BCEM 393 Learning Objectives

This document outlines the themes, topics and learning objectives for BCEM 393 (Introduction to Biochemistry). BCEM 393 is required for many programs offered within the Department of Biological Sciences. It is meant to provide a foundation in the field of biochemistry. This foundation is important for topics covered in many of the more advanced courses offered in the Department and for students for whom this is a terminal course in biochemistry.

Pre-requisites:
- BIOL 311 (with minimum grade of C-)
- CHEM 351 (with minimum grade of C-)

**BCEM 393 Lecture Portion**

<table>
<thead>
<tr>
<th>Theme</th>
<th>Topic(s)</th>
<th>Learning objectives</th>
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</table>
| Water is the medium of life.  | Water is required for the proper functioning of biomolecules and it is an active participant in biochemical processes. | At the end of this topic, students should be able to  
  - classify each of the four classes of biomolecules (*i.e.*, amino acids, lipids, carbohydrates, and nucleic acids) as hydrophilic, hydrophobic, or amphipathic  
  - describe how the following types of non-covalent interactions form: hydrogen bonds, ionic interactions, and van der Waals interactions  
  - describe what is meant by the “hydrophobic effect”  
  - explain why water is said to have chemical reactivity in biological systems by describing how the ionization of water leads to production of protons and hydroxide ions, and how the changing concentration of these ions can lead to changes in pH  
  - define the term “buffer” and list the components required to create a pH buffer  
  - describe why pH buffers are important in biological systems and how they function  
  - select an appropriate buffer system when given the desired pH of the biological system |
| Carbohydrates are required as a source of fuel, as protection, and for signalling. | Carbohydrates have the general formula \((\text{CH}_2\text{O})_n\) and can be aldoses or ketoses. | At the end of this topic, students should be able to  
- distinguish between aldoses and ketoses  
- recognize chiral centres in carbohydrates  
- define the terms “epimers” and “enantiomers”  
- draw aldoses and ketoses in Fischer and Haworth projections  
- define the terms “anomer” and “anomeric centre”, and distinguish between α-anomers and β-anomers  
- identify reducing sugars  
- draw glycosidic linkages to form oligosaccharides and polysaccharides from monosaccharides  
- distinguish between glycogen, starch, and cellulose in terms of structure, function, and properties |
|---|---|---|
| Carbohydrates can be attached to proteins to change their properties. | Lipids are required for fuel, for cell and organelle membranes, and for signalling. | Fatty acids are simple lipids. | At the end of this topic, students should be able to  
- distinguish between N- and O-linked glycosylation  
- explain why glycosylation changes the properties of a protein  
- distinguish between a glycosylated protein and a lectin |
| Fatty acids can be stored by covalently attaching them to glycerol to form in triacylglycerols. | Fatty acids can be covalently attached to glycerol or sphingosine to form lipids found in membranes. | At the end of this topic, students should be able to  
- define a lipid  
- draw a fatty acid and distinguish between saturated and unsaturated fatty acids  
- use the Greek letter, \(x:y\), and \(\Delta^z\) notations for fatty acids  
- relate the chemical structures of fatty acids (i.e., long, short, saturated, unsaturated) to their physicochemical properties  
- draw the covalent bonds in triacylglycerols  
- rationalize why triacylglycerols provide efficient storage of fuel  
- distinguish between nonpolar lipids (triacylglycerols) and polar lipids (glycerolipids, sphingolipids, and glycolipids) and describe the components found in each type of lipid  
- draw a lipid bilayer  
- relate the physicochemical properties of lipid bilayers to chemical structures of the fatty acids used as components  
- rationalize the permeability of lipid bilayers  
- describe how liposomes can be formed and how they are used for drug delivery  
- describe the structure of cholesterol  
- describe how it interacts with other membrane lipids |
<table>
<thead>
<tr>
<th>Lipids can be attached to proteins to change their properties.</th>
<th>At the end of this topic, students should be able to • identify the role of lipid modifications of proteins</th>
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<tbody>
<tr>
<td>Proteins are critical to biological processes in the cell.</td>
<td>Amino acids are the building blocks of proteins.</td>
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<tr>
<td>Proteins are chains of covalently bound amino acid residues that can adopt specific three-dimensional structures critical for protein function.</td>
<td>There are four levels of protein structure.</td>
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</table>

**Sub-topic A: Protein primary structure determines all higher levels of protein structure.**

At the end of this sub-topic, students should be able to
• draw peptide bonds and describe how they join amino acid residues
• identify the main chain or backbone, the side chains, the N-terminus, and the C-terminus of a polypeptide
• draw disulfide bonds and describe when they can occur
• estimate the molecular weight of a protein from the number of amino acid residues

**Sub-topic B: There are three types of secondary structure elements.**

At the end of this sub-topic, students should be able to
• distinguish among the hydrogen-bonding patterns of α-helices, β-sheets, and β-turns
• identify the backbone torsion angles ω (omega), φ (phi) and ψ (psi)
• explain why certain combinations of φ and ψ are favoured while others are not
• analyze and interpret φ and ψ angles on a Ramachandran diagram
• list the properties of right-handed α-helices (hydrogen-bonding pattern, typical φ, ψ angles, number of amino acid residues per turn, rise per residue, and location of side chains)
• list the properties of anti-parallel, parallel, and mixed β-sheets (hydrogen-bonding patterns, typical φ, ψ angles, distance travelled/amino acid residue, and location of side chains)
Sub-topic C: There are many different super-secondary motifs.

At the end of this sub-topic, students should be able to
- define the term “super-secondary motif”
- recognize the following two super-secondary motifs if presented with a ribbon diagram: helix-loop-helix and β-hairpin

Sub-topic D: Tertiary structure is the highest level of structure for monomeric proteins.

At the end of this sub-topic, students should be able to
- define the term “domain” and recognize domains in protein structures
- describe the non-covalent and covalent interactions important for the stability of tertiary structure
- estimate the dimensions of a protein from a ribbon diagram that includes an α-helix

Sub-topic E: Quaternary structure is the highest level of structure for oligomeric proteins.

At the end of this sub-topic, students should be able to
- describe the non-covalent and covalent interactions important for the stability of quaternary structure
- identify a protein with quaternary structure as a dimer, trimer, tetramer, and so on
- distinguish between homo-oligomers and hetero-oligomers

Sub-topic F: Proteins can lose their structure through chemical and physical means of denaturation.

At the end of this sub-topic, students should be able to
- describe the processes of protein denaturation and renaturation (protein folding)

Sub-topic G: Membrane proteins contrast with soluble proteins in that they are associated with membranes.

At the end of this sub-topic, students should be able to
- distinguish integral membrane proteins and peripheral membrane proteins
- explain how α-helices or β-sheets are used to cross the membrane
- explain how the potassium ion channel selects for potassium ions and transports them across membranes
<table>
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<tr>
<th>Proteins are best studied after purification.</th>
<th>At the end of this topic, students should be able to • describe the processes of ammonium sulphate precipitation, affinity chromatography, and gel filtration chromatography and determine under which conditions each technique could be used to purify a protein • calculate specific activity • explain how the purity of a protein sample can be judged using sodium dodecylsulfate polyacrylamide gel electrophoresis (SDS-PAGE) • set up and complete a protein purification table (where specific activity, yield, and purification level are calculated)</th>
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<tbody>
<tr>
<td>Catalysis speeds up chemical reactions so that they occur at the rates required for life.</td>
<td>Enzymes catalyze biochemical reactions.</td>
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<tr>
<td>Sub-topic A: Enzymes accelerate the rates of biochemical reactions.</td>
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<td>At the end of this sub-theme, students should be able to • distinguish reactions that are kinetically favourable from reactions that are thermodynamically favourable • define the terms “transition state” and “activation energy barrier” • describe how enzyme-catalyzed reactions can have a lower activation energy than uncatalyzed reactions</td>
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<td>Sub-topic B: Enzymes bind substrates in their active sites and stabilize the transition state.</td>
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<td>At the end of this sub-theme, students should be able to • describe features of an enzyme’s active site and list the types of interactions that could occur between an enzyme and its substrate • distinguish between the induced fit model and the lock and key model for substrate binding • distinguish between enzymes showing absolute and group specificity • draw Cleland representations for bisubstrate reactions to show an ordered, sequential reaction and a double displacement or ping pong reaction</td>
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<td>Sub-topic C: Enzymes have specific requirements to achieve full activity.</td>
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<td>At the end of this sub-theme, students should be able to • define the terms “temperature optimum” and “pH optimum” and rationalize why an enzyme’s activity would be maximal at these optima • define the term “cofactors” and explain why they are required by certain enzymes • distinguish between “prosthetic group” and “coenzyme/cosubstrate”</td>
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<tr>
<td>Sub-topic D: There are seven classes of enzymes, with each class responsible for catalysis of a different type of reaction.</td>
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At the end of this sub-theme, students should be able to
• classify enzymes into one of the seven major classes (oxidoreductases, transferases, hydrolases, lyases, isomerases, ligases, and translocases)

| Enzymes can be kinetically characterized. | **Sub-topic A: Some enzymes display Michaelis-Menten kinetics.**
At the end of this sub-theme, students should be able to
• define the term “initial velocity” and describe how it can be determined
• describe the effect of enzyme concentration on initial velocity
• draw a Michaelis-Menten plot and explain the effect of substrate concentration on initial velocity
• list two simplifying assumptions for Michaelis-Menten kinetics
• define $V_{\text{max}}$ and $K_m$, and determine their values using the Michaelis-Menten equation or a Lineweaver-Burk plot
• define and calculate the “turnover number” ($k_{\text{cat}}$)
• define the term “$k_{\text{cat}}/K_m$” and use it to compare an enzyme’s preference for different substrates
• distinguish between irreversible and reversible inhibitors
• distinguish between types of irreversible inhibitors
• distinguish between competitive, uncompetitive, and noncompetitive/mixed reversible inhibitors of an enzyme that displays Michaelis-Menten kinetics and describe their effects on $V_{\text{max}}$ and $K_m$

**Sub-topic B: Some enzymes display allostery.**
At the end of this sub-theme, students should be able to
• define allostery
• draw a sigmoidal plot indicating allostery
• identify the “committed step” in a metabolic pathway
• explain why allosteric enzymes would regulate the committed step
• distinguish between feed-forward activation and feedback inhibition
• distinguish between the concerted and sequential models for allostery
• distinguish among allosteric effectors, inhibitors, and activators
• distinguish between homotropic and heterotropic effects, and describe how each affects the sigmoidal curve of an allosteric enzyme
| Enzymes can be investigated to learn how they catalyze reactions. | Enzymes display common catalytic strategies.  
At the end of this sub-topic, students should be able to  
• distinguish among  
  • covalent catalysis,  
  • general acid-base catalysis,  
  • metal ion catalysis  
  • catalysis by approximation and orientation  

Sub-topic A: Chymotrypsin hydrolyzes peptide bonds.  
At the end of this sub-theme, students should be able to  
• describe how chymotrypsin breaks peptide bonds by describing/recognizing the substrates, acyl-enzyme complex, and products  
• describe the role of each member of the catalytic triad and of the oxyanion hole in the reaction mechanism  
• explain why chymotrypsin cleaves carboxy-terminal to a large, hydrophobic side chain  

Sub-topic B: Hemoglobin, considered an “honorary enzyme”, demonstrates allostery.  
At the end of this sub-topic, students should be able to  
• draw oxygen-binding curves  
• explain why allostery changes the oxygen-binding curve from hyperbolic to sigmoidal (myoglobin vs. hemoglobin)  
• describe at the molecular level how different allosteric effectors (protons, carbon dioxide, and 2,3-bisphosphoglycerate) affect the oxygen-binding affinity of hemoglobin  
• describe at the molecular level how fetal deoxyhemoglobin can obtain oxygen from maternal oxyhemoglobin  
• explain why sickle-cell anemia results from the difference of a single amino acid residue of hemoglobin  

| Metabolism | Digestion breaks down large molecules into smaller units for metabolism.  
At the end of this topic, students should be able to  
• contrast the digestion of proteins, carbohydrates, and lipids  
• identify zymogens and explain their role |
<table>
<thead>
<tr>
<th>Metabolism uses many of the same molecules in all forms of life.</th>
<th>At the end of this topic, students should be able to</th>
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<tr>
<td>• contrast anabolism and catabolism</td>
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<tr>
<td>• identify the high energy bonds in ATP and ADP</td>
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<td>• demonstrate how the hydrolysis of ATP can be coupled to an unfavourable reaction to lead to a favourable reaction</td>
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<td>• explain why creatine is a phosphoryl buffer</td>
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<td>• identify activated carriers of phosphoryl groups, electrons, and two-carbon fragments</td>
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<td>• relate oxidation of molecules to the release of energy</td>
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<tr>
<td>• define the energy charge of the cell</td>
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<th>Glucose is used in anaerobic metabolism as a source of fuel.</th>
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<td>• explain how the conversion of glucose into pyruvate through glycolysis generates ATP (must be able to recognize required cofactors and name/classify the enzyme for each step)</td>
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<td>• explain why glyceraldehyde 3-phosphate dehydrogenase uses a thioester intermediate for covalent catalysis</td>
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<td>• identify where oxidation-reduction takes place in glycolysis</td>
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<td>• describe how the three irreversible steps of glycolysis are regulated by allosteric effectors or covalent modification</td>
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<td>• contrast regulation in muscle with regulation in liver</td>
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<td>• describe how NAD⁺ is regenerated under anaerobic conditions by converting pyruvate to ethanol or lactate and why this is necessary (must be able to recognize required cofactors and name/classify the enzyme for each step)</td>
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<th>Glucose can be generated through gluconeogenesis when carbohydrate intake in the diet is too low.</th>
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<tr>
<td>• describe the formation of glucose from pyruvate through gluconeogenesis (must be able to recognize required cofactors and name/classify the enzyme for each step)</td>
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<td>• identify where the reactions take place in the cell</td>
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<td>• contrast glycolysis and gluconeogenesis</td>
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<td>• describe how gluconeogenesis is regulated by allosteric effectors or covalent modification to prevent the occurrence of futile cycles</td>
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<td>Topic</td>
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</table>
| Glucose is used in aerobic metabolism as a source of fuel. | describe how pyruvate is converted to acetyl-CoA through the bridge reaction (must be able to recognize required cofactors)  
• describe the mechanism of the pyruvate dehydrogenase complex  
• describe how the bridge reaction is regulated  
• identify the two stages of the tricarboxylic acid (TCA) cycle  
• describe each step of the TCA cycle (must be able to recognize required cofactors and name/classify the enzyme for each step)  
• describe the mechanism of the α-ketoglutarate dehydrogenase complex  
• describe the mechanism of succinyl-CoA synthetase  
• compare α-ketoglutarate dehydrogenase complex with pyruvate dehydrogenase complex  
• describe how the TCA cycle is regulated  
• describe how reducing power is converted to ATP in oxidative phosphorylation  
• describe how NADH and FADH$_2$ are oxidized in the electron transport chain and how electrons travel through each complex of the electron transport chain  
• describe how the passage of electrons through the electron transport chain creates an electrochemical gradient  
• describe how ATP synthase uses the electrochemical gradient to synthesize ATP  
• explain how shuttles regenerate NAD$^+$ for glycolysis |
| Nucleic acids are required for the transfer of information and the synthesis of proteins. | distinguish between nucleosides and nucleotides  
• describe the structure of DNA molecules in terms of backbone, grooves, bases, hydrogen bonding, base pairing, and packaging  
• describe the structure of RNA molecules in terms of backbone, hydrogen bonding, and base pairing  
• compare the structure of DNA and RNA and relate structural differences to the function of each molecule  
• distinguish Watson-Crick base pairs from non-Watson-Crick base pairs |
| Genetic information is passed on by the replication of DNA. | explain the roles of helicase, primase, DNA Pol III, DNA Pol I, and ligase in DNA replication by describing the reactions catalyzed by each enzyme in formation of the leading and/or lagging strand  
• describe the mechanism of DNA ligase  
• describe the elongation reaction catalyzed by DNA Pol III  
• identify where energy is consumed for replication |
| DNA can be damaged, and the cell can identify and repair damage. | At the end of this topic, students should be able to:  
- identify damaged bases in DNA and explain how damage occurs  
- explain how the cell recognizes damaged DNA  
- describe how cells remove damaged DNA  
- list the names and functions of enzymes used to repair damaged DNA |

| DNA is transcribed to produce RNA. | At the end of this topic, students should be able to:  
- distinguish the key features of the three steps of RNA synthesis: initiation, elongation, and termination  
- describe the activity of RNA polymerase from *E. coli* (αββ′ωσ) and the role of some individual subunits  
- elucidate how RNA polymerase identifies where to start and where to stop transcription, and recognize how it separates dsDNA  
- explain how transcription factors interact with DNA and regulate transcription  
- describe the structure, formation, and function of the 5′ cap on eukaryotic mRNA  
- explain how the 3′ end of eukaryotic mRNA is modified and recognize the enzymes involved  
- describe the two transesterification reactions that occur during splicing of eukaryotic mRNA |

| Proteins are synthesized from RNA. | At the end of this topic, students should be able to:  
- recognize base pairing interactions between mRNA codons and anticodons on tRNA molecules  
- explain why the presence of inosine on the tRNA anticodon contributes to degeneracy in the genetic code  
- describe the reactions catalyzed by aminoacyl-tRNA synthetase that facilitate tRNA charging  
- explain how aminoacyl-tRNA synthetase achieves specificity  
- state the direction in which DNA, mRNA, and proteins are synthesized  
- distinguish the key features of the three steps of protein synthesis: initiation, elongation, and termination  
- describe formation of the peptide bond during elongation  
- identify where energy is consumed by translation  
- recognize which amino acid side chains are commonly post-translationally modified by lipidation, glycosylation and phosphorylation and explain how these modifications affect protein function  
- describe how recombinant DNA technology is used to clone and express genes |
Laboratory component:

There are six laboratory exercises in BCEM 393. To accommodate the large number of laboratory sections in BCEM 393, each laboratory exercise is offered for a period of two weeks. This means that students only have one laboratory exercise every two weeks.