

## CHAPTER 4: CELLULAR METABOLISM

### OBJECTIVES:

1. Compare and contrast the major divisions of metabolism, in terms of a general descriptive sentence, additional descriptive terms, how energy is involved, whether bonds are formed or broken, and how water is involved. Also write a chemical reaction for each and give an example important in human metabolism.
2. Distinguish between kinetic and potential energy, and give examples of each.
3. List the general characteristics of an enzyme, explain how most enzymes are named, and discuss the mechanism by which most enzymes function (i.e. how do they react with their substrate and cofactor/coenzyme).
4. Define the term substrate.
5. Explain why most enzymes need a vitamin (coenzyme) or mineral (cofactor) to function.
6. Name the three components of ATP and describe its function in living cells.
7. Write a simple chemical equation showing the reversible action of ATP/ADP.
8. Write a balanced, summary equation for cellular respiration.
9. Define oxidation and reduction.
10. Compare glycolysis, the conversion step, Krebs Cycle, and electron transport in terms of:
  - a. their location in the cell;
  - b. whether oxygen is required;
  - c. initial compounds and end-products;
  - d. number of ATP molecules produced.
11. Construct a table illustrating the total production of ATP from a molecule of glucose.
12. Describe the fate of pyruvic acid in the absence of oxygen.
13. Distinguish between aerobic and anaerobic respiration in terms of energy production.

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### Objectives (continued)

14. Name the greatest reserve fuel in the body.
15. Name the specific substance that is required for each and every step of metabolism.
16. Explain why an enzyme that catalyzes a step in glycolysis would not be required for a step in Beta-oxidation.
17. Construct a molecule of DNA. Be sure to label parts fully (if using abbreviations, make sure to provide a key) and describe what will happen to this molecule during replication.
18. Describe the function of deoxyribonucleic acid (DNA) and RNA.
19. Describe the steps involved in DNA replication, name the location in the cell where DNA replicates, name the enzyme required for DNA replication, and explain the significance of the process.
20. Describe what is meant by "semi-conservative" replication.
21. Explain why protein synthesis is so ultimately important in living things.
22. Define the term *gene*, and give the approximate number of genes that compose the human genome.
23. Distinguish ribonucleic acid (RNA) from DNA, in terms of structural components, where each is located in a human cell, and the function of each.
24. Compare and contrast the two major steps involved in protein synthesis, in terms of a general description, where they occur in the cell, the molecules (including enzyme names) involved in each step, and the overall result.
25. Describe the role of messenger RNA (mRNA), transfer RNA (tRNA) and ribosomal RNA (rRNA) in protein synthesis.
26. Explain how amino acids are joined to form a protein.
27. Given a DNA sequence (gene) and an mRNA codon chart, determine the peptide (protein) which will result.
28. Define the term *mutation*, and explain its significance in protein synthesis.

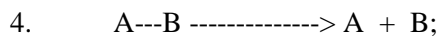
## CHAPTER 4: CELLULAR METABOLISM

I. **METABOLISM** = the sum an organism's chemical reactions.

A. **CATABOLIC REACTIONS** = breakdown reactions:

1. breaking down complex molecules into simpler ones; (i.e. polymers into monomers);
2. degradation, destructive, decomposition, digestion reactions;
3. Bonds are broken between monomers releasing energy (= EXERGONIC reactions);

water



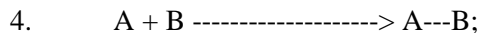
energy

5. Example is the pathway of reactions that break down glucose into carbon dioxide and water (i.e. cellular respiration), but which more importantly, release a lot of cellular energy (ATP).

B. **ANABOLIC REACTIONS** = building reactions:

1. building complex molecules from simpler ones; (i.e. monomers into polymers);
2. constructive, synthesis reactions;
3. Bonds are formed between monomers which now hold energy (= ENDERGONIC reactions);

energy



water

5. Example is using cellular energy (ATP) in order to build a protein from individual amino acids.

\* See Figures 4.1- 4.3 on page 103 to review several examples of these reversible reactions.

## CHAPTER 4: CELLULAR METABOLISM

### I. Metabolism (continued)

#### C. **ENERGY COUPLING** = the interaction between catabolism and anabolism:

1. Anabolic and catabolic reactions occur simultaneously in an organism;
2. The free energy released from catabolic reactions is immediately coupled (or used) to fuel anabolic reactions;
3. Example is using the energy released from the breakdown of glucose in order to build a protein.

#### D. **ENERGY** = the capacity to do work; takes one of 2 forms.

1. **Kinetic energy** = energy of motion;
  - a. water rushing through a dam which can in turn run a turbine;
  - b. energy released by breaking bonds of ATP.
2. **Potential energy** = stored energy;
  - a. energy harnessed in the water held back by a dam;
  - b. energy stored in the bonds of ATP.
3. Kinetic and potential energy is continuously being converted back and forth; (i.e. when potential energy is released it becomes kinetic energy).

**CHAPTER 4: CELLULAR METABOLISM**

**I. METABOLISM SUMMARY TABLE (Keyed on page 81 of this outline)**

	<b>ANABOLIC REACTIONS CONSTRUCTIVE RXN'S</b>	<b>CATABOLIC RXNS DEGRADATION RXNS</b>
GENERAL DESCRIPTION		
DESCRIPTIVE TERMS		
BOND FORMATION OR BREAKING?		
IS ENERGY REQUIRED OR RELEASED? NAME THAT TERM.		
HOW IS WATER INVOLVED? NAME THAT TERM		
EXAMPLE		

## CHAPTER 4: CELLULAR METABOLISM

### II. CONTROL OF METABOLISM: ENZYME ACTION

- A. Definition: Enzymes are biological (protein) **catalysts** that change (**increase**) **the rate of a chemical RXN** without being consumed by the RXN.
- B. Enzymes are **specific** for the substance they act on (**substrate**).
- D. Enzyme names typically end in the suffix **-ase**:
1. sucrase breaks down sucrose;
  2. a lipase breaks down a lipid,
  3. a protease breaks down a protein.
- E. Only a specific region of the enzyme molecule actually binds the substrate = **Active Site**.
1. The substrate and enzyme fit together like a "Lock and Key". See Fig 4.5, page 105.
- F. The active site of an enzyme may not always be exposed (recall the 3-d conformation of proteins), & a **cofactor or coenzyme** may be necessary to "activate" the enzyme so it can react with its substrate.
1. **Cofactor** = an ion of a metal (mineral)
  2. **Coenzyme** = vitamin.
- G. Enzymes are **recycled**.

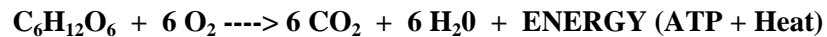


## CHAPTER 4: CELLULAR METABOLISM

### IV. CELLULAR RESPIRATION (CR)

A. Introduction: See Fig 4.6, page 107 for an overview of this process.

1. CR is how animal cells use energy stored in food to make energy (ATP).
2. All organic molecules (carbohydrates, fats, and proteins) can be processed to release energy, but we will only study the steps of CR for the breakdown of glucose ( $C_6H_{12}O_6$ ).
3. **Oxygen is required** to receive the maximum energy possible per molecule of glucose.
4. A balanced chemical equation representing the complete **catabolism of glucose** can be written as follows (but keep in mind that the breakdown of glucose actually involves many steps!):

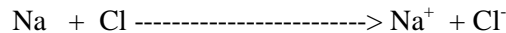


5. Note that this reaction is **EXERGONIC**. What can the cell do with this energy?

### B. OXIDATION: REDUCTION PROCESS OF CELLULAR RESPIRATION

1. Many of the reactions in the breakdown of glucose involve the **transfer of electrons ( $e^-$ )**.
  - a. These reactions are called oxidation - reduction (or redox) reactions;
2. In a redox reaction:
  - a. the **loss of electrons from a substance is called oxidation**, while
  - b. the **addition of electrons to a substance is called reduction**.
  - c. Example:

Oxidation



Reduction

## CHAPTER 4: CELLULAR METABOLISM

### IV. B. Redox Reactions of CR (continued)

3. An electron transfer can also involve the **transfer of a pair of hydrogen atoms** (which possess two electrons), from one substance to another.
  - a. The H atoms (and electrons) are eventually transferred to oxygen;
  - b. The transfer occurs in the final step of CR;
  - c. In the meantime, the H atom (electrons) are **usually passed to NAD<sup>+</sup>** (nicotinamide adenine dinucleotide);
  - d. red
$$\text{H:H} + \text{NAD}^+ \text{ -----} \rightarrow \text{NADH} + \text{H}$$
  - e. In the final step of CR:
    1. the electron transport chain;
    2. oxygen is the final electron acceptor;
    3. **NADH is oxidized**
    4. **ATP** is yielded.

### C. **Major Steps in Cellular Respiration:** See Fig 4.6, page 107.

The major steps in CR include glycolysis, a conversion step, the Krebs Cycle, and the Electron Transport Chain.

#### 1. **GLYCOLYSIS:**

- a. means "splitting of sugar";
- b. A **6-carbon sugar** is split into **two 3-C pyruvate** molecules;
- c. occurs in the **cytoplasm** of the cell;
- d. Oxygen is **not** required (i.e. anaerobic);
- e. Energy yield is :
  1. **2 Net ATP** per glucose molecule,
  2. **2 NADH** (stored electrons for ETS).
- f. Many steps are required;
- g. See Fig 4.10 page 109..

## CHAPTER 4: CELLULAR METABOLISM

### IV. Cellular Respiration (continued)

#### C. Major Steps in Cellular Respiration

##### 2. Conversion of Pyruvate to Acetyl CoA:

Under **aerobic** conditions (when O<sub>2</sub> is present):

- a. Pyruvate enters the **mitochondrion**;
- b. Pyruvate (3-C) is converted to acetyl CoA (2-C);
- c. Energy yield is 1 NADH per pyruvate in this step (i.e. **2 NADH** per glucose)
- d. **CO<sub>2</sub>** is released.
- e. See top of Fig 4.11, page 110.

##### 3. KREBS CYCLE

- a. occurs in the **mitochondrial matrix**;
- b. Acetyl CoA adds its 2 carbons to oxaloacetate (4C) forming citrate (6C);
- c. Energy yield is:
  1. **6 NADH** per glucose,
  2. **2 FADH<sub>2</sub>** per glucose;
  3. **2 ATP** per glucose.
- d. 2- CO<sub>2</sub> are released during this series of steps.
- e. involves many steps, each catalyzed by a different enzyme.
- f. See Fig 4.11, page 110.

##### 4. ELECTRON TRANSPORT CHAIN (ETC)

See Fig 4.12, page 112.

- a. is located in the **inner mitochondrial membrane** (recall "cristae");
- b. During electron transport, these molecules alternate between reduced and oxidized states as they accept and donate electrons.
- c. The **final electron acceptor is oxygen**.
- d. Yield of energy (ATP) from the ETC is:
  1. **3 ATP/NADH** and
  2. **2 ATP/FADH<sub>2</sub>**.

**CHAPTER 4: CELLULAR METABOLISM**

IV. Cellular Respiration (continued)

C. Major Steps in Cellular Respiration

5. Overall ATP Yield From Glucose in CR:

a. **4 ATP** are produced directly:

- m 2 from glycolysis;
- m 2 from Krebs.

b. **10 NADH** are produced:

- m 2 from glycolysis,
- m 2 from conversion, &
- m 6 from Krebs

which yield **30 ATP**.

c. **2 FADH<sub>2</sub>** are produced in Krebs which yield **4 ATP**.

**\*Net yield of ATP per glucose = 38 ATP.**

D. **SUMMARY OF CELLULAR RESPIRATION:** Keyed on page 82 of this outline.

	<b>GLYCOLYSIS</b>	<b>CONVERSION STEP</b>	<b>KREBS CYCLE</b>	<b>ELECTRON TRANSPORT CHAIN</b>
<b>LOCATION in cell</b>				
<b>Is Oxygen Required?</b>				
<b>Starting Product(s)</b>				
<b>End-Products</b>				
<b>TOTAL</b>				

## CHAPTER 4: CELLULAR METABOLISM

### IV. Cellular Respiration

#### E. Anaerobic Glycolysis

Recall that glycolysis results in pyruvate. If oxygen is not present (i.e. under anaerobic conditions), pyruvate can ferment in one of two ways:

##### 1. Alcohol Fermentation:

- a. Pyruvate is converted to ethanol;
- b. occurs in yeasts (brewing) and many bacteria.

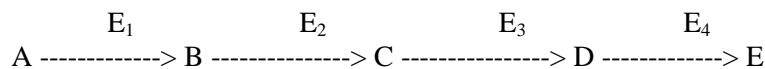
##### 2. Lactic Acid Fermentation:

- a. Pyruvate is converted to lactic acid, a waste product;
- b. occurs in many animal muscle cells;
- c. serves as an alternate method of making ATP when oxygen is scarce;
- d. accumulation causes **muscle soreness and fatigue**.

### V. Metabolism of Lipids: See overview in Fig 4.13, page 114.

- A. When liver glycogen stores are depleted, fats and proteins can be metabolized to produce ATP.
- B. **Stored fats are the greatest reserve fuel in the body.**
- C. Lipids are metabolized in a process called **beta oxidation**.
- D. The metabolism of an 18-C lipid will yield 146 ATP, while the metabolism of 3 glucoses (18-C) will yield 108 ATP.

### VI. Regulation of Metabolism: See Fig 4.15, page 115.



\* See Fig 4.16 on page 116 for a summary of the catabolism of proteins, carbohydrates, and fats.

## CHAPTER 4: CELLULAR METABOLISM

### VII. DNA REPLICATION:

DNA holds the genetic code which is passed from parents to their offspring. **During interphase** of the cell cycle, our DNA is replicated or duplicated so each new daughter cell is provided with an identical copy of this genetic material. In order to understand replication we must first look more closely at the structure of DNA molecules.

#### A. DNA (DEOXYRIBONUCLEIC ACID) STRUCTURE:

1. DNA is composed of **nucleotides**, each containing the following: See Fig 4.17, page 117.
  - a. a **pentose sugar** molecule (deoxyribose);
  - b. a **nitrogen-containing base**; Fig 4.18, page 117;
    - m a purine (double ring);
      1. adenine (A) or
      2. guanine (G);
    - m a pyrimidine (single ring);
      1. cytosine (C) or
      2. thymine (T);
  - c. a **phosphate group**.
2. Each DNA strand is made up of a backbone of deoxyribose sugars alternating with phosphate groups. See Fig 4.19, page 117.
3. Each deoxyribose sugar is linked to one of four nitrogen-containing bases: A,G,C, or T.
4. Each DNA molecule consists of two parallel strands of nucleotides running in opposite directions. See Fig 4.20, page 118.
5. The bases in these nucleotide strands are joined to a complement base on the opposite strand by hydrogen bonds forming: See Fig 4.21, page 118.
  - a. **adenine = thymine** (2 hydrogen bonds) pair and
  - b. **guanine = cytosine** (3 hydrogen bonds) pair.
6. The two strands are twisted into a **double helix**.

See Fig 4.22, page 119.

## CHAPTER 4: CELLULAR METABOLISM

### VII. DNA Replication (continued)

#### B. PROCESS OF DNA REPLICATION

See Fig 4.28, page 126.

1. DNA uncoils, and unzips (hydrogen bonds are broken between A=T and G=C);
  - a. Each free nucleotide strand now serves as a template (a set of instructions) for building a new complementary DNA strand.
2. DNA nucleotides that are present in the nucleoplasm begin to match up with their complements on the templates.
  - a. **DNA polymerase** (an enzyme) positions and links these nucleotides into a strand.
3. This results in two identical DNA molecules, each consisting of one old and one newly assembled nucleotide strand.
  - a. This type of replication is called **semi-conservative replication**.

## CHAPTER 4: CELLULAR METABOLISM

### VIII. PROTEIN SYNTHESIS:

The function of DNA is to control all cellular activities. The inherited DNA code instructs cells how to synthesize specific protein molecules (remember extreme importance of **enzymes** in controlling metabolic processes!). The portion of a DNA molecule that contains the genetic information for making one kind of protein is called a **gene**. In order to understand how DNA (confined to the nucleus) can direct the synthesis of proteins (which occurs in the cytoplasm), we must first look at the structure of RNA molecules.

#### A. RNA (RIBONUCLEIC ACID) STRUCTURE: See page 121.

1. RNA (like DNA) is composed of nucleotides, each containing the following:
  - a. a pentose sugar molecule (**ribose**);
  - b. a nitrogen-containing base;
    - m purine:
      1. adenine (A) or
      2. guanine (G).
    - m pyrimidine:
      1. cytosine (C) or
      2. **uracil (U)**;
  - c. a phosphate group.
2. Each RNA strand is made up of a backbone of ribose sugars alternating with phosphate groups.
3. Each ribose sugar is linked to either A, G, C, or U.
4. Each RNA molecule consists of a **single strand** of nucleotides.

#### B. TYPES OF RNA:

There are three types of RNA molecules which help the cell in protein synthesis:

1. **Messenger RNA (mRNA)** carries the code for the protein to be synthesized, from the nucleus to the protein synthesizing machinery in the cytoplasm (i.e. ribosome).
2. **Transfer RNA (tRNA)** carries the appropriate amino acid to the ribosome to be incorporated into the newly forming protein.
3. **Ribosomal RNA (rRNA)** along with protein make up the protein synthesizing machinery, the ribosome.

## CHAPTER 4: CELLULAR METABOLISM

### VIII. PROTEIN SYNTHESIS (continued)

C. Protein synthesis can be divided into 2 major steps: transcription and translation.

See Fig 4.25 on page 123 and 4.26 on page 122.

#### 1. TRANSCRIPTION

- a. occurs in the **nucleus** of the cell,
- b. is the process of copying the information (for a particular protein) from a DNA molecule, and putting it into the form of a **messenger RNA (mRNA)** molecule.
- c. As in DNA replication, the DNA strand unwinds and unzips (H-bonds are broken):
  - m Only one of the exposed templates (of the DNA molecule) is used to build the mRNA strand.
  - m **RNA polymerase** (an enzyme) positions and links RNA nucleotides (within the nucleus) into a strand.
- d. The message (mRNA):
  - m is **complementary** to the bases on the DNA strand (i.e If DNA sequence is TACGATTGCCAA, then the mRNA sequence is AUGCUAACGGUU);
  - m is in the form of a triple base code, represented by **codons** (i.e. AUG, CUA, ACG, GUU).
    1. Each codon on a mRNA molecule codes for one amino acid in the protein to be synthesized.
  - m can now **leave the nucleus** and travel to the protein-synthesizing machinery = **ribosome**.

## CHAPTER 4: CELLULAR METABOLISM

### VIII. Protein Synthesis (continued)

#### C. Major Steps (continued)

#### 2. TRANSLATION

See Fig 4.27, page 125.

- a. is the process by which the mRNA code, carried from the nucleus, is "translated" into a protein.
- b. occurs at **ribosomes** that are present in the **cytoplasm** or are attached to ER (RER).
- c. **Transfer RNA (tRNA)** molecules assist in translation by bringing the appropriate amino acid for each codon to the ribosome.
  - m The tRNA molecule has an **anticodon** which is complementary to the codon on the mRNA strand.
    1. If the codon for Glycine is GGG, then the anticodon on the tRNA molecule that carries Glycine to the ribosome is CCC.
- d. Two codons of the mRNA molecule are read in the ribosome at the same time.
  - m The tRNA molecules deliver their amino acids to the ribosome, and a **peptide bond** is formed between adjacent amino acids.
  - m The mRNA molecule is read codon by codon, with each corresponding amino acid being added to the chain of amino acids.
  - m A protein is formed.
- e. The mRNA molecule is read until a **stop codon** on the mRNA is reached:
  - m The protein is released into the cytoplasm;
  - m The mRNA molecule can be read again and again.

## CHAPTER 4: CELLULAR METABOLISM

### VIII. PROTEIN SYNTHESIS

#### D. SUMMARY TABLE (Keyed on page 83 of this outline)

MAJOR STEP		
GENERAL DESCRIPTION		
LOCATION IN CELL		
MOLECULES INVOLVED AND HOW?		
OVERALL RESULT		

## CHAPTER 4: CELLULAR METABOLISM

### VIII. PROTEIN SYNTHESIS

#### E. WORK SHEET

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DNA BASE SEQUENCE	mRNA BASE SEQUENCE	AMINO ACID SEQUENCE(*)	tRNA BASE SEQUENCE
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---

T

A

C

T

T

T

C

A

A

A

T

T

---

\* Use Messenger RNA Codon Table 4.1 on page 121 to determine appropriate amino acid sequence.

## CHAPTER 4: CELLULAR METABOLISM

### VIII. Protein Synthesis

#### F. Problems (continued)

The following genes code for what amino acid sequences?

1. T A C A A A C G T C C G T A C A T T

2. T A C G A T G T T C C G T T A A T T

3. T A C A A A C G T C C G T G C A T T

## CHAPTER 4: CELLULAR METABOLISM

### IX. Mutations

A. Definition: A change in the DNA sequence of a gene.

See Fig 4.29, page 127.

B. Effects of Mutations: See pages 129-130.

See how mutations may cause four inborn errors in the metabolism of Phenylalanine in Figure 4.30, page 130.

10. The Human Genome Project.

See pages 130-131.

**CHAPTER 2: CHEMICAL BASIS OF LIFE**  
Metabolism Comparison Table (outline page 64)

	<b>Anabolism SYNTHESIS REACTIONS</b>	<b>Catabolism DEGRADATION RXN'S</b>
<b>GENERAL DESCRIPTION</b>	Synthesis involves the building of a large molecule (polymer) from smaller building blocks (monomer).	Degradation involves the breakdown of polymer into individual monomers.
<b>DESCRIPTIVE TERMS</b>	building constructive anabolic	breakdown digestive decomposition catabolic
<b>BOND FORMATION OR BREAKING?</b>	Bonds are formed.	Bonds are broken.
<b>IS ENERGY REQUIRED OR RELEASED? NAME THAT TERM.</b>	Energy is required to form the bond. Endergonic	Energy is released when the bond is broken. Exergonic
<b>HOW IS WATER INVOLVED? NAME THAT TERM.</b>	Water is released when the bond is formed. Dehydration	Water is required to break the bond. Hydrolysis
<b>EXAMPLE</b>	Building a protein from individual amino acids; Building a triglyceride from glycerol and 3 fatty acids, etc	Breaking a protein into individual amino acids; Breaking starch down into monosaccharides, etc.

## CHAPTER 4: CELLULAR METABOLISM

### SUMMARY OF CELLULAR RESPIRATION (outline page 70)

	<b>GLYCOLYSIS</b>	<b>CONVERSION STEP</b>	<b>KREBS CYCLE</b>	<b>ELECTRON TRANSPORT CHAIN</b>
LOCATION	cytoplasm	mitochondria	mito matrix	mito inner membrane
Oxygen Required?	no	yes	yes	yes
Starting Product	glucose (6-C)	2 pyruvates (2 x 3C)	Acetyl CoA (2 x 2C)	10 NADH 2 FADH <sub>2</sub>
End-Products	2 pyruvates (2 x 3-C) 2 ATP 2 NADH	2 Acetyl CoA 2 NADH 2 CO <sub>2</sub>	6 NADH 2 FADH <sub>2</sub> 2 ATP 4 CO <sub>2</sub>	30 ATP 4 ATP 4 ATP
TOTAL				38 ATP

**CHAPTER 4: CELLULAR METABOLISM**

**PROTEIN SYNTHESIS SUMMARY TABLE (outline page 77)**

<b>MAJOR STEP</b>	<b>TRANSCRIPTION</b>	<b>TRANSLATION</b>
<b>GENERAL DESCRIPTION</b>	when the code (gene) for a protein to be synthesized is copied from the DNA and is put in the form of a Messenger RNA strand (mRNA)	when a strand of mRNA (carrying the code for the protein to be synthesized) is translated into a protein
<b>LOCATION IN CELL</b>	nucleus	at a ribosome either that is either free in the cytoplasm or on rough endoplasmic reticulum
<b>MOLECULES INVOLVED AND HOW?</b>	DNA: unwinds & unzips  RNA Polymerase (an enzyme) positions the complementary RNA nucleotides along the DNA template and zips up their backbone.	mRNA carries the protein code to the ribosome.  Ribosome if the protein synthesizing machinery.  Transfer RNA (tRNA) bring the appropriate amino acid to the ribosome to be incorporated into the protein. Many enzymes.
<b>OVERALL RESULT</b>	A strand of mRNA	A protein