CHAPTER 6 METABOLISM: ENERGY AND ENZYMES

Chapter Outline

6.1 Cells and the Flow of Energy

A. Energy
   1. Energy is capacity to do work; cells continually use *energy* to develop, grow, reproduce, etc.
   2. **Kinetic energy** is energy of motion; all moving objects have kinetic energy.
   3. **Potential energy** is stored energy.
      a. A rolling ball and a contracting muscle are forms of **mechanical energy**.
      b. Food is **chemical energy** that contains potential energy.
      c. When a moose lifts its leg, it converts chemical energy into mechanical energy.

B. Two Laws of Thermodynamics
   1. First law of thermodynamics (also called the law of conservation of energy)
      a. Energy cannot be created or destroyed; it can be changed from one form to another.
      b. In an ecosystem, sunlight energy is converted in photosynthesis to chemical energy of plant tissue; some of the chemical energy in the plant is converted to chemical energy in an animal which ultimately can become mechanical energy or heat loss.
      c. Photosynthesis uses solar energy to convert the energy-poor carbon dioxide and water into energy-rich carbohydrates.
      d. The plant or animal never create the energy; it flows through the system and dissipates as heat
   2. Second law of thermodynamics
      a. Energy cannot be changed from one form into another without a loss of usable energy.
      b. Heat is form of energy but quickly dissipates into the environment; because heat dissipates, it can never be converted back to the other forms of energy.

C. Cells and Entropy
   1. Every energy transformation makes the universe less organized and more disordered; entropy is a measure of this disorganization.
   2. When ions distribute themselves randomly across a membrane, entropy has increased.
   3. Organized/usable forms of energy as in the glucose molecule, have low entropy; unorganized/less stable forms have high entropy.
   4. Energy conversions result in heat and therefore the entropy of the universe is always increasing.
   5. It takes a constant input of usable energy from the sun from to produce the food you eat to keep you organized.

6.2 Metabolic Reactions and Energy Transformations

A. Metabolism
   1. Metabolism is the sum of all the biochemical reactions in a cell.
   2. In a reaction $A + B \rightarrow C + D$, A and B are **reactants** and C and D are **products**.
   3. **Free energy** (ΔG) is the amount of energy that is free to do work after a chemical reaction.
   4. Change in free energy is noted as ΔG; a negative ΔG means that products have less free energy than reactants; the reaction occurs spontaneously.
   5. **Exergonic reactions** have a negative ΔG and energy is released.
   6. **Endergonic reactions** have a positive ΔG; products have more energy than reactants; such reactions can only occur with an input of energy.

B. ATP: Energy for Cells
   1. **Adenosine triphosphate** (ATP) is the energy currency of cells; when cells need energy, they "spend" ATP.
   2. ATP provides a common energy carrier for many different types of reactions.
   3. When ATP becomes ADP + P, the energy released is sufficient for biological reactions with little wasted.
   4. ATP breakdown is coupled to endergonic reactions in a way that minimizes energy loss.
   5. ATP is a nucleotide composed of the base adenine and the 5-carbon sugar ribose and three phosphate groups.

6. When one phosphate group is removed, about 7.3 kcal of energy is released per mole. .

C. **Coupled Reactions**

1. A coupled reaction occurs when energy released by an exergonic reaction is used to drive an endergonic reaction.
2. ATP breakdown is often coupled to cell reactions that require energy.
3. ATP supply is provided by breakdown of glucose during cellular respiration.
4. Only 39% of the free energy of glucose is transformed into ATP; 61% is lost as heat.
5. ATP can have any of three functions.
   a. Chemical Work: ATP supplies energy to synthesize molecules to make up the cell.
   b. Transport Work: ATP supplies energy to pump substances across the plasma membrane.
   c. Mechanical Work: ATP supplies energy needed to perform muscle contraction, propel cilia, etc.

6.3 Metabolic Pathways and Enzymes

A. Reactions in Cells Are Orderly

1. A **metabolic pathway** is an orderly sequence of linked reactions; each step is catalyzed by a specific *enzyme*.
2. Metabolic pathways begin with particular reactant, end with end product, and have many intermediate steps.
3. One pathway leads to next; since pathways have the same molecules, one pathway can lead to several others.
4. Metabolic energy is captured more easily if it is released in small increments.
5. A **reactant** is a substance that participates in a reaction; a product is substance formed by the reaction.
6. Each step in a series of chemical reactions is assisted by an enzyme.
7. **Enzymes** are catalysts that speed chemical reactions without the enzyme being changed.
8. Every enzyme is specific in its action and catalyzes only one reaction or one type of reaction.
9. A **substrate** is a reactant for an enzymatic reaction.

B. Energy of Activation

1. Molecules often do not react with each other unless activated.
2. For metabolic reactions to occur in a cell, an enzyme must usually be present.
3. Without enzymes, activation is achieved by heating reaction flask to increase molecular collisions.
4. **Energy of activation (E_a)** is energy that must be added to cause molecules to react.

C. Enzyme-Substrate Complexes

1. Enzymes speed chemical reactions by lowering the energy of activation (E_a) by forming a complex with their substrate(s) at the *active site.*
   a. An **active site** is a small region on surface of the enzyme where the substrate(s) bind.
   b. When a substrate binds to an enzyme, the active site undergoes a slight change in shape that facilitates the reaction.
2. Only a small amount of enzyme is needed in a cell because enzymes are not used up.
3. Some enzymes actually participate in the reaction (e.g., trypsin).
4. A particular reactant(s) may produce more than one type of product(s).
   a. Presence or absence of enzyme determines which reaction takes place.
   b. If reactants can form more than one product, the enzymes present determine product produced.
5. Every cell reaction requires its specific enzyme; enzymes are named for substrates by adding "-ase."

D. Factors Affecting Enzymatic Speed

1. Enzymatic reactions can be rapid (e.g., $2H_2O_2 \rightarrow H_2O + O_2$ occurs 6,000 molecules/second with catalase).
   a. To achieve maximum product per unit time, there should be enough substrate to fill active sites.
   b. An optimal temperature and pH increases the rate of enzymatic reaction.
2. Temperature and pH
   a. As temperature rises, enzyme activity increases because there are more molecular collisions.
   b. Enzyme activity declines rapidly when enzyme is **denatured** at a certain temperature; results in change in shape of enzyme.
   c. Each enzyme has optimal pH that maintains its normal configuration.

3. Enzyme Concentration
   a. The amount of active enzyme also regulates the rate of enzymatic reactions.
   b. Cells activate genes when certain enzymes are needed; this is the first regulatory mechanism.
   c. Enzyme Cofactors
      1) Many enzymes require an inorganic ion or non-protein **cofactor** to function.
      2) Inorganic cofactors are ions of metals.
      3) The organic cofactors are **coenzymes** that assist enzymes or accept or contribute atoms to the reaction.
      4) Vitamins required in trace amounts for synthesis of coenzymes; they become part of a coenzyme's molecular structure; vitamin deficiency causes a lack of a specific coenzyme and lack of its enzymatic action.
   d. Phosphorylation of enzymes occurs when signal proteins turn on kinases; some hormones use this mechanism.
   e. Enzyme inhibition occurs when an active enzyme is prevented from combining with its substrate.
      1) When product is abundant, active sites are full and enzyme activity drops.
      2) When product is used up, inhibition is reduced and more product is produced.
      3) Concentrations of products can be kept within narrow ranges.
      4) Pathways can be regulated by feedback inhibition; end product of pathway binds at an **allosteric site** on the first enzyme of the pathway, shutting down the pathway.
      5) Cyanide inhibits an essential enzyme (cytochrome *c* oxidase) found in all cells.
      6) Penicillin blocks an active site of an enzyme unique to bacteria.

6.4 Oxidation-Reduction and the Flow of Energy

A. Oxidation-Reduction
   1. In oxidation-reduction (redox) reactions, electrons pass from one molecule to another.
   2. **Oxidation** is the loss of electrons.
   3. **Reduction** is the gain of electrons.
   4. Both reactions occur at the same time because one molecule accepts electrons given up by another molecule.

B. Photosynthesis
   1. Photosynthesis uses energy to combine carbon dioxide and water to produce glucose in the formula:
      $6\ CO_2 + 6\ H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$
   2. Water has been oxidized and carbon dioxide has been reduced.
   3. Input of energy is needed to produce the high-energy glucose molecule.
   4. Chloroplasts capture solar energy and convert it in the electron transport system into chemical energy of ATP.
   5. ATP is used along with hydrogen atoms to reduce glucose; when **$NADP^+$ (nicotinamide adenine dinucleotide phosphate)** donates hydrogen atoms ($H^+ + e^-$) to a substrate during photosynthesis, substrate has accepted electrons and is reduced.
   6. The reaction that reduces $NADP^+$ is:
      $NADP^+ + 2e^- + H^+ \rightarrow NADPH$

C. Cellular Respiration
   1. The overall equation for aerobic respiration is opposite that of photosynthesis:
      $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$
   2. When NAD removes hydrogen atoms ($H^+ + e$) during cellular respiration, the substrate has lost electrons and is oxidized.
      $NAD^+ + 2e^- + H^+ \rightarrow NADH$
   3. At the end of cellular respiration, glucose has been oxidized to carbon dioxide and water and ATP molecules have been produced.

D. Electron Transport System
   1. Both photosynthesis and respiration use an electron transport system consisting of membrane-bound carriers to pass electrons from one carrier to another.
   2. High-energy electrons are delivered to the system and low-energy electrons leave it.
   3. Each time electrons transfer to a new carrier, energy is released; ultimately this produces ATP.

E. ATP Production

1. ATP synthesis was known to be coupled to the electron transport system.
2. Peter Mitchell received 1978 Nobel prize for his chemiosmotic theory of ATP production.
3. In both mitochondria and chloroplasts, carriers of electron transport systems are located within a membrane.
4. H^+ ions (protons) collect on one side of membrane because they are pumped there by certain carriers.
5. The electrochemical gradient this establishes across the membrane is used to provide energy for ATP production.
6. Particles called ATP synthase complexes span the membrane; each complex contains a channel that allows H^+ ions to flow down their electrochemical gradient.
7. In photosynthesis, energized electrons lead to pumping of hydrogen ions across the thylakoid membrane; hydrogen ion flow through the ATP synthase complex couples this flow to formation of ATP.
8. During cellular respiration, glucose breakdown provides energy for a hydrogen ion gradient on the inner membrane of the mitochondria that also couples hydrogen ion flow with ATP formation.