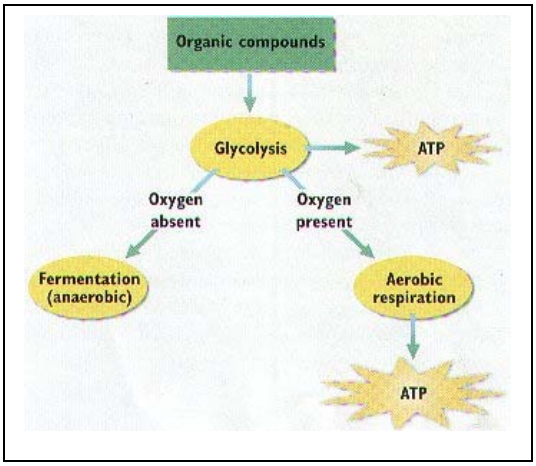
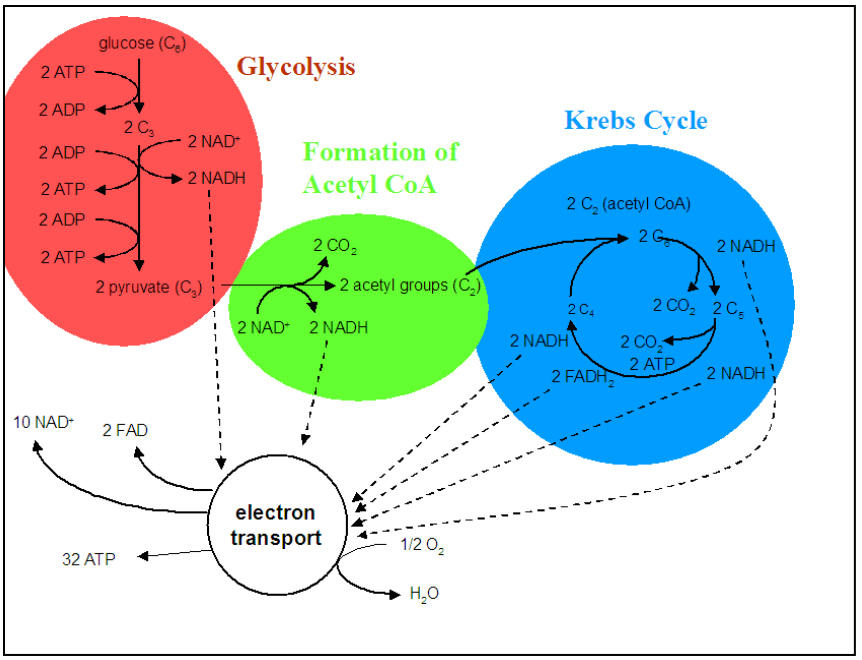
AP BIOLOGY – CHAPTER 7 Cellular Respiration Outline

I. How cells get energy.

A. Cellular Respiration

1. **<u>Cellular respiration</u>** includes the various metabolic pathways that break down carbohydrates and other metabolites and build up ATP.





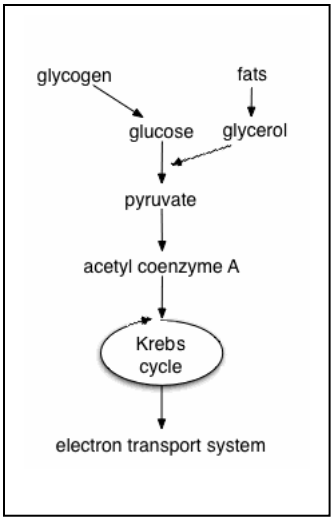
2. Cellular respiration requires oxygen and gives off CO2.
3. Aerobic respiration usually breaks down glucose into CO2 and H2O.
4. Overall equation for complete breakdown of glucose requires oxygen (is aerobic):
   C6H12O6 + 6O2 → 6 CO2 + 6 H2O + energy
5. Glucose is high-energy molecule; CO2 and H2O are low-energy molecules; process is exergonic and releases energy.
6. Electrons are removed from substrates and received by oxygen, combines with H+ to become water.
7. Glucose is oxidized and O2 is reduced.
8. Buildup of ATP is an endergonic reaction that requires energy.
9. Pathways of aerobic respiration allow energy in glucose to be released slowly; ATP is produced gradually.
10. Rapid breakdown of glucose would lose most energy as non-usable heat.
11. Breakdown of glucose yields synthesis of 36 or 38 ATP; this preserves 39% of energy available in glucose.

B. NAD+ and FAD

1. Each metabolic reaction in cellular respiration is catalyzed by its own enzyme.
2. As a metabolite is oxidized, NAD+ accepts two electrons and a hydrogen ion (H+); results in NADH + H+.
3. Electrons received by NAD+ and FAD are high-energy electrons and are usually carried to the electron transport system.
4. NAD+ is a coenzyme of oxidation-reduction since it both accepts and gives up electrons.
5. Only a small amount of NAD+ is needed in cells; each NAD+ molecule is used over and over.
6. FAD coenzyme of oxidation-reduction can replace NAD+; FAD accepts two electrons, becomes FADH2.

C. Phases of Complete Glucose Breakdown

1. **Aerobic respiration** includes metabolic pathways and one individual reaction:
   a. **Glycolysis** is the breakdown of glucose to two molecules of **pyruvate**.
      1) Enough energy is released for immediate buildup of two ATP.
      2) **Glycolysis** takes place outside the mitochondria and does not utilize oxygen.
   b. The transition reaction: pyruvate is oxidized to an acetyl group and CO_2 is removed.
   c. **The Krebs cycle**:
      1) This series of reactions gives off CO_2 and produces ATP.
      2) Produces two immediate ATP molecules per glucose molecule.
   d. **The electron transport system:**
      1) Series of carriers accepts electrons from glucose; electrons are passed from carrier to carrier until received by oxygen.
      2) Electrons pass from higher to lower energy states, energy is released and stored for ATP production.
      3) System accounts for 32 or 34 ATP depending on the cell.
2. **Pyruvate** is a pivotal metabolite in cellular respiration:
   a. If O_2 is not available to the cell, fermentation, an aerobic process, occur.
   b. During **fermentation**, glucose is incompletely metabolized to lactate or CO_2 and alcohol.
   c. **Fermentation** results in a net gain of only two ATP per glucose molecule.



II. Outside the Mitochondria: Glycolysis

A. Glycolysis

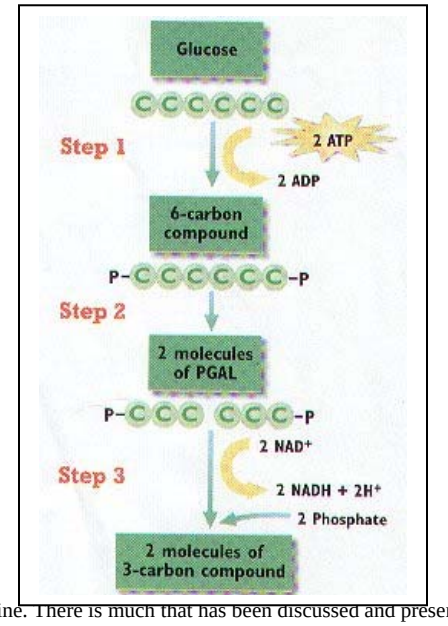
1. Occurs in the cytosol outside the mitochondria.
2. Is the breakdown of glucose to two pyruvate molecules.
3. Is universal in organisms; therefore, most likely evolved before Krebs cycle and electron transport system.

B. Energy Investment Steps

1. **Glycolysis** begins with addition of two phosphate groups activating glucose to react.
2. Two separate reactions use two ATP.
3. Glucose, a C6 molecule, splits into two C3 molecules, each with a phosphate group.

C. Energy Harvesting Steps

1. Two electrons and one hydrogen ion are accepted by NAD^+ and result in two NADH.
2. Enough energy is released from breakdown of glucose to **generate four ATP molecules**.
3. Two to four ATP molecules produced are required to replace two ATP molecules used in the **phosphorylation** of glucose.
4. **There is a net gain of two ATP from glycolysis**.
5. **Pyruvate enters mitochondria if oxygen is available and aerobic respiration follows.**
6. **If oxygen is not available, glycolysis becomes a part of fermentation.**



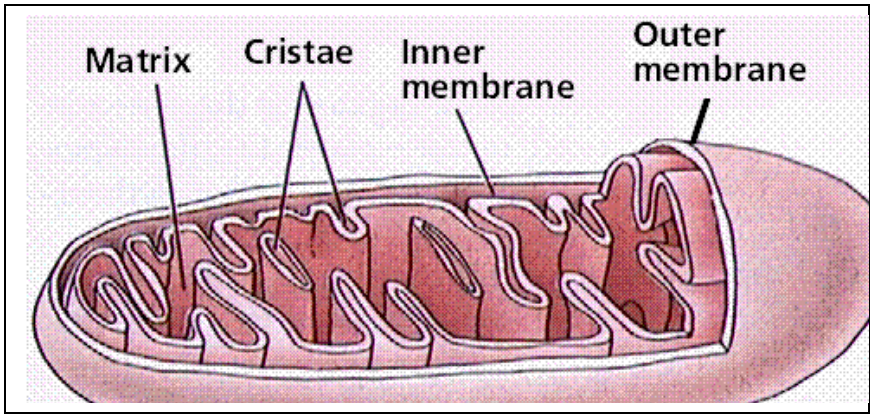
III Inside the Mitochondria

A. Aerobic Respiration

1. Involves the transition reaction, **the Krebs cycle, and the electron transport system**.
2. Is process in which pyruvate from glycolysis is broken down completely to CO2 and H2O.
3. Takes place inside **mitochondria**.

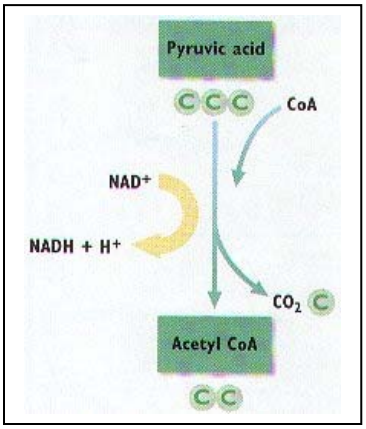
B. Mitochondria

1. A mitochondrion has a double membrane with an intermembrane space between the outer and inner membrane.
2. **Cristae** are the inner folds of membrane that jut into the matrix.
3. **Matrix** is the innermost compartment of a mitochondrion and is filled with gel-like fluid.
4. Transition reaction and **Krebs cycle enzymes are in matrix**; **electrons transport system is in cristae**.
5. **Most ATP produced in cellular respiration is produced in mitochondria**.



C. Transition Reaction

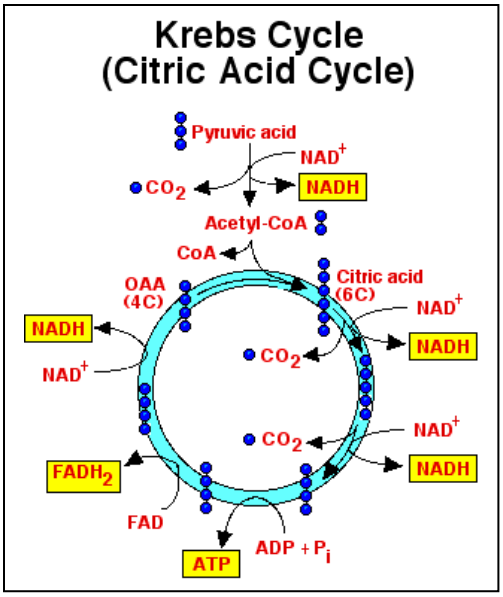
1. Transition reaction connects glycolysis to the Krebs cycle.
2. In this reaction, pyruvate is converted to a two-carbon acetyl group attached to **coenzyme A**.
3. This redox reaction removes electrons from pyruvate by dehydrogenase using NAD+ as coenzyme.
4. Reaction occurs twice for each original glucose molecule.



D. The Krebs Cycle

1. **Krebs cycle** reactions occur in matrix of mitochondria.
2. Cycle is named for Sir Hans Krebs, who received Noel Prize for identifying these reactions.
3. Cycle begins by adding C2 acetyl group to C4 molecule, forming citrate; also called the citric acid cycle.
4. The acetyl group is then oxidized to two molecules of CO2.
5. During the oxidation process, most electrons (e-) are accepted by NAD+ and NADH is formed.
6. In one instance, electrons are taken by FAD, forming FADH2.
7. NADH and FADH2 carry these electrons to electron transport system.

8. Some energy released is used to synthesize ATP by substrate-level phosphorylation, as in glycolysis.
9. One high-energy metabolite accepts a phosphate group and passes it on to convert ADP to ATP.
10. Krebs cycle turns twice for each original glucose molecule.
11. **Products of the Krebs cycle per glucose molecule include 4 CO2, 2 ATP, 6 NADH and 2 FADH2**



E. The Electron Transport System

1. **<u>Electron transport system</u>** is located in cristae of mitochondria; consists of carriers that pass electrons.
2. Some protein carriers are cytochrome molecules.
3. Electrons that enter the electron transport system are carried by NADH and FADH2.
4. NADH gives up its electrons and becomes NAD+; next carrier gains electrons and is reduced.
5. At each sequential oxidation-reduction reaction, energy is released to form ATP molecules.
6. Oxygen serves as terminal electron acceptor and combines with hydrogen ions to form water.
7. Because O2 must be present for system to work, it is also called oxidative phosphorylation.
8. NADH delivers electrons to system; by the time electrons are received by O2, three ATP are formed.
9. If FADH2 delivers electrons to system, by the time electrons are received by O2, two ATP are formed.
10. Coenzymes and ATP recycle
    a. Cell needs a limited supply of coenzymes NAD+ and FAD because they constantly recycle.
    b. Once NADH delivers electrons to electron transport system, it is free to pick up more hydrogen.
    c. Components of ATP also recycle.
    d. Efficiency of recycling NAD+, FAD and ADP eliminates need to synthesize them anew.

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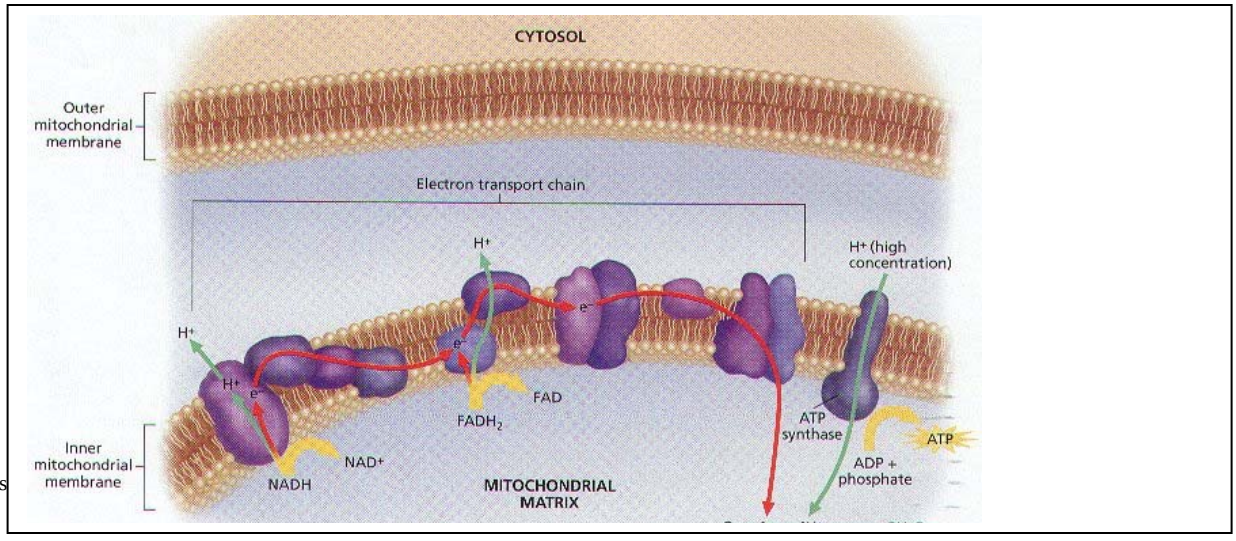
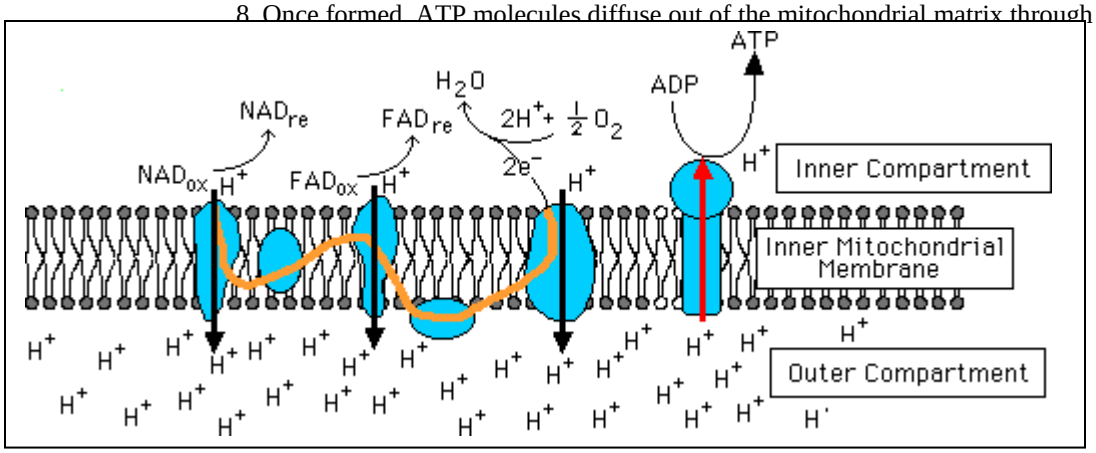


F. The Cristae of a Mitochondrion

1. Electron transport system consists of three protein complexes and two protein mobile carriers that transport electrons between complexes.
3. Energy released from flow of electrons down electron transport chain is used to pump H+ ions, carried by NADH and FADH2, into intermembrane space.
4. Accumulation of H+ ions in this intermembrane space creates a significant electrochemical gradient.
5. **ATP synthase complexes** are channel proteins that also serve as enzymes for ATP synthesis.
6. As H+ ions flow from high to low concentration, ATP synthase synthesizes ATP; actual mechanism is still unknown.
7. "**Chemiosmosis**" term used since ATP production tied to electrochemical (H+) gradient across a membrane.
8. Once formed, ATP molecules diffuse out of the mitochondrial matrix through channel proteins.



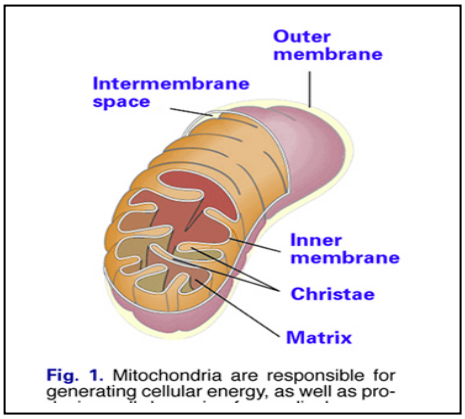
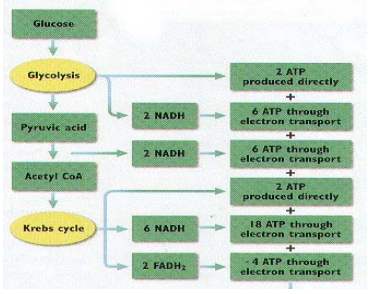


Fig. 1. Mitochondria are responsible for generating cellular energy, as well as pro-

G. Energy Yield From Glucose Breakdown

1. Substrate-Level Phosphorylation
   a. Per glucose molecule, there is a net gain of two ATP from glycolysis in cytosol.
   b. The Krebs cycle in the matrix of the mitochondria produces two ATP per glucose.
   c. Total of four ATP are formed outside of the electron transport system.
2. Oxidative Phosphorylation
   a. Most ATP is produced by the electron transport system.
   b. Per glucose, 10 NADH and two FADH2 molecules provide electrons and H+ ions to electron transport system.
   c. For each NADH formed within the mitochondrion, three ATP are produced.
   d. For each FADH2 formed by Krebs cycle, two ATP result since FADH2 delivers electrons after NADH.
   e. For each NADH formed outside mitochondria by glycolysis, two ATP are produced as electrons are shuttled across mitochondrial membrane by an organic molecule and delivered to FAD.
   f. Heart and liver cells, which have high metabolic rates are exception; NADH results in production of three ATP.
   g. Prokaryotes lack mitochondria; each NADH produces three ATP for total of 38 ATP.
3. Efficiency of Complete Glucose Breakdown
   a. Energy difference between total reactants (glucose and O2) and products (CO2 and H2O) is 686 kcal.
   b. ATP phosphate bond has energy of 7.3 kcal; 36 to 38 are produced during glucose breakdown for total of at least 263 kcal.
   c. Efficiency is 263/686 or 39% of available energy in glucose is transferred to ATP.



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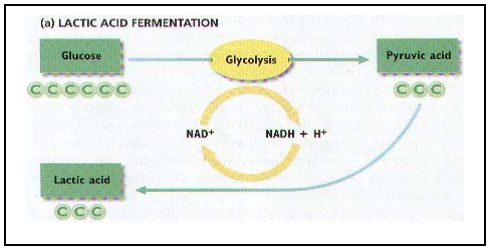
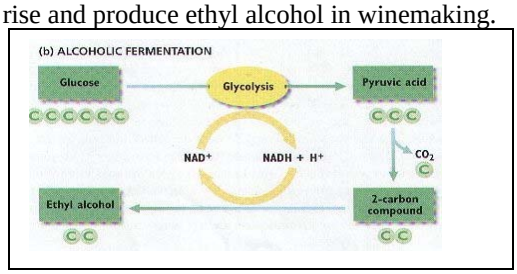
8.4 Fermentation

A. Cellular Respiration Includes Fermentation

1. **Fermentation** consists of glycolysis plus reduction of pyruvate to either lactate or alcohol and CO2.
2. NADH passes its electrons to pyruvate instead of to an electron transport system; NAD+ is then free to return and pick up more electrons during earlier reactions of glycolysis.
3. Examples:
   a. Anaerobic bacteria produce lactic acid when we manufacture some cheeses.
   b. Anaerobic bacteria produce industrial chemicals: isopropanol, butyric acid, propionic acid, and acetic acid.



   c. Yeasts use CO2 to make bread rise and produce ethyl alcohol in winemaking.



   d. Animals reduce pyruvate to lactate when it is produced faster than it can be oxidized by Krebs cycle.

B. Advantage and Disadvantage of Fermentation

1. Despite low yield of two ATP molecules, fermentation provides quick burst of ATP energy for muscular activity.
2. Disadvantage is that lactate is toxic to cells.
   a. When blood cannot remove all lactate from muscles, lactate change pH and causes muscles to fatigue.
   b. Individual is in oxygen debt because oxygen is still needed after exercising.
   c. Recovery occurs after lactate is sent to liver, converted into pyruvate; then respired or converted into glucose.

C. Efficiency of Fermentation

1. Two ATP produced per glucose molecule during fermentation is equivalent to 14.6 kcal.
2. Complete glucose breakdown to CO2 and H2O during cellular respiration results in 686 kcal of energy.
3. Efficiency of fermentation is 14.6/686 or about 2.1%; much less efficient than complete breakdown of glucose.

8.5 Metabolic Pool

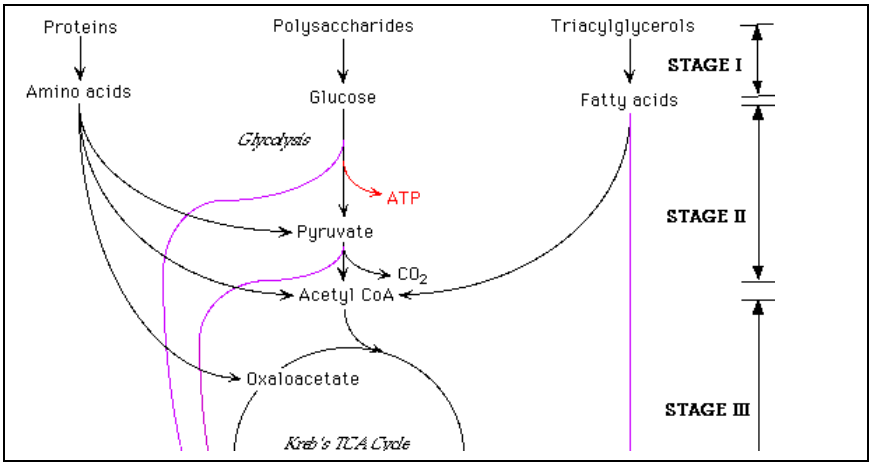
A. Degradative and Synthetic Reactions

1. Degradative reactions participate in catabolism and break down molecules; they tend to be exergonic.
2. Synthetic reactions participate in anabolism and build molecules; they tend to be endergonic.

B. Catabolism

1. Just as glucose was broken down in cellular respiration, other molecules undergo catabolism.
2. Fat breaks down into glycerol and three fatty acids.
   a. Glycerol is converted to **PGAL**, a metabolite in glycolysis.
   b. An 18-carbon fatty acid is converted to nine acetyl-CoA molecules that enter the Krebs cycle.
   c. Respiration of fat products can produce 216 ATP molecules; fats are efficient form of stored energy.
3. Amino acids break down into carbon chains and amino groups.
   a. Hydrolysis of proteins results in amino acids.
   b. ***R***-group size determines whether carbon chain is oxidized in glycolysis or the Krebs cycle.
   c. Carbon chain is produced in liver by removal of the amino group.

d. Amino group becomes ammonia (NH3), which enters urea cycle and becomes part of excreted urea.
e. Length of ***R***-group determines number of carbons left after deamination.



C. <u>Anabolism</u>

1. ATP produced during catabolism drives anabolism.
2. Substrates making up pathways can be used as starting materials for synthetic reactions.
3. Molecules used for biosynthesis constitute **<u>metabolic pool</u>**.
4. Carbohydrates can result in fat synthesis: PGAL converts to glycerol, acetyl groups join to form fatty acids.
5. Some metabolites can be converted to amino acids by transamination, transfer of an amino acid group to an organic acid.
6. Plants synthesize all amino acids they need; animal lack some enzymes needed to make some amino acids.
7. Humans synthesize 11 of 20 amino acids; remaining 9 **<u>essential amino acids</u>** must be provided by diet.