that help reabsorb these CRs. All roads of digestion lead to the liver. The liver has a similar functionality to small intestine. It can package these fatty acids into specialized protein carrier molecules called **VLDL**, very low-density lipoprotein and refers to the density of protein to hydrophobic molecules inside of it. When VLDL reaches the capillary bed, it can be acted upon by lipoprotein lipase again. It also releases cholesterol to cells.
- Back to the adipose cells. They have hormone receptors on their cell surfaces which can detect the levels of hormones that are circulating inside the body. Important because the major hormone that's floating around after we've eaten is insulin. Hours after a meal, insulin decreases and glucagon increases. They signal adipose cells to release all of the fatty acids from the triglyceride molecules into the bloodstream. They are hydrophobic, so the body allows these free fatty acid molecules to travel in and alongside large proteins in the blood called **albumin**. These are also made by the liver.
- Remember, most tissues (except RBCs and brain) can take up fatty acids and produce a lot of ATP from them to sustain them.
- During fasting, when the body needs to maintain blood glucose levels for the brain and RBCs, they cannot use these fatty acids. The process of gluconeogenesis, which occurs largely in the liver, requires a lot of ATP. So, the liver takes a lot of these fats and break them down to produce the ATP necessary to produce gluconeogenesis. Process of converting glucose into fatty acids is also halted when levels of insulin fall. That's because process of converting glucose to fatty acids also stimulated by insulin.

- Oxidation of fatty acids
  - **Saturated fatty acids**
    - No double bonds
    - Solid at room temperature
    - Higher melting point, boiling point, and Van der Waals
    - Maximum hydrogens, stack together
  - **Unsaturated fatty acids**
    - 1 or more double bonds - bent or kinked structure
    - Liquids at room temperature (= oils)
  - Location: β-oxidation occurs in the matrix of the mitochondria. Fatty esters get hydrolyzed into free fatty acids by lipases. e.g. triacylglycerol gets hydrolyzed into free fatty acids and glycerol.
  - With the help of ATP, the fatty acid is "activated" at the acid end by CoA (turns into a thioester)

    - A process called β-oxidation breaks down the fatty-CoA, 2 carbons at a time, to make acetyl CoA.
    - β-oxidation produces acetyl-CoA and also $FADH_2$ and NADH.
    - Acetyl-CoA feeds into the Krebs cycle, and $FADH_2$ and NADH feed into ETC.
    - On a per gram basis, fats give more energy than any other food source.
- Ketone bodies (BC)
    - Many of the tissues in our body that rely exclusively on glucose for the production of energy, are more flexible during starvation and start using a different fuel that our body switches to making several days after starvation called ketones. Ketones are effective, unlike fatty acids, because they are water soluble enough to cross the blood-brain barrier and allow us to produce ATP in times of starvation.
    - There is no type of product inhibition when it comes to fatty acid oxidation. So, acetyl-CoA levels can continue to rise. If fatty acid oxidation produces enough ATP in our cells, it'll feed back onto the ETC to slow down. This leads to an increase in reduced electron carrier molecules, like NADH, which inhibits Krebs cycle. So, acetyl-CoA molecule will no longer want to enter Krebs cycle and thus allows us to move acetyl-CoA towards production of ketones, mainly inside liver. Ketones can then leave the liver, go into the bloodstream, and other tissues like the brain can take out the ketones, convert them back into acetyl-CoA which can enter the Krebs cycle and contribute to the production of ATP.
- Anabolism of fats (BIO)
    - Acetyl-CoA, the two-carbon molecule located in the mitochondrial inner matrix, is a precursor for fatty acid synthesis. There are no proteins to shuttle acetyl-CoA into the cytoplasm. Citrate shuffle is able to transport citrate into cytoplasm which is broken up back into oxaloacetate and acetyl-CoA. For oxaloacetate to go back to pyruvate, we lose a carbon which is lost as a carbon dioxide. Simultaneously, we reduce a molecule of NAD+ to NADPH.
    - We are going to link acetyl-CoA together to form a large fatty acid chain. **Palmitic acid** (16-carbon fatty acid chain) happens to be the primary product of fatty acid synthesis in the body. This requires eight acetyl-CoA molecules (since they are 2 carbons each). 7 ATP molecules are required for this reaction. We need 14 NADPH molecules to reduce the carbonyl group in acetyl-CoA to just carbon-carbon bonds that are essentially attached to hydrogen only. We end up with 7 ADP and Pi and 14 NADP+. We also lose 6 water molecules.
    - First step of fatty acid synthesis is to charge up acetyl-CoA into a higher energy molecule called **malonyl-CoA**. This is thermodynamically unfavorable, so need to couple with ATP hydrolysis. We charge it up with a carbon dioxide molecule.
    - Now, we are ready to link the malonyl-CoA together to form the 16-carbon chain. The carbon dioxide plops off again to make this reaction thermodynamically favorable. We need the NADPH molecules to reduce the carbon double bonds. The addition of two NADPH molecules, loss of one water molecule, and loss of carbon dioxide group is for each subsequent addition of the two carbon subunits.
    - The first enzyme that carries out this activation step is **acetyl-CoA carboxylase**. It adds a carboxy group to the acetyl-CoA. It is the rate-limiting step of this entire fatty acid synthesis pathway. Thus, it is important to regulate this through allosteric and hormonal regulation. Citrate is an allosteric activator. Insulin activates this pathway. Long-chain fatty acids can inhibit this enzyme through product inhibition. Glucagon is a hormonal inhibitor, it signals adipose cells to release fatty acids for our cells to break down.
    - The enzyme that polymerizes the malonyl-CoA subunits together is called **fatty acid synthase**. It contains two identical subunits, each having a thiol group. Acetyl-CoA attaches to one and malonyl-CoA attaches to the other. The decarboxylation makes the carbon very nucleophilic and thus wants to attack the other carbon that is nearby, forming a carbon-carbon bond. The ultimate fate of these fatty acids is to be attached to a glycerol backbone to form a triacylglycerol molecule, that are sent off by the liver via VLDL to deliver these fats to rest of our tissues.

- Non-template synthesis: biosynthesis of lipids and polysaccharides (BIO)
    - Refer to above for biosynthesis of lipids
    - **Hemiacetal formation** = -OH attacks carbonyl group - produces ring form
    - **Acetal formation** = another -OH attack on same carbonyl group = produces polysaccharides if the -OH is from another monosaccharide
    - Reduction turns monosaccharides into polyalcohols
- Metabolism of proteins
    - Proteins are broken down into amino acids by peptidases.
    - The nitrogen in the amino acid is converted to urea (for desert animals, it is uric acid)
    - The carbon in the amino acid is converted to pyruvate or acetyl-CoA, (or other metabolic intermediates such as oxaloacetate), depending on what amino acid it is
    - The carbon products from amino acid metabolism can either feed into the Krebs cycle, fatty acid synthesis, or be the starting material for gluconeogenesis

Oxidative Phosphorylation (BIO, BC)

- Electron transport chain and oxidative phosphorylation, substrates and products, general features of the pathway
    - Location: the cristae (inner membrane of mitochondria)
    - Input NADH
    - Proton gradient
    - The electron transport chain (ETC) is essentially a series of redox reactions, where NADH gets oxidized to NAD+ and O_2 gets reduced to H_2O
    - The series of redox reactions consists of electrons passing from NADH to FMN, to Coenzyme Q, iron-sulfur complexes, and cytochromes (cytochrome b, c and aa_3) before finally being used to reduce oxygen
    - **NADH** is highest in energy, while O_2 is lowest in energy. When electrons are passed from NADH down a series of proteins and finally to O_2, energy is released
    - **$FADH_2$** is lower in energy than NADH, that's why it releases less energy when oxidized
    - $FADH_2$ skips FMN and passes its electrons to Coenzyme Q
    - Energy released from these reactions generates a proton gradient, which drives ATP synthase to make ATP. This is called oxidative phosphorylation.
    - **Proton gradient**
        - The energy released from passing electrons down the ETC is used to pump protons into the intermembrane space of the mitochondria
        - H^+ concentration is very high in the intermembrane space (higher than those in the matrix). Thus, this establishes an electrochemical gradient called the proton gradient. H^+ wants to migrate down the proton gradient (from the IMS back into the matrix), but it can only do this by going through ATP synthase
        - Like a water mill, ATP synthase harnesses the energy of the falling protons to convert ADP into ATP
    - ETC is inhibited by certain antibiotics, by cyanide, azide, and carbon monoxide
- Electron transfer in mitochondria
    - NADH, NADPH
        - NADH utilized in cellular respiration. It is produced in catabolic reactions and later used in ETC to obtain energy by converting NADH back to NAD^+.
        - NADPH primarily produced in the oxidative part of the PPP. NADPH used in a) anabolic synthesis to produce cholesterol, fatty acids, transmitter substances and nucleotides b) detoxifying processes as an antioxidant.
        - NADH and NADPH are both reductive agents.
    - Flavoproteins

        - Flavoproteins are proteins that contain a nucleic acid derivative of riboflavin: the Flavin adenine dinucleotide or flavin mononucleotide
        - They are located on the matrix face of the inner mitochondrial membrane and functions as a specific electron acceptor for primary dehydrogenases, transferring the electrons to the ubiquinone pool in the inner mitochondrial matrix
    - Cytochromes
        - Compounds consisting of heme bonded to a protein.
        - They function as electron transfer agents in many metabolic pathways, especially cellular respiration.
        - Cytochrome c transfers electrons from complex III to complex IV in ETC. It can only carry 1 e- at a time.
- ATP synthase, chemiosmotic coupling
    - Proton motive force
        - The energy released from passing electrons down the ETC is used to pump protons into the intermembrane space of the mitochondria
        - H^+ concentration is very high in the intermembrane space (higher than those in the matrix). Thus, this establishes an electrochemical gradient called the proton gradient. H^+ wants to migrate down the proton gradient (from the IMS back into the matrix), but it can only do this by going through ATP synthase
        - Like a water mill, ATP synthase harnesses the energy of the falling protons to convert ADP into ATP
    - Hydrogen going through ATP synthase is considered **chemiosmosis**.
    - Oxidation generates energy by the pushing of hydrogens out. Phosphorylation happens as the hydrogens experience chemiosmosis and go back in to turn the axle (F_1 ATPase) and push the ADP and phosphate groups together.
    - Substrate phosphorylation, on the other hand, is involved in glycolysis and is where you have an enzyme directly helping to peruse the ATP without any type of chemiosmosis or proton gradient.
- Net molecular and energetic results of respiration processes
    - Electron Transport Chain
        - Net yield of **34 ATP per glucose molecule** (never achieved because leaky mitochondrial membranes result in lower yields of ATP, so **usually ~32 ATPs** made)
        - 6 H2O formed when electrons unite with O2 at the end of ETC
- Regulation of oxidative phosphorylation
    - Major regulator is looking at the energy needs of the cells. If body has a lot of ATP, oxidative phosphorylation slows down. However, if we have lots of ADP, oxidative phosphorylation will be upregulated.
    - Although the presence of NADH is important as it is a substrate, <u>ADP levels are more likely to alert the ETC</u>. ATP levels are a **limiting factor** that alerts the ETC as compared to NAD+ levels. The body keeps NAD+ and NADH in a pretty stable ratio.
- Mitochondria, apoptosis, oxidative stress (BC)
    - Mitochondria is site of ATP production: an apparatus called the ATP synthase makes ATP from ADP by utilizing the proton gradient as the driving force.
        - Self-replication; have own DNA and ribosomes
            - Mitochondria replicate independently from the cell containing the mitochondria
            - Mitochondria do not share the same genome with its host
            - Mitochondria have their own ribosomes, which are different from the host's ribosomes in both sequence and structure
            - All serve to support the endosymbiosis theory
        - Inner and outer membrane
            - Inner membrane surrounds the matrix
            - Folds of the inner membrane make up the **cristae**

        - Between the outer and inner membrane is the intermembrane space
        - Intermembrane space is high in protons H+
        - Outer membrane separates the mitochondria from cytoplasm
    - Apoptosis (Programmed Cell Death)
        - Apoptosis = death that is clean and healthy
        - Apoptosis = activation of caspases that digest the cell from within
        - No spilling of cell contents
        - Afterwards, the apoptosed cell releases chemicals that attract macrophages, and gets engulfed
        - Apoptosis can be brought upon by development or immune response (infected/cancerous cells killed by cytotoxic T cells/natural killer cells)

Hormonal Regulation and Integration of Metabolism (BC)

- Higher level of integration of hormone structure and function
    - The endocrine gland is the main structure responsible for hormonal secretion in the endocrine system.
- Tissue specific metabolism
    - **Absorptive metabolic state**: series of metabolic reactions that your body does when food is in plenty.
        - **Liver**: glucose is transported to the liver. It can be stored as glycogen or converted into triglycerides, storage form of fat. Glucose must be converted into glycerol, as well as fatty acids. In the liver, we don't store triglycerides. It's stored mostly in adipose tissues and triglycerides can't be transported in the blood. So, they have to be converted into VLDL, which can be exported out of liver and into blood. Liver breaks down amino acids into keto acids. These α-keto acids give off ammonia when is excreted as waste, in the form of urea. If we want to store the energy that's in the keto acids, we convert them to fatty acids and those can be converted into triglycerides, which are later stored in adipose tissues. If liver needs energy during this Absorptive State, the keto acids can be broken down into Acetyl CoA and that Acetyl CoA goes through TCA and ETC to produce ATP.
        - **Adipose tissue**: glucose needs to be turned into triglycerides. The VLDL, from earlier, will be turned into fatty acids which are then combined with glycerol to form triglycerides.
        - **Muscle**: glucose can be taken up and has two pathways: can convert to its storage form in glycogen or converted to pyruvate if energy is needed. Muscle also takes up amino acids from proteins and are just stored as protein in the muscle.
        - **Brain**: brain consumes vast amount of energy. So, the glucose from the blood is taken up, converted to Pyruvate, and produces ATP so brain can do work.
    - **Post absorptive state**: body needs to take the stored energy and use it
        - **Liver**: glycogen is going to be broken down into glucose and glucose can then be exported out of the Liver into the blood and be used for energy all over the body. Amino acids are still taken up by Liver and converted into Keto Acids. They will be used to make glucose that can be exported and used by other parts of the body, some broken down to Acetyl-CoA to produce ATP for liver energy. Triglycerides will be converted into glucose. Fatty acids can also undergo second reaction, such that they can be broken down to form Ketones. They can be used in the brain.
        - **Adipose**: Triglycerides are broken down into glycerol and fatty acids can be exported into the blood and brought to the Liver to make more glucose.
        - **Muscle**: protein broken down into its amino acids which are exported into the blood and, just like the glycerol and fatty acids in adipose tissue, make their way to the Liver to be converted to α-keto acids then glucose. Glycogen converted to glucose converted to

Pyruvate to create Acetyl-CoA and produce energy for the muscles. If muscles low on oxygen, glucose can produce lactate (not as efficient and disturbs pH balance of blood).
        - Brain: brain just always uses energy. Brain takes glucose from blood, converts to Pyruvate and goes through cellular respiration to produce ATP. Ketones from Liver also used by Brain for energy in Post Absorptive State.
- Hormonal regulation of fuel metabolism
    - **Glucagon** = increases blood sugar (break down glycogen, stimulate gluconeogenesis)
        - Typically, abundant when body is fasting
    - **Insulin** = lower blood sugar (stimulates glucose uptake by cells)
        - Typically, abundant after a meal
- Obesity and regulation of body mass
    - **Insulin**, **leptin**, and **ghrelin** help regulate whether the energy or food that we've consumed is stored or if we let it pass through and become waste. The things that we do to get rid of energy or consume energy include basal metabolic rate or amount of energy we burn at rest.
    - Leptin is a hormone that lives in our fat tissue, our adipose tissue, and goes to hypothalamus, part of the brain that tells us we're not hungry
    - Highlights importance of having correct hormones flowing through bloodstream to talk to the brain based on the nutrients or diet you have to regulate your body mass.

Content Category 2A: Assemblies of molecules, cells, and groups of cells within single cellular and multicellular organisms

Plasma Membrane (BIO, BC)

- General function in cell containment
- Composition of membranes
    - Lipid components (BIO, BC, OC)
        - **Phospholipids**
            - Lipid made of glycerol, two fatty acid tails, and a phosphate-linked head group
            - Biological membranes usually involve two layers of phospholipids with their tails pointing inward, an arrangement called a phospholipid bilayer
        - **Steroids**
            - Maintains membrane fluidity and stability (cholesterol)
            - Can bind to steroid hormone receptors
        - **Waxes**
            - Contributes to stability
            - Forms barrier against water
    - Protein components
        - **Integral membrane proteins** = integrated into membrane
            - At least on hydrophobic region that anchors them to the hydrophobic core of the phospholipid bilayer
            - Those that span entire membrane are called transmembrane proteins
        - **Peripheral membrane proteins** = outside and inside surfaces of membranes
            - Attached either to integral proteins or to phospholipids
            - Do not stick into the hydrophobic core of the membrane (more loosely attached)
    - Fluid Mosaic Model
        - Describes the membrane as protein boats floating in a sea of lipids
    - Membrane dynamics
        - Everything in the cell moves around
        - Uncatalyzed movement (trans-bilayer diffusion)
            - Phospholipid on the outer leaflet (extracellular part of membrane) move into the inner leaflet (intracellular part of membrane) or vice versa
            - Very slow movement = no catalyst
        - Lateral Diffusion
            - Movement of phospholipid from side to side
            - Fast type of movement

        - Catalyzed Movement
            - Need a catalyst (protein)
            - Uses ATP, protein is called flippase
            - Floppase also uses ATP to bring phospholipid from inner leaflet to the outer leaflet
        - *Many ways to move phospholipids around the membrane
- Solute transport across membranes
    - Thermodynamic considerations
        - **Diffusion**: Thermodynamically spontaneous process
            - Movement of solutes from higher concentration to lower concentration create a negative free energy change (Delta G)
            - As a result, energy will be produced as solutes move across the membrane
            - Increases the entropy of a system and decreases the free energy
            - Chemical concentration gradient and electrical gradient dictate direction of diffusion
    - Osmosis
        - Colligative properties; osmotic pressure (GC)
            - Colligative properties: properties based on NUMBER of particles present, rather than type
            - Osmosis: water diffuses freely across the membrane, but not ions (so osmosis occurs readily)
            - Spontaneous net movement of solute molecules through a semi-permeable membrane into a region of higher solute concentration, in the direction that tends to equalize the solute concentrations on the two sides
            - **Osmotic Pressure**: "Pulling" pressure generated by concentration gradient encouraging osmosis
                - Force that moves water down the concentration gradient
                - Greater the difference in tonicity across the semi-permeable membrane, the greater the osmotic pressure
                - In capillaries: **osmotic pressure** encourages flow of blood from tissues into capillaries. **Hydrostatic pressure** (created by slow movement of blood) counteracts osmotic pressure and encourages flow from capillaries into tissue
    - **Passive Transport**
        - Any thermodynamically favorable movement of a solute across a membrane (down the gradient)
        - No energy is required due to the concentration gradient driving the movement of the solute
        - Simple diffusion: solute diffuses through the membrane without any help from a protein
        - e.g. Steroid Hormones
    - **Active Transport**
        - Sodium/Potassium Pump
            - Secondary active transport that maintains negative potential across lipid bilayer
            - Pump 3 Sodium (Na^+) out, 2 Potassium (K^+) in
            - Cell maintains negative resting potential
        - Requires energy input
        - Always involves a protein
        - Primary active transport: ATP hydrolysis is coupled to transport molecules

            - Secondary active transport: ATP is first used to create a gradient, then potential energy is used to transport the molecules (indirectly use ATP)
    - Membrane channels
        - To help ions cross the membrane, there are ion channels
    - Membrane potential
        - The resting potential of the cell membrane is negative because of the sodium potassium pump
    - Membrane receptors
        - Transmit signals from the extracellular space into the cytoplasm
        - Ligand: hormones and neurotransmitters that require membrane receptors to cross the plasma membrane
        - The binding of membrane receptors triggers production of second messengers
        - Hormone types:
            - **Small, hydrophobic**: cross membrane, act on transcription usually, cause the increase of membrane/target proteins in a cell
            - **Large, lipophobic**: binds to receptor on cell membrane, could cause activation of second messenger which kicks off chemical cascade
        - The same signaling molecule can have different effects depending on cell location
    - Exocytosis and Endocytosis
        - Endocytosis types:
            - **Phagocytosis**: ligands signal for membrane to engulf particles
            - **Pinocytosis**: engulfs extracellular fluid, takes up solute
            - **Receptor-mediated endocytosis**: takes up ligands
        - Exocytosis
            - Same as endocytosis but backwards
    - Intercellular junctions (BIO)
        - **Gap junctions**
            - Small tunnels connecting cells
            - Action potentials, small molecules, ions can propagate through them
            - Present in cardiac and smooth muscle
        - **Tight junctions**
            - Forms watertight seal from cell to cell – prevents fluids from moving past
            - Can act as barrier to prevent fluid from seeping past cells
            - Present in endothelial cells
        - **Desmosomes**
            - Join two cells at a single point
            - Present in cells that experience stress due to sliding (skin, intestinal epithelium)

Membrane-Bound Organelles and Defining Characteristics of Eukaryotic Cells (BIO)

- Defining characteristics of eukaryotic cells: membrane bound nucleus, presence of organelles, mitotic division
- Nucleus
    - Compartmentalization, storage of genetic information
        - Nuclear membrane/nuclear envelope surrounds the nucleus
        - Genetic information is stored inside the nucleus as DNA
    - **Nucleolus**: location and function
        - Non-membrane bound area in nucleus
        - Transcribes rRNA and assembles ribosomal subunits
    - **Nuclear envelope**, **nuclear pores**
        - Nuclear envelope: double phospholipid bilayer wrapping around the nucleus
        - Nuclear pores: large holes perforating envelope

        - Let's RNA out but not DNA
- Mitochondria
    - Site of ATP production
    - Inner and outer membrane structure (BIO, BC)
        - Inner membrane invaginates to form cristae
        - Electron transport chain takes place along inner membrane
        - Intermembrane space separates outer and inner membranes
        - Outer membrane permeable to small molecules (inner membrane is almost impermeable to these → need to maintain chemiosmotic gradient)
    - Self-replication
        - Mitochondria have circular DNA that self-replicates (inherited by the mother)
- **Lysosomes**: membrane-bound vesicles containing hydrolytic enzymes
    - Digests things like food and viral/bacterial particles
    - Things that you want to digest gets into a vacuole by endocytosis or phagocytosis, and then the vacuole fuses with the lysosome (anything inside gets digested by the hydrolytic enzymes)
    - Rupture during apoptosis (lysosome count increases before apoptosis)
        - Cells also shrinks and **caspases** (protease enzymes) are activated
    - Hydrolytic enzymes are activated by low pH
        - pH lowered by lysosome pumping protons into its interior after binding to a food vesicle
- Endoplasmic reticulum
    - Rough and smooth components
        - **RER**: synthesizes almost all proteins to be secreted out of cell
        - **SER**: involved in gluconeogenesis and fat storage (in liver), detoxification of alcohol, cholesterol formation. Function depends on cell type
    - Rough endoplasmic reticulum sites of ribosomes
        - Ribosomes on cytosolic side of RER
        - Ribosomes attach to the outside of the RER and synthesis of protein into the lumen
    - Double membrane structure
        - Double membrane separates ER lumen from cytosol
    - Role of membrane biosynthesis
        - Supplies membrane with proteins and lipids
        - Can facilitate membrane expansion
    - Role in biosynthesis of secreted proteins
        - Enzymes essential for biosynthesis could be secreted
- **Golgi apparatus**: general structure and role in packaging and secretion
    - Flattened, membrane bound sacs
    - Organizes and concentrates proteins into vesicles full of proteins
    - Can secrete proteins out of cell or back into mitochondria or ER
- **Peroxisomes**: organelles that collect peroxides
    - Vesicles in cytosol involved production and breakdown of hydrogen peroxide
    - Also involved in lipid and protein storage, detoxification, and regulation of oxygen concentration
    - Essential for lipid breakdown, detoxification of drugs and chemicals in liver
    - Prevent damage from oxygen radicals

Cytoskeleton (BIO)

- General function in cell support and movement
- **Microfilaments**: compositions and role in cleavage and contractility
    - Composition: **actin filaments, globular subunits**
    - Roles
        - Cleave: pinches cytoplasm during cytokinesis
        - Contractility: interact with myosin to cause muscle contractions

- **Microtubules**: composition and role in support and transport
    - Composition: **made up of 13 tubulin filaments arranged in a hollow tube**
    - Roles
        - Support: support shape of the cell
        - Transport: serves as platform for vesicle (dynein and kinesin)
    - Also moves chromosomes around the cell (spindle apparatus)
- **Intermediate filaments**: role in support
    - Not as flexible as the other two
    - Primarily used for structural rigidity
    - Keratin = intermediate filament
- Composition and function of cilia and flagella
    - Composition: **9 pairs of microtubules form a circle around 2 lone microtubules (9 + 2 arrangement)**
    - Function: move fluid to cause cell or nearby substances to move
- Centrioles, microtubule organizing centers (MTOC)
    - MTCO: attaches "-" end of microtubule
    - Centriole: production of flagella and cilia, form the **centrosome** (major MTOC in animal cells)
    - Microtubules radiate out of these barrel shaped structures, which are made of microtubules themselves

Tissues Formed From Eukaryotic Cells (BIO)

- Epithelial cells
    - **Lines inside and outside of organs**
    - 2 types
        - Single layer: found in alveoli, capillaries
        - Stratified: multiple layers, found in stomach, esophagus
- Connective tissue cells
    - Two components of connective tissue
        - 1) Cells
        - 2) Matrix
            - Matrix can be made up of ground substance and fibers (need at least one)
    - **Extracellular matrix**: molecular network that holds tissue cells in place
        - Fibroblasts secrete fibrous proteins that make the matrix
    - Consistency, rigidity of matrix varies from cell to cell
    - 3 Classes of molecules making up animal cell matrices
        - 1) Glycosaminoglycans and proteoglycans: provides pliability to matrix
        - 2) Structural proteins: provide strength to matrix
        - 3) Adhesive proteins: help individual cells within tissues stick together

Content Category 2B: The structure, growth, physiology, and genetics of prokaryotes and viruses

Cell theory (BIO)

- History and development
    - Robert Hooke observed under a microscope what appeared to be cells.
    - German botanist Matthias Schleiden looked at all sorts of plants under a microscope and noticed all had the same microscopic structure.
    - German scientists Theodor Schwann looked all nervous systems of different animals and noticed all had similar structures that were these cells.
    - German physician and pathologist, Rudolph Virchow observed bacteria that divided and formed two bacteria that were identical = binary fission.
    - French scientist Louis Pasteur did a famous experiment known as the Swan-Neck Bottle experiment proved that all cells come from preexisting cells.
- Impact on biology
    - Proved that cells were the basic structural, functional, and biological unit of life and cells come from preexisting cells.

Classification and Structure of Prokaryotic Cells (BIO)

- Prokaryotic domains
    - **Archaea**
        - Single-celled organisms that are visually similar to bacteria but contain genes and several metabolic pathways that are more similar to eukaryotes than bacteria.
        - Considered extremophiles in that they were most commonly isolated from harsh environments with extremely high temperatures, high salinity, or no light.
        - While some are photosynthetic, many are chemosynthetic and able to generate energy from inorganic compounds, including sulfur- and nitrogen-based compounds, such as ammonia
        - Due to similarities to eukaryotes, it is hypothesized that eukaryotes and domain Archaea share a common origin. Both start translation with methionine, contain similar RNA

polymerases, and associate their DNA with histones. However, Archaea contain a single circular chromosome, divide by binary fission or budding, and overall share a similar structure to bacteria. Interestingly, Archaea are resistant to many antibiotics.

- **Bacteria**
  - All bacteria contain a cell membrane and cytoplasm, and some have flagella or fimbriae (similar to cilia). Because bacteria and eukaryotes often share analogous structures, it can be difficult to develop medicines that target only bacteria.
  - Bacterial flagella and eukaryotic flagella are distinct enough that scientists are able to develop antibacterial vaccines that specifically target bacterial flagella. Also, many antibiotics target the bacterial ribosome, which is significantly smaller than the eukaryotic ribosome.

- Major classifications of bacteria by shape
  - **Bacilli** (rod-shaped)
  - **Spirilli** (spiral-shaped)
  - **Cocci** (spherical)
- Lack of nuclear membrane and mitotic apparatus
  - Bacteria **do not have a membrane-enclosed nucleus**. Their genetic material is located in an irregular region called the **nucleoid**. Bacteria do not have spindles and asters that make up the eukaryotic mitotic apparatus. Instead, the prokaryotic cytoskeleton helps pull the replicated DNA apart.
- Lack of typical eukaryotic organelles
  - Bacteria don't have Golgi, ER, mitochondria, chloroplasts
- Presence of cell wall in bacteria
  - Bacterial **cell wall** is made of peptidoglycan, a polysaccharide-protein molecule. In contrast, plant cell wall is made of cellulose and fungi cell wall is made of chitin.
- Flagellar propulsion, mechanism
  - Bacterial flagella is made of **flagellin**. In contrast, eukaryotic flagella is made of **microtubules**.
  - The mechanism of the bacterial flagella is rotation. A rotor at the base of the flagella drives the rotation, powered by a proton or sodium gradient. (Compare this to eukaryotic flagella, which is powered directly by ATP)

Growth and Physiology of Prokaryotic Cells (BIO)

- Reproduction by fission
  - DNA replicates
  - Replicated DNAs separate by attached to the cell membrane as the cell elongates (in contrast to mitosis, no spindle fibers needed)
  - Cytokinesis divides the parent cell into two daughter cells
- High degree of genetic adaptability, acquisition of antibiotic resistance
  - Mutation
  - **Transformation**: bacteria take in plasmids and DNA fragments and integrates them into the genome
  - **Transduction**: bacteriophages undergoing lysogenic life cycle incorporate the viral DNA into the bacterial genome
  - **Conjugation**: bacteria transfer DNA between one another through the sex pilus
- Exponential growth
  - Bacterial growth starts off being exponential because of the nature of binary fission. Later, when food becomes short, and it gets crowded, growth slows and eventually plateaus
- Existence of anaerobic and aerobic variants
  - **Obligate aerobe** = must have oxygen for growth
  - **Obligate anaerobe** = dies when oxygen is present
  - **Facultative anaerobe** = doesn't need oxygen for growth, but grows better with oxygen

- Parasitic and symbiotic
    - **Parasitic** = bacteria benefits at the expense of the host. Disease causing bacteria are examples of parasitic relationships.
    - **Mutualistic** = both bacteria and host benefits. For example, the E. coli in your gut; the natural flora on your skin
    - **Commensalistic** = one benefits while the other has no effect
- Chemotaxis
    - Movement in a direction corresponding to a gradient of increasing or decreasing concentration of a particular substance/chemical

Genetics of Prokaryotic Cells (BIO)

- Existence of plasmids, extragenomic DNA
    - Plasmids are double stranded DNA
    - A plasmid can exist and replicate independently of the genomic DNA, or be integrated into it
    - Plasmids are inherited
    - Plasmids are not essential for growth and reproduction in the wild
- **Transformation**: incorporation into bacterial genome of DNA fragments from external medium
    - When a bacterium dies, it lyses and spills many DNA fragments into the environment
    - Another bacteria encounters these DNA fragments, takes them in, and integrates them into its own genome
    - If the DNA fragments contained an antibiotic resistant gene, then the transformation just made the bacteria antibiotic resistant
- **Conjugation**
    - Transfers genetic material between bacteria via a pillus
    - A bacterium able to make the pillus (F+) has a plasmid that contains the pillus genes
    - F+ bacteria can transfer the plasmid to an F-bacteria
    - Conjugation can also transfer some genomic DNA (because F+ plasmid can integrate into the chromosome)
- **Transposons** (also present in eukaryotic cells)
    - They are a heterogeneous class of genetic elements that can insert at new locations on chromosomes. Classified into three major groups:
        - Class I, retrotransposons; Class II, DNA transposons; Class III, miniature inverted-repeat transposable elements
    - Transposons have direct repeat flanking sequences that are not part of the transposons, and terminal inverted repeats that are part of the transposons. DNA transposons translocate via a cut-and-paste mechanism, retrotransposons translocate via a copy-and-paste mechanism.
    - Transposons cause significant changes in genome organization and gene sequence. They can give insertion/deletion mutant and chromosomal inversion mutant. They are used as tools in gene delivery or targeted mutation.

Virus Structure (BIO)

- General structural characteristics (nucleic acid and protein, enveloped and non-enveloped)
    - Nucleic acid can be DNA or RNA, single stranded or double stranded
    - Protein coat covers the nucleic acid
    - Some viruses have an envelope derived from the host's cell membrane, while others lack it (non-enveloped)
        - Enveloped viruses bud off the host's membrane
        - Non-enveloped viruses cause the host to burst to release viral particles
    - Smaller than bacteria
- Lack organelles and nucleus

    - Viruses don't have any organelles or a nucleus. The genetic material is simply packed inside a protein coat.
- Structural aspects of typical bacteriophage
    - Head stores genetic material
    - Sheath provides a passageway for genetic material to be injected into the host bacteria
    - Tail fibers attach to the host bacteria
- Genomic content - RNA or DNA
    - Viruses can contain either RNA or DNA as their genomic content
    - Out of the RNA viruses, those that convert their genome into DNA inside their host are called **retroviruses**
- Size relative to bacteria and eukaryotic cells
    - Viruses are roughly 100 times smaller than bacteria, and 1000 times smaller than eukaryotic cells

Viral Life Cycle (BIO)

- Self-replicating biological units that must reproduce within specific host cell
    - Viruses cannot replicate by themselves. They depend on the host's replication organelles to replicate. The host's ribosomes will make the necessary protein coats and polymerases that replicate the viral genetic material. Retroviruses contain their own reverse polymerase to convert RNA to DNA before the host's polymerases take over
- Generalized phage and animal virus life cycles
    - Attachment to host, penetration of cell membrane or cell wall, and entry of viral genetic material
    - Use of host synthetic mechanism to replicate viral components
        - Host's ribosomes synthesize the necessary enzymes. Host's ATP provides necessary energy. The host also provides the raw materials such as nucleotides and amino acids.
    - Self-assembly and release of new viral particles
        - The coat proteins and viral genetic material will assemble into viral particles by themselves
- Transduction: transfer of genetic material by viruses
    - 1. Virus infects cell: host DNA degraded into fragments, viral DNA takes over control
    - 2. Host DNA fragment gets packed into virus progeny by accident
    - 3. Virus progeny infects another cell, injects previous host's DNA fragment
    - 4. Fragment enters cell, finds its homologous counterpart, and crossover
- Retrovirus life cycle: integration into host DNA, reverse transcriptase, HIV
    - 1. Retrovirus enters the host
    - 2. Viral reverse transcriptase converts viral RNA genome into double-stranded DNA
    - 3. Virally encoded enzyme, called integrase, adds in viral DNA into the host's genome at a random place
    - 4. When the host replicates, the viral DNA gets replicated also
- Prions and viroids: subviral particles
    - **Viroids** are smaller than viruses because they're only made of a single strand of circular RNA. Before, they were only found to infect plants. Today, they have been found in humans, in the case of Hepatitis D.
        - It's thought to be catalytic RNA, meaning it can make or break covalent bonds. It can self-cleave to create more viroids. Don't confuse with virions which are whole viruses.
    - **Prions** have no genetic material, no DNA or RNA. They are only made of proteins. A prion protein tends to be in a beta-sheet conformation (normal protein generally in shape of an alpha helix). It's thought that because prion protein and normal protein made of same amino acids, they are the same protein but in a different shape. When the beta-sheet comes in contact with the alpha-helix, it will change the α-helix to a β-sheet. As more and more become β-sheets, this creates protein deposits. This happens somewhere in the brain, normal cleanup still happens. This leaves huge holes in your brain as the proteins are removed, causing disease.

Content Category 2C: Processes of cell division, differentiation, and specialization

Mitosis (BIO)

- Mitotic process: prophase, metaphase, anaphase, telophase, interphase
    - **Prophase**: *condensation of chromatin into chromosomes*, centrioles move to opposite poles of cell, microtubules begin to form
    - **Metaphase**: chromosomes align across equator of cell
    - **Anaphase**: sister chromatids pulled apart, cytokinesis begins
    - **Telophase**: nuclear membrane reforms, chromosomes de-condense, cytokinesis continues
- Mitotic structures
    - Centrioles, asters, spindles
        - **Centrioles**: located in center of centrosomes, move to opposite ends of cell
        - **Asters**: microtubules radiating from centrioles
        - **Spindle microtubules**: microtubules connecting the two centrioles
    - Chromatids, centromeres, kinetochores
        - **Chromatid**: two identical copies of a chromosome, joined together by a *centromere*
        - **Kinetochore**: located at center of centromere of joined chromatids, structure of protein and DNA
        - Kinetochore microtubules: connect centromeres to centrosomes/centrioles.
            - Their shortening pulls sister chromatids apart
    - Nuclear membrane breakdown and reorganization

        - Starts to break down in anaphase, finishes in telophase
        - Nuclear membrane reorganizes in telophase
    - Mechanisms of chromosome movement
        - Kinetochore microtubule shortening pulls sister chromatids apart
- Phases of cell cycle: G0, G1, S, G2, M
    - **G1**: cell growth. Protein, RNA, and phospholipid synthesis highly active
    - **G0**: non-growing state, most protein production takes place here
    - **S**: preparing cell for mitosis, a lot of DNA replication
    - **M**: mitosis, division of nucleus
    - **G2**: cell prepares to divide, RNA and proteins (esp tubulin) are produced
- Growth arrest (cell arrested for many reasons)
    - Too much genomic mutation/damage causes cell to arrest in M phase
    - Contact inhibition: normal epithelial cells stop growing when it gets crowded such that it's touching adjacent cells
    - Lack of food can also cause growth arrest
- Control of cell cycle
    - Checkpoints
        - **G1 checkpoint**
            - If conditions are favorable for division → S; if not → G0
                - Favorable conditions based on cell size (Large = ready)
        - **G2 checkpoint**
            - Checks for mitosis promoting factor (MTF)
                - High MTF levels indicates aligned chromosomes → mitosis is triggered
- Loss of cell cycle controls in cancer cells
    - Two types of mutations that can cause cancer
        - Deactivation of checkpoint protein (tumor repressor)
        - Activation of gene causing proliferation of cell (oncogene)

Biosignaling (BC)

- Oncogenes, apoptosis
    - Carcinogens can trigger transcription of oncogenes
    - Failure of normal cellular controls:
        - Cancer cells continue to grow and divide in situations normal cells would not
        - Cancer cells fail to respond to cellular controls/signals that would halt this growth
        - Cancer cells avoid apoptosis (self-destruction) that normal cells undergo when extensive DNA damage is present
        - Cancer cells stimulate angiogenesis (cause new blood vessels to grow to nourish the cancer cell)
        - Cancer cells are immortal while normal cells die after a number of divisions
        - Cells can metastasize – break off and then grow in another location
- Gated ion channels: let ions from one side of the membrane to another
    - Voltage gated:
        - Na and K voltage gated ion channels: involved in action potential. Speed at which they open are different
        - Ca2+ voltage gated channels: located at presynaptic side of synaptic cleft. Action potential causes channels to open, Ca2+ to flow into cell. This causes efflux of NT vesicles
    - Ligand gated
- Receptor enzymes: bind NT's or hormones and triggers processes in cell
    - NT binding to receptor makes postsynaptic side more permeable to ions. This completes the transfer of the neural impulse
    - NT's released back into cleft after binding to receptor

        - Need ways to get rid of NT's in cleft
            - Destroy using an enzyme in the cleft
            - Reabsorb into presynaptic cleft
            - Diffuse out of cleft
- G protein-coupled receptors
    - Example of secondary messenger system
    - Binding of NT to this receptor causes release of an attached G-protein's alpha subunit
    - Alpha subunit release in postsynaptic neuron, has a variety of effects:
        - 1) Activates separate specific ion channels
        - 2) Activate a second messenger (ex: cAMP)
        - 3) Activate intracellular enzymes
        - 4) Activate transcription

Reproductive System (BIO)

- Gametogenesis by meiosis
    - Sperm production
        - 1) Spermatogonia, diploid progenitor cells that give rise to sperm, undergo mitosis to produce two diploid copies called *primary spermatocytes*
        - 2) Primary spermatocytes undergo meiosis I to produce two unique, haploid, secondary spermatocytes
        - 3) Secondary spermatocytes undergo meiosis II to make spermatids
        - 4) Spermatids undergo process of maturation where they lose cytoplasm, gain a tail to make mature sperm
        - 5) Ejaculation sends them through vas deferens, into urethra, and then out of the penis
        - Sperm production occurs in the *seminiferous tubules*
        - Hormones influencing sperm production
            - **FSH**: stimulates Sertoli cells which surround and nurture spermatocytes and spermatids (FSH → Sertoli cells)
            - **LSH**: stimulates Leydig cells which release testosterone to stimulate germ cells to differentiate into sperm (LH → Leydig Cells)
    - Ovum production
        - 1) Follicle (comprised of egg and zona pellucida, viscous substance around the egg) is formed in the ovaries
        - 2) Theca cells grow around the follicle to form the *secondary follicle*
        - 3) Theca cells secrete androgen when stimulated with LSH. Androgen is converted to estradiol and secreted into blood
        - 4) Follicle grows and bulges from ovary
        - 5) Estradiol levels rise rapidly, cause dramatic increase in LH secretion (**luteal surge**)
        - 6) Luteal surge causes ovulation (bursting of follicle, release of egg)
        - 7) Egg swept into Fallopian tube, remaining follicle left behind becomes the **corpeus luteum**, which secretes estradiol and progesterone throughout pregnancy or for two weeks before degrading into the **corpus albicans** if impregnation doesn't occur
        - Two divisions of ovarian cycle:
            - **Follicular Phase**: beings with development of follicle, ends at ovulation
            - **Luteal Phase**: begins at ovulation, ends with degeneration of corpus luteum into corpus albicans
        - 3 Phases of the ovarian cycle:
            - 1) Menstruation (follicle first develops, ends as follicle matures)
            - 2) Proliferation Phase (follicle matures, ends at ovulation)
            - 3) Secretory Phase (ovulation and corpus luteum secretes progesterone, estradiol, ends as luteum degrades into albicans)

- Ovum and Sperm
    - Differences in formation
        - Primary oocytes only made before birth in females. Occurs constantly after puberty in males
        - Primary oocytes arrested in Prophase I until menstrual cycle releases hormone signal for meiosis to continue
        - Secondary oocytes are not equal. One receives all the cytoplasm and becomes an actual secondary oocyte. Another doesn't and becomes a polar body to be discarded
        - Secondary oocyte arrested at metaphase II. Released from ovary and travels down fallopian tube
            - Meiosis only continues when oocyte is penetrated by sperm during fertilization
    - Differences in morphology
        - Sperm: separated into 3 sections (head, midpiece, and tail), very little cytoplasm
            - Head: contains genetic information, only parts that penetrate egg in fertilization
            - Midpiece: contains mitochondria which power tail
            - Tail: propels sperm through fallopian tube
        - Ovum: non-motile = round
    - Relative contribution to next generation
        - Sperm contributes DNA only (the egg actively destroys sperm mitochondria)
        - Egg contributes DNA + everything else (mitochondria, organelles, epigenetics)
- Reproductive sequence: fertilization; implantation; development; birth
    - 1. Fertilization: sperm + egg → zygote
    - 2. Implantation:
        - 1. Zygote
        - 2. Morula (solid ball)
        - 3. Blastula (sea urchins) or blastocyst (mammals)
        - 4. The blastocyst is the one that implants in the endometrium
    - 3. Development:
        - 1. Zygote
        - 2. Blastocyst
        - 3. Implantation
        - 4. Gastrulation
        - 5. Organogenesis
    - 4. Birth:
        - Switch from getting oxygen from mom's blood → breathing
        - Switch from getting nutrients from mom's blood → suckling
        - Fetal circulation (which bypasses lungs and liver) → normal circulation (by closing off ducts and openings)
    - Note: One X chromosome is deleted in female somatic cells HOWEVER, both are present in female reproductive cells

Embryogenesis (BIO)

- Stages of early development (order and general features of each)
    - Fertilization
        - 1) Enzymes in sperm acrosome (head) dissolve outer layer of egg (zone pellicuda)
        - 2) Cell membranes of sperm head and oocyte fuse on contact, sperm nucleus enters cytoplasm of oocyte
        - 3) *Cortical reaction* occurs, preventing other sperm from fertilizing same egg
        - 4) Oocyte undergoes second meitotic division to become an ovum, releases second polar body
        - **5) Nuclei of sperm and ovum fuse to make a zygote**

- Cleavage
  - 1) Zygote multiplies to a **morula**
- Blastula formation
  - 1) Morula divides, makes **blastocyst** (hollow ball of cells with a small mass on one side)
  - 2) Blastocyst lodges in uterus in a process called **implantation**, fuses with uterine tissue to form **placenta**
  - 3) Placenta HCG prevents degeneration of corpus luteum
  - 4) Intercell communication in blastula causes blastocyst cells to differentiate (inner cells become embryo, outer cells become placenta)
- Gastrulation
  - First cell movements
  - **Formation of primary germ layers (endoderm, mesoderm, ectoderm)**
- Neurulation
  - Gastrulation develops into a neurula, notochord causes neural plate and neural tube to form via induction
  - Cells close to neural tube become neural crest
  - Ectoderm → brain and spinal cord (by folding into a tube)

- Major structures arising out of primary germ layers
  - **Endoderm** – digestive tract, respiratory tracts, liver, pancreas, thymus, thyroid
  - **Mesoderm** – blood cells, connective tissues (bones, muscles, tendons) and various organs (kidneys, heart, gonads, dermis of skin)
  - **Ectoderm** – epidermis of skin, nervous system, eyes, spinal cord
- Neural crest
  - **Neural crest** cells located at the tip of each neural fold
    - Migrate outward to form the PERIPHERAL NERVOUS SYSTEM
      - Includes:
        - Sensory ganglia, autonomic ganglia, adrenal medulla, Schwann cells
  - **Neural tube** gives rise to the CENTRAL NERVOUS SYSTEM
- Environment-gene interaction in development

Mechanisms of Development (BIO)

- Cell Specialization = commitment followed by differentiation
  - **Determination** = irreversible commitment to become a certain cell type
  - **Differentiation** = becoming a cell type and adopting its specialized functions
    - Epidermal cells produce keratin to protect skin against abrasion
    - Myocyte produce actin and myosin to make muscles contract
    - Neurons make neurotransmitters to transmit electrochemical impulses
  - Tissue Types:
    - **Epithelial** = skin, lining of organs
    - **Connective** = blood, bone, tendons, ligaments, cartilage
    - **Nervous** = brain, spinal cord, nerves
    - **Muscle** = skeletal, smooth, and cardiac muscles
- Cell-cell communication in development
  - Cells in blastula communicate with each other to coordinate development of placenta and embryo
  - **Induction**: one group of cells changing the behavior of an adjacent group of cells
  - Inducer: the one that sends the signal for the other to change
  - Responder: the one that gets the signal and changes
    - For example, the optic vesicle is able to induce the ectoderm to develop into lens
  - Induction mechanisms: physical touching of cells (juxtracine) or by releasing chemicals (paracrine)

- Cell Migration
    - Process by which neural crest cells travel to various locations in body (remember the PERIPHERAL NERVOUS SYSTEM, its everywhere!)
- Pluripotency: Stem Cells
    - Stem cells in blastocyst are pluripotent (can become most cells, depends on location in blastula)
- Gene regulation in development
    - Differential gene transcription:
        - Modification of DNA (methylations) can shut off or turn on genes
        - Modification of histones (methylations, acetylations) that wrap the DNA can shut off or turn on genes
            - **Acetylation of histone proteins DECREASES positive charge on lysine residues and weakens interaction of DNA with histone**
                - **Results in open DNA = easier transcription**
            - **Methylation of genes often results in SILENCING of gene expression**
        - To make or not to make transcription factors can regulate what genes get transcribed
    - Differential RNA processing:
        - Selecting what RNA make it outside the nucleus to be translated
        - Alternative splicing of RNA
    - Translation regulation:
        - Some mRNA is made to last longer than others (more proteins translated off of it), and some are made to be rapidly degraded (less proteins translated off of it)
        - Selective inhibition of translation of stored RNA in the oocyte (get translated only when needed after fertilization)
    - Post-translational regulation
        - Some proteins are inactive until modified by certain enzymes
        - Active proteins can be selectively marked for degradation by ubiquitin
- Programmed cell death
    - Regulated by protein activity (not at level of transcription or translation)
- Existence of regenerative capacity in various species
    - Some systems (skin, liver, and blood) have multipotent stem cells which can regenerate these systems as needed (since these systems are injured or lost often)
- Senescence and aging
    - **Senescence**: process by which cells stop proliferating in response to environmental stressors and are cleared away by immune cells (allows for shaping of tissues) → Loss of cell's power of division and growth (as you age ya know)
        - Implicated in aging

Content Category 3A: Structure and functions of the nervous and endocrine systems and ways in which these systems coordinate the organ system

Nervous System: Structure and Function (BIO)

- Major functions
    - High level control and integration of body systems
        - Frontal lobe: carries out executive functions like planning, impulse inhibition
        - Cerebellum: integrates, processes sensory, motor, vestibular input
        - Cerebrum: processes and interprets sensory information. Impose higher level meaning on this information based on previous experience. Top-down influence
    - Adaptive capability to external influences
    - Sensory input

        - Sensory = afferent
        - Nerve impulses conveyed to the CNS
    - Motor output
        - Motor = efferent
        - Nerve impulses from CNS to effector organs
    - Integrative and cognitive abilities
- Organization of vertebrate nervous system
    - Categories of nervous systems
        - CNS = Central Nervous System = Brain and spinal cord
            - Brain
            - Spinal cord
        - PNS = Peripheral Nervous System = Everything else, deal with sensory and motor functions
            - Sensory = Afferent = Nerves carrying signal toward CNS
            - Motor = Efferent = Nerves carry signal toward effector organs
                - Somatic Nervous System = Voluntary = Controls skeletal muscles
                - Autonomic Nervous System = Involuntary = Effects visceral organs
                    - Sympathetic division = fight or flight response
                    - Parasympathetic division = Rest
    - Divisions of brain (in ascending order of complexity)
        - "Lower brain," brainstem, cerebellum, diencephalon (thalamus, hypothalamus)
            - Brainstem: controls basic involuntary functions, includes medulla, pons, midbrain
                - Medulla: regulates cardiovascular and respiratory systems
                - Pons: coordinates communication between motor cortex and cerebellum
                - Midbrain: relay station for auditory, visual signals
            - Cerebellum: see above
            - Thalamus: processes all sensory information before it reaches a higher cortical level
            - Hypothalamus: maintains homeostasis. Works together with pituitary gland to exercise feedback control of hormone release
                - Ex. release of hormone → greater enzyme activity → signals to brain don't need more hormone → hypothalamus tells pituitary to chill
        - "Higher brain," Cerebrum
            - Frontal lobe: see above
            - Motor, somatosensory cortex: topographic map, homunculus
            - Limbic system: made up of hippocampus, amygdala. Concerned with memory and emotion
    - Lateralization of cortical functions
        - Language: production and comprehension localized in left hemisphere
        - Emotion: left hemisphere more involved with positive emotions, right with negative emotions
- Sensor and effector neurons
    - Sensor = senses, carries sensory signals from body to CNS
    - Effector = causes an effect = carries motor signals from CNS to body
- Sympathetic and parasympathetic nervous system: antagonistic control
    - Sympathetic = prepares body for activity = fight or flight response
        - Increase heart rate, blood pressure
        - More blood flow to muscles, less to digestive system
        - Pupil dilation
        - Break down glycogen to release glucose into blood
    - Parasympathetic = prepares body to rest = rest and digest response

        - Decrease heart rate, blood pressure
        - Less blood to muscles, more to digestive system
        - Pupil constriction
        - Synthesizes glycogen for storage from glucose
    - Both innervate the same organs, have opposing influences on the same organs, their signals *compete* with each other = antagonistic control
    - Location of sympathetic and para cell bodies relative to the things they effect
        - Sympathetic: far from effectors (because need distance to generate strong, coordinated signal needed for flight or flight)
        - Parasympathetic: close to effectors, give more uncoordinated signals
        - Effector: organ or muscle that responds to neural innervation
    - Type of NT's used by each
        - Parasympathetic: acetylcholine
        - Sympathetic: epinephrine or norepinephrine
- Reflexes
    - Feedback loop, reflex arc
        - **Feedback loop** = positive feedback (reinforce initial event), negative feedback (counteracts initial event), or reflex arc (usually a type of negative feedback)
            - Positive feedback = uterine contraction lead to oxytocin release, which causes more uterine contractions
            - Positive feedback = blood clotting platelets activated at wound site attract more platelet activation and clumping
            - Negative feedback = drop in blood pressure causes ADH release, which increases it. Conversely increase in blood pressure causes a drop in ADH
            - Reflex arc = withdrawal from a painful stimulus = negative feedback
            - Reflex arc = knee jerk = tapping the knee tendon causes sudden stretching of the muscle, which lead to contraction of that muscle that creates the knee jerk = negative feedback
        - Reflex arc = receptor → sensory neuron → integration center → motor neuron → effector
            - Receptor = site of stimulus
            - Sensory neuron = carries impulse from receptor to integration center
            - Integration center = connects sensory to motor neuron via synapse inside the CNS
                - Monosynaptic = no interneuron, direct synapse of sensory to motor
                - Polysynaptic = interneuron(s) present
            - Motor neuron = carries impulse toward effector
            - Effector = site of response to the stimulus
        - Examples of reflexes: knee-jerk, withdrawal from pain
        - Effects on flexor and extensor muscles
            - During the knee-jerk, in addition to contracting the extensor, the reflex relaxes the flexor
            - Golgi tendon reflex: sudden contraction of the quads (extensor), causes a negative feedback that relaxes the quads and contracts the hamstrings (flexor)
    - Role of spinal cord and supraspinal circuits
        - Spinal cord provides the synapse (or synapses if it's polysynaptic) for the reflex arc
        - Even though the reflex arc bypasses the brain, the brain is still aware of it happening
        - Reflex sends signals to CNS via spinal cord, CNS perceives stimulus and prepares more complex response
        - Supraspinal circuits: descend from CNS to inhibit reflexes, fine tune them so they proceed smoothly
- Integration with endocrine system: feedback control

    - Feedback control in hypothalamus. Communicates with pituitary
    - Pituitary sends out hormones which have effect → signal of hormone effects ready by hypothalamus → hypothalamus tells pituitary to chill

Nerve Cell (BIO)

- **Cell body**: site of nucleus, organelles
    - Contains nucleus and organelles just like any other cell
    - Has well-developed RER and golgi (makes lots of proteins)
- **Dendrites**: branched extensions of cell body
    - Receptive region of the nerve = gets input
    - Branching helps increase surface area for reception
- **Axon**: structure and function
    - Axon = conducting region of the nerve
    - Axon terminals = secretory regions of nerve
    - Other names for axon terminal = synaptic knob = bouton
- Myelin sheath, Schwann cells, insulation of axon
    - **Myelin sheath** = covers the axon intermittently, with gaps called nodes of Ranvier
    - Purpose of myelin sheath is to speed up conduction by insulating the nerve in intervals. This intermittent insulation causes action potential to jump from one node of Ranvier to the next
    - **Schwann cells** = makes myelin sheath in the peripheral nervous system by wrapping around the axon
    - **Oligodendrocytes** = the central nervous system analogue of Schwann cells, makes myelin sheath around CNS axons
    - **Insulation of axon** = achieved by myelin sheath. Insulation occurs in intervals, which causes action potential to jump from one node of Ranvier to the next
    - Myelin sheath is a good insulator because it is fatty and does not contain any channels
- **Nodes of Ranvier**: propagation of nerve impulse along axon
    - Action potential jumps from one node of Ranvier to the next
    - This jumping of action potential speeds up conduction in the axon
- Synapse: site of impulse propagation between cells
    - Synapse = conduction from one cell to another
    - Axodendritic synapse = axon terminal of one neuron (presynaptic) → dendrite of another neuron (postsynaptic)
    - Axosomatic synapse = axon terminal of one neuron (presynaptic) → cell body of another neuron (postsynaptic)
    - Axoaxonic synapse (rare) = axon terminal of one neuron (presynaptic) → axon hillock of another (postsynaptic)
- Synaptic activity: transmitter molecules
    - Transmitter molecules = neurotransmitters
    - Action potential → release of neurotransmitters by presynaptic axon terminal → picked up by receptor of postsynaptic neuron
    - Release of neurotransmitter = exocytosis of vesicles containing neurotransmitters. Triggered by calcium influx when action potential reaches axon terminal.
    - Neurotransmitter reception = diffusion of neurotransmitter across the synaptic cleft, binds to receptor, opens up ion channels that causes a change in membrane potential of the postsynaptic neuron (graded potential). If this graded potential is large enough, it will trigger a full-fledged, all-or-nothing action potential in the postsynaptic neuron
    - Neurotransmitters are quickly eliminated (destroyed by enzymes, reuptake by presynaptic terminal, or diffuse away) so that they don't persistently stimulate the postsynaptic neuron
    - **Neurotransmitter molecules**:
        - Acetylcholine (ACh)

        - Norepinephrine (NE)
        - Dopamine
        - Serotonin
        - Histamine
        - ATP
        - GABA
    - Synaptic knobs
        - Another name for axon terminal
        - Contains vesicles of neurotransmitters waiting to be exocytosed
        - Action potential reaching the synaptic knob causes an influx of calcium, which signals the vesicles to fuse with cell membrane (exocytosis) to release the neurotransmitters into the synaptic cleft
    - Fatigue
        - Continuous synaptic activity → depletion of neurotransmitters → fatigue
    - Propagation between cells without resistance loss
        - Action potential is all-or-nothing
        - As long as neurotransmitters cause the postsynaptic cell to reach a certain threshold potential, the action potential induced is just as large as the presynaptic action potential
        - In summary, propagation between cells involves no resistance loss because the postsynaptic action potential is just as large as the presynaptic potential - all action potentials are all-or-nothing
    - Firing of synapse causes change in postsynaptic membrane potential
        - **EPSP**: excitatory postsynaptic potential, adds up to cause action potential
        - **IPSP**: inhibitory postsynaptic potential, adds up to discourage action potential
    - Acetylcholine vs epinephrine in parasympathetic, sympathetic nervous systems
        - All preganglionic neurons in autonomic and postganglionic neurons in parasympathetic nervous system use acetylcholine
        - Postganglionic neurons in sympathetic nervous system use epinephrine
- Resting potential: electrochemical gradient
    - Na^+-K^+ pump = 3 Na^+ out, 2 K^+ in = net negative to the inside, net positive to the outside
    - K^+ leakage = the resting cell membrane has channels that allow K^+ to leak out, but don't allow Na^+ to leak in = net negative to the inside, net positive to the outside
    - Resting potential is -70 mV because the cell is more negative on the inside, and more positive on the outside
    - Electrochemical gradient = combination of electrical and chemical gradient = both electrical potential and ion concentration gradient across membrane
- Action potential
    - Stages of an action potential:
        - 1. **Resting**: cell at rest, sodium-potassium pump maintaining resting potential (-70 mV). Lots of sodium outside, lots of potassium inside. Ion channels closed so the established ion gradient won't leak
        - 2. **Depolarization**: sodium channels open, positive sodium rushes inside, membrane potential shoots up to +30 mV. Lots of sodium inside, lots of potassium inside.
        - 3. **Repolarization**: potassium channels open, sodium channels close, positive potassium rushes outside, membrane potential drops back down. Lots of sodium inside, lots of potassium outside (opposite of resting state)
        - 4. **Hyperpolarization**: potassium channels don't close fast enough, so membrane potential drops below resting potential for a bit
        - 5. **Refractory period**: sodium-potassium pump works to re-establish the original resting state (more potassium inside, sodium outside). Until this is done, the neuron can't generate another action potential.

        - Absolute refractory period = from depolarization to the cell having re-established the original resting state
        - Relative refractory period = after hyperpolarization till resting state re-established
    - Threshold, all-or-none
        - When a stimulus (graded potential) depolarizes above a threshold value, an action potential will occur
        - Action potentials are all-or-none, meaning that if it occurs, all action potential have the same magnitude
        - One graded potential just barely makes the threshold value, another overshoots it a lot, but both will cause same action potential
    - Sodium/potassium pump
        - 3 sodium out
        - 2 potassium in
        - Net positive out
        - Causes membrane to be more negative on the inside, hence negative membrane potential
- Excitatory and inhibitory nerve fibers: summation, frequency of firing
    - Excitatory = stimulates an action potential to occur
    - Excitatory synapse = receptor binding causes postsynaptic potential to be more positive (depolarization) = if it gets above threshold, action potential results
    - Inhibitory = inhibits an action potential from occurring
    - Inhibitory synapse = receptor binding causes postsynaptic potential to be more negative (hyperpolarization) = makes it more difficult to reach threshold
    - Summation = two or more nerves firing at the same time
        - Two subthreshold excitatory nerves firing at the same time can sum to reach the threshold
        - A threshold excitatory nerve and an inhibitory nerve firing at the same time, and the resultant signal won't reach the threshold
    - Frequency = firing, then quickly firing again
        - If the first fire is subthreshold, fire again before the previous depolarization dies, and the new depolarization will be even higher than the first time
- Glial cells, neuroglia
    - Qualities of glia
        - Capable of cell division, multiply to fill empty space in CNS after trauma
        - Do not convey electrical signals
        - Often responsible for brain cancer
    - 6 types of glial cells
        - 1) **Microglia**: macrophages, break down debris and potentially harmful microbes
        - 2) **Ependymal cells**: help circulate cerebrospinal fluid
        - 3) **Satellite cells**: support ganglia (neuronal bodies in PNS)
        - 4) **Astrocytes**: star shaped cells in CNS, give physical support to neurons and maintain mineral and nutrient balance in interstitial space
        - 5) **Oligodendrocytes**: myelinate multiple axons at one time in CNS, arms extend outwards which myelinate
        - 6) **Schwann cells**: myelinate single axons in PNS
    - White vs grey matter: white = myelinated fiber tracts, grey = bundles of neuron bodies

Electrochemistry (GC)

- Concentration cell: direction of electron flow, Nernst equation
    - Half reactions
        - Oxidation half reaction describes the species that loses electrons (increases in charge)
        - Reduction half reaction describes the species that gains electrons (decreases in charge)
    - Reduction potential = potential of the reduction half reaction

- Oxidation potential = potential of the oxidation half reaction = reverse the sign of the reduction potential
- Cell potential = Reduction potential + Oxidation potential
- Direction of electron flow
  - Electrons always flow from the Anode to the Cathode. Mnemonic: A to C in alphabetical order.
  - Oxidation (at the anode) produces electrons (and cations) and shoots out electrons toward the cathode. The cathode receives those electrons and uses them for reduction.
  - Naturally, the species with the highest oxidation potential (lowest reduction potential) will be the anode, and the species with the highest reduction potential will be the cathode
  - Electrons flow in wires and electrodes, while ions flow in the electrolyte solution, thus creating a completed circuit
- Nernst equation

$$E = E^0 + \frac{RT}{nF} \ln \frac{[\text{Ox}]}{[\text{Red}]}$$

  - At 298 K, and in base 10 log form, the equation is
    - $E = E^\circ + .06/n \log(Q)$
  - Used to find potential difference in a cell in nonstandard conditions

Biosignaling (BC)

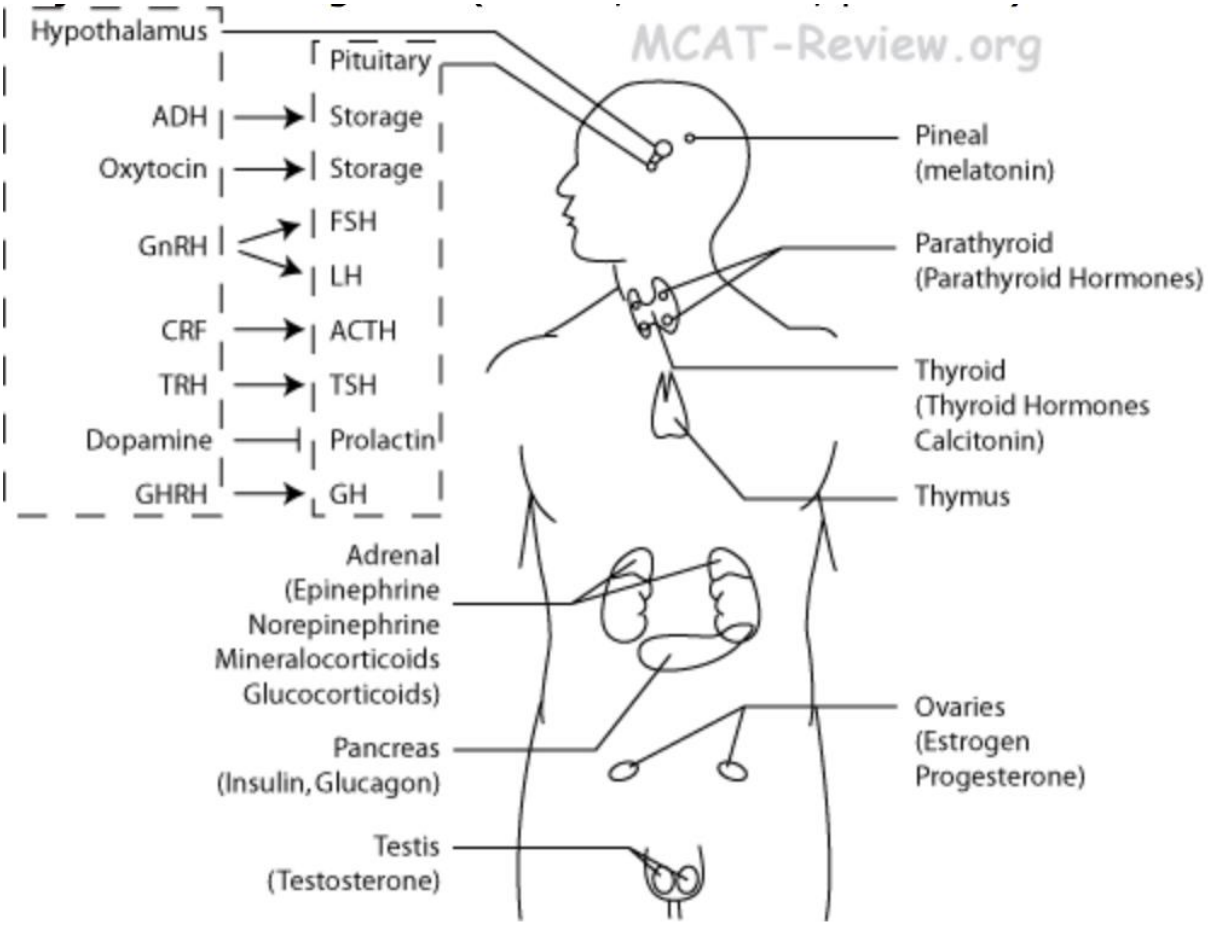
- Gated ion channels: let ions from one side of membrane to another
  - **Voltage gated**
    - Na and K voltage gated channels: involved in action potential. Speed at which they open are different
    - Ca^{2+} voltage gated channels: located at presynaptic side of synaptic cleft. Action potential causes channels to open, Ca^{2+} to flow into cell. This causes efflux of NT vesicles
  - **Ligand gated**
    - Transmembrane proteins activated by binding of a specific ligand
    - "Lock and key" model
    - When ligand binds to allosteric site, channel opens up
- Receptor enzymes: bind neurotransmitters or hormones and trigger processes in cell
  - Neurotransmitter binding to receptor makes postsynaptic side more permeable to ions. This completes the transfer of the neural impulse
  - Neurotransmitters released back into cleft after binding to receptor
    - Need ways to get rid of neurotransmitters in cleft
      - Destroy using an enzyme in the cleft
      - Reabsorb into presynaptic side
      - Diffuse out of cleft
- G protein-coupled receptors
  - Example of secondary messenger system
  - Binding of neurotransmitter to this receptor causes release of an attached G-protein's alpha subunit
  - Alpha subunit release in postsynaptic neuron has variety of effects:
    - 1) activates separate specific ion channels
    - 2) activate a second messenger (ex. cAMP)
    - 3) activate intracellular enzymes
    - 4) activate transcription

Lipids (BC, OC)

- Description, structure
    - Description; varying structures but all have *low solubility* in water and *high solubility* in nonpolar organic solvents
        - Major classes: fatty acids, triacylglycerols, phospholipids, glycolipids, sphingolipids, steroids, terpenes, waxes
    - **Steroids**
        - Four-ringed structures
        - Maintain membrane stability, fluidity. Precursor for steroid hormones
            - Cholesterol and membrane fluidity
                - **Moderate to high temps**: Cholesterol makes membranes more rigid by attracting adjacent phospholipid tails
                - **Low temps**: Cholesterol makes membrane more fluid by filling in gaps between phospholipid tails
    - **Terpenes** and terpenoids
        - Part of pigments in the body
        - ex. Vitamin A (important for vision)

Endocrine System: Hormones and Their Sources (BIO)

- Function of endocrine system: specific chemical control at cell, tissue, and organ level
    - Endocrine system = make hormones = specific control of all target cells of that hormone
- Definitions of endocrine gland, hormone
    - Endocrine glands secrete hormones into surrounding tissue fluids
    - Endocrine vs exocrine, autocrine, paracrine
        - **Endocrine**: hormone, no duct, acts long distances
        - **Exocrine**: non-hormone secretions into ducts
        - **Autocrine**: local chemicals, act short distances on themselves
        - **Paracrine**: local chemicals, act short distances on other cells
    - **Hormone** = chemicals that regulate metabolism and function of cells
- Major endocrine glands: names, locations, products



- Hypothalamus, Posterior Pituitary (hydrophilic, peptide)
  - Releasing hormones/factors stimulates pituitary to release its hormone
  - GnRH = Gonadotropin Releasing Hormone = stimulates pituitary to release FSH and LH
  - CRF = Corticotropin Releasing Factor
  - TRH = Thyroid Releasing Hormone
  - Dopamine = inhibits prolactin release
  - GHRH = Growth Hormone Releasing Hormone
  - ADH = Antidiuretic Hormone = Vasopressin = water reabsorption in kidney = conserve water, increase blood pressure
  - Oxytocin = stimulates uterine contractions during labor, also milk secretion during suckling
- Anterior Pituitary (hydrophilic, peptide)
  - **F**SH = Follicle Stimulating Hormone = Stimulate ovary follicles to mature, testis to produce sperm
  - **L**H = Luteinizing Hormone = LH surge triggers ovulation, stimulates testis to produce testosterone
  - **A**CTH = AdrenoCorticoTropic Hormone = Stimulates adrenal cortex to release glucocorticoids and mineralocorticoids
  - **T**SH = Thyroid Stimulation Hormone = Stimulate thyroid to release thyroid hormones
  - **P**RL = Prolactin = Stimulates breast to product milk
  - **E** = Endorphins
  - **G**H = Growth Hormone = Stimulates growth of muscle, bone, burns fat
- Pineal: makes melatonin, which makes you sleepy at night
- Thyroid (hydrophilic AND hydrophobic, tyrosine AND peptides)
  - Thyroid hormones: increase metabolism, requires iodine
  - Calcitonin: turns blood Ca^{2+} into bone. Lowers blood Ca^{2+}

- Parathyroid (hydrophilic, peptide)
  - Makes Parathyroid Hormone (PTH), which increases blood Ca^{2+} by bone resorption, dietary calcium absorption, and calcium reabsorption in kidneys
  - Gut: increases calcium uptake in gut
  - Kidney: increases phosphate excretion, forming insoluble calcium phosphate when phosphate reacts with calcium
- Thymus: stimulates T cells to develop
- Adrenal cortex (hydrophobic, steroids)
  - Mineralocorticoids = aldosterone = increase Na^+ and water retention, raises blood pressure
  - Glucocorticoids = cortisol = longer-term stress response compared to medulla hormones, responds more to chronic instead of acute stress
  - Androgens = testosterone
- Adrenal medulla (hydrophilic, tyrosine)
  - Supplement nervous system activity by secreting neurotransmitters into the blood (provides slower, more generalized sympathetic nervous system response)
  - Epinephrine and norepinephrine = fight or flight response
    - Constrict blood vessels of internal organs/skin, dilate blood vessels on skeletal muscle
- Pancreas (hydrophilic, peptide)
  - Glucagon = increases blood sugar (break down glycogen, stimulate gluconeogenesis)
  - Insulin = lower blood sugar (stimulates glucose uptake by cells)
- Testes and ovaries
  - Hormones stimulate reproductive development functions
  - Testosterone (testes): facilitates male puberty and spermatogenesis
  - Progesterone and estrogen (ovaries): facilitates female puberty, menstruation, and pregnancy
- Placenta
  - Secretes peptide hormone to prepare uterus to support pregnancy
  - HCG signals for ovaries to continue making progesterone and estrogen → suppresses menstruation, allowing for buildup of uterine wall

- Major types of hormones
  - 3 major types of hormones:
    - **Peptide**
      - Water soluble
      - binds to membrane-bound receptor, triggers second messenger system
      - Manufactured in RER as *prepohormones*, cleaved in ER, cleaved and glycosylated in Golgi and then packaged for export
    - **Steroid**
      - Fat soluble
      - Binds to carrier proteins for transport in bloodstream, diffuses through cell membrane and binds to receptors in cytosol and mitochondria.
      - Acts on level of transcription so primary mechanism of action is increasing certain protein levels in the effector
      - Manufactured in SER and mitochondria
    - **Tyrosine**
      - Either water or fat soluble
      - Thyroid hormones (fat soluble)
        - Diffuses through membrane to bind to receptors in the nucleus
        - Strong affinity for binding protein, increases duration of its effects
        - Primary mechanism of action: increasing transcription of certain genes

        - Epinephrine and norepinephrine (water soluble)
            - Dissolve in blood to bind to receptors on target tissue
            - Act mainly through secondary messenger cAMP
- Neuroendocrinology - relation between neurons and hormonal system

Endocrine System: Mechanisms of Hormone Action (BIO)

- Cellular mechanisms of hormone action
    - **Water soluble hormones**
        - Cannot cross the plasma membrane
        - Bind to membrane receptors on the outside of cells
        - Secondary messengers then relay the signal inside the cell
    - **Lipid-soluble hormones**
        - Able to cross the plasma membrane
        - Directly activate genes
    - **cAMP pathway**:
        - 1) Amino acid hormone binds membrane receptor
        - 2) G protein activated
        - 3) Adenylate cyclase activated
        - 4) cAMP made
        - 5) Protein kinase cascade
    - **Phospholipid pathway:**
        - 1) Amino acid hormone binds membrane receptor
        - 2) G protein activated
        - 3) Phospholipase C activated
        - 4) Membrane phospholipid split into DAG and IP3
        - 5) DAG triggers protein kinase cascade
        - 6) IP3 release Ca^{2+} from the ER
    - **Steroid pathway:**
        - 1) Steroid hormone (and thyroid hormone even though it's amino acid based) goes inside the cell
        - 2) Hormone binds receptor inside the cell (cytoplasm or nucleus)
        - 3) Hormone-receptor complex (transcription factor) turns certain genes on inside the nucleus
- Transport of hormones: blood supply
    - Hormones travel long distances via blood and lymph
- Specificity of hormones: target tissue
    - Specificity depends on the target cells having the receptors for the hormone, and non-target cells lacking receptors for the hormone
    - Cells can either upregulate or downregulate the receptors they express
- Integration with nervous system: feedback control
    - The nervous system can modulate and override normal control of hormones based on the status of the body. For example, the body's blood "normal" glucose level is set higher when you're under stress
    - Hormones can modulate the nervous system. For example, low estrogen levels during menses give you a bad mood
    - Normal control of hormones
        - Humoral: glands directly respond to chemical levels in the blood (parathyroid response to low blood calcium)
        - Neural: glands release hormones when stimulated by nerves (fight or flight response)
        - Hormonal: glands release hormones when stimulated by other hormones
- Regulation by second messengers

- Second messengers are molecules that relay signals received at receptors on the cell surface - such as the arrival of protein hormones, growth factors, etc. - to target molecules in the cytosol and/or nucleus
- The amplify the strength of the signal
- 3 major classes of second messengers:
  - Cyclic nucleotides (e.g. cAMP and cGMP)
    - Binding of hormone to its receptor activates a G protein which activates adenylyl cyclase
    - The resulting rise in cAMP turns on appropriate response in cell by either (or both):
      - Changing molecular activities in cytosol using Protein Kinase A (PKA) - a cAMP dependent protein kinase that phosphorylates target proteins
      - Turning on a new pattern of gene transcription
  - **Inositol triphosphate (IP_3) and diacylglycerol (DAG)**
    - Peptide and protein hormones activate the intracellular enzyme **phospholipase C** - hydrolyzes phospholipids
    - DAG remain in inner membrane and recruits **Protein Kinase C** (PKC) - a calcium dependent kinase that phosphorylates many other proteins that bring about changes in the cell
    - **Inositol-1,4,5-triphosphate** (IP_3) diffuses through cytosol and binds to receptors on ER causing release of Ca^{2+} into cytosol
  - Calcium ions (Ca^{2+})
    - Most widely used intracellular messengers
    - Can trigger many events such as muscle contraction, exocytosis, activation of T cells and B cells, adhesion to extracellular matrix, apoptosis, and biochemical changes mediated by Protein Kinase C

Content Category 3B: Structure and integrative functions of the main organ systems

Respiratory System (BIO)

- General function
  - Gas exchange, thermoregulation
    - Gas exchange: takes place through passive diffusion**. pO2 is high in the lungs and low in the capillaries.** Causes O2 to diffuse into the capillaries. **pCO2 is low in the lungs but high in the capillaries**, so CO2 diffuses into the lungs of exhalation
      - **Ficks Law**: rate of diffusion is directly proportional to SA and differential partial pressure across the membrane, inversely proportional to membrane thickness
  - Protection against disease: particulate matter
    - Nasal cavity traps dust particles
      - Nasal hairs and mucus trap dust particles. Cilia move them towards the pharynx, so they can be removed via spitting/swallowing
- Structure of lungs and alveoli
  - Before entering lungs, trachea splits into left and right bronchi. Each bronchi branch to many bronchioles. Bronchioles terminate in alveolar sacs composed of many alveoli
    - **Alveoli** are interface for exchange of CO2 and O2. Introduces respired oxygen into blood and gets CO2 from blood for expulsion via exhalation (HIGH SA)
- Breathing mechanisms
  - Diaphragm, rib cage, differential pressure
    - Inspiration and expiration governed by **differential pressures** in chest cavity and airway
    - **Inspiration**: medulla oblongata signals for diaphragm (thin sheet of skeletal muscle) to contract. Makes pressure in air cavity and alveoli more negative so atmospheric pressure forces air into low pressure areas
    - **Expiration**: medulla oblongata stops signaling, diaphragm relaxes
  - Resiliency and surface tension effects
    - **Resiliency**: refers to elasticity of lungs. Increases pressure in lungs, chest cavity, and alveoli, expelling air to the outside atmosphere
    - **Surface tension effects**: thin layer of water on inside of alveoli that creates a high surface tension due to H-bonding. Effect is amplified because alveoli has a large SA:V ratio. This exerts collapsing force on the alveolus and opposes lung expansion
      - Countered by excretion of a **surfactant**, which breaks up IMFs between water molecules
- Thermoregulation: nasal and tracheal capillary beds; evaporation, panting
  - Panting: increases moisture on lungs, encourages evaporation which cools down body
  - Capillary beds help to fan out blood over a large SA
- Particulate filtration: nasal hairs, mucus/cilia system in lungs
- Alveolar gas exchange
  - Diffusion, differential partial pressures
    - Passive diffusion of O2 into the blood due to concentration gradient of O2 between alveoli and blood
  - **Henry's Law** (GC)
    - Concentration of O2 dissolved in blood is directly proportional to partial pressure of O2 in equilibrium with the blood

            - Higher partial pressure of O2 in alveoli → more O2 dissolved in blood
        - **Greater pressure = greater solubility of gas**
- pH control
    - Deoxygenated hemoglobin acts as blood buffer by accepting excess protons from CO2 to bicarbonate reaction
    - Respiratory system controls pH by **adjusting breathing rate**
        - More breathing = expel more CO2 = increase pH
        - Less breathing = retain more CO2 = decrease pH
- Regulation by nervous control
    - CO2 sensitivity
        - Central and peripheral chemoreceptors detect CO2 concentrations. The medulla interprets these signals and regulates breathing accordingly
            - Regulating breathing allows for control of [CO2]

Circulatory System (BIO)

- Functions: circulation of oxygen, nutrients, hormones, ions and fluids, removal of metabolic waste
- Role of thermoregulation
    - Arterioles and capillaries can regulate heat exchange
- Four-chambered heart: structure and function
- Endothelial cells
- Systolic and diastolic pressure
    - **Systole**: when the ventricles contract
    - **Diastole**: when entire heart relaxes and then atria contract
    - **Systolic Pressure**: Higher blood pressure. Pressure during systole phase
    - **Diastolic Pressure**: Lower blood pressure. Pressure when heart relaxes, atria contract
- Pulmonary and Systemic circulation
    - **Systemic Circulation**: directs oxygenated blood towards *tissues* and returns deoxygenated blood to heart
        - 1) Blood from **left ventricle** of the heart pumped to **aorta**
        - 2) Aorta branches into smaller **arteries** which then branch into smaller **arterioles**
        - 3) Arterioles branch into still smaller **capillaries** which drops O2 off at tissue
        - 4) Blood from capillaries collected into **venules**
        - 5) Venules converge into larger **veins**
        - 6) Veins converge into **superior and inferior venae cavae**
        - 7) Vena cavae empty into **right atrium** of the heart
    - **Pulmonary Circulation**: directs deoxygenated blood towards *lungs* and returns oxygenated blood to heart
        - 1) Deoxygenated blood from **right ventricle** of the heart pumped to **pulmonary arteries**
            - Pulmonary arteries are **only arteries which carry *deoxygenated blood***
        - 2) Branches into smaller **arteries** which then branch into smaller **arterioles**
        - 3) Arterioles branch into smaller **capillaries** in lungs which pick up O2 from lungs
        - 4) Blood from capillaries collected into **venules**
        - 5) Venules converge into large **veins**
        - 6) Veins converge into the **pulmonary veins** which lead to the heart
        - 7) Pulmonary veins empty into **left atrium** of the heart
- Arterial and venous systems (arteries, arterioles, venules, veins)
    - Structural and functional differences
        - Functional
            - Arterial system (arteries, arterioles, capillaries) carry oxygenated blood
            - Venous system (venules, veins, venae cavae) carry deoxygenated blood

        - Arteries: **pressure store**
        - Arterioles: smaller than arteries but still wrapped in smooth muscle
        - Capillaries: exchange of materials within tissues
        - Veins: **volume store** for blood travelling back to heart, reservoir
    - Pressure and flow characteristics
        - Contraction of smooth muscle around arteries and arterioles regulate blood pressure and reroute blood
        - Pressure is inversely related to cross-sectional area
            - **Capillaries have highest cross-sectional area, arteries lowest**
        - Pouseille's Law
            - Shows radius has VERY LARGE EFFECT on blood flow
-

Q	Flow rate
P	Pressure
r	Radius
η	Fluid viscosity
l	Length of tubing

$$Q = \frac{\pi \mathrm{P} r^4}{8\eta l}$$

- Capillary beds
    - Mechanisms of gas and solute exchange
        - Capillary walls are only one cell thick. Enable nutrients to cross capillary walls based on differential pressures
        - 4 methods for crossing capillary walls:
            - 1) Pinocytosis
            - 2) Diffusion or transport through capillary cell membranes
            - 3) Movement through pores (fenestrations) in cells
            - 4) Movement through space between the cells
    - Mechanism of heat exchange
        - Thin walls enable heat exchange with surroundings
    - Source of peripheral resistance
- Composition of blood
    - Plasma, chemicals, blood cells
        - **Erythrocytes** (red blood cells): no nucleus or organelles, basically only contain hemoglobin
        - **Leukocytes** (white blood cells): contain organelles but not hemoglobin
        - **Albumins**: transport fatty acid and steroids, control osmotic pressure
            - Increase in albumin in blood causes influx of interstitial fluid, increasing blood pressure
        - **Fibrinogen**: protein that clots plasma in blood
        - Most plasma proteins made in the **liver**
    - Erythrocyte production and destruction; spleen, bone marrow
        - RBC's made from stem cells in bone marrow. Destroyed by being passed through narrow

channels in spleen
    - Regulation of plasma volume
        - Volume of blood regulated by altering amount of water in plasma
- Coagulation, clotting mechanisms
- Oxygen transport by blood
    - Hemoglobin, hematocrit
        - **Hemoglobin**: protein which binds O2, allosteric binding, so binding of O2 once increases affinity in future binding
        - **Hematocrit**: ratio of volume of RBCs to total volume of blood
    - Oxygen content
    - Oxygen affinity
        - Sigmoidal binding curve (indicates allosteric binding)
        - The less affinity of O2 for hemoglobin, the GREATER amount of O2 can get to tissues (Hb can let go of O2) – TOW RIGH
        - **2,3-BPG**: decreases affinity of O2 for hemoglobin
            - Released in high CO2, H+ ion concentrations, or in high T environments
        - CO2: binding to Hb causes **decreased** affinity for O2
- Carbon dioxide transport and level in blood
    - **Overall path of CO2 transport**
        - 1) CO2 diffuse into red blood cells from tissues
        - 2) Carbonic anhydrase converts CO2 to bicarbonate
        - 3) Bicarbonate flows down its concentration gradient from RBC's into plasma cells
        - 4) Plasma cells flow to lungs, bicarbonate diffuses back to RBC's and is converted to CO2
        - 5) Process repeats
    - Exponential binding curve
    - Increased pCO2 in lungs → increased CO2 in blood → more CO2 bound to hemoglobin
    - Effect of O2 on CO2 binding
        - **Haldane effect**: Oxygenation of Hb causes affinity for CO2 to be lowered. Facilitates transfer of CO2 from blood to lungs (oxygenation of Hb at alveoli causes dissociation of CO2)
    - 3 ways CO2 is carried to blood:
        - 1) Dissolved in solution
        - 2) As bicarbonate ← **By FAR most dominant**
        - 3) Carbamino compounds
    - Bicarbonate
        - CO2 and H2O react to make HCO3- and H+
            - Reaction catalyzed by **carbonic anhydrase**
        - Reaction is in equilibrium, direction depends on concentration of species, which vary based on location
            - In tissues: **CO2 concentration high, so rxn proceeds →**
            - In lungs: **pCO2 low, so rxn proceeds ←**
        - **Chloride shift**: decreases negative charge in blood by absorbing chloride ions into plasma cells and releasing bicarbonate in turn
- Nervous and endocrine control
    - Nervous control of heart contractions
        - **Sinoatrial (SA) node**: group of specialized cardiac muscle cells. Contract at regular intervals without PNS input. Contractions propagate via gap junctions. Causes heart contractions.
        - **Atrioventricular (AV) node**: Action potential from SA node propagates here. Slower to depolarize than SA node so atria can finish contracting before ventricles being to

- **Baroreceptor reflex**: Nervous regulation of blood pressure, fast
    - Communicates with SNS or PNS to alter BP by slowing/speeding up contractions
    - PNS: counteracts increase in BP by slowing contractions
    - SNS: counteracts decrease in BP by increasing contractions
- **Renin-anginotension-alderosterone system**: Hormonal regulation of blood pressure, slow-acting
    - Secretion of renin triggers a cascade of enzymatic effects leading to increased intake and retention of water
    - More water → higher blood volume → higher blood pressure
    - ADH and aldosterone are involved in this effect

Lymphatic System (BIO)

- Structure of lymphatic system
    - Open system
        - Interstitial fluid gets in by flowing over overlapping endothelial cells. Particles force themselves into cracks between cells.
            - Cells overlap in such a way that once they're in, particles can't get out
    - Processed fluid drains out of lymph via *thoracic duct* and *right lymphatic duct*
        - Right lymphatic duct drains lymph from right arm and head. Thoracic arm gets rest of body
    - 2 ways fluid is propelled through lymph:
        - 1) Smooth muscle around larger lymph vessel walls pushes lymph through
        - 2) Lymph vessels are squeezed by adjacent skeletal muscle, body movements, arterial pulsations, and compression from objects outside the body
- Major functions
    - Equalization of fluid distribution
        - Collects excess interstitial fluid that results from fluid exchange in capillary beds and returns it to the blood
    - Transport of proteins and large glycerides
        - Removes proteins and large glycerides that are too big to get taken up by capillaries
    - Production of lymphocytes in immune reactions
        - Lymph nodes contain lymphocytes which are stimulated to respond to pathogens
    - Return of materials to the blood
        - Recycles materials by passing it through lymph nodes, which both filter particles and trigger a potential immune response
        - Filtered lymph returned to blood

Immune System (BIO)

- Innate (non-specific) vs. adaptive (specific) immunity
    - **Innate**: occurs quickly at the start of an infection, non-specific
    - **Adaptive**: slower to occur, specific
        - **Primary response**: immune response for first exposure to an antigen, takes about 20 days to reach its full potential
        - **Secondary response**: immune response after first exposure to an antigen, takes 5 days to reach its full potential
- Adaptive immune system cells
    - **T-lymphocytes**: cell-mediated immunity
        - 4 types: helper T-cells, memory T-cells, suppressor T-cells, killer T-cells
            - **Helper T-cells**: activate B and T lymphocytes to make secondary immune response possible
            - **Memory T-cells**: recognize a specific antigen during secondary immune response

(similar to memory B-cells)
- **Suppressor T-cells**: negative feedback and regulatory role in immune system
- **Killer T-cells**: perforate infected cells to destroy them
  - Can kill many cells without being destroyed themselves

- **B-lymphocytes**: humoral or antibody-mediated response
  - Effective against free-floating pathogens. Can't act against invading substances within body cells
  - B-lymphocytes synthesize antibodies
    - Antibodies can either float freely or attach to B-lymphocytes and become B-cell receptors
  - Differentiate into *plasma cells* and *memory-B cells* during primary response after BCR (B-cell receptor) recognizes appropriate antigen
    - **Plasma cells**: synthesize free antibodies
    - **Memory B-cells**: immune cells that recognize the specific antigen, remain in blood

- Innate immune system cells
  - **Phagocytes**: earliest responders. Class of cells which eat dangerous substances and destroy them
    - Macrophages: first responders, can engulf ~100 bacteria at once
    - Neutrophils: arrive after macrophages, stored in bone marrow until they're needed. Drawn to infected area by chemicals released by infected tissue or the infection itself. Can engulf ~20 bacteria at once
    - Monocytes: circulate in blood until they're needed. Leak out through capillaries. Once they're in infected tissue, they mature to become macrophages
  - Pus: fluid made of dead macrophages and neutrophils (which die after engulfing bacteria)
- Tissues
  - Bone marrow: synthesize B and T cells, site of clonal selection for B-cells
  - Spleen: site of lymphatic tissue and B and T cell activation
  - Thymus: site of maturation and clonal selection for T cells
  - Lymph nodes: site of activation of B and T cells
- Concept of antigen and antibody
  - Antigen: potentially harmful foreign particle
  - Antibody: particle which can recognize and bind to an antigen
    - 4 ways an antibody promotes pathogen destruction
      - 1) Binds to a pathogen, marks it for consumption by macrophages and natural killer cells
      - 2) Bound antibody may trigger a cascade involving blood proteins which perforate the antibody
      - 3) Antibodies may cause antigens to stick together or, for toxins, block their chemically active portions
      - 4) Antibodies may attach their bases to *mast cells*. These release histamines and other chemicals when the antibody binds to a pathogen
- Antigen presentation
  - MHC's (Major histocompatibility complex (display antigens for recognition
  - Signal 1 and Signal 2: signals needed for B and T cell action. *Both* must be present for activation to occur
    - **Signal 1**: BCR and TCR recognize its appropriate antigen
      - T-cells: Signal 1 received from professional APCs. APCs engulf pathogens and display antigen on MHC II's.
      - B-cells: Signal 1 received when an antibody binds to multiple BCR's on the same cell

        - **Signal 2**: "danger signal," received when there's an actual infection occurring. "Oh shit, this antigen is harmful"
            - T-cells: Signal 2 provided by activation of innate immune system (ex: increase in circulating cytokines)
            - B-cells: Signal 2 provided by signals from helper T-cells
- **Clonal selection**: selects for B and T cells that do their job well
    - Positive selection: allows T and B cells, which can recognize host MHC's to survive. Those that can't undergo apoptosis
    - Negative selection: lets T and B cells which don't attack host cells survive. Those that do undergo apoptosis
    - Opposing processes ensure only good T and B cells are kept
- Antigen-antibody recognition
    - Process by which an antibody recognizes a foreign particle
    - Antigenic determinant: binding portion of antibody, highly specific for a certain pathogen
- Structure of antibody molecule
    - Y-shaped, with "variable regions" making up the arms of the Y
    - Variable regions can bind specifically to antigens, determines specificity
    - **Disulfide bonds** hold the antibody together
- Recognition of self vs. non-self, autoimmune diseases
    - Failure in negative selection (destroying lymphocytes which attack healthy cells) can cause autoimmune diseases
- Major histocompatibility complex
    - Membrane proteins which display antigens for recognition by immune system
    - 2 classes of MHC's
        - **MHC I**: Display antigens derived from *intracellular pathogens* (viruses, some bacteria). *Endogenous pathway*
            - All nucleated cells have these since all nucleated cells can be attacked by intracellular pathogens
        - **MHC II**: Display antigens derived from *extracellular pathogens*. *Exogenous pathway*.
            - **Only cells that phagocytose need these**, since these pathogens must be phagocytosed to enter the cell
            - Professional antigen-presenting cells (APCs): Cells that phagocytose extracellular bacteria for the sole purpose of displaying their antigens. WAY TO TAKE ONE FOR THE TEAM. WHAT A HOMIE CELL.
                - e.g., Macrophages, some B-cells, dendritic cells
    - Steps for how antigens are processed to be displayed on MHC's
        - 1) **Antigen uptake**: pathogen is either already in the cell (MHC I) or needs to be phagocytosed (MHC II)
        - 2) **Antigen processing**: pathogen processed into smaller peptides in cytosol (exogenous) or in vesicles (endogenous)
        - 3) **Peptide-MHC association**: antigens associate with MHC in the ER (endogenous) or via fusion with vesicles (exogenous)
        - 4) **Cell surface expression**: antigen-MHC complex placed on cell surface for interaction with appropriate immune cells

Digestive System (BIO)

- **Ingestion**
    - Saliva as lubrication and source of enzymes
        - **α-Amylase**: breaks down glucose polymers
        - Saliva lubricates the food in esophagus, helping it move down

- Ingestion; esophagus, transport function
    - Chewing increases SA of food, enabling more enzymatic activity
    - Bolus: clump of food chewing shapes food into
        - Bolus is pushed into esophagus
    - **Peristalsis**: a contraction of smooth muscle in the digestive tract; moves food down
- **Stomach**
    - *Main purpose of stomach*: to break down macromolecules for absorption in small intestine
    - Storage and churning of food
        - Churns food into *chyme* (semi-fluid mass)
    - Low pH, gastric juice, mucal protection against self-destruction
        - Stomach has pH of 2
            - Helps denature proteins and kill bacteria
        - Gastric juice: combination of acid, enzymes, and hormones that maintains low pH
        - 4 primary secretory cells in the stomach
            - 1) **Mucous cells**: secrete mucous to lubricate stomach wall and protect it from acidic environment
            - 2) **Chief cells**: secrete pepsinogen (zymogen to pepsin)
            - 3) **Parietal cells**: secrete HCl
                - This lowers pH of stomach, increases pH of blood
            - 4) **G cells**: activated to release gastrin, which stimulates parietal cell activity
        - All secretory cells secrete mucous
    - Production of digestive enzymes, site of digestion
        - Produces pepsin to break down proteins
            - First site of protein breakdown
    - Structure (gross)
        - Fundus: can expand to hold gas, excess food
        - Body: where digestion takes place
        - Pylorus: prevents undigested food from getting in small intestine
- **Liver**
    - Structural relationship of liver with gastrointestinal system
    - Production of bile
    - Role in blood glucose regulation, detoxification
        - Detoxification
            - Capillaries in digestive tract feed into the hepatic portal vein
            - Hepatic portal vein carries blood from digestive system to liver, which screens it for toxins
            - Now detoxified blood goes to vena cava
- **Bile**
    - Storage in GALL BLADDER
    - Function: emulsify fats and enable enzymes to access them easier
- **Pancreas**
    - Production of enzymes
        - Trypsin and chymotrypsin: degrade proteins
        - Pancreatic amylase: hydrolyzes polysaccharides to tri/disaccharides
        - Lipase: degrades fats
    - Transport of enzymes to small intestine
        - Gall bladder: stores bile and transports it to the small intestine by funneling it through the cystic duct, the common bile duct, and then the pancreatic duct
            - Bile: emulsifies fat, increasing their SA so they can be digested
- **Small intestine**

- Absorption of food molecules and water
    - **Duodenum** performs chemical digestion of chime in preparation for absorption
    - **Jejunum** and **ileum** absorb food and water
    - Lacteals and capillary network of villi uptake fats and other macromolecules
        - Lacteals uptake fats into the lymph
        - Capillary network uptake fats into blood
- Function and structure of villi
    - Structure
        - Line walls of small intestine
        - Contain a capillary network and a lymph vessel (*Lacteal)*
        - **Microvilli**: smaller villi which project off of villi, increase SA even more
            - Brush border: fuzzy appearance of villi due to thousands of microvilli, contains many digestive enzymes which break down food into their constituent parts
    - Function
        - Increases SA of small intestine
        - Absorb fats and nutrients
- Production of enzymes, site of digestion
    - Sites of digestion
        - Pancreas produces digestive enzymes which break down food in lumen of small intestine
        - Clumps of broken down food broken down to smallest parts by enzymes in brush border
    - Production of enzymes
        - Pancreas aids in production of digestive enzymes since small intestine is so specialized in absorption
- Neutralization of stomach acid
    - Stomach acid is neutralized in the duodenum by bicarbonate (which is released by the pancreas)
    - pH of the duodenum is 6
- Structure (anatomic subdivisions)
    - Duodenum, jejunum, ileum
        - Duodenum digests food
        - Jejunum and ileum absorb food

- **Large intestine**
    - Absorption of water
        - Primary purpose of large intestine is **reabsorption of water and electrolytes**
    - Bacterial flora
        - Large intestine contains bacterial flora which produce vitamins from partially digested food
    - Structure (gross)
        - Ascending colon
        - Transcending colon
        - Descending colon
        - Sigmoid colon
        - Rectum
- **Rectum**: storage and elimination of waste, feces
    - Rectum stores feces until it is eliminated through the anus
- Muscular control
    - Peristalsis: contraction of digestive tract muscles that pushes food down

- Endocrine control
    - Hormones
        - **Gastrin**: increases HCl production when stomach is full, released in stomach
        - **Secretin**: regulates pH, signals for the pancreas to release bicarbonate and enzymes after chyme gets to small intestine, released in duodenum
        - **Gastric inhibitory polypeptide**: released in response to fat and protein digestion in duodenum, decreases motor activity of stomach and stimulates pancreatic enzyme activity
        - **Cholecystokinin**: released in response to fat and causes gallbladder contraction and pancreatic enzyme secretion, released in duodenum
    - Target tissues
        - Brain stimulates the stomach, which signals the small intestine, which signals the pancreas
- Nervous control: the enteric nervous system
    - **Enteric nervous system**: network of neurons around digestive organs, help to regulate digestive processes

Excretory System (BIO)

- Roles in homeostasis
    - Blood pressure
    - Osmoregulation
    - Acid-Base balance
    - Removal of soluble nitrogenous waste
- Kidney structure
    - Cortex
        - Outer portion of kidney
    - Medulla
        - Inner portion of kidney
- Nephron structure
    - **Glomerulus**
        - Capillary bed surrounding Bowman's Capsule
    - **Bowman's Capsule**
        - Fenestrations: a filter for blood, screens out blood cells and large protein
            - Blood from capillary bed pushed through fenestrations via hydrostatic pressure
        - Arterioles: supply blood to glomerulus and take it away
            - **Afferent arteriole**: supplies blood to glomerulus, constriction decreases blood flow and hydrostatic pressure, decreasing filtration
            - **Efferent arteriole**: takes blood away from glomerulus, constriction increases hydrostatic pressure, increasing filtration
    - **Proximal Tubule**
        - Secretion
            - Toxins, drugs, solutes secreted into filtrate by specialized cells
            - Hydrogen ions secreted via an antiport system driven by the sodium concentration gradient
        - Reabsorption
            - Valuable nutrients that were accidentally filtered out are reabsorbed back into the Proximal Tubule via passive or active transport
    - **Loop of Henle**
        - Descending Loop of Henle
            - Low permeability to salt, high permeability to water

            - Causes filtrate osmolarity to increase
        - Ascending Loop of Henle
            - High permeability to salt, low permeability to water
            - Causes filtrate osmolarity to decrease
    - **Distal Tubule**
        - Secretion
            - Secretes K, H, and HCO3 into filtrate
        - Reabsorption
            - Reabsorbs Na and Ca2+ into cortex
        - Net effect is to lower filtrate osmolarity
        - Collecting tubule
            - Acted upon by ADH to allow for water reabsorption
            - Not the same as the collecting duct
    - **Collecting duct**
        - Carries filtrate back into medulla
        - Acted upon by ADH
            - ADH = always digging holes, pokes holes in collecting duct to drain it
- Formation of urine
    - Glomerular filtration
        - Blood passed through fenestrations in glomerulus, filters out blood cells and large proteins, leaving plasma
    - Secretion and reabsorption of solutes
        - Aldosterone
            - Reabsorbs sodium in distal tubule back into blood
            - **Ultimately causes more water to flow into blood, increasing blood pressure** without changing blood osmolarity
        - **Juxtaglomerular apparatus**
            - Monitors filtrate pressure in the distal tubule
            - Secretes renin when filtrate pressure is too low
                - Renin increases blood pressure
    - Concentration of urine
    - **Counter-current multiplier mechanism**
        - How the kidney can constantly move fluid through itself
        - Steps
            - 1) **Single effect** causes filtrate concentration to decrease and medulla solute concentration to increase
            - 2) Increase in medulla solute concentration causes water in descending loop to flow into medulla to equilibrate
            - 3) Dilute filtrate in ascending limb gets pushed out of loop, concentrated filtrate in descending limb gets shifted towards the bottom hairpin turn
        - Takeaways
            - Active transport is necessary to establish a solute concentration in the medulla
            - The medulla's high solute concentration helps to reabsorb water into the body and concentration urine
- Storage and elimination: ureter, bladder, urethra
    - Urine produced in kidney, emptied into renal pelvis
    - Renal pelvis is emptied by the ureter
    - Ureter carries urine to the bladder
    - Relaxation of urinary sphincter empties urine out of bladder into urethra
- Osmoregulation: capillary reabsorption of H2O, amino acids, glucose, ions

    - Single effect
        - Process in ascending Loop of Henle where active transport of solutes from filtrate into medulla establishes a solute gradient
            - Concentration of solute is higher outside the tubule than inside the tubule
        - Dilutes filtrate and concentrates the medulla in the ascending limb and concentrates filtrate in the descending limb
- Muscular control: sphincter muscle
    - Relaxation of urinary sphincter in bladder allows for urination

Reproductive System (BIO)

- Male and female reproductive structures and their functions
    - Gonads
    - Genitalia
    - Differences between male and female structures
- Hormonal control of reproduction
    - Male and female sexual development
    - Female reproductive cycle
    - Pregnancy, parturition, lactation
    - Integration with nervous control

Muscle System (BIO)

- Important functions
    - Support: mobility
    - Peripheral circulatory assistance
    - Thermoregulation (shivering reflex)
- Structure of three basic muscle types: striated, smooth, cardiac
    - **Striated**
        - Connects one bone to another via two points: origin and insertion
            - *Origin*: a muscle's attachment around the midpoint of a larger, stationary bone
            - *Insertion*: a muscle's other attachment to the end of a smaller bone that moves relative to the origin bone
        - Functions
            - Two major functions are movement and stabilization of body position
            - **Peripheral circulatory assistance**: contractions help to squeeze blood and lymph
            - Thermoregulation: shivering reflex is the rapid contraction of skeletal muscle, controlled by the hypothalamus
        - Lever arm
            - When you pick something up, muscle insertion is between the joint and the object
            - **Takes more force than the weight of the object to pull the object up** (object is farther from the joint than the insertion)
                - This allows for more control over the movement and a less bulky body
        - Contain multiple nuclei
        - Striated = composed of sarcomeres
    - **Cardiac**
        - Forms a net around the heart that contracts in upon itself
            - Not connected to bone
        - Intercalated discs
            - Discs separating cardiac muscle cells
            - Contain gap junctions that allow for quick propagation of AP's
        - Cardiac muscle is striated too (composed of sarcomeres)

        - Innervation
            - Sympathetic innervation increases heart rate
            - Parasympathetic innervation via the vagus nerve decreases the heart rate
        - One nucleus
    - **Smooth**
        - Two types
            - **Single-unit**: gap junctions between single unit muscle allows for fast propagation of electric signal. This enables single-unit smooth muscle fibers to act in a coordinated manner
                - Found in smaller arteries and veins, digestive tract
            - **Multi-unit**: each muscle fiber is directly attached to a neuron. This enables fibers to act independently of other fibers in the same area
                - Found in large arteries and respiratory system
        - No sarcomeres
        - Intermediate filaments
            - Attached to *dense bodies*
                - Similar to Z-lines. Contraction of thick and thin filaments cause intermediate filaments to pull dense bodies together
        - One nucleus
- Muscle structure and control of contraction
    - T-tubule system
        - T-tubule: divots in the sarcolemma which allow for AP to propagate quickly along a muscle fiber
    - Contractile apparatus
        - **Sarcomere**: smallest functional unit of the contractile apparatus, made up of thin and thick filaments
        - Muscle fiber: bundle of sarcomeres
        - Fasciculus: bundles of muscle fibers
        - Muscle: bundles of fasciculi
    - Sarcoplasmic reticulum
        - **Myofibril**: sarcomeres positioned end to end, many mitochondria are wedged b/w the myofibrils in a muscle fiber
        - **Sarcoplasmic reticulum**: specialized endoplasmic reticulum of muscle cells, surrounds myofibrils
        - **Sarcolemma**: modified plasma membrane that wraps around many myofibrils to make a muscle fiber
        - **Muscle fiber**: sarcolemma wrapped around many myofibrils and the sarcoplasmic reticulum
        - **Fasciculus**: many muscle fibers bound together
        - **Muscle**: composed of many fasciculi bound together
    - Fiber type
        - **Type I (slow twitch):** red colored (b/c contains lots of myoglobin for oxygen storage), has a slow contractile velocity and produces a small amount of force but has a high resistance to fatigue and uses aerobic metabolism for energy
        - **Type II A (fast twitch):** red colored (lots of myoglobin), has a fast-contractile velocity and produces high force but not as resistant to fatigue as type I fibers, uses long-term anaerobic metabolism for energy
        - **Type II B (fast twitch):** white colored (little myoglobin, lots of glycogen), has a very fast contractile velocity and very high force production but fatigues very easily, uses short-term anaerobic metabolism for energy
    - Contractile velocity of different muscle types

        - Contractile velocity in ascending order for muscle fibers
            - Type I < Type II A < Type II B
- Regulation of cardiac muscle contraction
    - Plateau after depolarization
        - Cardiac muscle is slow to repolarize
            - Plateau not seen in neuronal action potentials (repolarization is quick)
        - Slow voltage-gated calcium channels allow Ca2+ to enter and stay in the membrane, maintaining depolarization
        - Purpose: lengthens time of contraction to give heart enough time to refill with blood
            - Plateau is critical in allowing the heart to work as a pump
- Oxygen debt: fatigue
    - **Oxygen debt**: when the body needs excess oxygen after exercise to metabolize the lactic acid produced from anaerobic glycolysis
- Nervous control
    - Motor neurons
        - Attaches to the motor end plate, releases acetylcholine once excited
            - Note: **only striated muscle uses acetylcholine** (skeletal and cardiac)
        - **Motor unit**: a motor neuron and all the muscle fibers it innervates
            - Motor units vary in size
            - Small motor units activated first, and larger ones activated as needed to create smooth movements
        - Acetylcholine
            - Excites skeletal muscle, inhibits cardiac muscle
    - Neuromuscular junction, motor end plates
        - Motor end plate: easily excitable region of muscle where neuromuscular junction is located
        - Neuromuscular junction: the synapse between the motor neuron and the motor end plate
    - Sympathetic and parasympathetic innervation
    - Voluntary and involuntary muscles
        - **Skeletal muscles are voluntary** (somatic nervous system control)
        - **Cardiac and smooth muscles are involuntary** (autonomic nervous system control)

Specialized Cell – Muscle Cell (BIO)

- Structural characteristics of striated, smooth, and cardiac muscle
- Abundant mitochondria in red muscle cells: ATP source
    - Type I (slow twitch muscle) has a lot of mitochondria. This is b/c it relies on aerobic metabolism to generate ATP for contractions
- Organization of contractile elements: actin and myosin filaments, cross bridges, sliding filament model
    - Actin and myosin filaments
        - **Thick filaments**: made of several myosin strands wrapped around each other, with globular myosin heads protruding out the ends
        - **Thin filaments**: made of actin, with the proteins troponin and tropomyosin on each end participating in contraction
    - **Sliding filament model**: depicts how myosin and actin work together by sliding across each other
        - 1) Myosin head is in high-energy "cocked" position, with ADP and P bound to it
        - 2) Ca2+ binds to troponin on actin, causing tropomyosin to reveal myosin binding sites on actin
        - 3) Myosin head binds to actin, forming a *cross bridge*
        - 4) Myosin kicks off ADP and P, causing the head to bend back to assume a low energy

position. This drags the actin back as well, contracting it
        - 5) ATP binds to myosin, causing it to detach from the now contracted actin
        - 6) ATP is hydrolyzed to ADP and P. The energy of hydrolysis is used to recock the myosin head
- Sarcomeres: "I" and "A" bands, "M" and "Z" lines, "H" zone
    - **Z-line**: border separating two sarcomeres. Where actin filaments attach
    - **H-zone**: area in the center of the sarcomere where there's only myosin
    - **M-line**: midpoint of the sarcomere
    - **A-band**: area where myosin is present (including where it overlaps with actin), includes the H-zone and M-line
    - **I-band**: area where actin is present
- Presence of troponin and tropomyosin
    - Proteins on the end of actin filaments which enable contraction of muscle
        - Troponin: Ca2+ binds to troponin
        - Tropomyosin: Ca2+ binding to troponin signals for tropomyosin to reveal the active sites for myosin binding
- Calcium regulation of contraction
    - Motor neuron releasing acetylcholine causes action potential to propagate across sarcolemma
        - T-tubules: infoldings of the sarcolemma which allow for faster propagation of an AP
    - **Action potential causes Ca2+ channels in sarcoplasmic reticulum to open, causing Ca2+ to flow out and increasing [Ca2+] around sarcomeres**
    - Ca2+ binds to troponin, allowing myosin and actin filaments to slide

Skeletal System (BIO)

- Functions
    - Structural rigidity and support
    - **Calcium storage**
        - Calcium in bone
            - Most calcium in bone is stored as the mineral *hydroxyapatite*, which provides compressive strength
            - Some calcium is stored as calcium salts (e.g. CaHPO4) which buffer plasma Ca2+ levels
        - Maintains gradient
            - Too much free calcium in the blood causes membranes to be hypoexcitable (harder to excite)
            - Maintains gradient of high calcium concentration outside of cells, low calcium concentration in cytosol
    - Physical protection
    - Energy storage (adipose cells in bone marrow)
- Skeletal structure
    - Specialization of bone types, structures
        - Two broad bone types
            - **Spongy bone**: contain red bone marrow, produce red blood cells, found in the center of a bone
            - **Compact bone**: contains lamellae and Haversian canals usually form a shell around spongy bone
            - **Medullary cavity**: contain yellow bone marrow, which holds adipose cells for fat storage. A hollow cavity within compact bone
        - Four specialized bone types
            - **Long**: long shaft that's important for strength, composed of spongy and compact

bone (e.g. leg, arm, finger bones)
- **Short**: cuboidal shape (e.g. ankle, wrist bones)
- **Flat**: provide organ protection and large areas for muscle attachment (e.g. ribs, sternum, shoulder blades)
- **Irregular**: irregular shape and variable amounts of spongy and compact bone (e.g. pelvis, ossicles in the ear)

▪ Structures
- Compact bone: constantly being remodeled by osteoblasts and osteoclasts
  - Osteoclasts burrow tunnels in compact bone, osteoblasts fill these holes in
  - **Lamellae**: concentric rings formed by osteoblasts filling in holes
  - **Haversian canals**: open hole in center of lamellae that contain blood and lymph vessels and allow for blood and nutrient exchange
    - Volkmann's canals: lateral canals connecting different Haversian canals
  - **Osteons**: entire system of lamellae and a Haversian canal

o Join structures
- **Fibrous joints**: very tightly held together by fibrous connective tissue. Maintains a fixed relationship between two bones, allows for very little movement (e.g. joints holding the skull bones together)
- **Cartilaginous joints**: tightly held together by cartilage. Maintains a fixed relationship but allows for slight flexibility, allowing joint to absorb energy and protect bones in trauma
- **Synovial joints**: not held together by cartilage on ends of bones, bones are separated by a capsule filled with synovial fluid. Allows for a wide range of motion
  - **Synovial fluid**: provides nourishment to cartilage, removes microbes and particles

o Endoskeleton vs. Exoskeleton

- Bone structure
  - Calcium/protein matrix
    - Inorganic materials that surround four types of bone tissue cells
  - Cellular composition of bone
    - 1) **Osteoprogenitor cells**: differentiate into osteoblasts, only bone cell that undergoes mitosis
    - 2) **Osteoblasts**: form bone by releasing collagen and other organic compounds which form bone. Incapable of mitosis. Eventually are envelopes by the matrix they release and differentiate into osteocytes
    - 3) **Osteocytes**: exchange nutrients and waste materials with the blood. Incapable of mitosis
    - 4) **Osteoclasts**: consume bone and release minerals into the blood. Thought to have developed from white blood cells
- Cartilage: structure and function
  - Structure
    - Composed primarily of collagen
    - High tensile strength (can be stretched without breaking)
  - Function
    - Provides cushion, connectivity, and elasticity to joints
    - Helps give shape and structure to various body parts (e.g. ears)
- Ligaments, tendons
  - **Ligaments**: connective tissue linking bone to bone
  - **Tendons**: connective tissue linking muscle to muscle
- Endocrine control
  - Opposing effects: PTH and calcitonin

        - **Parathyroid hormone**: stimulates osteoclasts to release Ca2+ into the blood, breaking down bone
        - **Calcitonin**: stimulates osteoblasts to store excess calcium as bone, building up bone
    - Vitamin D: promotes calcium absorption in the digestive system to restore calcium stores in bone

Skin System (BIO)

- Structure
    - Layer differentiation, cell types
        - 2 principle parts
            - Epidermis: superficial layer
            - Dermis: deeper tissue
        - Epidermis
            - 4 types of epidermis cells
                - 1) **Keratinocytes**: provide water impermeability and strength to skin
                    - Keratinization: keratinocytes rise to the top layer of the epidermis, dying in the process and creating a protective layer of keratin
                - 2) **Melanocytes**: transfer melanin to keratinocytes
                - 3) **Langerhans cells**: interact with Helper T-cells in immune system
                - 4) **Merkel cells**: connect with motor neurons to sense touch
            - 4 layers of epidermis (bottom to top)
                - Bottommost layer contains Merkel and stem cells
                    - Stem cells give rise to more keratinocytes and other cell types
                - Topmost layer contains dead keratinocytes, creating a protective layer
        - Dermis
            - 5 different elements
                - 1) Collagen and elastic fibers: provide strength, elasticity
                - 2) Sensory receptors: contains touch, pain, temperature, and pressure receptors
                - 3) Hair follicles: traps heat around skin to maintain body heat, also plays a role in touch sensation
                - 4) Oil gland: associated with hair follicles, dumps oil onto skin and hair
                - 5) Sweat glands
    - Relative impermeability to water
        - Skin is basically impermeable to water, which protects against dehydration and maintains ideal solute concentrations
- Functions in homeostasis and osmoregulation
    - Homeostasis
        - Skin prevents the diffusion of water, protecting against dehydration
    - Osmoregulation
        - Sweating and excretion allow for skin to maintain solute concentration in body
            - Sweat if there's too much solute in body
- Functions in thermoregulation
    - Hair, erectile musculature
        - Hairs can be erected via sympathetic stimulation
        - This insulates warm air next to the skin
    - Fat layer for insulation
        - Located between dermis and epidermis
        - Insulates heat when epidermis begins to get colder
    - Sweat glands, location in dermis
        - **Eccrine** sweat glands: located everywhere along dermis, responds to temperature, releases sweat to cool body

        - **Apocrine** sweat glands: located in central regions of the dermis, responds to stress, releases acrid sweat
    - Vasoconstriction and vasodilation in surface capillaries
        - **Vasoconstriction**: caused by blood being shunted away from capillaries of the skin, reduces heat loss
        - **Vasodilation**: caused by blood being directed towards surface capillaries, increases heat loss
- Physical protection
    - Nails, calluses, hair
    - Protection against abrasion, disease organisms
        - Skin is a physical barrier from abrasion, disease
- Immune control
    - Specialized cells in epidermis provide immunity
- Blood reservoir / Hormonal control
    - Vessels in dermis can hold a lot of blood / sweating, the vasos

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

Translational Motion (PHY)

- Units and dimensions
  - One dimension = magnitude of length or distance only
  - Two dimensions = length or distance on a 2D plane (xy coordinates)
  - Three dimensions = length or distance in 3D space (xyz coordinates)
  - Four dimensions = length or distance in 3D space at a given time (xyzt coordinates)
- Vectors, components
  - Scalar: without direction
    - e.g. length, time, mass
  - Vector: with direction
    - e.g. displacement, acceleration, force
  - Components: the portion of the vector in a given direction
- Vector addition
  - You can directly add vectors if they are in the same direction
  - To add vectors in different directions, you must add their x, y, and z components. The resulting components make up the added vector
  - The vector sum of all components of a vector equal to the vector itself
  - Operation involving a vector and a vector may or may not result in a vector (kinetic energy from the square of vector velocity results in scalar energy)
  - Operation involving a vector and a scalar always results in a vector
  - Operation involving a scalar and a scalar always results in a scalar
- Speed, velocity (average and instantaneous)
  - Speed: scalar, no direction, rate of change in distance
  - Velocity: vector, has direction, rate of change in displacement

$$speed_{average} = v_{avg} = \frac{l}{t}$$

  - Average speed:

$$velocity_{average} = \boldsymbol{v}_{avg} = \frac{\boldsymbol{s}}{t}$$

  - Average velocity:
  - Instantaneous speed is the speed at an instant (infinitesimal time interval)
  - Instantaneous velocity is velocity at an instant (infinitesimal time interval)
  - Instantaneous speed equals instantaneous velocity in magnitude
  - Instantaneous velocity has a direction, instantaneous speed does not
  - The direction of instantaneous velocity is tangent to the path at that point
- Acceleration
  - Acceleration is the rate of change in velocity
  - Average acceleration: $\boldsymbol{a}_{avg} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{\boldsymbol{v}_f - \boldsymbol{v}_i}{t}$
    - Uniformly accelerated motion along a straight line
    - If acceleration is constant and there is no change in direction, all of the following applies:
    - The value of speed/velocity, distance/displacement are interchangeable in this case, just keep a mental note of the direction

$$s = v_{avg} t$$

$$v_{avg} = \frac{v_f + v_i}{2}$$

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t}$$

$$v_f^2 = v_i^2 + 2as$$

$$s = \frac{1}{2} a t^2 + v_i t$$

$$l_f = l_i + s$$

- For Cartesian coordinates, take upward and rightward motion as positive; down and left as negative
- For free falls, take downward as positive

Force (PHY)

- Newton's First Law, inertia
  - Law of inertia states: without an external force acting on an object, nothing will change about that object in terms of speed and direction
  - In the absence of an external force:
    - Something at rest will remain at rest
    - Something in motion will remain in motion with the same speed and direction
    - Objects are "inert" to changes in speed and direction
- Newton's Second Law (F=ma)
  - The unit for force is the Newton. $N = kg \cdot m/s^2$
  - Both force and acceleration are vectors because they have direction
- Newton's Third Law, forces equal and opposite
  - Every action has an equal and opposite reaction
- Friction, static and kinetic
  - Friction is a force that is always in the direction to impede the sliding of surfaces.
  - Static friction: $F_s = \mu_s N$ Kinetic friction: $F_k = \mu_k N$
  - μ is the coefficient of friction and N is the normal force
    - Friction is a vector, however its direction is always opposite to the motion of surface involved
    - Coefficient static friction is always larger than the coefficient of kinetic friction
    - Lubricants reduce friction because they change surface properties and reduce the coefficient of friction
- Center of mass
  - The center of mass is the average distance, weighted by mass

$$x_{cm} = \frac{\sum x_i m_i}{\sum m_i} \quad y_{cm} = \frac{\sum y_i m_i}{\sum m_i} \quad z_{cm} = \frac{\sum z_i m_i}{\sum m_i}$$

- In a Cartesian coordinate, the center of mass is the point obtained by doing a weighted average for all the positions by their respective masses
- You can set the point of reference anywhere and use relative coordinates

Equilibrium (PHY)

- Vector analysis of forces acting on a point object
  - Static vs dynamic equilibrium: static = no net force, no movement; dynamic = no net force, movement
  - In equilibrium: sum of all forces and torques acting on a system equal zero
  - If NOT in equilibrium: *center of mass* is accelerating *translationally* and/or its parts are accelerating *rotationally*
- Torques, lever arms
  - Torque is the angular equivalent of force - it makes things rotate, have angular acceleration, change angular velocity and direction
    - Convention is that positive torque makes things rotate counterclockwise and negative torque makes things rotate clockwise
  - Depends on:
    - Component of force perpendicular to the position vector (vector extending outwards from center of mass)
    - Distance between point where force is applied and point where rotation occurs (greater distance = greater torque)
  - Lever arm consists of a lever (rigid rod) and a fulcrum (where the center of rotation occurs)
    - Torque is the same at all positions of the lever arms (both on the same side and on the other side of the fulcrum)

$$F_1 l_1 = F_2 l_2$$

  - If you apply a force at a long distance from the fulcrum, you exert a greater force on a position closer to the fulcrum
  - The catch: you need to move the lever arm through a longer distance

Work (PHY)

- Work done by a constant force: $W = Fd \cos \theta$
  - Work = energy transfer for any reason other than a temperature difference
- Mechanical advantage
  - Mechanical advantage = little input force (effort) → large output force
  - Using ramps can achieve mechanical advantage
    - Double distance of ramp = halving force needed
  - Using the lever arm can achieve mechanical advantage
    - Doubling length of lever arm = halving force needed
  - Using pulleys can achieve mechanical advantage
    - Vectors of tension going up help to lift force up
    - Work required to lift mass hasn't changed, just force
- Work Kinetic Energy Theorem
  - Work on an object can transform into kinetic energy
    - When you push on an object, it will move: $Fd = \frac{1}{2} mv^2$
    - When gravity does work on an object, it will move: $F_{weight}h = mgh = \frac{1}{2} mv^2$
  - Kinetic energy of an object can do work

        - A moving object can slide against friction for a while before coming to a stop: ½ mv^2 = $F_{friction}d$
    - Sign conventions: negative = energy going out of system, positive = energy going into system
- Conservative forces
    - If a force doesn't dissipate heat, sound or light, then it is a conservative force
    - Work done by conservative forces are path independent
    - Conservative forces are associated with potential energy
    - For example, the force from a spring can be stored as spring potential energy
    - Gravitational force can be stored as gravitational potential energy
    - Electromagnetic forces are also conservative
    - Non-conservative includes frictional forces and human exertion. When friction acts on an object, the heat and sound released cannot be recovered. When you flex your arm, you lose heat that cannot be recovered (you cannot re-absorb the heat you lost)

Energy of Point Object Systems (PHY)

- Kinetic Energy: KE = ½ mv^2; units
    - Unit = Joule
    - Speed is more important than mass for the KE because speed is squared
- Potential Energy
    - PE = mgh (gravitational, local)
    - PE = ½ kx^2 (spring)
- Conservation of energy
    - Two types of energy transfer: heat and work
        - Heat: energy transferred due to change in temperature
        - Work: energy transferred due to any other reason
    - Principles of conservation
        - Energy OUT of a system = Energy coming IN
        - Total energy BEFORE = Total energy AFTER
        - Total energy of a system = Sum of all forms of energy in that system
    - Law of conservation of mechanical energy: when only conservative forces are acting, sum of mechanical energies remains constant
- Power, units
    - Power is the rate of energy use OR work per unit time
    - P = Fv cosθ, Power in applying a F to an object causing it to move at speed v
        - Cosθ ensures force is moving in direction of velocity
    - Unit = Watt, or Joule per second
    - 3 categories of systems:
        - Open: can exchange mass and energy
        - Closed: can exchange energy but not mass
        - Isolated: can't exchange energy or mass

Periodic Motion (PHY)

- Amplitude, frequency, phase
    - Amplitude (A): how high the peaks are or how low the troughs are, in meters
        - The displacement is how far the wave vibrates / oscillates about its equilibrium (center) position
        - The amplitude is the maximum displacement
        - Amplitude is correlated with the total energy of the system in periodic motion. Larger amplitude = greater energy
    - Period (T): the time it takes for one cycle, in seconds
        - T = $1/f$

    - Frequency (f): the rate, or how many cycles per second, Hertz (cycles per second)
        - $f = 1/T$
        - Sometimes, frequency is in rpm (revolutions per minute) rpm = cycles per second x 60
    - Angular frequency (ω): the rate, in how many radians per second
        - $\omega = 2\pi f$
        - ω is also called angular velocity
    - Phase
        - In phase: the waves are 0 or 2π radians (0 or 360˚) apart. The resulting amplitude (sum of the waves) is twice the original
        - Completely out of phase: the waves are π radians (180˚) apart. The resulting amplitude is zero
        - Out of phase: resulting amplitude is between 0 and twice the original
- Transverse and longitudinal waves: wavelength and propagation speed
    - Transverse wave: wave displacement is perpendicular to the direction of motion
        - Light
        - Electromagnetic radiation
        - A standing wave by oscillating a string side ways. The speed for such a wave = √(string tension/mass per unit length of the string)
        - Know that tense, light strings can produce faster transverse waves
    - Longitudinal wave: wave displacement is parallel to the direction of motion
        - Sound
        - Pressure wave
        - Earthquakes

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

Fluids (PHY)

- Density, specific gravity
  - Density: "heaviness" of a *fluid*, intensive property (analogous to mass in solids)
    - P = m/v, units: kg/m^3
    - Gases don't separate based on polarity, separate based on **density** (liquids separate based on both)
  - Specific gravity: density of a substance compared to density of water, S.G. = $p_{substance} / p_{water}$
    - Meant to give us a better sense on how "heavy" a fluid actually is by comparing it to water, whose weight we have a good idea of
- Buoyancy, Archimedes' Principle
  - Buoyancy: Force that a standing fluid exerts on an object floating, submerged, or sunk in it
    - $F_B = p_{fluid}V_{fluid}g$
      - Shows buoyant force is proportional to how much fluid an object displaces
        - The deeper an object sinks, the more fluid it displaces
  - Archimedes Principle: Buoyant force is = in magnitude to mass of fluid displaced
    - $F_B = m_{fluid}g$
  - 3 special cases of Buoyant Force
    - **1) The Floating object**
      - When the upwards buoyant force = the downwards force of gravity *before* an object is submerged
      - **$F_B = m_{object}g$**
        - Shows magnitude of buoyant force = weight of object
      - **$M_{fluid} = m_{object}$**
        - Shows mass of fluid displaced is = to mass of object
      - Fraction of object submerged = **$p_{object}/p_{fluid} = V_{fluid}/V_{object}$**
        - For a floating object, this **ratio must be = to or < 1**
    - **2) The Submerged Object**
      - Mass AND volume of the object and fluid displaced are =
      - **$V_{object} = V_{fluid}$, $m_{object} = m_{fluid}$**
        - This means that **$p_{object} = p_{fluid}$**
      - $F_B = F_g$
    - **3) The Sunk Object**
      - Displaces V_{fluid} = to its own volume
        - May displace a different amount of mass, accounts for why it's sunk (mass contributes to F_g)
      - **$V_{object} = V_{fluid}$**
      - **$P_{fluid} / p_{object} = m_{fluid} / m_{object}$**
      - Apparent weight of sunk object is less than the actual weight because both F_B and F_N counter F_g but only F_N represents apparent weight
        - **$F_B + F_N = F_g$**
        - **$F_g = m_{object}g$**
        - **% of apparent weight lost = p_{fluid} / p_{object}**
- Hydrostatic pressure
  - Pascal's Law
    - Pressure applied at any point to an enclosed fluid will distribute itself evenly throughout

all the fluid
        - **P = F/A,** P is constant while F and A are mutable and proportional to each other
    - Hydrostatic pressure**: P = pgh** (pressure vs. depth)
        - Pressure of an enclosed fluid is a function of depth
        - **Add pressures of multiple fluids in an enclosed area to get total pressure**
        - **If the fluid is open to the atmosphere, the $P_{total} = pgh + P_{atm}$**
            - *Air is a fluid too. Open container basically has the fluid of air sitting on top of the other fluids*
- Viscosity: Poiseuille Flow
    - Poiseuille's Law

Q	Flow rate
P	Pressure
r	Radius
η	Fluid viscosity
l	Length of tubing

$$Q = \frac{\pi \Pr^4}{8\eta l}$$

    -
        - Used with *real fluids*
        - Finds volume flow rate of a real fluid in terms of pressure, viscosity (n), pipe length, and pipe radius
    - Viscosity
        - As viscosity of a fluid increases, flow rate decreases
- Continuity Equation (**A x v = constant**)
    - Cross sectional area vs. velocity
        - Smaller the cross-sectional area → the greater the velocity
        - Shows uniform translational kinetic energy increases as cross sectional area decreases
- Concept of turbulence at high velocities
- Surface tension
    - Describes intensity of IMFs of a fluid per unit length
        - Factors affecting surface tension
            - Weakened at higher T's (IMF's more unstable)
            - Affected by properties of the fluid
        - Pulls inwards on fluids in droplets and make them assume a spherical shape
    - Capillary action: phenomenon where fluid is pulled up a thin tube, mediated by surface tension
        - In a tube filled with fluid, if…
            - **Cohesive forces (IMF's within a fluid) are stronger**, then surface of fluid is **convex**
            - **Adhesive forces (IMF's between a fluid and the tube) are stronger**, the surface of fluid is **concave**
- Bernoulli's Equation
    - Pressure, kinetic energy, and potential energy of an ideal fluid is constant throughout that fluid
        - Restates conservation of energy in terms of densities and pressures
    - $P_o + 1/2pv_o^2 + pgh_o = k$
        - Note: h does not = y
            - H = height above an arbitrary point, y = total distance beneath a surface

        - $v_o = \sqrt{2gh}$ (derived from kinematics equation)
    - At a constant height, as *velocity increases, pressure decreases*
- Venturi effect, pitot tube
    - Pitot tube
        - U-shaped, horizontal tube with one open end and mercury in the loop. Fluid flows into the open end and pushes the mercury up
        - Takes height out of Bernoulli's equation
        - **Purpose: determines velocity of fluid flowing past it**
    - Venturi tube
        - Horizontal tube with a constricted region in the middle
        - Measure differential pressures in non-constricted and constricted region
        - **Purpose: determine the velocity of a fluid flowing within it**
    - Venturi effect: *as cross sectional area of a pipe decreases, pressure decreases*

Circulatory System (BIO)

- Arterial and venous systems: pressure and flow characteristics
    - Filtration across capillaries
        - 2 factors in determining direction and rate of filtration in a capillary: 1) hydrostatic pressure gradient between blood pressure and interstitial pressure 2) oncotic pressure (a type of osmotic pressure)

Gas Phase (GC, PHY)

- Absolute temperature, (K) Kelvin Scale
    - Absolute zero = -273 deg C
    - Kelvin to Celsius converter
        - K = C + 273, absolute zero = 0 K
    - Temperature = KE <u>per mole</u> of molecules, *intensive property*
        - Temp vs. thermal energy: thermal energy is extensive, describes total energy of molecular motion. Temperature is intensive, describes average energy per unit
- Pressure, simple mercury barometer
    - Pressure: KE of a group of molecules <u>per volume</u> occupied, *intensive property*
        - Translational KE = energy due to motion from one location to another
    - Mercury barometer: way of measuring atmospheric pressure
        - Procedure
            - 1) Invert a test tube filled with mercury on an uncovered bath open to the atmosphere
            - 2) Some mercury falls into the bath, some stays in the test tube
            - 3) Plug the height of the remaining mercury into the equation: $P_{atm} = pgh$
                - P_{atm} = atmospheric pressure, p = density of mercury, g = 9.8 m/s^2, h = height of mercury remaining in test tube
        - Rationale: pressure of the atmosphere pushing DOWN on the bath is related to how much mercury is left in the test tube
        - mmHg = how high in millimeters the mercury level is
- Molar volume at 0 deg. C and 1 atm = 22.4 L/mol
    - At STP, one mole of any gas will occupy 22.4 liters
- Ideal gas
    - Definition: 4 qualities
        - 1) Gas molecules have no size, zero molecular volume (not the same as the size of the container)
        - 2) Gas molecules don't exert attractive or repulsive forces on one another (no IMF's)
        - 3) Gas molecules have completely elastic collisions

        - 4) Average KE per gas molecule is proportional to the overall temperature of the gas
    - Ideal Gas Law: PV = nRT
        - *Unless told otherwise, MCAT gases are ideal*
        - T: the temperature of the gas (taken in K for ideal gas)
            - Ideal gases are in thermal equilibrium with surroundings. Both gas and surroundings are at same temperature
        - V: the volume of the container the gas is in
            - 2 types of containers:
                - 1) Flexible: volume of container changes depending on the temperature, pressure, and amount of gas within
                - 2) Rigid: volume is fixed and cannot change
        - P: pressure exerted by the gas on the container
            - For a *flexible* container, P = the external pressure
                - If it didn't, the container would stretch or shrink until P = external temperature
            - Pressure of gas in the atmosphere is always 1 atm
    - Boyle's Law: PV = constant
        - Pressure and volume are *inversely proportional* to keep PV a constant value
    - Charles' Law: V/T = constant
        - Increase in temperature leads to greater KE and speed per molecule. They speed up and start to collide with each other more, increasing the volume
        - Volume and temperature are *directly* proportional to keep V/T constant
    - Avogadro's Law: V/n = constant
- Kinetic Molecular Theory of Gases
    - Heat capacity at constant volume and at constant pressure (PHY)
        - Effect of constant volume and pressure on heat capacity
            - Constant volume: if V is constant, a system can do no PV work so all E exchange must be in the form of heat. This means less E is needed to get to capacity required to change T by 1 C or K.
            - Constant pressure: P is constant so V can change. This means the system can do PV work as well so some E put in will go towards raising the V instead of changing the T. More E required to get to capacity
            - $C_{constant\ V} < C_{constnat\ P}$
    - Boltzmann's Constant (PHY): used to calculate average KE of a single molecule in a given fluid, $k = 1.38*10^{-23}\ J\ K^{-1}$
        - K.E. = 3/2 RT
            - R = ideal gas constant, T = temperature in K, K.E. = average KE per mole of molecules
- Deviation of real gas behavior from Ideal Gas Law
    - Qualitative
        - Deviations occur when gas molecules get close together
            - B/c of volume of gas particles and electrostatic forces between gas particles (Coulombs Law)
        - Deviations caused by high pressures or low temperatures
    - Quantitative (Van der Waals' Equation)
        - $P_{real} < P_{ideal}$
            - Gas molecules exhibit mostly attractive forces on one another. Pulls gas molecules inwards, lowers collisions on container walls, and lowers P
        - $V_{real} > V_{ideal}$
            - Gas molecule size comes into play in a real gas. Volume of gas molecule increase

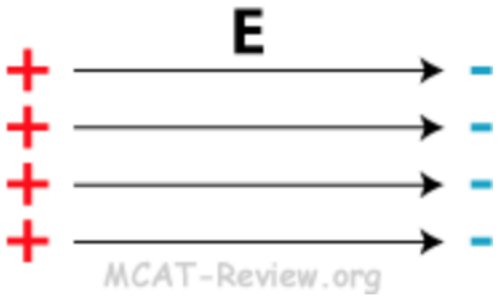
the actual volume

- Partial pressure, mole fraction
  - In a mixture of gases, amount of pressure each gas contributes is proportional to how many molecules it contributes to the mixture
  - Partial pressure: amount of pressure contributed by a single gas to a mixture
    - $P_a = x_a P_{total}$
      - P_a = partial pressure of gas a, x_a = molar fraction of gas a
  - Rxns involving gases can have their equilibrium constant written in terms of partial pressures
    - K_p = partial pressures of products / partial pressure of reactants
    - $K_p = K_c(RT)^{\Delta n}$
  - Vapor pressure
    - Vapor pressure: Pressure created by molecules above liquid surface at eq. Driven by <u>entropy difference between liquid and gas phases</u> (bigger difference → liquid wants to assume lower entropy more → higher vapor pressure)
      - Molecules on liquid surface get enough KE to break off into open space above liquid
      - Molecules in open space crash down into liquid
      - Equilibrium is reached when rate of molecules leaving surface and molecules re-entering equals each other. Pressure at this equilibrium is <u>vapor pressure</u>
      - **High vapor pressure = weaker bonds in solution, positive heat of solution**
      - **Low vapor pressure = stronger bonds in solution, negative heat of solution**
    - Differences in vapor pressure and partial pressure of solute in open space causes <u>evaporation</u> and <u>condensation</u>
      - Evaporation: partial pressure of solute is less than vapor pressure
      - Condensation: partial pressure of solute is greater than vapor pressure
      - Boiling: atmospheric pressure (sum of all partial pressures in open space) equals vapor pressure
    - Vapor pressure is fixed at a given <u>temperature</u> (only factor that matters)
    - Raoult's Law
      - For a <u>nonvolatile solute</u> (solute with no vapor pressure)
        - Nonvolatile solute increases entropy of liquid phase while not increasing entropy of gas phase (doesn't break off into open space)
          - This lowers the entropy difference between liquid and gas (the driving force for vapor pressure), thereby lowering vapor pressure
        - More nonvolatile solute = less vapor pressure
        - $P_v = X_a P_a$
          - Vapor pressure of solution = mole fraction of liquid "a" * vapor pressure of the pure liquid "a"
- Dalton's Law relating a partial pressure to composition
  - Total pressure a gaseous mixture exerts is the sum of the partial pressure of each of its constituent gases

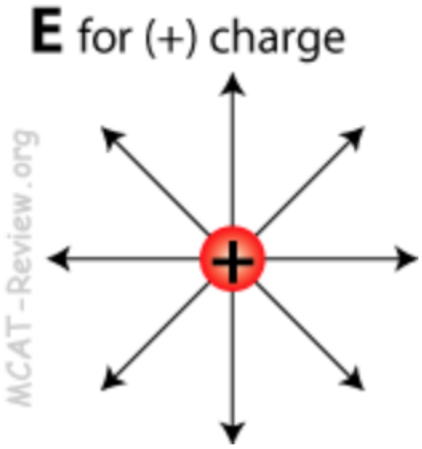
Content Category 4C: Electrochemistry and electrical circuits and their elements

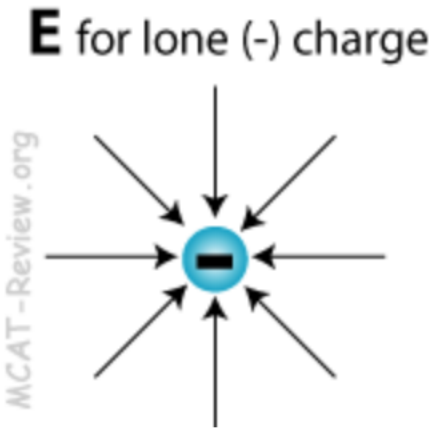
Electrostatics (PHY)

- Charge, conductors, charge conservation
  - Charges are either positive or negative. Zero is neutral
    - Like charges repel, unlike charges attract
    - Charge is quantized, and the unit of charge is the Coloumb
  - Conductors are materials in which charges can move freely. Metals are good conductors
  - Law of conservation of charge
    - Charge can never be created nor destroyed. Isolating a negative charge also isolates a positive charge and vice versa
- Insulators
  - Insulators are materials in which charges cannot move freely. Nonmetals are good insulators
- Coloumb's Law
  - $\mathbf{F = kq_1q_2/r^2}$
  - $\mathbf{k = 9E9\ Nm^2/C^2}$
  - If the charges have the same sign, the force is repulsive
  - If the charges have opposite signs, the force is attractive
- Electric field **E**: electrostatic force per unit charge
  - Field strength
    - Field strength decreases as distance between charges increases
    - For an infinitely large, flat electric plate, field strength is constant
      - Lines have nowhere to spread. Without spreading, field strength can't diffuse
  - Field lines



    - Representations of fields, point in the direction of the field (positive to negative)
    - Lines that are closer together denote stronger fields than lines that are farther apart
    - Drawn from positive to negative
  - Field due to charge distribution
    - Inside of a hollow sphere would have no electric field
      - This is because a field line has to start on a positive charge and end on a negative charge. No positive charge to start on in a hollow sphere
      - No gravitational field in a hollow sphere, so probably no electric field either





    - Electric fields come out of positive charges, and goes into negative charges
    - The unit for electric field is N/C, or Newtons per Coloumb
    - Field comes out of the positive end and goes into the negative end of a dipole
    - Field lines for two negative charges are the same as those for two positive charges except the direction of the field lines would be reversed
        - The direction and magnitude of the field at any point in space can be calculated as the vector sum of all the field components there
    - Electric field in between a capacitor is uniform until it reaches the end of the capacitor
    - Electric field for wires runs radially perpendicular to the wire
    - Electric field for a cylinder runs perpendicular to the cylinder, and is zero inside the cylinder
- Electrostatic energy, electric potential at a point in space
    - Electric potential
        - As potential increases, a charge's ability to do work increases
            - Voltage = work that can be done in an electric field per unit charge (Coulomb)
        - Formulas for potential
            - **U = qEd**
                - E = electric field strength, q = charge, d = displacement in direction opposite of field
            - **$U = kq_1q_2/r$**
                - k = constant, r = distance between two charge centers
    - Voltage
        - Work that can be done in an electric field per unit charge (Coulomb)
            - Measure of the strength of an electric field. Higher voltage = a charge can have more electric potential in there
        - Different from electric potential in that…
            - Electric potential: refers to the potential electric field energy of a charge "q" and is dependent on the value of the charge
            - Voltage: depends on the strength of the electric field itself rather than a specific charge within that field

Circuit Elements

- Current $I = \Delta Q/\Delta t$, sign conventions, units
    - Current is the rate of charge flow through the cross-section of a conductor (wire)
    - Traditionally, the direction of current is taken as the flow of positive charges
    - The unit for current is Coulombs per second, C/s
- Electromotive force, voltage
    - Electromotive force (emf) is really not a force, but a potential difference, with the unit voltage

- A battery is a source of emf
- If the battery has no internal resistance, then potential difference across the battery = EMF
- If the batter has internal resistance, then potential difference across battery = EMF - voltage drop due to internal resistance

- Resistance
  - Ohm's Law: I = V/R
    - Electric current (I) equals potential difference (V) divided by resistance ®
  - Resistors in series
    - $\mathbf{R_{tot} = R_1 + R_2 + \ldots}$
  - Resistors in parallel
    - $\mathbf{1/R_{tot} = 1/R_1 + 1/R_2 + \ldots}$
    - Voltage
      - Resistors in parallel experience the *same voltage drop*
      - Current flowing through each resistor in parallel is *different* (can be calculated using voltages and resistances of each resistor)
        - If parallel resistors have same individual resistances, then total current through each parallel resistor is I/n
          - I = current of circuit, n = number of parallel wires
  - Resistivity $\mathbf{R = \rho * L/A}$
    - Resistivity vs. resistance
      - Resistivity: an *intrinsic* property of a substance to resist charge flow
      - Resistance: the quantitative measurement of an object's ability to resist charge flow (taking into account shape and size of the object)
    - Resistivity formula
      - Finds the resistance of a *wire* of length L and with a cross sectional area A
      - Shows resistance is directly proportional to the length of a wire and inversely proportional to the cross-sectional area of a wire
  - Resistance and temperature
    - $R = R_0[1+\alpha(T-T_0)]$
    - Resistance is directly related to temperature
  - Resistance and Power
    - Power: joules per second
    - $\mathbf{P = I^2R = V^2/R = IV}$
      - Shows that greater resistance for a resistor = less power drained
      - The greater the current, voltage through a resistor = more power drained

- Capacitance
  - Parallel plate capacitor
    - Function: place to temporarily store energy in a circuit
    - Composition: two plates made from conductive material separated by small distance
      - Separation of charges creates an E-field
      - Larger surface area of plates = smaller E-field
      - Larger charge on plates = larger E-field
    - $\mathbf{C = Q/V = \kappa\varepsilon_0 A/d}$
    - Greater capacitance is created by a greater charge on plates (Q) for a given voltage (V), greater plate area (A), or smaller distance between plates (d)
    - V = Ed, where V is voltage across capacitor, E is electric field between capacitor, and d is the distance between capacitor plates
  - Energy of a charged capacitor
    - $\mathbf{U = Q^2/2C = \frac{1}{2}\, Q\Delta V = \frac{1}{2}\, C(\Delta V)^2}$
    - U is the potential energy of the charged capacitor, Q is charge stored (magnitude of either +Q or -Q on one of the plates), C is capacitance

    - Capacitors in series
        - $\mathbf{1/C_{tot} = 1/C_1 + 1/C_2 + \ldots}$
    - Capacitors in parallel
        - $\mathbf{C_{tot} = C_1 + C_2 + \ldots}$
    - Dielectrics
        - **Dielectric** = nonconducting material
        - Inserting a dielectric between the plates of a capacitor increases the capacitance by either increasing Q (if V is constant) or decreasing V (if Q is constant)
        - $\mathbf{V = V_0/\kappa}$
        - $\mathbf{C = \kappa C_0}$
- Conductivity
    - Conduction: when charge moves along an object
        - An object conducting charge also *resists* the movement of charge (resistivity)
    - What makes a good conductor?
        - Allows electrons to move freely (metals), doesn't hold them in place (diamond, glass)
    - Metallic: conduct charge through transfer of electrons with no chemical change occurring as a result
        - Ex. metals. It's electrons from a "sea of electrons" conducive to electron flow
    - Electrolytic: conduct charge through a flow of ions through a membrane. Ion flow entails a transfer of matter
        - Ex. salt bridge. Ions flow across the membrane to maintain neutral charge in half cells
- Meters
    - **Ammeter**
        - Measures current in a circuit
        - Connected in series (allows all current flowing through circuit to flow through the meter as well)
        - Resistance is near zero (so that current can flow through it unobstructed)
    - **Voltmeter**
        - Measures potential difference between two points on a circuit
        - Connected in parallel to the circuit
        - Resistance is basically infinite (to avoid drawing a current and thereby changing the potential difference)
    - **Multimeter**
        - Functions both as an ammeter and voltmeter (have to switch between the two functions)

Magnetism (PHY)

- Definition of magnetic field **B**
    - Magnetic field **B** exists in a region of space if a moving charge experiences a force due to its motion in that region
    - The unit for magnetic field is the Tesla (T) or N•s/m•C
- Motion of charged particles in magnetic fields, Lorentz force
    - $\mathbf{F = qvB \sin\theta}$
    - θ is the angle between the charge velocity and magnetic field. Sometimes the $\sin\theta$ is omitted as θ is assumed to be 90°
    - The force is always perpendicular to both the magnetic field and to the velocity of the charge
    - You can use the right-hand rule to predict the direction of the force. The thumb is the direction of a positive charge, the middle finger is the direction of the magnetic field, and the palm faces the direction of the force
    - Special scenarios / cases
        - Charge moving in a circle
            - $F = qvB = mv^2/r$

- You are setting the electromagnetic force equal to the centripetal force, which maintains the orbit. Using this equation, you can solve for whatever the question asks you
- Current carrying wires
  - **F = qvB sinθ = (I•t)vB sinθ = (I•t)(L/t)B sinθ = ILB sinθ**
  - I is current, L is length of wire
  - Consider the current in the wire as moving positive charges (by tradition, the direction of the current is defined as the direction of moving positive charges)
  - You can calculate direction of the force on the wire in the same way using the right-hand rule. Just treat the direction of current the same as direction of velocity of a positive charge
  - Two wires will attract each other if the current is in the same direction
  - Two wires will repel each other if the current is in opposite directions

Electrochemistry (GC)

- Electrolytic cell
  - Electrolysis
    - Hooking up a power source to a galvanic cell and forcing reactions to run in reverse
    - Allows metal that's normally reduced to be oxidized and vice versa
    - Nonspontaneous
  - Anode, cathode
    - **Anode**: Positively charged, oxidation takes place here
    - **Cathode**: Negatively charged, reduction takes place here
      - Cathode is negative b/c additional power enables the more species to be reduced
  - Electrolyte: compound that forms ions in aqueous solution
    - Ionized or ionizable components of an electrochemical cell
  - Faraday's Law relating number of elements deposited (or gas liberated) at an electrode to current
  - Electron flow; oxidation, and reduction at the electrodes
    - Electrons flow from cathode to anode
- Galvanic or Voltaic cells
  - Half-reactions
    - Each half-cell has its own half-reaction
    - Subtracting anode half-rxn reduction potential from cathode half-rxn reduction potential = EMF of cell
    - Nernst equation

$$E = E^0 + \frac{RT}{nF} \ln \frac{[\text{Ox}]}{[\text{Red}]}$$

    - At 298 K and in base 10 log form, the equation is
      - $E = E^\circ + .06/n \log(Q)$
    - Used to find potential difference in a cell in nonstandard conditions
  - Reduction potentials; cell potential
    - Reduction potentials: components of a cell potential
      - Cannot occur by itself, every reduction half rxn needs an accompanying oxidation half rxn
      - More positive potential = rxn more likely to proceed
    - Cell potential: sum of standard state potentials for each half reaction

        - SHE: standard hydrogen electrode, oxidizes H_2 to H^+ to get e^-'s. Reduction potential (anodal) of this half reaction is *zero*
            - Cell potential with SHE at anode is reduction potential of electrodes used in conjunction with SHE
    - Direction of electron flow
        - Electrons flow from anode to cathode (- to +)
        - Salt Bridge
            - At least one phase in a voltaic cell must be impermeable to electrons
            - Purpose: Salt bridge connects two liquid phases of galvanic cell, allowing for *free movement of ions*, this *prevents charge differences between solutions* (*half-cells*)
                - Salt bridge carries current through movement of ions, not electrons
            - Electrons can only flow across electrodes if there isn't a charge difference between solutions (*uneven charge of electrodes and equal charges of solutions create the potential difference necessary for charge movement*)
- Concentration cell
    - Like galvanic cell, except potential difference is 0 and ion concentrations differ. Ion concentrations drive electron movement
        - In galvanic, potential difference drives electron movement
    - Two half-cells contain the same half-reaction, keeping potential difference 0
        - Only the ion concentration between half cells differ
    - Salt bridge still present to prevent ion concentration from equilibrating
    - Electron flow
        - Electrons flow from half-cell with more negative ions to that with more positive ions
- Batteries
    - Electromotive force, Voltage
    - Lead-storage batteries
        - Anode and cathode
            - Anode made of lead, cathode made of lead oxide
            - Discharges in presence of sulfuric acid
        - Behave as both galvanic and electrolytic cell
            - Galvanic: happens when it's in use. Lead is anode and lead oxide is cathode. Forms lead sulfate (hazardous compound) and water
            - Electrolytic: happens when battery needs to recharge. Voltage must be applied for rxn to proceed
        - Can provide large currents necessary for car starts, backup generators. However, produce hazardous lead sulfate which complicates disposal
    - Nickel-cadmium batteries
        - Unlike lead storage batteries, its electrolytes aren't consumed during discharge
        - Arranged in cylindrical configuration to reduce resistance

Specialized Cell - Nerve Cell (BIO)

- Myelin sheath, Schwann cells, insulation of axon
    - Myelin sheath = covers the axon intermittently, with gaps called nodes of Ranvier
    - The purpose of myelin sheath is to speed up conduction by insulating the nerve in intervals. This intermittent insulation causes action potential to jump from one node of Ranvier to the next
    - Schwann cells = makes myelin sheath in the peripheral nervous system by wrapping around the axon
    - Oligodendrocytes = the central nervous system analogue of Schwann cells, makes myelin sheath around CNS axons
    - Insulation of axon = achieved by the myelin sheath. Insulation occurs in intervals, which causes action potential to jump from one node of Ranvier to the next

    - Myelin sheath is a good insulator because it is fatty and does not contain any channels
- Nodes of Ranvier: propagation of nerve impulse along axon
    - Action potential jumps from one node of Ranvier to the next
    - This jumping of action potential speeds up conduction in the axon

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

Sound (PHY)

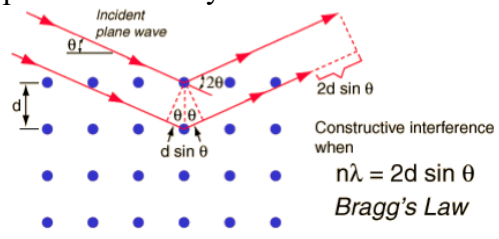
- Production of sound
  - Occurs via vibration of a source which produces waves
    - Waves: propagation of a vibration from one point to another. Often seen as transferring energy from point to point
      - Mechanical wave: needs a medium through which to propagate (sound)
        - Longitudinal wave: displaces medium parallel to direction of wave propagation
        - Transverse wave: displaces medium perpendicular to wave propagation
      - Electromagnetic wave: doesn't need a medium to travel through (light), can travel in a vacuum
- Relative speed of sound in solids, liquids, and gases
  - Wave's velocity is determined by the medium it travels through (for both sound and light waves)
    - If a wave travels from one medium to another, its velocity changes
    - Velocity increases proportionally with the *temperature* of the medium
    - Frequency is *not changed* when a wave switches mediums. *Wavelength* changes.
      - Frequency is determined by the wave's source. Wavelength is determined by the medium
  - Two characteristics of a medium that dictate velocity of waves
    - 1) Elasticity, or its resistance to change in shape
      - Increase in elasticity results in an *increase* in velocity
      - Increases as intermolecular attractions become stronger
    - 2) Inertia, or its resistance to change in motion
      - Increase in inertia results in a *decrease* in velocity
      - Decreases as mass and density increase
  - **$V = \lambda f$**
    - Velocity equals frequency*wavelength
      - Effectively a measurement of distance over time. Wavelength is distance. Frequency is time.
    - Period: the time it takes for a wave to travel one wavelength
      - **$P = 1/f$**
    - Increase in velocity is associated with an increase in wavelength
- Intensity of sound, decibel units, log scale
  - Measure of average rate of energy transfer per unit area, the power of a wave
  - Depends on density of medium, wave frequency, and wave velocity
    - Directly proportional to the squares of frequency and amplitude (these two factors have the largest effect on intensity)
  - Total energy is *constant* for a propagating wave
    - As a wave propagates outwards, its SA increases. This causes intensity to *decrease* (less

energy per SA)
    - Log scale
        - Decibels: describes how loud a sound seems to be (intensity level)
            - Has a *logarithmic* relationship to intensity
        - **Intensity level = 10log (I/I_o)**
            - I = final intensity value, Io = initial intensity level
            - **Key takeaway**: If the intensity of a sound increases by a FACTOR of 10, the decibels (intensity level) increases by an ADDITION of 10
- Attenuation (Damping)
- **Doppler Effect**: moving sound source or observer, reflection of sound from a moving object
    - Moving sound source
        - Change in frequency
            - As source moves TOWARDS an OBSERVER, relative distance between wavefronts decreases, INCREASING THE FREQUENCY
            - Doppler effect is associated with a change in frequency
        - Doppler formula
            - **$\Delta f/fs = v/c$ AND $\Delta\lambda/\lambda = v/c$**
                - Δf = change to the source frequency, fs = source frequency, v = relative velocity of the source and observer, c = wave velocity
            - **$Fo = fs +/- \Delta f$ AND $\lambda o = \lambda +/- \Delta\lambda$**
    - Reflection of sound
        - Beats
            - Sound can be emitted from a stationary observer, bounce off a moving object, and get back to that observer with a different frequency
        - Formulas
            - **$\Delta f/fs = 2v/c$**
                - Exactly the same as the other formula except you are multiplying velocity by 2
                    - This makes sense because sound needs to travel twice over the same distance
- Pitch
    - A measure of how “high” or “low” something sounds
    - Correlates with frequency
        - High note has high f, low note has low f
- Resonance in pipes and strings
    - String: generates transverse waves
        - Fixed at both ends: ends of strings are nodes
    - Pipes: generates longitudinal waves
        - Both ends open
            - Air particles at open end move with maximum displacement (free to move b/c not confined to the pipe as the ends are open)
            - Pressure at both ends are relatively equal
        - One end closed
            - Air particles are closed end cannot oscillate
            - Air pressure is greater at closed end (wave bounces off wall, particles at end pressed against closed end of the pipe)
        - Both ends closed
            - Air particles at closed ends move with zero displacement and generate max pressure
            - Air pressure at both ends are relatively equal

- Node vs. Antinode
  - **Node**: point of maximum destructive interference for a wave collision (two waves converge to a single point)
    - Nodes are present at the closed end of a pipe and on the ends of a fixed string
  - **Antinode**: point of maximum constructive interference for a wave collision (two waves' peaks are farthest apart)
    - Antinodes are present at the open end of a pipe
- Attenuation
  - Decrease in amplitude of a wave
  - Can be caused by reflection or spreading of sound waves
  - Attenuation causes intensity to decrease
- Harmonics
  - **L = lambda(n/2)**
    - L = length of string producing sound, n = harmonic of sound produced
    - Lambda = 2L/n
      - Shows that wavelength = twice the length of the string over the number harmonic of sound produced
  - **$f_n = nf_1$**
    - Shows that harmonic frequency = n times the fundamental frequency. 1st harmonic is 3 times the fundamental frequency, etc.
  - Beat frequency: frequency produced when two tones with different frequencies are emitted at the same time
    - **Beat freq. = $| f_2 - f_1 |$ n**
- Ultrasound
- Shock waves
  - Conical wave front produced when velocity of the sound source exceeds the velocity of the sound
  - Mach number
    - Ratio of the velocity of the source over the velocity of the wave
    - **Mach number = v_s/v**

Light, Electromagnetic Radiation (PHY)

- Concept of Interference: Young Double-Slit Experiment
  - Concept
    - Light waves that are out of phase collide, undergo destructive interference
  - Young's Double-slit Experiment
    - Monochromatic light is projected onto two small slits, split into two beams which create light/dark patterns
    - Path length difference: difference in lengths that light from two slits travel to reach a certain point
    - Constructive Interference occurs when path length difference between is a multiple of lambda
    - Destructive Interference occurs when path length is a multiple of lambda/2
    - Formulas for maxima and minima
      - **Max**: **$d\sin\theta = m\lambda$**
      - **Min**: **$d\sin\theta = (m+1/2)\lambda$**
        - Θ = angle between the 0th order maximum and the mth order maximum; m = order of the maximum (1, 2, 3, ….); d = distance between the slits
- Thin films, diffraction grating, single-slit diffraction
  - Thin film interference

        - Main idea: light shown at a thin film can undergo constructive or destructive interference
            - Sub idea: light undergoes a phase change of ½ when it reflects off a material with a greater index of refraction
        - Destructive interference
            - *Thin film thickness is a multiple of ½ the wavelength of light*, reflected and refracted light rays are in phase
                - Note: When light reflects off a thin film, it undergoes a phase change of ½
        - Constructive interference
            - *Thin film thickness is a multiple of ½ the wavelength of light*, reflected and refracted rays are out of phase
        - Note: if the material behind the thin film has a higher index of refraction, then the above formulas are switched around (b/c it undergoes another phase change of 1/2)
            - Destructive interference is now caused by a film with a thickness of a multiple of ¼ the wavelength
            - Constructive interference is now caused by a film with a thickness of ½ the wavelength
    - Diffraction grating
        - Light is passed through many slits spaced very closely together
        - More slits = narrower and more defined maxima, wider dark regions between maxima
        - Uses same formulas as double-slit diffraction
- Other diffraction phenomena, X-ray diffraction
    - X-ray diffraction
        - X-rays diffracted by passing them through crystals
            - X-rays have VERY small wavelengths. Crystals' atoms have spacing around the same wavelength as x-rays, allowing for diffraction
            - Rays reflect off of distinct surfaces within the crystal (reflecting planes)
        - Formulas
            - **2dsinθ = mλ**
                - d = distance between reflecting planes; θ = angle between the reflective plane and the ray
    - 

- Polarization of light: linear and circular
    - Linear
        - Polarization in x or y axis
        - Light that's vertically polarized passing through a horizontal polarizer will be made unpolarized
    - Circular
        - Electric fields of constant magnitude changing direction in a rotary manner produces circularly polarized light
- Properties of electromagnetic radiation
    - Velocity equals constant c, in vacuo
        - Can proceed in vacuum (doesn't need a medium to propagate through)
    - 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

- Order of electromagnetic spectrum (highest to lowest wavelength)
  - Radio waves → infrared → visible light → ultraviolet → x-rays → gamma rays
- Light is produced when an electron transitions from higher (excited) to lower (ground) energy states
  - 3 ways an electron can move to higher (excited) energy states
    - 1) An atom is bombarded by high speed particles (i.e. electrons)
    - 2) An atom absorbs a photon of light
      - When the excited electron loses E, it emits fluorescent light
    - 3) An atom is subjected to high temperatures
      - When the excited electrons lose E, they emit incandescent light
- Deriving frequency from wavelength
  - Freq. = c/λ

- Visual spectrum, color
  - 3.90*10^-9 to 9*10^-9 nm wavelength spectrum
  - Wavelengths of color (highest to lowest)
    - Red → yellow → green → blue

Molecular Structure and Absorption Spectra (OC)

- Infrared region
  - Intramolecular vibrations and rotations
    - Infrared radiation used to create vibrations and rotations in intermolecular bonds
    - Intermolecular bonds vibrate at different frequencies. When frequency of infrared radiation = resonance frequency of a bond, that bond absorbs IR energy.
      - IR measures frequency of absorption
  - Recognizing common characteristic group absorptions, fingerprint region
    - 1600 to 3500 cm^-1, most predictable section of IR spectrum
    - Bond absorptions
      - C=O: 1710, single peak
      - O-H (carboxylic acid): 2500-3000, broad peak, overlaps with C-H
      - O-H (alcohol): 3300, single peak
      - C-H (saturated): 2800-3000, multiple peaks
      - C-H (aldehyde): 2700, single peak
      - C-N: 2200, single peak
      - N-H (amine): 3300, small nipple-shaped peak
      - N-H (amide): 3300, large double pick
    - Fingerprint region
      - 600 to 1400cm^-1 region, complex vibrations that distinguish similar compounds from one another
- Visible region (GC)
  - Absorption in visible region gives complementary color (e.g. carotene)
    - Compound with 8 or more double bonds have absorbance in visible region
    - Ex. Beta-carotene
      - Precursor of vitamin A found in carrots, 11 conjugated double bonds, absorbs blue-green light
        - Reflects *complementary color* red-orange, giving carrots this color
  - Effect of structural changes on absorption (e.g. indicators)
- Ultraviolet region
  - π-Electron and non-bonding electron transitions
    - UV light bumps pi electrons from bonding to non-bonding orbitals (from HOMO to LUMO)

        - In conjugated systems, HOMO and LUMO are much closer
        - Pi electron movement from HOMO to LUMO changes absorbance of compound
    - Compound systems
        - Conjugated systems absorb more UV rays than nonconjugated systems
        - **$A = \varepsilon cl$**
            - A = absorbance, ε = molar absorptivity, c = product of concentration of sample, l = path length of light through cell
            - Absorbance dependent on inherent absorptivity of compound, concentration of compound, and distance it has to travel through compound
- NMR spectroscopy
    - Concerned with hydrogen atoms, other odd-number elements
    - Protons in a magnetic field; Equivalent protons
        - Spin states
            - Protons in nuclei can have their rotations aligned with (alpha) or against (beta) an external magnetic field
                - Beta nuclei are in higher energy state
            - Nuclei can be induced to go from low-energy alpha to high-E beta by photon collision
            - When they go back to alpha, they release energy which is detected by NMR
        - NMR spectrum
            - Graph of magnetic field strengths absorbed by hydrogen, carbon, other odd-number atomic number atoms at a *specific frequency*
                - Magnetic field strength varies but frequency is held constant
            - Greater area of a peak = greater number of H's there
        - Chemically equivalent protons/hydrogens
            - Groups of hydrogens denoted by the same peak on NMR
            - These are hydrogens whose position on a compound is indistinguishable via NMR
    - Electron-shielding
        - Position of peaks dictated by electron shielding
            - Electron withdrawing groups lower shielding → decrease magnetic field strength required for resonance → peaks are more downfield
            - Opposite true for electron donating groups
    - Integral trace
        - Line drawn above peaks that rises each time it goes over a peak
        - Rise is proportional to number of chemically equivalent hydrogens in the peak beneath it
    - Spin-spin splitting
        - Splitting of peaks caused by neighboring hydrogens
            - Neighboring hydrogen: hydrogen connected to an atom adjacent to the atom the other hydrogen is connected to
        - Number of peaks = n + 1
            - N = number of neighboring hydrogens
        - Carbon-13 NMR does NOT have splitting
- Mass Spectrometry
    - Uses electron bombardment instead of electromagnetic radiation

Geometrical Optics (PHY)

- Reflection from plane surface: angle of incidence equals angle of reflection
    - Angles (measured from a line NORMAL to the surface)
        - Angle of incidence: see below
        - Angle of reflection: angle at which light reflects off a surface

- Refraction, refractive index n; Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
  - Angles (measured from a line NORMAL to the surface)
    - Angle of incidence: angle at which light strikes a surface
    - Angle of refraction: angle at which light is refracted on other side of surface
  - Refraction's effects on light's properties
    - Frequency: not changed
    - Wavelength: changes
      - From lower to higher index of refraction, wavelength decreases
      - From higher to lower index of refraction, wavelength increases
    - Velocity: changes
      - From lower to higher index of refraction, velocity decreases and wave fronts cluster closer together
      - From lower to higher index of refraction, velocity increases and wave fronts get more spread out
  - Snell's Law
    - Measures extend to which light is bent when transferring between mediums
- Dispersion, change of index of refraction with wavelength
- Conditions for total internal reflection
  - **Critical angle = $\sin^{-1}(n_2/n_1)$**
    - At the critical angle, no light is refracted
- Spherical mirrors
  - Center of curvature (R)
    - Radius of curvature of mirror, all points on curved mirror are *equidistant* from this
  - Focal length
    - **F = R/2**
    - Point where light rays actually converge/appear to converge
  - Converging and diverging mirrors
    - Converging
      - Light rays converge *in front of mirror*
      - Created by concave mirrors
    - Diverging
      - Light rays coverge *behind mirror*
      - Created by convex mirrors
  - Real and virtual images
    - Virtual: **upright image on the opposite side of the observer, same side as the object (negative sign)**
      - Diverging mirrors and lenses **always form virtual images**
    - Real: **inverted images on the same side as the observer, opposite side of the object (positive sign)**
      - Converging lenses and mirrors **can form BOTH virtual and real images**
        - Mirrors: beyond focal point = real; Within focal point = virtual
        - Lenses: beyond focal point = virtual; Within focal point = real
- Thin lenses
  - Converging and diverging lenses
    - Converging
      - Light rays converge *opposite of the object side of lens*
      - Created by convex lenses
    - Diverging
      - Light rays converge on *object side of lens*
      - Created by concave lenses

- Use of formula **1/p + 1/q = 1/f**, with sign conventions (Thin Lens Equation)
  - Used to calculate object distance (p) and image distance (q) for mirrors or lenses
  - Sign conventions
    - p: positive when objects are "where they belong" (on observer side for mirror, object side for lens)
    - q: positive when image is real (same side as observer), negative when image is virtual (opposite side as observer)
    - f: positive for a converging lens or mirror, negative for a diverging lens or mirror
- Lens strength, dopters
  - Magnification

Magnification Equation

$$M = \frac{h_i}{h_0} = -\frac{d_i}{d_0}$$

  -
    - h = height of image/object
    - d = distance of image/object from the mirror/lens
  - Diverging vs. converging
    - Diverging mirrors/lenses always form smaller images
    - Converging mirrors/lenses form larger images UNLESS the object is outside their radii of curvature

- Combination of lenses
  - How to deal with these problems
    - One lens at a time, consider the image of the first mirror/lens as the object of the second
  - Magnification
    - **$M = M_1M_2$**
    - Magnification of a two-lens system = products of magnification of lenses
  - Power
    - **$P = P_1 + P_2$**
    - Power = sum of the powers of the two lenses
  - Practical applications
    - Microscopes and telescopes
      - 2 lenses: objective and eyepiece
      - Light first hits the objective, which creates a real, inverted image
      - Image created by the objective acts as the object for the eyepiece, which flips it to be a virtual upright image
        - Image created by telescope/microscope appears inverted
    - Human eye
      - Cornea bends light a LOT, lens bends light a little for fine control
      - Focusing on…
        - Near objects: ciliary muscles contract, making lens bulge and making focal point closer to lens
        - Far objects: ciliary muscles relax, making lens thin and making focal point farther away from lens
      - Myopia and hyperopia
        - **Myopia** (nearsightedness): lens bends light too much, corrected with diverging lens
        - **Hyperopia** (farsightedness): lens doesn't bend light enough, corrected with converging lenses

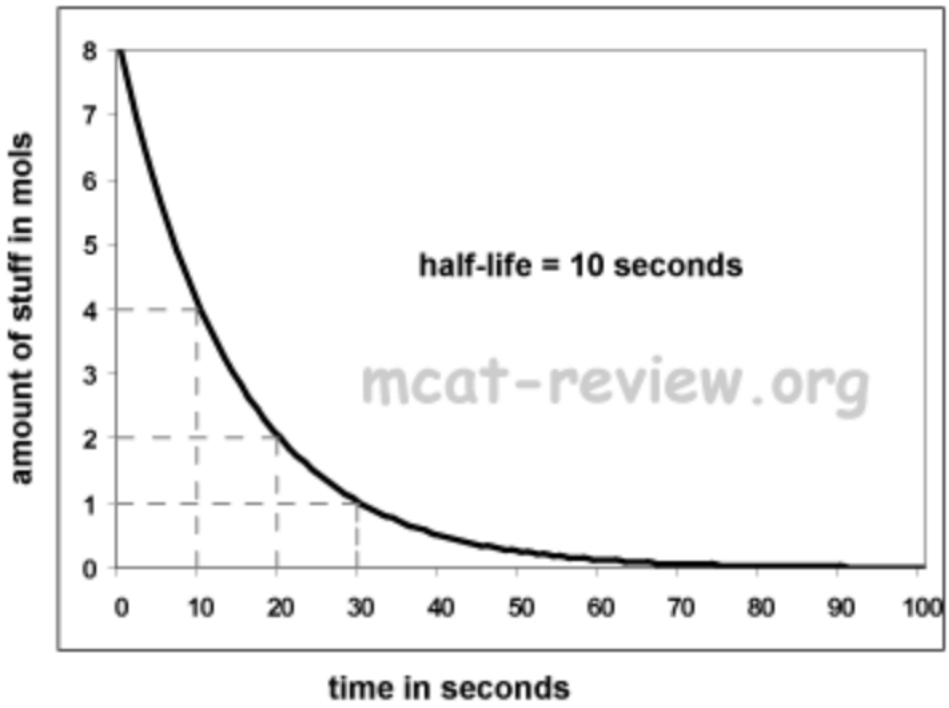
- Lens aberration

    - Only parabolic lenses have a single focal point
        - Spherical lenses may produce distorted images
    - *Chromatic Aberrations*
        - Higher frequency light focuses closer to the lens than low-frequency light
            - Only occurs if light of different frequencies pass through a lens *simultaneously*
    - *Spherical aberrations*
        - Only parabolic lenses have a single focal point
        - Rays further from the center of the lens arrive at a different focal point than those closer to the center
- Optical Instruments, including the human eye

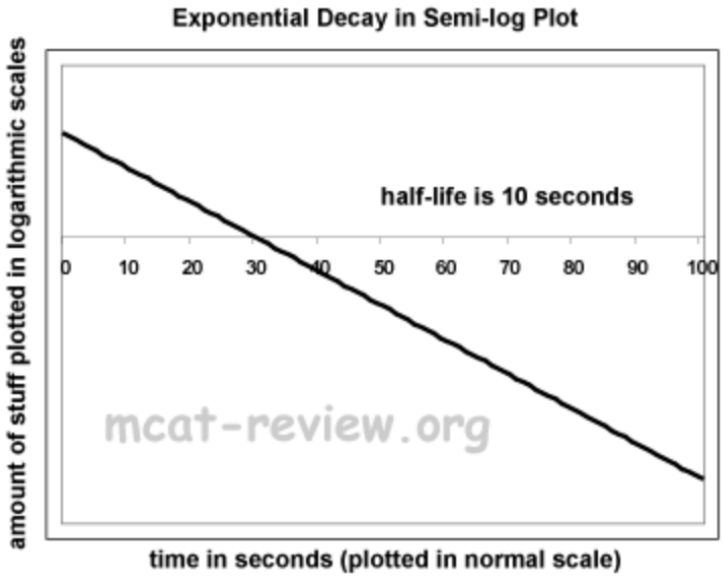
Content Category 4E: Atoms, nuclear decay, electronic structure, and atomic chemical behavior

Atomic nucleus (PHY, GC)

- Atomic number, atomic weight
  - Atomic number = number of protons
    - Defines an element
    - When two things have same number of protons, they are the same element
  - Atomic weight = weighted average of atomic mass for all isotopes of a given atom
    - Atomic mass = number of protons + neutrons
    - Atomic mass used for an isotope
    - Atomic weight used for an element
- Neutrons, protons, isotopes
  - **Neutrons** = neutral particles in nucleus
  - **Protons** = positive particles in nucleus
  - **Isotopes** = things with same number of protons, but different number of neutrons
  - **Nucleons** = protons or neutrons
- Nuclear forces, binding energy
  - Two forces are at work in the nucleus: strong force and electromagnetic force
  - Strong force binds nucleons together, and therefore contribute to binding energy
  - Electromagnetic force due to electrostatic repulsion between the positively charged protons in the nucleus
  - Nucleus stays together because the strong force is much stronger than electromagnetic repulsion
  - Strong force also called the "nuclear force"
- Radioactive decay
  - α, β, γ decay
    - **α decay**: $^{216}_{84}Po \rightarrow ^{212}_{82}Pb + ^{4}_{2}\alpha$ Ejection of a helium nucleus at a relatively low speed
    - **β decay**: $^{32}_{15}P \rightarrow ^{32}_{16}S + ^{0}_{-1}\beta$, Ejection of a high speed electron
    - **γ decay**: $^{222}_{86}Rn \rightarrow ^{222}_{86}Rn + ^{0}_{0}\gamma$ Release of a high energy electromagnetic wave
  - Half-life, exponential decay, semi-log plots
    - Half-life is the time it takes for the amount of something to half due to decay
    - After 1 HL, amount decreases by half
    - After 2 HL, amount decreases by a factor of 4
    - After 3 HL, amount decreases by a factor of 8
    - Exponential decay:



- Semi-log plots: convert exponential curves into straight lines
  - Something that curves up becomes a straight line with positive slope
  - Something that curves down becomes a straight line with negative slope
  - For exponential decay, a semi-log plot graphs log of amount vs time
  - For exponential decay, a semi-log plot is a straight line with negative slope
  - Semi-log plot intercepts the x axis where the original y value is 1

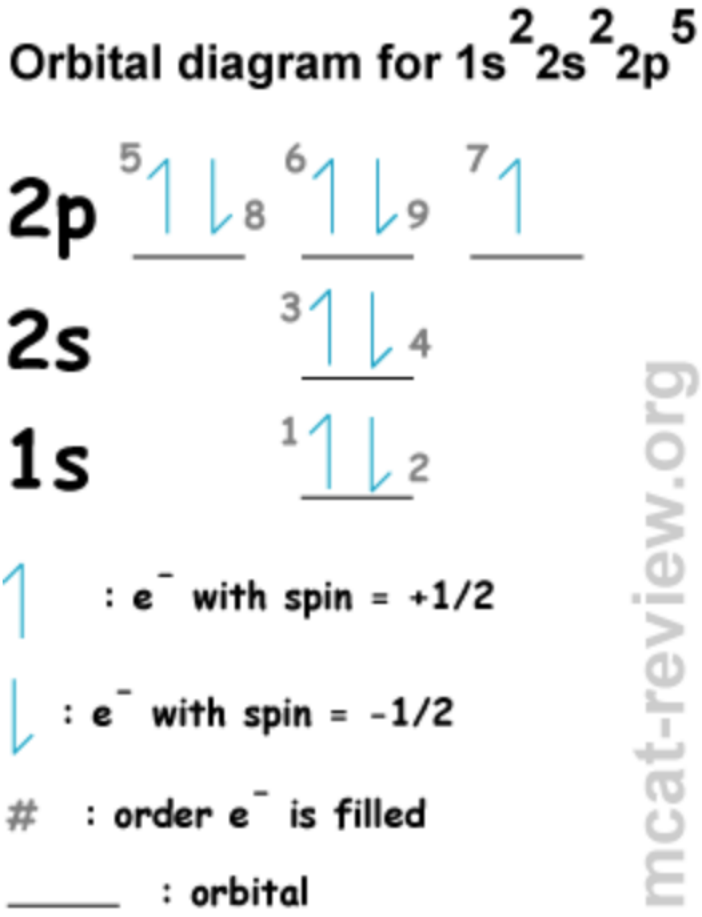


- Mass spectrometer
  - Mass spec is when you bombard a molecule with electrons
  - When electrons smash into your molecule, it is fragmented into ions
    - The faster (higher energy) the bombarding electron, the more fragmentation
    - The more fragmentation, the smaller the molecular ion peak
  - These ions have a characteristics mass to charge ratio (m/e or m/z)
  - A magnetic field resolves (separates) the different m/z ions so they can be individually detected and plotted on a spectrum
  - Resulting spectrum plots Relative abundance vs the m/z ratio

- The parent peak, or molecular ion peak, is the peak that depicts the ion of the molecule without fragmentation. It has the highest m/z ratio
- Peaks clustered really close to one another depicts isotopes
- Base peak is the tallest peak (most abundant species)
- Useful for:
  - Measuring molecular weight of a molecule
  - Identify molecule by fragmentation patterns
  - Identify heteroatoms by their characteristic isotope ratios

Electronic Structure (PHY, GC)

- Orbital structure of hydrogen atom, principal quantum number *n*, number of electrons per orbital (GC)
  - In the Bohr model, the hydrogen electron orbits the nucleus.
  - In quantum mechanics, hydrogen electron exists in a spherical probability cloud around the nucleus
  - The principle quantum number, n, defines what shell the electron is in
  - n values start from one: 1,2,3 … etc
  - Higher n shells are higher in energy (if subshells are the same)
  - There are n^2 orbitals per shell
  - There are 2 electrons per orbital
  - Thus, there are $2n^2$ electrons per shell
- Ground state, excited states
  - Electrons are normally in their ground state
  - When they absorb energy, they get promoted to excited states
  - Excited states are higher in energy than ground states
  - Excited state electrons come back down to the ground state via release of energy
- Absorption and emission line spectra
  - The absorption spectrum shows what wavelengths of light are absorbed
  - The absorption spectrum looks like black lines on a rainbow background
  - The emission spectrum shows what wavelengths of light are emitted
  - The emission spectrum looks like colored lines on a black background
  - The absorption spectrum corresponds to the emission spectrum in pattern
  - The emission spectrum shifts to a slightly longer wavelength
- Use of Pauli Exclusion Principle
  - 2 electrons in the same orbital must be of different spins
- Paramagnetism and diamagnetism
  - **Paramagnetic** = substance has unpaired electrons
  - **Diamagnetic** = all of the substance's electrons are paired
- Conventional notation for electronic structure (GC)



- Bohr atom
  - Electron orbiting the nucleus in a circular orbit
  - Larger n values have larger orbiting radii
- Heisenberg Uncertainty Principle
  - States that you can never simultaneously know the exact position and exact speed of an object because everything in the universe behaves both like a particle and wave at the same time
- Effective nuclear charge (GC)
  - **Effective nuclear charge = nuclear charge - shielding electrons**
  - Shielding electrons are those that stand between the nucleus and the electron we are interested in
  - Shielding electrons are those that are in subshells closer to the nucleus (lower in energy) than the electron we are interested in
  - MCAT questions usually give diagram of the Bohr model, in which case, the shield electrons are those that orbits at a smaller radius
  - The higher the effective nuclear charge for an electron, the more stable it is (higher ionization energy, not easily knocked off)
  - Effective nuclear charge increases for outer electrons as you go across (left to right) the periodic table
- Photoelectric effect
  - Incident light on metallic surfaces will cause the emission of electrons
  - The kinetic energy of the ejected electron does not depend on the intensity of the light
  - The kinetic energy depends on the energy of the individual photons, not how much total light there is. A high intensity radio source would not produce the photoelectric effect at all because no individual photons would have sufficient energy, even though there was high energy overall, while low intensity x-rays would lead to the photoelectric effect

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

- **Alkali metals**

    - Single valence electron - low ionization energy, very reactive
    - Wants to lose that electron to achieve empty valence shell
    - More reactive as you go down because of increasing radii
    - Reacts with oxygen to form oxides
    - Reacts with water to form hydroxides and releases hydrogen
    - Reacts with acids to form salts and releases hydrogen
    - Most commonly found in the +1 oxidation state
- **Alkaline earth metals**: their chemical characteristics
    - 2 valence electrons - relatively low ionization energy, quite reactive
    - Wants to lose both electrons to achieve empty valence shell
    - More reactive as you go down because of increasing radii
    - Reacts with oxygen to form oxides
    - Reacts with water to form hydroxides and releases hydrogen
    - Reacts with acids to form salts and releases hydrogen
    - Most commonly found in the +2 oxidation state
- **Halogens**: their chemical characteristics
    - 7 valence electrons (2 from s subshell and 5 from p subshell) - high electron affinity, very reactive
    - Wants to gain one electron to achieve full valence shell
    - More reactive as you go up because of decreasing radii
    - Reacts with alkali metals and alkaline earth metals to form salts
    - Most commonly found in the -1 oxidation state
- **Noble gases**: their physical and chemical characteristics
    - Full valence shell of 8 - high ionization energy couple with low electron affinity
    - Don’t react
    - Found in the oxidation state of 0
- **Transition metals**
    - High conductivity due to free flowing (loosely bound) outer d electrons
    - In the presence of ligands (when in a chemical complex), the d orbitals become nondegenerate (different in energy)
    - Electron transitions between nondegenerate d orbitals gives transition metal complexes vivid colors
    - Varied oxidation states - but always +
- **Representative elements**
    - Representative elements include the s block and p block of the periodic table
    - No free flowing (loosely bound) outer d electrons
    - Valence shell fills from left (1 electron) to right (8 electrons)
    - Standard nomenclature: I A, II A, III A, IV A, V A, VI A, VII A, VIII A
- Metals and non-metals
    - Metals are to the left of metalloids
    - Non-metals are to the right of metalloids
    - Metalloids: diagonal line from Boron to Polonium: B, Si, As, Te, Ge, Sb, (Po)

Chemical properties	
Metals	Non-metals
Likes to lose electrons to gain a + oxidation state (good reducing agent).	Likes to gain electrons to form a - oxidation state (good oxidizing agent).
Lower electronegativity - partially positive in a covalent bond with non-metal.	Higher electronegativity - partially negative in a covalent bond with metal.
Forms basic oxides.	Forms acidic oxides.
Physical properties	
Good conductor of heat and electricity	Poor conductor of heat and electricity
Malleable, ductile, luster, solid at room temp(except Hg)	Solid, liquid, or gas at room temp. Brittle if solid and without luster.

- **Oxygen group**
  - The group (column) that contains oxygen
  - Oxygen and sulfur are chemically similar (if question asks you what element you can substitute for oxygen and keep same chemical reactivity, choose sulfur)
  - Se - Te - Po - non-metal - metalloid - metal (or metalloid)

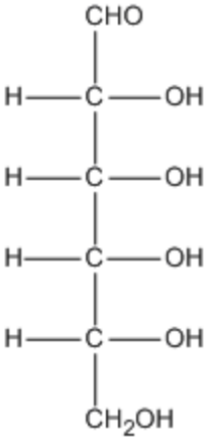
The Periodic Table - Variations of Chemical Properties with Group and Row (GC)

- Valence electrons
  - Electrons in the outer shell
  - Ranges from 1 to 8 from left to right of the representative elements
  - The valence electron rule does not apply to transition metals
- First and second ionization energy
  - Definition of first IE: the energy needed to knock off the first valence electron
  - Definition of second IE: energy needed to knock off the second valence electron
  - Prediction from electronic structure for elements in different groups or rows
    - IE decreases as you go down because of increasing radii
    - IE increases as you go right because of decreasing radii
    - Highest peaks are noble gases
    - Lowest troughs are alkali metals
    - Local maxima occurs for filled subshells and half-filled p subshells
    - Second IE is always higher than the first IE (usually a lot higher)
    - Alkali metals and hydrogen: first ionization energy very low. Second ionization much higher.
    - Alkaline earth metals: first ionization energy low. Second IE also low
- Electron affinity
  - Definition: electron affinity is the amount of energy released when something gains an electron (how easily it can gain an electron)
  - Variation with group and row
    - As you go down a group, EA decreases because of larger radii
    - As you go across (left to right) a row, EA increases
    - Highest peaks are for the halogens
    - Lowest for noble gases
- Electronegativity
  - Definition: electronegativity is how much something hoards electrons in a covalent bond

    - Comparative values for some representative elements and important groups
        - Electronegativity increases toward the top right
        - Fluorine is the most EN element
        - Things around fluorine are highly EN: N, O, Cl, Br
        - Halogens are EN, especially toward the top of the group
        - Noble gases can be very EN if they participate in bond formation (Kr and Xe)
        - Non-metals are more EN than metals
        - Covalent bond is a sharing of electrons between elements
        - The more EN element in a covalent bond gets a larger share of electrons and has a partial negative charge
        - The less EN (more electropositive) element in a covalent bond gets a smaller share of the electrons and has a partial positive charge
        - If the EN difference is too great, an ionic bond occurs instead of a covalent one
        - Ionic bonds result from a complete transfer of electrons from the electropositive element to the electronegative element
- Electron shells and the sizes of atoms
    - Electron shells
        - Defined by the principle quantum number - the n value
        - Going down the periodic table means jumping to the next shell
        - As you fill to the next shell (Ne to Na), the effective nuclear charge decreases because the old shell stands in between the nucleus and the new shell
        - Filling to the next shell causes a jump in atom size because of decreased effective nuclear charge
        - As you go down a group (Na to K0, the atomic size increases even though the effective nuclear charge stays the same, because higher shells have a larger radius than lower shells
        - Going across the periodic table means filling up the same shell (by going through subshells)
        - As you fill up a shell, the effective nuclear charge increases because the atomic number (protons) is increasing while the same-shell electrons you add do not shield one another
        - With increasing effective nuclear charge, the electrostatic attraction ($F=kQq/r^2$) between the nucleus and the electrons increases, so the atom becomes more compact
        - The increasing effective nuclear charge and electrostatic attraction is why going across a periodic table means decreasing atomic size
    - Sizes of atoms
        - Size increases as you go down a column
        - Size decreases as you go across (to the right of) a row
        - Atomic sizes may overlap if you zigzag on the periodic table
- Electron shells and the sizes of ions
    - Sizes of ions
        - Number of protons affects how attracted the electrons
        - Higher # of protons pulls electrons closer, reducing the radius
        - Pay attention to whether the molecule has lost electrons in its outer subshell

Stoichiometry (GC)

- Molecular weight
    - Molecular weight is numerically equal to molecular mass (amu)
    - 1 amu = 1 g/mol
    - ^{12}Carbon has 12 amu and weighs 12g/mol
- Empirical versus molecular formula

molecular structure	molecular formula	empirical formula
	$C_6H_{12}O_6$	CH_2O

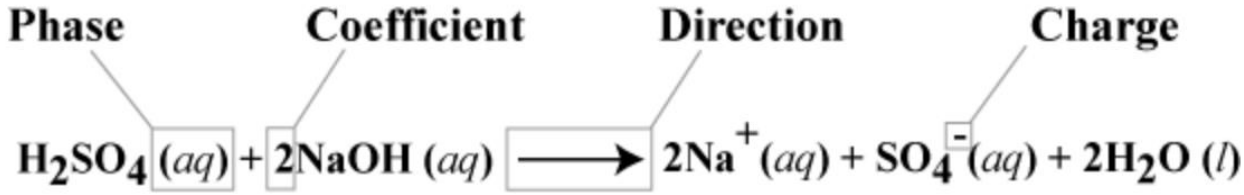
- Empirical formula is what you get after dividing everything in the molecular formula by the highest common factor

- Metric units commonly used in the context of chemistry
  - Molarity = M = mol/L
  - Molality = m = mol/kg
  - Mass = kg. Molar mass = g/mol
- Description of composition by percent mass
  - %mass = mass of species of interest / total mass * 100
- Mole concept, Avogadro's number N_A
  - 1 mole = 1 mol = 1 Avogadro's number = 6.02E23 molecules
- Definition of density
  - Density = mass/volume = kg/m^3
  - Often in chemistry, specific gravity is used
  - S.G. = number of times the density of water = density of substance / density of water
  - Density of water = 1 g/mL = $1g/cm^3$
  - S.G. of water = 1 g/cm^3 / 1 g/cm^3 = 1
  - Density of lead = 11 g/cm^3
  - S.G. of lead = 11 g/cm^3 / 1 g/cm^3 = 11
  - S.G. is unitless
- Oxidation number
  - Common oxidizing and reducing agents

oxidizing agents	reducing agents
Oxygen O_2, Ozone O_3, Permanganates MnO_4^-, Chromates CrO_4^{2-}, Dichromates $Cr_2O_7^{2-}$, peroxides H_2O_2, lewis acids, stuff with a lot of oxygens	Hydrogen H_2, metals (such as K), Zn/HCl, Sn/HCl, LAH (Lithium Aluminium Hydride), $NaBH_4$ (Sodium Borohydride), lewis bases, stuff with a lot of hydrogens

  - Disproportionation reactions
    - An element in a single oxidation state reacts to form 2 different oxidation states
    - Disproportionation can occur when a species undergo both oxidation and reduction
    - For example: $2Cu^+ \rightarrow Cu + Cu^{2+}$
      - Here, the Cu^+ acts as both oxidizing and reducing agent and simultaneously reduce and oxidize itself
      - The oxidized Cu^+ becomes Cu^{2+}

        - The reduced Cu^+ becomes Cu
- Description of reactions by chemical equations
    - Conventions for writing chemical equations



        - Phases
            - (s) = solid
            - (l) = liquid
            - (g) = gas
            - (aq) = aqueous (dissolved in water)
        - Coefficient
            - An equation with coefficients is a balanced equation
        - Direction
            - A single head arrow denotes the reaction goes to completion in the direction of the arrow
            - A double-sided arrow denotes a reaction in equilibrium
            - A double-sided arrow with one side larger than the other denotes an equilibrium in favor of the side of the larger arrow
        - Charge
            - Denotes charge and magnitude, for example +, -, 2+, 5-, … etc
            - Neutral charges are not denoted
    - Balancing equations, including redox equations
        - Balance the combustion of propanol: $C_3H_8O + O_2 \rightarrow CO_2 + H_2O$
        - Pick out atom (or group) that is easiest to balance (usually represented in only 1 term on both sides of the equation. In this case it is carbon
        - $\mathbf{C_3H_8O} + O_2 \rightarrow \mathbf{3CO_2} + H_2O$
        - The next easiest to balance is hydrogen
        - $\mathbf{C_3H_8O} + O_2 \rightarrow \mathbf{3CO_2} + \mathbf{4H_2O}$
        - Leave the hardest to last, oxygen. O is present in every term of the equation, so if we tried to balance O first, we'd have a hard time.
        - $\mathbf{C_3H_8O + 9/2\ O_2 \rightarrow 3CO_2 + 4H_2O}$
        - Even though we balanced every term, we're not done yet. We need to get rid of any fractions, so multiply every term by 2
        - $\mathbf{2C_3H_8O + 9O_2 \rightarrow 6CO_2 + 8H_2O}$
        - Balancing oxidation-reduction (redox) equations
            - 1. Separate into half reactions
                - There will be 2 half equations: one will be oxidation, the other reduction
                - Half equations contain only species of interest - those containing the atom that undergoes a change in oxidation state
                - Anything that is not covalently attached to the atom is not part of the species of interest
                - Anything that does not undergo a change in oxidation state is a spectator ion/species
            - 2. Balance each of the half reactions
                - Balance both charge and atoms
                - To balance one oxygen atom:

        - Under acidic conditions: add H_2O to the side that needs the oxygen atom, then add H^+ to the other side
        - Under basic conditions: add $2OH^-$ to the side that needs the oxygen atom, then add H_2O to the other side
    - The Ion-Electron Method: you balance out the atoms first, then charge
    - The Oxidation-State Method: treat the species of interest as a single atom (those that undergo a change in oxidation number) then balance it
- 3. Recombine the half reactions
    - Multiply each half reaction by a factor, such that when you add them together, the electrons cancel out
    - It's like you're trying to solve a simultaneous equation and you want to eliminate the electron term
- 4. Finishing touches
    - Combine any identical species on the same side of the equation
    - Cancel out any identical species on opposite sides of the equation
    - Add back in the spectator ions
    - For the oxidation-state method, now is also the time to balance out the oxygens and hydrogens
    - Check to make sure that both sides of the equation have equal number of atoms and neutral net charge

- Example using ion-electron method: $K_2Cr_2O_7$ (aq) + HCl (aq) → KCl (aq) + $CrCl_3$ (aq) + H_2O (l) + Cl_2 (g)
    - 1. Separate into half reactions
        - Reduction: $Cr_2O_7^{2-}$ → Cr^{3+}
        - Oxidation: Cl^- → Cl_2
        - Species of interest for the oxidation reaction is Cl^-, not HCl, because the H^+ is not covalently attached to our atom of interest, and the hydrogen proton breaks off in aqueous solution
        - Similarly, we use $Cr_2O_7^{2-}$ and not $K_2Cr_2O_7$
        - K^+ is the spectator ion
    - 2. Balance each of the half reactions
        - The Ion-Electron Method: you balance out the atoms first, then charge
            - Balancing atoms for the reduction half reaction (Ion-electron method):
                - 1. $Cr_2O_7^{2-}$ → Cr^{3+}
                - 2. $Cr_2O_7^{2-}$ → $2Cr^{3+}$
                - 3. $Cr_2O_7^{2-} + 14H^+$ → $2Cr^{3+} + 7H_2O$
            - Balancing charge for the reduction half reaction (Ion-electron method):
                - 1. $Cr_2O_7^{2-} + 14H^+ + 6e^-$ → $2Cr^{3+} + 7H_2O$
            - Do the same thing for the oxidation half reaction (Ion-electron method):
                - 1. Cl^- → Cl_2
                - 2. $2Cl^-$ → Cl_2
                - 3. $2Cl^-$ → $Cl_2 + 2e^-$
    - 3. Recombine the half reactions
        - $Cr_2O_7^{2-} + 14H^+ + 6e^-$ → $2Cr^{3+} + 7H_2O$
        - $2Cl^-$ → $Cl_2 + 2e^-$
        - Multiply everything in the second equation by 3
        - $6Cl^-$ → $3Cl_2 + 6e^-$
        - Add the two equations together

        - $Cr_2O_7^{2-} + 14H^+ + 6e^- + 6Cl^- \rightarrow 2Cr^{3+} + 7H_2O + 3Cl_2 + 6e^-$
    - Finishing touches
        - Except for the electrons, there are no like terms to combine or cancel at this time
        - $Cr_2O_7^{2-} + 14H^+ + 6Cl^- \rightarrow 2Cr^{3+} + 7H_2O + 3Cl_2$
        - For the ion-electron method, the equation is already balanced. However, you need to add back in the spectator ions. When adding back the spectator ions, whatever you do to the left side, you do to the right
        - To the left side: the dichromate came in counter-ioned with K+, so add 2K+
        - To the right side: do the same
        - $K_2Cr_2O_7 + 14H^+ + 6Cl^- \rightarrow 2Cr^{3+} + 7H_2O + 3Cl_2 + 2K^+$
        - Referring back to the original equation, the H's and Cl's on the left came in as HCl, so in order to balance the extra 14 - 6 = 8 H's, you add 8 Cl's. As always, if you add 8 Cl's to the left, go ahead and add the same to the right
        - $Kr_2Cr_2O_7 + 14HCl \rightarrow 2Cr^{3+} + 7H_2O + 3Cl_2 + 2K^+ + 8Cl^-$
        - Done focusing on the left side. A quick look at the right side shows that we need to combine 2 of the Cl^- with the 2 K^+, and the remaining 6 Cl^- goes with the Cr. Thus, the final balanced redox equation is:
        - $K_2Cr_2O_7$ (aq) + 14HCl (aq) $\rightarrow$ $2CrCl_3$ (aq) + $7H_2O$ (l) + $3Cl_2$ (g) + 2KCl (aq)
- Example using oxidation state-method: $K_2Cr_2O_7$ (aq) + HCl (aq) $\rightarrow$ KCl (aq) + $CrCl_3$ (aq) + H_2O (l) + Cl_2 (g)
    - 1. Separate into half reactions (same as the ion-electron method)
        - Reduction: $Cr_2O_7^{2-} \rightarrow Cr^{3+}$
        - Oxidation: $Cl^- \rightarrow Cl_2$
    - 2. Balance each of the half reactions
        - The Oxidation-State Method: focus on atom of interest
            - Balancing the atom of interest for the reduction half reaction (Oxidation-state method)
                - 1. $Cr_2O_7^{2-} \rightarrow Cr^{3+}$
                - 2. $Cr_2O_7^{2-} \rightarrow 2Cr^{3+}$
                - 3. Each oxygen is 2^- so the 2 Cr on the left must be 6^+
                - $2Cr^{6+} \rightarrow 2Cr^{3+}$
            - Balancing charge for the atom of interest in the reduction half reaction (Oxidation-state method)
                - 1. $2Cr^{6+} + 6e^- \rightarrow 2Cr^{3+}$
            - Do the same thing for the oxidation half reaction (Oxidation-state method)
                - 1. $Cl^- \rightarrow Cl_2$
                - 2. $2Cl^- \rightarrow Cl_2$
                - 3. $2Cl^- \rightarrow 2Cl^0$
                - 4. $2Cl^- \rightarrow 2Cl^0 + 2e^-$
    - 3. Recombine the half reactions
        - $2Cr^{6+} + 6e^- \rightarrow 2Cr^{3+}$
        - $2Cl^- \rightarrow 2Cl^0 + 2e^-$
        - Multiply everything in the second equation by 3:
        - $2Cr^{6+} + 6e^- \rightarrow 2Cr^{3+}$
        - $6Cl^- \rightarrow 6Cl^0 + 6e^-$
        - Add the two equations together

        - $2Cr^{6+} + 6e^- + 6Cl^- \rightarrow 2Cr^{3+} + 6Cl^0 + 6e^-$
    - 4. Finishing touches
        - Except for the electrons, there are no like terms to combine or cancel at this time…
        - $2\ Cr^{6+} + 6Cl^- \rightarrow 2Cr^{3+} + 6Cl^0$
        - Convert the atoms of interest into species of interest by referring back to original equation
        - $K_2Cr_2O_7 + 6HCl \rightarrow 2CrCl_3 + 3Cl_2$
        - Now unlike the ion-electron method, where the equation is balanced and you only add back spectator ions at this stage of the game, the oxidation state method requires you to balance the equation again. This is because after you convert the atoms of interest back to their species of interest, the equation is no longer balanced.
        - Start with the oxygens. On the left you have 7 O, so add 7 H_2O to the right
        - $K_2Cr_2O_7 + 6HCl \rightarrow 2CrCl_3 + 3Cl_2 + 7H_2O$
        - Now take care of the hydrogens. You have 6H on the left, but 14H on the right. That means you should add 8 more H's to the left to make a total of 14. All 14 H's on the left should be in the form of HCl (refer back to the original equation. Note, HCl here is both the species of interest and spectator species. Some of the HCl contributes to the $Cl^- \rightarrow Cl_2$ oxidation, but the other portion of the HCl doesn't undergo redox. It merely provides the H^+ for the water and the Cl^- for the KCl and $CrCl_3$)
        - $K_2Cr_2O_7 + 14HCl \rightarrow 2CrCl_3 + 3Cl_2 + 7H_2O$
        - Now you see there's 14 Cl to the left, and 12 Cl to the right. You need 2 more Cl's on the right. Referring back to the original equation, all the right-sided cl's come in the form of KCl (don't modify the Cl_2 since you've already correctly balanced it by the oxidation state method. when balancing equations at this stage, only play around with water and the spectator species)
        - $K_2Cr_2O_7 + 14HCl \rightarrow 2CrCl_3 + 3Cl_2 + 7H_2O + 2KCl$
        - Upon examination of the equation, every atom is balanced. So the final balanced redox equation is:
        - $K_2Cr_2O_7$ (aq) + 14HCl (aq) $\rightarrow$ $2CrCl_3$ (aq) + $3Cl_2$ (g) + $7H_2O$ (l) + 2KCl (aq)
- Limiting reactants
    - Limiting reactant is reactant that will get all used up first
    - What is the limiting reactant for the following reaction?
        - $3X_{ox} + A_{red} \rightarrow 3X_{red} + A_{ox}$
        - Given: you use 60g of X_{ox} and 63g of A_{red}
        - Given: the molecular weight of X_{ox} is 2 amu, and A_{red} is 7 amu
        - The first thing you do is convert everything in moles. 1 amu = 1 g/mol
        - X_{ox}: 60 g/ 2 amu = 30 mols
        - A_{red}: 63 g/ 7 amu = 9 mols
        - Now here's where stoichiometry comes in: divide the mols by the stoichiometric coefficient of the species:
        - 30 mols / 3 = 10 for X_{ox}
        - 9 mols / 1 = 9 for A_{red}
        - Now compare the values. 9 is the smallest, so A_{red} is the limiting reactant.
- Theoretical yields
    - The theoretical yield is how much of the product will be made based on the stoichiometry

- In calculating the theoretical yield, first find out what your limiting reactant is. Then, use your limiting reactant as the stoichiometric basis to calculate how much product you will get.
- In real life, experimental yield less than theoretical yield because of loss during steps of the reaction
- What is theoretical yield for $3X_{red}$
  $3X_{ox} + A_{red} \rightarrow 3X_{red} + A_{ox}$
  If you react 60g of X_{ox} with 63g of A_{red} given that the molecular weight of X_{ox} is 2 amu, A_{red} is 7 amu, and X_{red} is 10 amu?
  - First, find who's the limiting reagent
  - Using the method above, limiting reactant is A_{red}
  - Next, take the amount in mols of the limiting reactant (9 mols according to the above calculation) and do the stoichiometry to get to how many mols of $3X_{red}$ this will yield
  - 9 mols of A_{red} * 3 mols of X_{red} per 1 mol of A_{red} = 27 mols
  - Lastly, convert mols to grams: 27 mols * 10 g/mol = 270g
  - The theoretical yield for the above reaction is 270g of X_{red}
- Say you did an actual experiment of the above reaction and you managed to obtain 243g X_{red}, then the experimental yield is 243g
- **Percent yield = experimental yield / theoretical yield x 100**
- For the above experiment, the percent yield would be 243 / 270 x 100 = 90%

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

Acid/Base Equilibria (GC, BC)

- Bronsted-Lowry definition of acid, base
  - BL acid: H+ donor
  - BL base: H+ acceptor
- Ionization of water
  - K_w, its approximate value ($K_w = [H+][OH-] = 10^{-14}$ *at 25°C, 1 atm)*
    - Kw is constant at a given temperature
    - Addition of acid does not change Kw
      - It's dependent on both H and OH concentrations
  - Definition of pH: pH of pure water
- Conjugate acids and bases (e.g. NH4+ and NH3)
  - Stability of conjugate acid/base dictates strength of original acid/base
- 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
    - Dissociation of weak acids in water cause 3 reactions to occur:
      - $HA + H_2O \leftrightarrow A^- + H_3O^+$
      - $A + H_2O \leftrightarrow HA + OH^-$
      - $H_2O + H_2O \leftrightarrow H_3O^+ + OH^-$
    - Many equilibrium shifts occur as a result of adding a weak acid
      - 1) Addition of weak acids shifts equation of 1st reaction to the right, *increasing* H_3O^+
      - 2) Addition of weak acid shifts equation of 2nd reaction to the left, *decreasing* OH^-
        - Since the amount of CB for a weak acid is usually low, OH isn't reduced by much
    - Net results of adding a weak acid
      - [H_3O^+] increases significantly, [OH^- decreases insignificantly]
  - Hydrolysis of salts of weak acids or bases
  - Calculation of pH of solutions of salts of weak acids or bases
    - 1) Find K_a of the acid (usually given to you)
    - 2) Solve using the eq. constant. Set it equal to concentration of the products of dissociation (A^- and H_3O^+, which concentrations "x" as we don't know how much weak acid dissociated) over concentration of reactants (HA, with a concentration of original concentration minus x)
    - 3) Remove x from denominator (it's probably hella small) and solve
- Equilibrium constants Ka and Kb: pKa, pKb
  - K_a
    - Dissociation constant of an acid in water
    - $HA + H_2O \leftrightarrow H_3O^+ + A^-$
    - $K_a = \frac{[H^+][A^-]}{[HA]}$

- K_b
  - Dissociation constant of base in water
  - $B + H_2O \leftrightarrow HB^+ + OH^-$
  - $K_b = \frac{[HB^+][OH^-]}{[B]}$
- $K_aK_b = K_w$
- Difference between Ka/b and Ksp
  - Ka/b measure the tendency of an acid/base to *dissociate* (lose or gain a proton) in solution
  - Ksp measures a solid's *solubility* (it's tendency to go to the aqueous phase)
    - Ksp implies a phase change while Ka/b don't necessarily

- Buffers
  - Salts
    - Ionic compounds that dissolve in water
    - Conjugates
      - Species that form after the removal of a H^+ or the addition of OH (if H^+ can't be removed from a salt)
  - Definition and concepts (common buffer systems)
    - Made from equal and copious amounts of a weak acid and it's CB
      - pK_a of that weak acid should be close to the pH that you wish to buffer the solution at
    - Addition of acid would be offset by the copious amounts of base already present
    - pH of buffered solution can be found by *Henderson-Hasselbach equation*
      - $pH = pK_a$ (of weak acid) + $\log[A^-]/[HA]$
  - Influence on titration curves

Ions in Solutions (GC, BC)

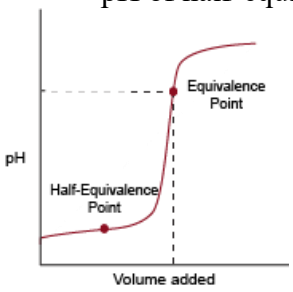
- Solution formation
  - 3 steps
    - 1) Breaking of intermolecular bonds b/w solute molecules (endothermic)
    - 2) Breaking of intermolecular bonds b/w/ solvent molecules (endothermic)
    - 3) Forming of intermolecular bonds b/w solvent and solute (exothermic)
  - Thermodynamics
    - For MCAT solutions, enthalpy change = internal energy change
    - Solution formation *usually* leads to increased entropy since combined mixture is more disordered than separate pure substances
      - Exception: when a gas dissolves in a liquid or solid. In this case, entropy change is negative
  - Heat of solution: total heat absorbed or released when something is dissolved in solution
    - Positive H_{sol} = formation of weaker intermolecular bonds
      - Heat absorbed when old intermolecular bonds in solute/solvent were more stable than those created when solvent and solute react
    - Negative H_{sol} = formation of stronger intermolecular bonds
      - Heat released when new intermolecular bonds formed in reaction of solute/solvent are more stable than old ones holding solute/solvent together
- Anion, cation: common names, formulas and charges for familiar ions (e.g. NH4+ ammonium, PO43- phosphate, SO42- sulfate)
- Hydration, the hydronium ion
- Amphoteric: a substance that can act as either an acid or base

Solubility (GC)

- Units of concentration (e.g. molarity)
- Solubility product constant; the equilibrium expression of Ksp
    - Ksp = equilibrium of a solvation reaction
        - Includes products only
            - Leaves out solids and pure liquids (usually on reactant side)
        - Measure of how inclined compound is to dissolve
    - In an ideally dilute solution (high solvent to solute ration), **solvent obeys Raoult's law and solute obeys Henry's law**
- Common-ion effect, its use in laboratory separations
    - Common-ion effect
        - Happens when a soluble compound containing one of the ions in the Ksp is dissolved in the solution
        - More of the common ion on the right side → equilibrium pushes reaction leftwards → **decrease in solubility**
        - Does NOT affect value of Ksp
        - Does NOT affect value of saturated solution (no leverage to shift equilibrium in, added salt containing common-ion can't dissociate)
    - Complex ion formation
    - Complex ions and solubility
        - Greater size or charge of ionic compounds tends to make them less likely to dissolve
    - Solubility and pH
        - Acid removes hydroxide from solution
            - More acid → less hydroxide concentration → equilibrium shifts towards side with hydroxide

Titration (GC)

- Two reasons for titration
    - 1) To find the concentration of a substance
    - 2) To find the pKa or pKb and the Ka or the Kb
- Indicators
    - Used to find the equivalence point in a titration
    - Usually a weak acid whose CB is a different color
        - Color can change from acid → CB or from CB → acid
            - Therefore, depending on which species you start at, there are two pH's where color change can occur
            - Range of an indicator: pH values of two points of color change
    - Endpoint: point where the indicator changes color
        - Finding range of color change for an indicator
            - Lower range = pKa – 1
            - Upper range = pKa + 1
        - You want to use an indicator whose pKa is closest to the equivalence point of the titration
- Neutralization
    - Basis of neutralization: acids release H+ and bases release OH- which join to form water
    - Neutralizations are highly exothermic
        - $H^+ + OH^- \leftrightarrow H_2O$ is very product favored, K > 1
        - Standard free energy = -RTln(K)
            - **If K>1, then G is negative**
- Interpretation of the titration curves
    - Graph is represented in a sigmoidal curve

- Equivalence point: the midpoint of the titration curve
  - For a monoprotic acid: when there's equal amounts of acid and base in solution
  - When a strong acid is titrated with a strong base, the equivalence point is pH 7
  - For titrations where acid and base are of different strengths
    - If acid is *weaker* than the base, then the equivalence is >7
    - If the acid is *stronger* than the base, then equivalence is <7
- Half-equivalence point: point where ½ of acid has been neutralized by the base (concentration of CB is equal to the concentration of remaining acid)
  - **Only happens for weak-strong acid-base titrations**
  - pH where the solution is most resistant to pH changes (best for buffering)
  - pH of half-equivalence point = pKa of the weak acid
- 

- Weak acid/weak-base titrations
  - Similar shape to strong/weak acid/base titrations (half-eq and eq point) but compressed pH range

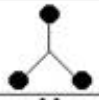
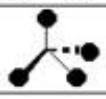
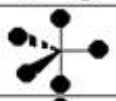
- Solving for pH's at points on the titration curve
  - Half-equivalence point
    - Use of Henderson-Hasselbach equation (since pH of the solution at this point equals the pH of the weak acid)
    - $$pH = pK_a + \log \frac{[\text{conjugate base}]}{[\text{acid}]}$$
  - Equivalence Point
    - Find the pH by first finding the pOH and subtracting that from 14
    - Steps
      - 1) Find the Kb by dividing Kw and Ka
      - 2) Set Kb = to [OH-][HA]/[A-], solve to find the OH- concentration
      - 3) Find pOH, subtract that from 14
- Redox titration
  - Strong oxidizing agent is titrated, resulting voltage change measured
  - Like a normal titration but measures changes in electrical potential, not pH, of a solution
  - Interpretation of curves
    - Curve ascends slowly at first, then quite suddenly, then ascends slowly again
    - Equivalence point: when voltage suddenly shoots up, indicates where all moles of a reducing agent have been oxidized

Content Category 5B: Nature of molecules and intermolecular interactions

Covalent Bond (GC)

- Lewis Electron Dot formulas:
    - Formulas are drawn in such a way that an octet is achieved on each atom. Exceptions include boron column (form 3 bonds and have a six-tet), large elements (3rd row and below such as the 10-tet P in PO_4^{3-} and the 12-tet S in SO_4^{2-}), and radicals (compounds with an odd # total electrons that result in a single, unpaired electron)
    - Rules of thumb
        - Carbon: 4 bonds total (meaning 4 total bonds, can be either 4 single bonds or two double bonds) and no lone pairs e.g. CH_4, CO_2
        - Oxygen: O can be
            - O: 2 bonds total, 2 lone pairs e.g. H_2O, O_2
            - O^{1-}: 1 bond, 3 lone pairs, formal charge of -1
            - O^{1+}: 3 bonds, 1 lone pair, formal charge of +1
        - Nitrogen: N can be
            - N: 3 bonds total, 1 lone pair e.g. Amine or ammonia NH_3
            - N^+: 4 bonds, 0 lone pair, formal charge of +1 e.g. NH_4^+
        - Halogens: 1 bond, 3 lone pairs. e.g. CCl_4
        - Hydrogen: 1 bond, 0 lone pair (exception to octet rule)
        - Carbocation: C^+ has 3 bonds, no lone pairs, formal charge +1
        - Carbanion: C^- has 3 bonds, 1 lone pair, formal charge -1
        - Boron: 3 bonds, 0 lone pairs (exception to octet rule). e.g. BH_3
    - Resonance structures
        - When there are more than 1 satisfactory Lewis structures for a molecule, they are called resonance structures
        - You can visualize the molecule "shifts" between each of its resonance structures really fast, spending more time in the more stable resonance structures.
        - Stable properties:
            - Octet rule is satisfied in every atom (except for boron group and hydrogen)
            - No formal charges
            - If there must be formal charges, like charges are apart and unlike charges are close together
    - Formal charge
        - Formal charge = valence electron # in the unbonded atom - electron # in the bonded atom
        - Electron # in the bonded atom = dots around the atom + lines connected to the atom
        - Common formal charges:
            - Oxygen with only a single bond: -1
            - Oxygen with no bond but have an octet: -2 (oxygen usually exists as the diatomic O_2 and have a double bond to themselves)
            - Carbon with only 3 bonds: either +1 if carbocation or -1 if carbanion
            - Nitrogen with 4 bonds: +1
            - Halogen with no bonds, but have an octet: -1 (Halogens usually exist as a diatomic and have a single bond to themselves such as Cl_2)

        - Boron with 4 bonds: -1. e.g. BH_4^-
    - Lewis acids and bases
        - Lewis acid accept electron pairs. They don't have lone pairs on the central atom. e.g. BF_3
        - Lewis base donate electron pairs. They have lone pairs on their central atom. e.g. NH_3
- Partial ionic character
    - Covalent bonds between atoms with dissimilar EN's have a partial ionic character
    - Role of electronegativity in determining charge distribution
        - The more EN atom receives a partial negative charge
        - The less EN atom receives a partial positive charge
    - Dipole Moment
        - Molecules with asymmetrical partial charge distribution have a dipole moment e.g. H_2O has a dipole moment because the molecule is bent and the oxygen-side of the molecule is partially negative
        - Dipole moment depends on charge and distance
            - The greater the EN difference, the greater the charge and hence the dipole moment
            - The greater the distance separating the charges, the greater the dipole moment
        - Molecules with symmetrical partial charge distribution do not have dipole moments. e.g. CCl_4 does not have a dipole moment because the partially negative chlorine atoms are arranged symmetrically in a tetrahedron. The symmetry cancels out their individual dipole moments
        - Things with a dipole moment are said to be polar
- σ and π bonds
    - Hybrid orbitals: sp^3, sp^2, sp and respective geometries
        - Hybrid orbitals: combination of sigma and pi orbitals. Average out characteristics of original orbitals. Equal energy levels
            - Sigma bonds formed in overlap of hybrid orbitals, pi bonds formed in overlap of p orbitals
        - Determining hybrid orbitals formed by an atom: count number of sigma bonds and lone pairs. Match this number up to sum of superscripts in the hybrid name (sp^2, sp^3, etc.)
        - Orbital character: superscripts determine what percent character the orbital is. sp is 50% s, 50% p. sp^2 is 33% s, 66% p
            - The more s character = the more stable
            - Pi bonds are less stable than sigma bonds
    - Valence shell electron pair repulsion and the prediction of shapes of molecules (e.g., NH_3, H_2O, CO_2)
        - VSEPR (valence shell electron pair repulsion) theory: Electrons in an orbital minimize their energy by moving as far away from other electrons as possible, causes bond angles and geometric conformations

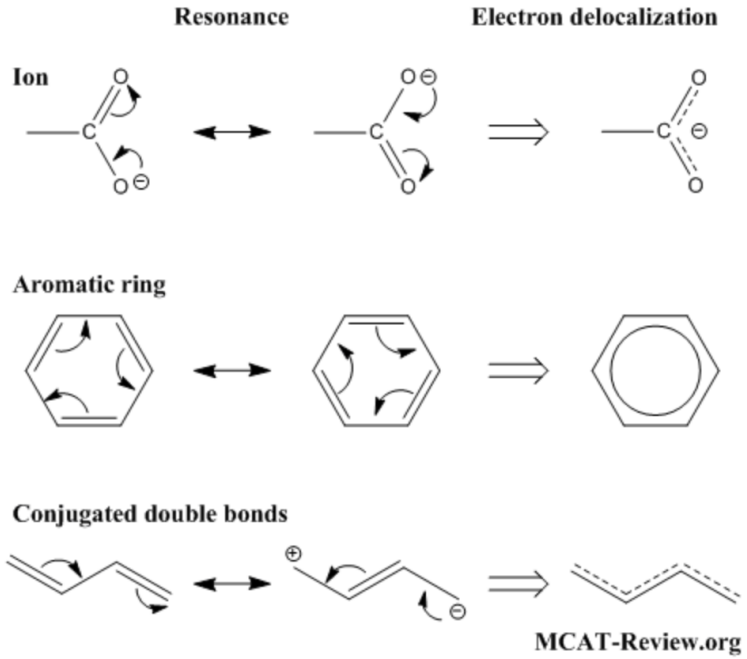
Areas of electron density	Number of Lone Pairs	Shape Name	Drawn
2	0	Linear	
3	0	Trigonal Planar	
3	1	Bent	
4	0	Tetrahedral	
4	1	Trigonal Pyramid	
4	2	Bent	
5	0	Trigonal Bipyramidal	
5	1	See Saw	
5	2	T shaped	
5	3	Linear	
6	0	Octahedral	
6	1	Square Pyramid	
6	2	Square Planar	
6	3	T Shaped	
6	4	Linear	

- Lone pairs are ignored when determining molecular shapes

- Structural formulas for molecules involving H, C, N, O, F, S, P, Si, Cl

	# valence e^-	Usual # bonds	Typically found in
H	1	1	Hydrocarbon (alkane, alkene, alkyne), hydride. All organic compounds contain hydrogen.
C	4	4	Alkane, alkene, alkyne, aromatic rings. All organic compounds contain carbon.
N	5	3	Amine, amide, imine, hydrazone, oxime, nitro compound, diazo compound, nitrile/cyanide, azide
O	6	2	Alcohol, ether, aldehyde, ketone, carboxylic acid, acyl halide, anhydride, amide, ester, ozone
F	7	1	Fluoride
S	6	2 or 6	Thiol, sulfide, sulfate, sulfite
P	5	3 or 5	Phosphorous compound, phosphate, phosphite
Si	4	4	Silane, silicon dioxide
Cl	7	1	Chloride, hypochlorite, chlorite, chlorate, perchlorate

- Delocalized electrons and resonance in ions and molecules



  - Resonance structures result from electrons not being fixed in position (that's why you "push" electrons when drawing resonance structures
  - When electrons are not fixed in position, they are delocalized electrons
  - For all practical purposes, resonance and electron delocalization mean the same thing
  - In ions, resonance and electron delocalization occurs to "distribute" the charge around
  - In molecules, resonance and electron delocalization occurs in aromatic rings and conjugated double bonds

- Multiple bonding
  - Effect on bond length and bond energies
    - Multiple bonding decreases bond length
    - Multiple bonding increases bond energy
  - Rigidity in molecular structure

        - Multiple bonding increases rigidity in molecular structure
        - Single bonds can rotate but double and triple bonds can't
        - Even partial double bonds like those found in the peptide bond prevents free rotation
- Stereochemistry of covalently bonded molecules (OC)
    - Isomers: same molecular formula, different structural formula
        - **Structural (constitutional) isomers**
            - Same molecular formula, but different connectivity
            - Positional isomers: structural isomers that have same functional groups positioned differently
            - Functional isomers: structural isomers that have different functional groups
        - **Geometric isomers**
            - Same molecular formula, same connectivity, different orientation across double bond
            - When both sides of the double bond contain the same 2 groups, then cis and trans are used
            - Cis = same side, Trans = opposite sides
            - When different groups are attached to either side, Z and E is used
            - Z is when higher priority groups same side across double bond
            - E is when higher priority groups on different sides across double bond
        - **Stereoisomers** (e.g., Diastereomers, enantiomers, cis/trans isomers)
            - $2^{\#\ \text{chiral}}$ - #meso = different stereoisomers
            - Enantiomers are mirror images of each other. That means ALL chiral centers in one enantiomer is reversed in the other
            - You can't have stereoisomers if you don't have a chiral center
            - Diastereomers - more than one chiral center, inversion of stereochemistry on some but not all of its chiral centers. e.g. (R)-(R) vs (R)-(S)
            - Meso compounds may have chiral centers, but as a molecule, they are achiral and optically inactive
            - Meso compounds reduce the total number of stereoisomers
            - Stereoisomers have the same chemical properties
            - Enantiomers have the same physical properties
            - Diastereomers have different physical properties
            - Note: in biological molecules, people use D and L for R and S, respectively
        - **Conformational isomers**: have some molecular formula, same connectivity, same stereochemistry, but can rotate about a single bond to switch between different conformations
            - Technically, conformational isomers are not really isomers because you don't have to break any bonds to convert from one conformation to another. They are more accurately called conformers
            - Conformers about a single bond
                - **Eclipsed**
                    - Syn-periplanar: highest torsional strain, most unstable, bulky groups eclipse each other
                    - Anticlinal eclipsed: high torsional strain, unstable, bulky groups eclipse hydrogens
                - **Staggered**
                    - Gauche: low torsional strain, stable, bulky groups 60˚ staggered
                    - Anti: lowest torsional strain, most stable, bulky groups 180˚ staggered
                - Single bonds will rotate such that it achieves the most stable conformation

- Conformers of cyclohexose
    - **Chair**: most stable, everything is staggered
    - **Twist boat**: less stable, things are not completely eclipsed
    - **Boat**: least stable, everything is eclipsed
    - Hexose rings will twist and turn to achieve the most stable conformation
- Torsional strain: the strain due to eclipsing of groups across a single bond
- Steric interactions
    - Axial: most unstable because axial groups are orientated with a high degree of clashing
    - Equatorial: most stable because the equatorial groups are orientated away from one another
    - Bulky groups like to be in the equatorial position
- Most stable conformation: completely staggered (chair), with bulky groups in the equatorial position
- Least stable conformation: completely eclipsed (boat), with bulky groups in the axial position

- Polarization of light, specific rotation
    - Light is an electromagnetic wave; they are waves of electric and magnetic fields (in phase, but perpendicular to each other and also to the direction of propagation)
    - Normal light has the EM fields in all directions (in a 360˚ circle perpendicular to the direction of propagation)
    - Polarized light has EM fields all in one direction
    - Specific rotation: chiral molecules containing a single enantiomer will rotate polarized light (to varying degrees) either to the left or to the right. This is why chiral molecules are said to be "optically active"
    - Left rotation: (-) or *l* or levorotatory
    - Right rotation: (+) or *d* or dextrorotatory
    - Caution: (+) or (-) does NOT correspond to R/S configurations
    - Caution: d and l is NOT the same as D and L. Upper case letters denote absolution configurations in sugars
- Absolute and relative configuration
    - Steps in assigning (R) and (S)
        - a) Is the carbon center chiral?
        - b) Assign priorities according to Cahn-Ingold-Prelog rules
        - c) Turn molecule such that lowest priority group is at the back
        - d) Rotate from 1^{st} to 2^{nd} to 3^{rd} priority group like a steering wheel. It's (R) if you end up turning right and (S) if you end up turning left
    - Relative configuration is defined in relationship to another chiral center. The direction that a molecule rotates plane-polarized light is the prime example
    - Conventions for writing *R* and *S* forms
        - If only 1 chiral center
            - (R/S)-molecule, where R/S is the absolute configuration and molecule is the name of the compound
        - If more than 1 chiral center
            - (#R/S, #R/S)-molecule, where # is the carbon number (in ascending order), R/S is absolute configuration, and molecule is name of compound
    - Conventions for writing *E* and *Z* forms
        - If only 1 double bond
            - (E/Z)-molecule, where E/Z is the geometric configuration across the double bond, and molecule is the name of the compound
        - If more than 1 double bond

        - (#E/Z, #E/Z)-molecule, where # is the carbon number (the smaller one in the double bond, in ascending order), and molecule is the name of the compound
    - Cahn-Ingold-Prelog rules for assigning priority
        - Assign atom with higher MW greater priority
        - e.g. $CH(OH)_2$ vs CH_2F
            - Doesn't matter how many oxygen atoms there are, because fluorine has greater MW so fluorine has higher priority

Liquid Phase - Intermolecular Forces (GC)

- **Hydrogen bonding**
    - Weak interaction between a partially positive H and a partially negative atom
    - Technically, hydrogen bonds are a special type of dipole-dipole interaction
    - Hydrogen bonding increases the boiling point
    - Partially positive H are also called hydrogen bond donors. They are hydrogens that are bonded to either F, O, or N
    - Partially negative atoms are also called hydrogen bond acceptors. They are most commonly F, O, or N
    - Do ethers form hydrogen bonds with other ethers? No, because ethers do not have a partially positive H (donor)
    - The more polar a bond is, the stronger the hydrogen bond. The H-F bond is the most polar, followed by the H-O bond, and lastly the H-N bond
- **Dipole Interactions**
    - All polar molecules exhibit dipole-dipole interactions. This is where the polar molecules align such that opposites attract
    - Dipole-dipole interactions increase the boiling point, though not as significantly as hydrogen bonding.
    - Dipole interactions are stronger the more polar the molecule is
    - Ion-dipole interactions are similar to dipole-dipole interactions but it's stronger because it is no longer an interaction involving just partial charges. Instead, it is an interaction between a full charge (ion) and a partial charge (dipole)
    - Ion-dipole interactions get stronger when you have larger charge magnitude of the ion, and large polarity of the dipole molecule
- **Van der Waals' Forces** (London dispersion forces)
    - Also called dispersion forces
    - Dispersion forces exists for all molecules but are only significant for non-polar molecules. For polar molecules, dipole forces are predominant
    - Dispersion forces result from induced and instantaneous dipoles
    - Induced dipoles: when a polar molecule interacts with a non-polar molecule, then polar molecule induces a dipole in the non-polar molecule
    - Instantaneous dipoles: Non-polar molecules have randomly fluctuating dipoles that tend to align with one another from one instant to the next
    - Dispersion forces get stronger for larger molecules. For example, decane ($C_{10}H_{22}$) has a stronger dispersion force than ethane (C_2H_6)

Content Category 5C: Separation and purification methods

Separations and Purifications (OC, BC)

- **Extraction**: distribution of solute between two immiscible solvents
  - Separates based on **solubility**
  - Procedure
    - 1) Create an aqueous layer and a less dense organic layer (which contains the things you want to extract)
    - 2) You can use the *weak acid* to protonate *strong bases*, causing them to become polar and mix with the aqueous layer
    - 3) You can use a *strong acid* to protonate the remaining *weak bases*, causing them to become polar and mix
    - 4) You can use a *weak base* to deprotonate *strong organic acids*
    - 5) You can use a *strong base* to deprotonate *weak acids* which remain
  - Phenol-chloroform extraction
    - Used to separate nucleic acid from cellular proteins, isolates DNA and RNA
- **Distillation**
  - Separates based on **boiling point**
  - Procedure:
    - 1) Get mixture of two volatile liquids with BPs at least 20 degC apart
    - 2) Boil the mixture *slowly* so that the more volatile liquid boils first
    - 3) First liquid to boil is condensed in a cool tube
  - Effect of positive deviations to Raoult's Law
    - This can occur in non-ideal solutions. Predicted vapor pressure of the solution is higher than it should be at a given molar fraction
    - Causes the solution to boil at a lower temperature than either compound, *cannot be separated by distillation*
  - Fractional distillation
    - More precise method, separates liquids with closer BPs
    - Vapor is run through glass beads, allowing compound with the higher BP to repeatedly condense and fall back into the solution
- **Crystallization**
  - Separates based on **pure substances forming crystals easier than impure substances**
  - Usually an exothermic process
    - Why? Same reason H_{soln} can be exothermic
      - IMF's in salts must be broken (endothermic) and bonds with solution form (exothermic)
      - In this case, bonds that form when creating crystal lattice are more stable than those in the original salts
- **Chromatography**: Basic principles involved in analytic process
  - Column chromatography
    - **Mobile Phase**: solution containing mixture; **Stationary phase**: column containing polar beads, (usually SiO_2)
    - Procedure
      - Solid phase traps polar compounds as solution is passed through column
    - Variants

        - Gas-liquid chromatography
            - Mobile phase: mixture dissolved into a heated carrier gas; Stationary phase: liquid phase bound to a column
            - Procedure
                - 1) Gas passed over liquid phase
                - 2) Compounds in mixture equilibrate with liquid phase at different rates
                - 3) Outputs a graph that shows peaks corresponding with different gaseous components that eluted at different times. Area under each peak corresponds to amount of each molecule eluted
            - Used for more complex separations
        - High pressure liquid chromatography
            - Column and solution system is put under high pressure
        - Size exclusion
            - Use beads to separate out molecules based on **size**, molecular weight
            - Larger molecules elute first
        - Ion-exchange chromatography
            - Separates based on **net surface charge**
        - Affinity chromatography
            - Separates based on **highly specific binding interactions**
    - **Paper chromatography**
        - Mobile phase: sample spotted on polar paper and nonpolar solvent; Stationary phase: polar paper
        - Procedure
            - 1) A mixture is spotted on some polar paper, one end of which is then placed in a nonpolar solvent
            - 2) Capillary action causes nonpolar solvent to move up paper, dissolving the same as it passes over it
            - 3) More polar elements of sample are attracted to polar paper, move more slowly up the paper
        - **R_f factor**: way of determining polarity of a component, identifying different components
            - R_f for a component = $\frac{Distance\ traveled\ by\ component}{Distance\ traveled\ by\ solvent}$
            - Nonpolar compounds: R_f close to 1; Polar compounds: lower R_f
    - Thin-layer chromatography
        - Like paper chromatography but use coated glass or a plastic plate for stationary phase and visualize results using an iodine vapor chamber
- Separation and purification of peptides and proteins (BC)
    - Electrophoresis
        - Nucleic Acids
            - **Gel electrophoresis**
                - Separates based on **charge and size**
                - Electric field causes negatively charged nucleic acids to move. **Porous mixture traps larger nucleic acids while smaller nucleic acids can move faster through the matrix**
                    - Pores can't be used to separate proteins (they're too big)
        - Proteins
            - **SDS PAGE**
                - Separates based on **size**
                - Denatures proteins and coats them with detergent to give them same charge to mass ratio. Then runs them through electrophoresis

        - **Isoelectric focusing**
            - Separates based on **isoelectric points**
            - Gel with a stable pH gradient is stationary phase. Proteins start off at low pH end and travel down this gradient via electrophoresis. Negative cathode end pulls positively charged proteins down gradient. Protein stops moving when it reaches its isoelectric point (no net charge, can't be pulled anymore)
    - Qualitative Analysis
    - Chromatography
        - Size-Exclusion
        - Ion-Exchange
        - Affinity
- Racemic mixtures, separation of enantiomers (OC)
    - Differences in crystallization
        - Enantiomers form crystals that rotate light differently. Visualizing these crystals directly can be used to separate enantiomers
    - Stereospecific enzymes
        - Only react with one enantiomer, creating a mixture that can be separated with other separation techniques
    - Conversion to diastereomers
        - Enantiomers can be converted to diastereomers. Diastereomers have more different physical and chemical properties that are better for separation

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

Nucleotides and Nucleic Acids (BC, BIO)

- Nucleotides and nucleosides: composition
    - See above
    - Sugar phosphate backbone
        - See above
    - Pyrimidine, purine residues
        - See above
- Deoxyribonucleic acid: DNA; double helix
    - The "double" in the double helix means that DNA is found in a double-stranded form - 2 single-stranded chains of DNA stuck to each other via hydrogen bonding of the base pairs
    - The 2 single-strands are anti-parallel to each other. Going from 5' to 3' of one strand means going from 3' to 5' of the other strand.
    - The "helix" in the double helix means that the entire thing is wound up in a spiral
- Chemistry (BC)
    - The phosphate group(s) of a nucleotide are acidic. The two protons of the phosphate group of AMP are governed by pK_+'s of 3.8 and 6.2, respectively, so at neutral pH, the dianion of AMP predominates. The negatively charged phosphate groups present in DNA and RNA give the molecules an overall negative charge which enables electrophoretic separation in the laboratory.
- Other functions (BC)
    - ATP is a nucleotide, which stores the energy liberated during conversion of carbohydrates to carbon dioxide and water in metabolism. The energy is stored by means of the phosphate ester linkages (many enzyme processes are coupled with phosphate ester hydrolysis)
    - Hydrolysis of the terminal phosphate linkage of ATP is accompanied by an internal energy decrease for two main reasons. ATP is highly negatively charged with four negative charges present on the phosphate groups (two on the terminal phosphate and one each on the two others). Hydrolysis enables the separation of these negative charges from each other. Secondly, there is greater resonance stabilization in ADP than in ATP.

Amino Acids, Peptides, Proteins (OC, BC)

- Amino acids: description
    - Absolute configuration at the α position
        - L and D is different from R and S. L is not always S, and D is not always R.
        - If priority of NH_2 > COOH > R, then L=S and D=R. For example, L-Alanine = S-Alanine
        - If the priority of NH_2 >R > COOH, then L=R, and D=S. For example, L-Cysteine = R-Cysteine
        - L-amino acids are more common in nature, and are the type found in proteins. D-amino acids are less common in nature, and are never found in proteins
    - Dipolar ions
        - At low pH, amino acids exist in the cationic form
        - At high pH, amino acids exist in the anionic form
        - At pH = pI, amino acids exist in the zwitterion form, which is overall neutral
    - Classification
        - Acidic or basic
            - If the R group contains carboxylic acid, then it's an acidic amino acid. There are two acidic aa: aspartic and glutamic acid

                - If the R group contains an mine group, then it's a basic amino acid. There are three basic aa: lysine, arginine, and histidine
            - Hydrophilic or hydrophobic
                - Hydrophobic: If the R group doesn't contain any of the stuff below
                - Hydrophilic: IF the R group contains acids, bases, amines or alcohols
    - Synthesis of α-amino acids (OC)
        - **Strecker Synthesis**
            - Starting material: R-aldehyde
            - Reagents: cyanide (KCN), ammonium (NH_4Cl)
        - **Gabriel Synthesis**
            - Starting material: R-halide
            - Reagents: 1. phthalimide, 2. NH_2-NH_2
            - Product: Amino acid with the -R group originally on the halide
- Peptides and proteins: reactions
    - Sulfur linkage for cysteine and cysteine
        - Cysteine = side chain with the thiol group
        - Cystine = 2 cysteines forming a disulfide bond
    - Peptide linkage: polypeptides and proteins
        - Peptide bond = amide bond
        - Peptide bond is formed by amine group attacking the carbonyl carbon
    - Hydrolysis (BC)
        - Peptide bond is very difficult to hydrolyze. It requires a strong base, or a biological enzyme
- General Principles
    - Primary structure of proteins
        - Primary structure = sequence
        - Primary structure of proteins is read from N-terminus to C-terminus
    - Secondary structure of proteins
        - Secondary structure = repetitive motifs formed by backbone interactions
        - Backbone interactions = hydrogen bonding between the NH and C=O
        - Two most common secondary structures are α helices and β pleated sheets
        - The α helix is right-handed, with the R groups sticking outward
        - In β sheets, R groups stick out above and below the sheet
    - Tertiary structure of proteins
        - 3D structure of proteins
        - Caused electrostatic side chain - side chain interactions
    - Isoelectric point
        - pH at which the molecule is neutral
        - Acidic amino acids and proteins with lots of acidic side chains have a lower isoelectric point
        - Basic amino acids and proteins with lots of basic side chains have a higher isolectric point

The Three-Dimensional Protein Structure (BC)

- Conformational stability
    - Hydrophobic interactions
        - Hydropathy plot
            - Used to measure number of hydrophobic regions in a multidomain protein
            - Region with positive hydropathy index indicates a hydrophobic region
    - Solvation layer (entropy)

        - Nonpolar aa's pushed towards inside of a protein. Solvation layer of water forms around proteins
- Quaternary structure
    - Separate chains/subunits joining together
    - Caused by covalent disulfide bonding of cysteine side chains
- Denaturing and Folding
    - Amino acid sequence vital for folding
    - Factors causing denaturing
        - Urea → disrupts H-bonding
        - Salt/pH change → disrupts ionic bonds
        - Mercaptoethnaol → disrupts H-bonding
        - Organic solvents → disrupts hydrophobic forces
        - Heat → disrupts all forces

Non-Enzymatic Protein Function (BC)

- Two protein types: globular and structural
    - Globular: for enzymes, receptors, channels, transport
    - Structural: made of long polymers, used for structure, movement
- Binding
    - Special feature of some proteins is the capability to bind other molecules with non-covalent interactions
    - Protein binding characterized by affinity and specificity for the binding target
- Immune System
    - High degree of protein variability allows for a key feature of the adaptive (or acquired) immune system, the production of antibodies
    - An antibody is a type of protein that has a unique and very specific binding site that will readily bind its target, called an antigen, such that its target is inactivated or tagged for immune response
    - Glycoproteins: proteins with carbs attached. Includes antigens on red blood cells
- Motor
    - Motor protein can perform mechanical work by coupling exergonic (energy releasing) ATP hydrolysis to a conformational change that allows for interaction with the protein's target substrate
    - Muscle contraction achieved through a process of the motor protein myosin binding and releasing its microfilament (actin) substrate
    - Myosin also acts on microfilaments of the cytoskeleton to generate cellular movement
    - Two other types of motor proteins, kinesins and dyneins, act on microtubules and play a role in transport within the cell
    - **Kinesin** is microtubule "tracks" to deliver cellular cargo (e.g. chromosomes during mitosis), generally in an anterograde direction (center to periphery)
    - **Dynein** is used in retrograde cargo transport in the axons of neurons, and is capable of sliding microtubules in relation to one another, generating the movement of cilia and flagella

Lipids (BC, OC)

- Description, Types
    - Storage
        - Triacylglycerols
            - Glycerol + 3 Fatty acids → Triacylglycerol
            - The reverse of triacylglycerol synthesis is saponification
        - Free fatty acids: **saponification**
            - Saponification is the ester hydrolysis of triacylglycerols using a strong base

        - Traditionally, the base that is used is lye, the common name for sodium or potassium hydroxide
        - Result is basic cleavage of the fatty acid, leaving the sodium salt of the fatty acid and glycerol
        - The fatty acid salt is known as soap
- Structural
    - Phospholipids and phosphatides
        - Lipids with phosphate group attached
        - Amphipathic, can form micelles
    - Sphingolipids (BC)
        - Phosphoglycerides but with a sphingosine backbone. In cell membrane
    - Waxes
        - Ester linkage between long chain alcohol and fatty acids. Very water-repellant
- Signals/cofactors
    - **Fat-soluble vitamins**
        - Include vitamins A, D, E, and K
        - Dissolve in fat and can be stored in your liver and fat tissue until needed
        - Vitamin A, or carotene, important in vision, growth and development, and immune function
            - Most significant metabolite of vitamin A is the aldehyde form, retinal, which is a component of the light-sensing molecular system in the human eye
            - Carotene = carrots high in vitamin A, known to improve vision
        - Vitamin D, or cholecalciferol, can be consumed or formed in a UV-driven reaction in the skin.
            - In liver and kidneys, vitamin D is converted to calcitriol, the biologically active form of vitamin D
            - **Calcitriol** increases calcium and phosphate uptake in the intestines, which promotes bone production
            - Lack of vitamin D can result in rickets, condition seen in children and characterized by underdeveloped, curved long bones as well as impeded growth
            - Vitamin D regulates calcium, remember it is frequently added to milk to aid in absorption of calcium
        - Vitamin E
            - Characterized by substituted aromatic ring with long isoprenoid side chain and are characteristically hydrophobic
            - Aromatic ring reacts with free radicals, destroying them
            - This prevents oxidative damage, an important contributor to the development of cancer and aging
        - Vitamin K
            - Vital to posttranslational modifications required to form prothrombin, and important clotting factor in the blood
            - Aromatic ring of vitamin K undergoes a cycle of oxidation and reduction during the formation of prothrombin
            - Also required to introduce calcium-binding sites on several calcium-dependent proteins
            - Vitamin K for Koagulation
    - **Steroids**
        - Nonpolar and can travel across the plasma membrane
        - Type of lipid = nonpolar molecule

- Metabolic derivatives of terpenes
- Characterized by having four cycloalkane rings fused together: three cyclohexane and one cyclopentane
- Steroid functionality determined by oxidation status of these rings, as well as functional groups they carry
- Steroid hormones, secreted by endocrine gland, travel on protein carriers to distant sites where they bind to specific high-affinity receptors and alter gene expression levels

▪ **Prostaglandins** (BC)

- Regulate the synthesis of cyclic adenosine monophosphate (cAMP), which is a ubiquitous intracellular messenger
- In turn, cAMP mediates the actions of many other hormones
- Downstream effects include powerful effects on smooth muscle function, influence over the sleep-wake cycle, and the elevation of body temperature associated with fever and pain

Carbohydrates (OC)

- Description
  - Nomenclature and classification, common names
    - See above
  - Absolute configuration
    - See above
  - Cyclic structure and conformations of hexoses
    - See above
  - Epimers and anomers
    - See above
- Hydrolysis of the glycoside linkage
  - See above
- Keto-enol tautomerism of monosaccharides
  - Ketose monosaccharide can tautomerize to make an aldose
- Disaccharides (BC)
  - Sucrose: 1, 1’ glycosidic link between glucose and fructose. α with respect to glucose, β with respect to fructose
  - Maltose: α 1-4’ glycosidic linkage; two glucoses
  - Lactose: β 1-4’ galactosidic linkage; a glucose and a galactose
- Polysaccharides (BC)
  - Cellulose: β 1-4’ glycosidic linkage: a chain of glucose molecules
  - Amylose: α 1-4’ glycosidic linkage, a chain of glucose molecules
  - Amylopectin: α 1-4’ glycosidic linkages; branched chain of glucose with α 1-6’ glycosidic bonds forming the branches
  - Glycogen: same bonds as amylopectin but has more branches and used for more storage

Aldehydes and Ketones

- Description
  - Nomenclature
    - Suffix: -one for ketones; -al for aldehydes
  - Physical properties
    - Planar stereochemistry: perfect for nucleophilic attack. Nu can attack from either plane
    - Polarity: partial positive charge on the carbon, makes it readily able to accept electrons/be protonated
    - One of the most reactive carbonyl species. Only less reactive than acid anhydrides

- Important reactions
  - Nucleophilic addition reactions at C=O (tend to undergo addition b/c they have bad leaving groups on their carbonyl C)
    - Acetal, hemiacetal
      - Acetal: formed when reacting a ketone or alcohol with 2 equivalents of alcohols. Occurs in acidic conditions (Basic conditions can only get to the hemi form) Cannot easily degrade back to aldehyde or ketone and can't be nucleophilicaly attacked
        - Acetal as a protecting group: convert an aldehyde/ketone into an acetal to prevent it from reacting with a Nu. Then react it w/ acid to remove acetal protection
      - Hemiacetal: formed when reacting a ketone or alcohol with 1 equivalent of alcohol. Occurs in more acidic or basic conditions (not in between). Exists in equilibrium with aldehydes and ketones. Can be Nu attacked to form an acetal.
      - Mechanism:
        - 1) carbonyl O (formation of hemi) or -OH (formation of acetal) is protonated first
        - 2) Nu attack occurs on central C. Either breaks pi bond to form a hemiacetal or causes -OH to leave to form an acetal
    - Imine, enamine
      - Like ketones and enols but with nitrogen. Imines are more stable than enamines b/c N group next to C=C is electron withdrawing. However, enamines are more stable than enols b/c enols have O group next to C=C
      - Reaction to make these occur in acidic conditions by reacting *amine* with *carbonyl*
      - Mechanism:
        - 1) Amine attacks carbonyl C
        - 2) -OH group formed from carbonyl O is protonated by an acid catalyst
        - 3) Two different paths for imines and enamines
          - Imines: N-H bond broken, electrons used to make pi bond between C and N
          - Enamines: C-H bond on alpha carbon broken and form a pi bond connecting alpha C to Nu attacked C
    - Hydride reagents
      - Reducing agents have more H's, oxidizing agents have more O's
      - LAH, $NaBH_4$
    - Cyanohydrin
      - CN^- attacks carbonyl C to produce cyanohydrin
      - Cyanohydrin converted to *carboxylic acid* when exposed to acid and H_2O
  - Oxidation of aldehydes
    - Aldehydes oxidize to carboxylic acids. Ketones do not oxidize further.
    - Tollen's reagent: A diamine silver cation will oxidize aldehyde to carboxylate anions. Reduces the silver ions to solid silver. The formation of a silver mirror indicates the presence of an aldehyde. If you want to form the carboxylic acid, you would need to then protonate your carboxylate anion. Tollen's does not react with alcohols to form ketones. Glucose can be used to make silver mirrors.
  - Reactions at adjacent positions: enolate chemistry
    - Keto-enol tautomerism (a-racemization)
      - Enols are less stable (C=C weakened by electronegative O)
      - Tautomerization can be catalyzed by acid or base
      - Enolate: anion of an enol. Formed in basic conditions

        - Aldol condensation, retro-aldol
            - Carbonyl becomes a nucleophile by being reduced by base to an enolate. Enolate attacks another alpha-C to form alkoxide ion. Alkoxide is protonated to produce aldol.
            - Aldols are unstable, dehydrate by heat to become *enal* (aldol but -OH is a double bond)
        - Kinetic versus thermodynamic enolate
            - Kinetic enolate: less substituted enolate product. Reaction to form it has lower activation energy but the product is less stable
                - Favored when a bulkier base is used (harder for it to reach internal area of molecule to react) and at lower temperatures
            - Thermodynamic enolate: more substituted enolate product. Reaction has a higher activation energy but more stable product
                - Favored when there's more heat
    - General principles
        - Effect of substituents on reactivity of C=O; steric hindrance
            - Bulky groups on either side of C=O blocks access to the electrophilic carbon, so reactivity goes down
        - Acidity of a -H; carbanions
            - Alpha proton is acidic because the resulting carbanion is stabilized by resonance

Alcohols (OC)

- Description
    - Nomenclature
        - Prefix: hydroxyl, hydroxyl
        - Suffix: -ol, alcohol
    - Physical properties (acidity, hydrogen bonding)
        - Hydrogen bonding
        - Higher boiling point than the same compound without the alcohol group
        - Water soluble as long as molecule does not contain a lone hydrophobic region
    - Infrared absorption of OH group: 3300 cm^{-1} and broad due to hydrogen bonding
- Important reactions
    - Oxidation
        - $KMnO_4$ and CrO_3 oxidize primary alcohols to carboxylic acids, but PCC (Pyridine Chlorochromate) and other weak oxidizing agents will only oxidize a primary alcohol to the aldehyde
        - Secondary alcohols always oxidize to the ketone
        - Tertiary alcohols do not oxidize
    - Substitution reactions: S_N1 or S_N2, depending on alcohol and derived alkyl halide
        - R-OH + HX $\leftrightarrows$ R-X + H_2O
        - Factors that favor S_N1: stable carbocation, tertiary carbon center, protic solvent
        - Factors that favor S_N2: unstable carbocation, primary carbon center, aprotic (but polar) solvent
        - All substitution reactions need a good leaving group
        - **S_N1** = unimolecular reaction, intermediate carbocation formed
        - **S_N2** = bimolecular reaction, passes through transition state
    - Protection of alcohols: the best protecting group is the trimethylsilyl group
        - To protect, add Cl-$SiMe_3$ to R-OH
        - The alcohol gets "capped" into R-O-$SiMe_3$
        - To deprotect, add F^-
    - Preparation of mesylates and tosylates

        - Makes alcohol a better leaving group
        - This is a nucleophilic substitution reaction. Alcohol is a Nu, attacks tosyl/mesylate
        - Sulfonates $R\text{-}SO_3^-$ are good leaving groups
        - R can be:
            - Methane, which makes methanesulfonate
            - Toluene, which makes tosylate
            - Trifluoromethane, which makes triflate
        - Mesylates can be prepared by reacting an alcohol (R-OH) with mesyl chloride (MsCl)
        - Tosylates can be prepared by reacting an alcohol (R-OH) with tosyl chloride (TsCl)

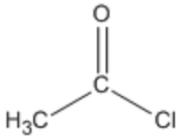
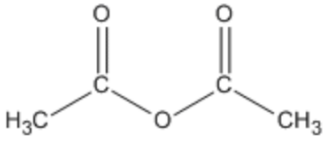
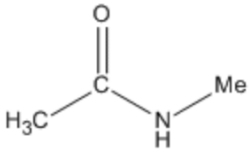
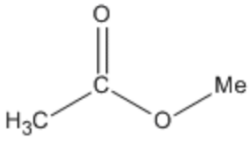
Carboxylic Acids (OC)

- Description
    - Nomenclature
        - Carbonyl carbon of carboxylic takes priority over all other groups when naming a molecule
        - Naming salts of carboxylic acids: Replace -ic with -ate (acetic acid → acetate)
        - Suffix: -ic or -oic to end of name of R group
    - Physical properties
        - Can act as electrophile for Nu attack at carbonyl C (b/c planar, polarity) OR can act as an acid (deprotonate -OH group, resonance stabilized)
        - Can form dimers by H-bonding to each other. This increases their BP
            - < 4 C's in a carboxylic acid = soluble in water
            - > 5 C's in a carboxylic acid = less soluble in water
            - > 10 C's in a carboxylic acid = not soluble in water
        - Soluble in nonpolar solvents (dimer form can solvate without the H-bonds holding it together being compromised)
- Important reactions
    - Carboxyl group reactions (tend to undergo *substitution*, not addition, b/c they have good LG's on their carbonyl C's)
        - Amides (and lactam), esters (and lactone), anhydride formation
            - Acid chloride formation: carboxylic acid + HX
            - Ester formation: carboxylic acid + ROH
            - Amide formation: carboxylic acid + RNH_2
            - Anhydride formation: carboxylic acid + RCOOH
        - Reduction
            - Performed with $LiAlH_4$, $NaBH_4$. 2 equations reduce carboxylic acids and their derivatives to alcohols
            - $NaBH_4$ is weaker. Can only reduce ketones and aldehydes (not carboxylic acids and esters)
        - Decarboxylation
            - Occurs for β-keto acids
            - Oxidation of carboxylic acid to gas. Unusually high activation energy
    - Reactions at 2-position, substitution
        - Carboxylic acid derivatives tend to lose an H on their alpha carbon. This can be substituted for a halide
            - Halogenation: $RCOOH + X_2$ → halogenation at the alpha carbon (2 carbon)
        - Substitution reactions: $RCOOH + E^+$ → substitution at the alpha carbon (2 position)
            - 1. Carboxylic acid converted to Acyl Halide, which can enolize
            - 2. Acyl Halide tautomerizes to its enol form by abstraction of acidic alpha hydrogen

- 3. Halogen (or some other E^+) gets attacked by alpha position
- 4. Revert back to carboxylic acid. The net effect is that the alpha H get substituted by an electrophile

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

- Description
  - Nomenclature

	suffix	example
Acid chlorides	-oyl chloride	ethanoyl chloride 
Anhydrides	-oic anhydride	ethanoic anhydride 
Amides	-amide	N-methyl ethanamide 
Esters	-oate	methyl ethanoate 

  - Physical properties
    - C=O is polar, so there are dipole-dipole interactions
    - No hydrogen bond exists in acid chlorides, anhydrides, or esters unless there is an -OH group somewhere
    - Amides can hydrogen bond because of the N-H group. In fact, hydrogen bonding involving the amide backbone of polypeptides form the secondary structure of proteins.
    - Amides have higher boiling points than the other acid derivatives.
    - Acid derivatives have higher boiling points than alkanes because of the C=O dipole interactions
- Important reactions
  - Nucleophilic substitution: Nucleophile attacks the carbon center of the C=O group
    - Acid halides
      - Nucleophilic substitution of an acid halide makes a carboxylic acid derivative and a HX acid
      - Ex. carboxylic acid + alcohol → ester + HX
    - Carboxylic acid
      - Nucleophilic substitution of carboxylic acid forms an ester
      - This is a low yield reaction b/c strong acid catalyzes reverse reaction of ester back to a carboxylic acid. Yield can be adjusted with LeChatlier's
    - Amides

            - Amides formed when amine substitutes on carboxylic acid or one of its derivatives
        - Can be done under either acidic or basic conditions
            - Acidic yields ROH or HX group. Basic yields their anions
    - Transesterification: ester + alcohol → new ester
        - Ester
            - An alkoxy group of an ester can be replaced by reacting it with another alcohol group. Which product the reaction prefers can be modified by adding excess of either alcohol or alcoxy group
        - Can be done under either acidic or basic conditions
            - Acidic yields ROH or HX group. Basic yields their anions
    - Hydrolysis of amides: the leaving group is not NR_2^-, it is the neutral amine
        - The O in water functions as Nu attacking the electrophilic C in C=O, creating tetrahedral intermediate
        - Protonate the N group to make it a good LG
- General principles
    - Relative reactivity of acid derivatives: Acid chloride > Anhydride > Esters > Amides
        - Acid halides are the most reactive derivatives because halides are good leaving groups
        - Amides are the most stable derivatives because NR_2^- is a terrible leaving group. Also, the C-N bond has a partial double bond characteristic. Proteins are made of peptide bonds, and they are very stable
    - Steric effects
        - Bulky groups around the C=O group helps protect the carbon center from nucleophilic attack
    - Electronic effects
        - Groups that can redistribute and stabilize negative charges are good leaving groups. For example, the anhydride has a good leaving group - the carboxylate ion - because the COO^- can redistribute the negative charge to both oxygens via resonance
    - Strain (e.g., β-lactams)
        - Amides have a double bond characteristic between the carbon and nitrogen. This means that the C-N bond cannot rotate
        - Normally, sigma bonds in a ring rotate to achieve most stable conformation, but this cannot occur for C-N bond if ring contains an amide
        - Because C-N bond in an amide cannot rotate, rings that contain amides have higher strain
        - An example of this is β-lactam, which is basically a 4-membered ring with 1 amide in it

Phenols (OC, BC)

- Oxidation and reduction (e.g., hydroquinones, ubiquinones): biological $2e^-$ redox centers
    - Phenol gets oxidized to benzoquinone using numerous organic reagents
    - You could reduce benzoquinone to hydroquinone
    - **Ubiquinone**, or Coenzyme Q, is an important part of ETC
        - When ubiquinone is reduced to ubiquinol, NADH is oxidized to NAD^+
        - NADH, thus, serves as the reducing agent

Polycyclic and Heterocyclic Aromatic Compounds (OC, BC)

- Biological aromatic heterocycles
    - Heterocycle is a cyclic compound that contains a heteroatom (any atom other than carbon) in the ring
    - Thymine, a biological molecule, contains the pyrimidine ring and therefore is aromatic and has some extra stability associated with it

- Imidazole is aromatic, and thus Histamine which contains this functional group, is a biological aromatic heterocycle

Content Category 5E: Principles of chemical thermodynamics and kinetics

Enzymes (BC, BIO)

- Classification by reaction type
- Mechanism
  - Substrates and enzymes 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)

- How the laws of thermodynamics relate to each other (game analogy)
  - Zeroth law: says temperature exists and it can equilibriate, sets ground rules for the game
  - First law: says change in energy always = sum of heat and work, says you can't win
  - Second law: says temperature and pressure flow downhill from greater to less and that net entropy of the universe is always increasing, says you can't even break even
  - Third law: says absolute zero is untenable since zero energy can't be achieved, says you can't even end the game

- Thermodynamic system – state function
    - **State function**: properties that describe the *current state* of the system. Not affected by how the systems got to their state, just the properties of their current state (ex: temperature, pressure, volume)
    - **Path function**: properties that depend on the pathway used to achieve a state (ex: work, heat)
    - Thermodynamic systems can't describe systems on a molecular scale. Thermodynamic systems average out all molecular interactions to find an average. Molecular scale means the sample size is too small
    - Internal energy: collective energy of molecules measured on a microscopic scale. Many different types
        - Vibrational energy: created by back-and-forth motion of atoms
        - Rotational energy: created by rotation of a molecule around its center of mass
        - Translational energy: created by movement of a molecule's center of mass
        - Electronic energy: potential electric energy created by attractions between electrons and their nuclei
        - Intermolecular potential energy: intermolecular dipole forces
        - Rest mass energy: described by E = mc^2
- Two ways to transfer energy between systems: heat and work
    - Difference between heat and work: directional collisions vs. random collisions
        - Work is done by energy transfer through ordered molecular collisions
            - More constrained the molecules are (higher the P lower the V) = greater capacity to do work
        - Heat is done through random collisions between high energy and low energy particles
- Zeroth Law – concept of temperature
    - Temperature: thermal energy per mol of molecules
- First Law – conservation of energy in thermodynamic processes
    - Total energy of system and surroundings always conserved
    - $\Delta E = q + w$
        - Energy change of a system = heat flow into the system + work done on the system
        - For closed systems, only internal energy change takes place, ΔU is used instead of ΔE
            - If no change in volume occurs as well, omit work. $\Delta U = q$
    - Energy transferred out of a system during expansion (ΔE negative)
    - Energy transferred into a system during contraction (ΔE positive)
- PV diagram: work done = area under or enclosed by curve (PHY)
    - Work = any energy transfer that's not heat
    - System performs PV work by changing it's size or shape using energy from the system
        - Ex: piston expanding
    - Formula for PV work: $\mathbf{W = -P\Delta V}$
        - Volume must be constant
        - Note how negative work = work done by the system (if V expands). Positive work = work done ON the system
            - Keep in mind the MCAT might try to define work done by the system as positive
    - PV diagram: x-axis = P; y-axis = V
        - Work = area under the PV curve
        - Work is a path function. Different curve/path results in a different amount of work
- Second Law – concept of entropy
    - $\mathbf{\Delta S_{system} + \Delta S_{surroundings} = \Delta S_{universe}}$
    - Entropy as a measure of "disorder"
        - Entropy: energy trying to spread itself evenly throughout the universe
        - Entropy of an isolated system will never decrease. Since the universe is an isolated system, entropy of the universe never decreases

        - Rxn must increase entropy of the universe to proceed
            - Entropy increases with *number, size, volume, and temperature*
    - Relative entropy for gas, liquid, and crystal states
- Third law – absolute zero
    - Says zero entropy can only take place at absolute zero. However, this is unattainable so third law can only be realized in theory
- Measurement of heat changes (calorimetry), heat capacity, specific heat
    - Calorimetry: measuring changes in heat flow of rxn by monitoring temp change of a calorimeter coupled to the rxn to find the change in enthalpy
        - Two types: constant pressure and constant volume
            - Coffee cup calorimeters (constant pressure):
                - Rxn takes place in chamber with open top. Constant pressure of local atmosphere dictates pressure
                - Use insulated chamber to prevent heat exchange w/ surroundings
                - Used to measure <u>heats of reaction</u> and <u>enthalpy</u> b/c no heat from rxn is lost to surroundings
            - Bomb calorimeter (constant volume):
                - Rxn takes place in rigid, sealed off container
                - Use insulated chamber to prevent heat exchange with surroundings
                - Measures internal energy change by finding q from $q = C\Delta T$
                    - C of calorimeter is known, T change can be measured after the reaction
        - Important for calorimeter chamber to be *thermally insulated* from the surroundings. No heat exchange between system and surroundings
    - Heat capacity: How much E must be added to a substance to change its temp by 1 C or K
        - <u>More bonds in a molecule = greater heat capacity</u>
            - This is b/c E is redirected to stretching these bonds instead of raising T
        - <u>More IMF's between molecules = greater heat capacity</u>
            - This is b/c IMF's must be broken using E to raise temperature. Some E has to be redirected to do this
        - T will always increase when E is added to a substance at a constant V and P
        - Formula for heat capacity: $q = mc\Delta T$
        - Specific heat capacity: intrinsic property, heat capacity per unit mass
            - $Q = mc\Delta T$
        - $\Delta H_{rxn} = -\Delta H_{calorimeter}$
- Heat transfer – conduction, convection, radiation (PHY)
    - **Conduction**: heat transfer through molecular collisions. Requires direct physical contact
        - Thermal conductivity (k): an object's ability to conduct heat, depends on composition and temperature (composition more so)
    - **Convection**: heat transfer through fluid
        - Driven by differences in pressure and density, drives warm fluid in direction of cooler fluid
        - Ex. Hot air rises, causing cooler air from ocean to move in
    - **Radiation**: thermal energy transfer via electromagnetic waves
        - Newton's law of cooling: a body's rate of cooling is proportional to the temperature difference between a body and it's environment
        - Emissivity: fraction of radiation absorbed by a surface (depends on surface composition)
            - Higher emissivity = higher amount of radiation absorbed
- Endothermic/exothermic reactions (GC)
    - Enthalpy, H, and standard heats of reaction and formation

        - Enthalpy: Used to measure changes in heat. Sum of internal energy and work.
            - **$\Delta H = \Delta U + P\Delta V$**
                - H = enthalpy
                - U = internal energy
                - P = pressure, V = volume
            - When only PV work is done at constant pressure and volume, $\Delta H = q$
                - This is b/c no non=PV work means $P\Delta V$ value is 0
        - Standard enthalpy of formation (H_f^o): change in heat for a reaction that creates one mole of that compound from its raw elements in their standard states
            - Standard state: *reference form* of a substance
            - Positive H_f^o change = endothermic reaction, heat flows into system
            - Negative H_f^o change = exothermic reaction, heat flows out of system
    - Hess' Law of Heat Summation
        - Sum of enthalpy changes for each step equals total energy change
        - Forward reaction has the opposite change in enthalpy as reverse
        - Energy reaction diagram
            - Y-axis: "energy" can be enthalpy, Gibbs, or energy: x-axis: rxn progresses
            - Difference between initial and final energy states is <u>constant</u> regardless of changes in activation energy
- Bond dissociation energy as related to heats of formation (GC)
- Free energy: G (GC)
    - Gibbs free energy: way of finding entropy change in both system and surroundings using <u>only information about the system</u>, $\Delta G = \Delta H - T\Delta S$
        - ΔG shows how much non-PW work is "free" for a reaction, determines if a reaction is spontaneous or not
        - ΔG, ΔH, and ΔS only refer to changes in the SYSTEM, not the surroundings
    - Both ΔS and ΔH are required in determining if a reaction proceeds spontaneously
    - G is an extensive property, state function (like enthalpy, entropy)
- Spontaneous reactions and ΔG^o (GC)
    - Negative ΔG^o means a reaction proceeds spontaneously
    - ΔG^o value depends on both ΔH and ΔS
- Coefficient of expansion (PHY)
- Heat of fusion, heat of vaporization
    - Heat of vaporization is usually greater than heat of fusion
        - Usually break more bonds from liquid to gas than solid to liquid
- Phase diagram: pressure and temperature
    - Phase diagram indicates phases of a substance at different pressures and temperatures
    - **Critical temperature**: temperature at which a substance cannot be liquefied regardless of pressure
        - Critical pressure: pressure at the critical temperature
        - Critical point: point defined by the intersection of the critical T and P
    - Solids and gases favored at extreme conditions, liquids favored in intermediate conditions
    - Difference in water's phase diagram
        - Line between solid and liquid phase has NEGATIVE slope. This allows solid water to be less dense than liquid water
        - Normally, this line has a POSITIVE slope

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

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

- Rate law, rate constant
  - Rate law: finds the rate of a reaction by factoring in rate law and concentrations of reactants
  - Experimentally determining rate law:
    - 1) Compare reaction rates in two trials where concentrations of all reactants except for one stay constant
    - 2) Compare how changing concentration of one reactant affects reaction rate
      - If reactant A is doubled and rate doubles, then order of reactant A is one. If A is doubled and rate quadruples, then order is two
- Reaction order
  - $Rate_{forward} = k[A]^a[B]^b$, rate law = a + b
  - **Zero order**: rxn rate is independent of concentration of any reactant
    - *Graph: [A] over t, slope of –k is linear and downwards*
  - **First order**: rxn rate is directly proportional to concentration of a single reactant
    - *Graph: ln[A] over t, slope of –k is linear and downwards*
  - **Second/Third order**: rxn rate is proportional to a single reactant's concentration raised to the second/third power OR the product of concentrations of multiple reactants

- Rate-determining step
  - In multistep reactions, rate of the slowest occurring step is the <u>rate determining step</u>
  - Rate-determining step determines the rate law for the reaction
- Dependence of reaction rate upon temperature
  - Activation energy
    - Requirements to reach activation E
      - 1) Particles must be traveling at a sufficient velocity
      - 2) Particles must collide in the correct orientation
    - Activated complex or transition state
    - Interpretation of energy profiles showing energies of reactants, products, activation energy, and ΔH for the reaction
  - Use of Arrhenius Equation
    - Used to find rate constant (k). Rate constant dictates rate of reaction (directly proportional)
      - If it affects rate constant, it affects rate of reaction in the same way
      - Rate constant is inversely proportional to activation energy, directly proportional to temperature and collision frequency
    - 3 factors affecting k
      - 1) **Pressure**: higher pressure increases rate constant (relevant for gases)
      - 2) **Catalysts**: presence of catalyst increases rate constant
      - 3) **Temperature**: temperature increases rate constant
    - **p = steric factor**, takes into account correct orientation of molecules hitting each other and frequency of collisions
- Kinetic control versus thermodynamic control of a reaction
  - **Kinetic control**: controls <u>speed</u> of a reaction, governed by E_a
    - Pertains to top half of a reaction energy diagram (where transition state peak is)
  - **Thermodynamic control**: controls <u>whether or not a reaction will occur</u>, governed by ΔG of the reaction
    - Pertains to bottom half of reaction energy diagram
- Catalysts
  - If concentration of catalyst far outweighs reactant, then rxn order is zero
  - Increases rates of forward and reverse reactions
  - Can lower E_a, increases steric factor, or both

        - However, does not affect overall change in energy, difference between final energies of reactants and products stays the same, only the E_a changes
    - Two types: heterogeneous and homogenous
        - **Heterogeneous**: different phase than reactants of products. Rate of catalysis depends on strength of attraction between reactant and catalysts (ex: liquid catalyst adsorbs, or sticks to, a solid reactant). Rxn rate enhanced by increasing surface area of catalyst
            - Too little attraction: catalyst can't adsorb to reactant, little effect on reaction rate
            - Too much attraction: catalyst doesn't want to let go, little effect on reaction rate
            - Want to get just the right amount
        - **Homogeneous**: same phase as reactants and products
    - Total rate law of catalyzed reactions = rate law of original reaction + rate law of catalyzed reaction
        - Ex: Rate law of acid catalyzed reaction = $k_0[A] + k_{H^+}[H^+][A]$
        - B/c even with catalyst, original reaction will still occur
- Equilibrium in reversible chemical reactions
    - **Law of Mass Action**
        - Rate of any reaction is proportional to the concentrations of the different species in the reaction (according to the equilibrium constant)
    - Equilibrium Constant

$$K_{eq} = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

        -
    - Reaction Quotient (Q)
        - Same formula as equilibrium constant but reaction isn't necessarily at equilibrium
        - Value of Q relative to K_{eq} can tell us about direction rxn will proceed:
            - **Q = K: rxn is at equilibrium**
            - **Q > K: rxn shifts leftwards, towards reactants (too much P)**
            - **Q < K: rxn shifts rightwards, towards products (too much R)**
    - Application of Le Chatelier's Principle
        - Change in concentration, pressure, or temperature causes a system at equilibrium to shift in a direction to reduce the stress
            - **Change in concentration** → rxn shifts in direction of less concentrated side
            - **Increase in pressure** → rxn shifts towards side of rxn with less moles of gas
            - **Increase in temperature** → rxn shifts away from the side of the equation with more heat (towards gaseous side)
- Relationship of the equilibrium constant and ΔG^o
    - To determine if a reaction is spontaneous under specific conditions (not just standard conditions), both Q (concentrations of reactant and product) and ΔG must be considered
    - $\Delta G = \Delta G^o + RT\ln(Q)$
        - Can be rewritten as $\Delta G^o = -RT\lin(K)$
            - If Keq = 1, then $\Delta G^o = 0$
            - If Keq > 1, then $\Delta G^o < 0$
            - If Keq < 1, the n $\Delta G^o > 0$
            - This only determines spontaneity at a specific temperature (Keq and ΔG^o values depend on TEMPERATURE)