Cellular Respiration: Harvesting Chemical Energy

Chapter 9

- Objectives
  - Define oxidation and reduction, and, in general terms, explain how redox reactions are involved in energy exchanges.
  - Name the three stages of cellular respiration and state the region of the eukaryotic cell where each stage occurs.
  - In general terms, explain the role of the electron transport chain in cellular respiration.
  - Explain where and how the respiratory electron transport chain creates a proton gradient.
  - Distinguish between fermentation and anaerobic respiration

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Introduction

- Harvesting chemical energy forms part of a cycle involving mitochondria and chloroplasts

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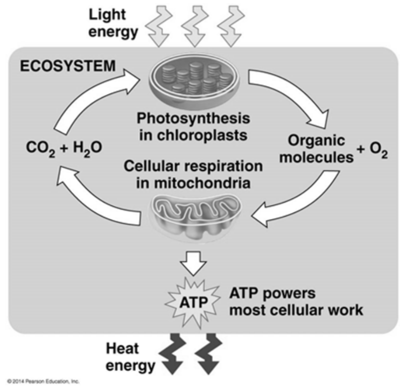

Catabolic Pathways and Production of ATP

- Slow burning of food generates ATP
  - the breakdown of organic molecules is exergonic
- In the absence of O_2 food molecules are "fermented"
  - sugars are partially degraded

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- Cellular respiration is the most prevalent and efficient catabolic pathway
  - consumes oxygen and organic molecules such as glucose and yields ATP

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- To keep working cells must regenerate ATP
  - cell respiration stores energy in ATP molecules
    - overall equation:
      - $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy
    - efficiency ~40% compared with car ~25%
- Energy is used for body maintenance and voluntary activity
  - average human needs ~2200kcal/day

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Redox Reactions: Oxidation and Reduction

- Catabolic pathways yield energy due to the transfer of electrons
- Paired endergonic-exergonic reactions are known as redox (reduction-oxidation) reactions
  - redox reactions transfer electrons from one reactant to another by oxidation and reduction
    - in oxidation a substance loses electrons, or is oxidized
    - in reduction a substance gains electrons, or is reduced

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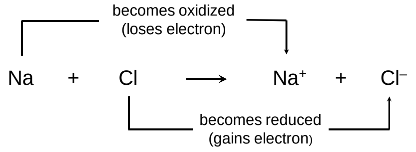
- Example of a redox reaction



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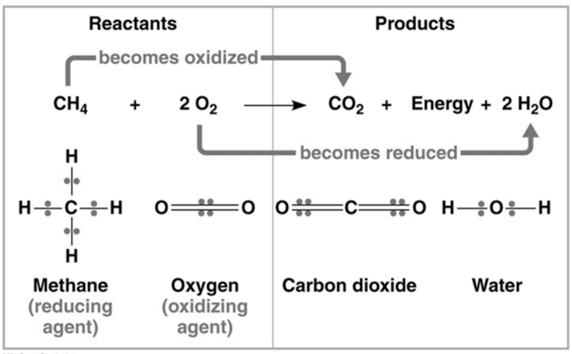
- Some redox reactions do not completely exchange electrons
  - they change the degree of electron sharing in covalent bonds



Oxidation of Organic Molecules During Cellular Respiration

- In cellular respiration energy is obtained by transferring electrons from organic molecules to oxygen
  - during cellular respiration glucose is oxidized and oxygen is reduced

becomes oxidized

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

becomes reduced

- Movement of H^+ represents electron movement
  - involves a series of steps coupling endergonic and exergonic reactions
    - each step involves electrons moving from a higher energy bond to a lower energy bond
  - oxygen atoms are the final electron acceptors
    - bind with hydrogen to form water

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Stepwise Energy Harvest via NAD^+ and the Electron Transport Chain

- Cellular respiration oxidizes glucose in a series of steps
- Electrons from organic compounds are usually first transferred to NAD^+, a coenzyme
  - hydrogen carriers (like NAD^+) shuttle electrons

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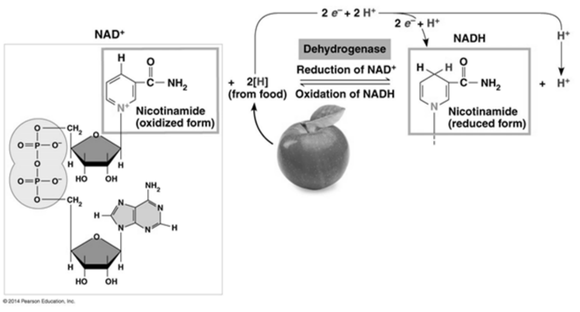

- NADH, the reduced form of NAD^+ passes the electrons to the electron transport chain
  - energy is released when electrons “fall” from hydrogen carrier to oxygen
- If electron transfer is not stepwise a large release of energy occurs
  - this energy is released in the reaction of hydrogen and oxygen to form water

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- The electron transport chain passes electrons in a series of steps instead of in one explosive reaction
  - NADH releases energetic electrons, regenerating NAD^+
  - the electrons enter the electron transport chain

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- A series of redox reactions passes electrons from one molecule to next
  - the ultimate electron acceptor is oxygen
- The energy from the electron transfer is used to form ATP

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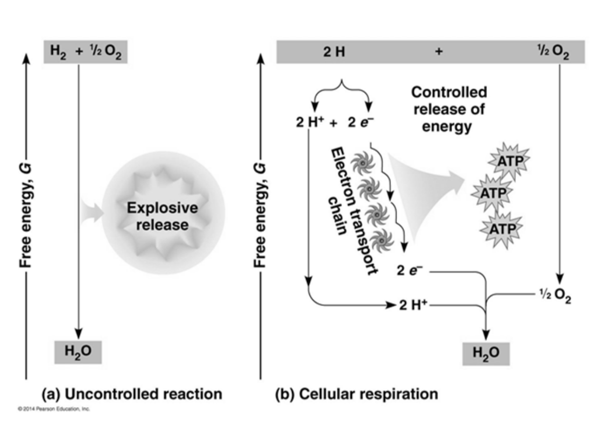

The Stages of Cellular Respiration: A Preview

- Respiration is a cumulative function of three metabolic stages
  - Glycolysis-in the cytoplasm
    - breaks down glucose into two molecules of pyruvate
  - Citirc acid cycle-in the mitochondrial matrix
    - completes the breakdown of glucose
  - Oxidative phosphorylation-in the inner mitochondrial membrane
    - driven by the electron transport chain
    - generates ATP

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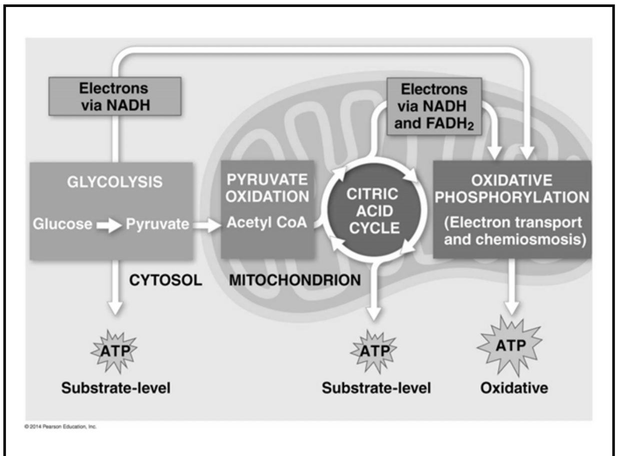
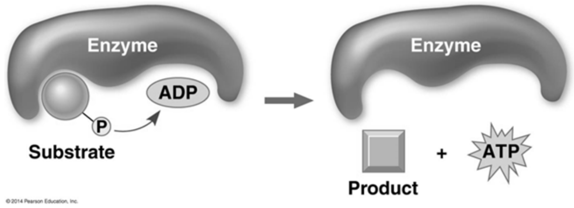


- Both glycolysis and the citric acid cycle can generate ATP by substrate-level phosphorylation
  - does not involve either electron transport chain or ATP synthase
  - ADP phosphorylated by an enzyme using a PO_4^- group from phosphorylated substrate



Glycolysis

- Harvests energy by oxidizing glucose to pyruvic acid in cytoplasm
  - glycolysis means "splitting of sugar"
    - breaks down glucose into pyruvate
    - occurs in the cytoplasm of the cell
  - nine steps involved
    - there is a separate enzyme for each step
    - also requires ADP, phosphate and NAD^+
    - ATP required to form initial intermediates

- Broken into two phases:
  - steps 1-4 are preparatory and require ATP input
    - energy investment phase
  - steps 5-9 are energy-releasing and make ATP and NADH
    - energy payoff phase
- net energy gain is 2 ATP and 2 NADH for each glucose

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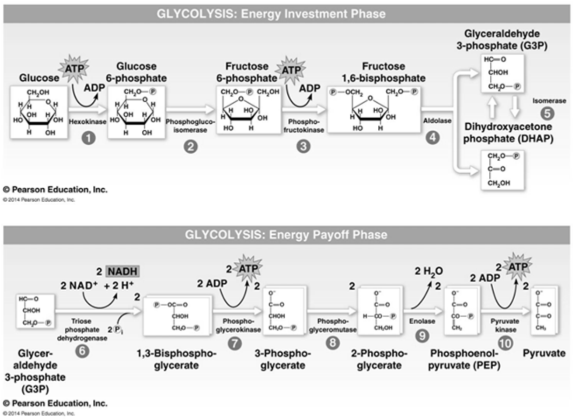

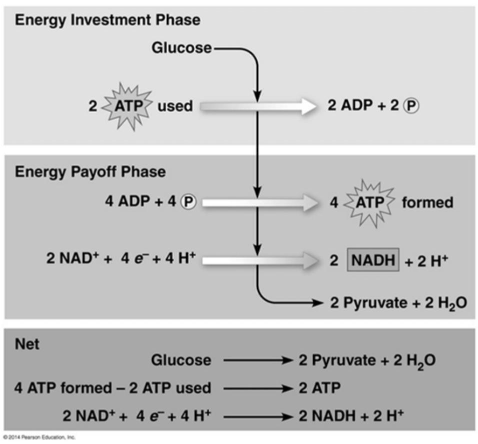

The Citric Acid Cycle

- The citric acid cycle takes place in the matrix of the mitochondrion
- Pyruvic acid is chemically processed before entering the citric acid cycle
  - occurs in mitochondrial matrix

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- The pyruvate is oxidized
  - reduces NAD^+ to NADH
- The pyruvate is stripped of a carboxyl group
  - releases CO_2
- The resulting acetyl is complexed with coenzyme A (CoA) forming acetyl CoA
- The net energy gain is 2 NADH for each glucose
  - one per pyruvate

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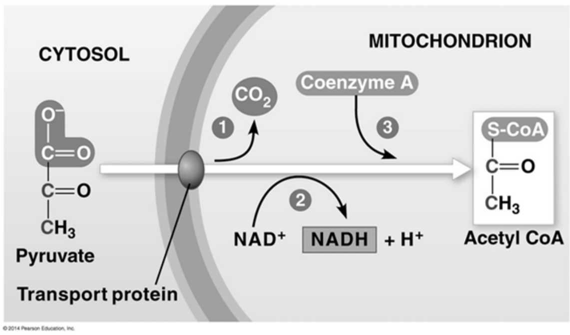

- The citric acid cycle completes oxidation of organic molecules, releasing many NADH and FADH
  - occurs in mitochondrial matrix
- The cycle involves eight steps which result in the conversion of acetyl CoA to 2 CO_2
  - requires ADP, phosphate, NAD^+, FAD, and oxaloacetate

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- The eighth step regenerates oxaloacetate
  - CoA released during first step
- The net energy gain is 2 ATP, 6 NADH and 2 $FADH_2$ for each glucose

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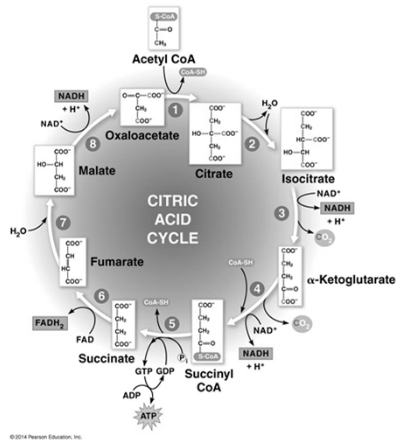

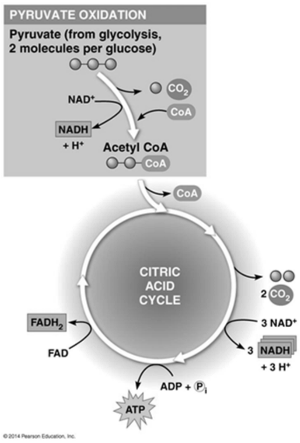

Oxidative Phosphorylation

- Oxidative phosphorylation is responsible for most ATP production
  - electron transport chain is a series of protein complexes in the inner mitochondrial membrane (cristae)
  - The complexes oscillate between reduced and oxidized states
  - H^+ are transported from inside the matrix to intermembrane space as redox occurs

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The Pathway of Electron Transport

- NADH and $FADH_2$ donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation
  - in the electron transport chain electrons from NADH and $FADH_2$ lose energy in several steps
  - At the end of the chain electrons are passed to oxygen, forming water

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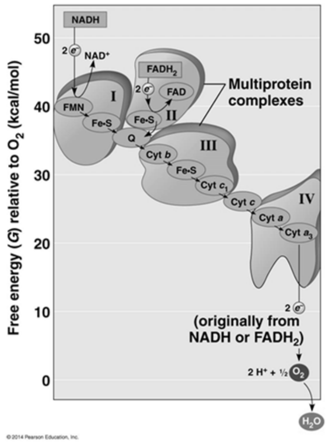

Chemiosmosis: The Energy-Coupling Mechanism

- ATP synthase is the enzyme that actually makes ATP
  - H^+ gradient drives ATP synthesis in matrix as H^+ are transported through ATP synthase
- At certain steps along the electron transport chain electron transfer causes protein complexes to pump H^+ from the mitochondrial matrix to the intermembrane space

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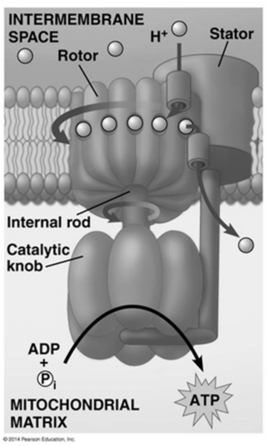

- The resulting H^+ gradient stores energy
  - this gradient drives chemiosmosis in ATP synthase and is referred to as a proton-motive force
- Chemiosmosis is an energy-coupling mechanism that uses energy in the form of a H^+ gradient across a membrane to drive cellular work
- Net energy gain is 32 ATP for each glucose

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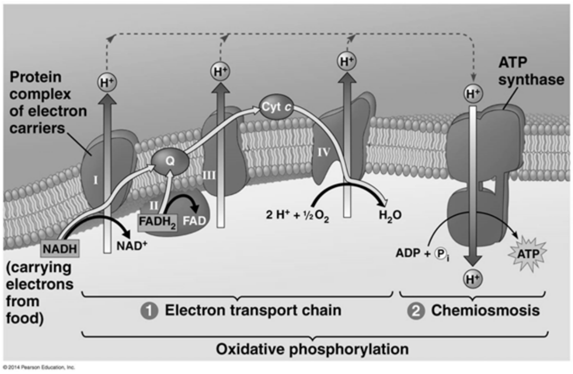

- Some poisons function by interrupting critical events in respiration
  - rotenone, cyanide and carbon monoxide block various parts of electron transport chain
  - oligomycin blocks passage of H^+ through ATP synthase
  - uncouplers, like dinitrophenol, cause cristae to leak H^+
    - cannot maintain H^+ gradient

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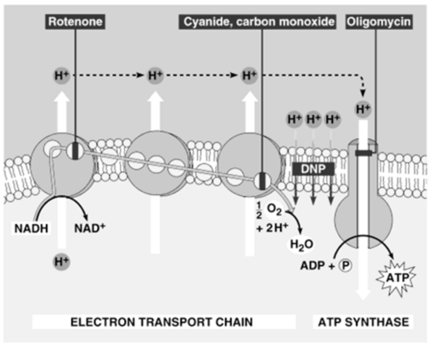
Figure 6.13 Poisons interrupt cellular respiration



An Accounting of ATP Production by Cellular Respiration

- Each glucose molecule yields up to 32 ATP
  - glycolysis in cytoplasm yields some ATP in absence of O_2, but mostly prepares for mitochondrial steps that require O_2
  - the citric acid cycle in mitochondrial matrix produces some ATP, but mostly strips out CO_2 and produces energy shuttles
  - oxidative phosphorylation produces many ATP but only if O_2 present

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  - 3 ATP produced for each NADH and 2 ATP produced for each $FADH_2$
- About 40% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making approximately 32 ATP

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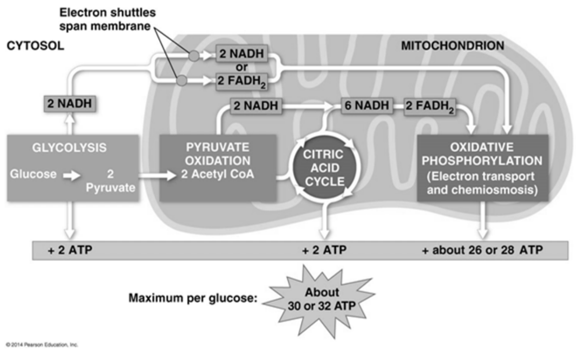

Fermentation

- Cellular respiration relies on oxygen to produce ATP
  - in the absence of oxygen cells can still produce ATP through fermentation
- Fermentation recharges NAD^+ pool so glycolysis can continue in absence of oxygen
- Glycolysis can produce ATP with or without oxygen, in aerobic or anaerobic conditions
  - couples with fermentation to produce ATP

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- Fermentation consists of glycolysis plus reactions that regenerate NAD^+, which can be reused by glyocolysis
  - in alcoholic fermentation in yeast and bacteria results in ethanol; product is toxic
  - in lactic acid fermentation in many animals and bacteria results in lactic acid; causes muscle fatigue

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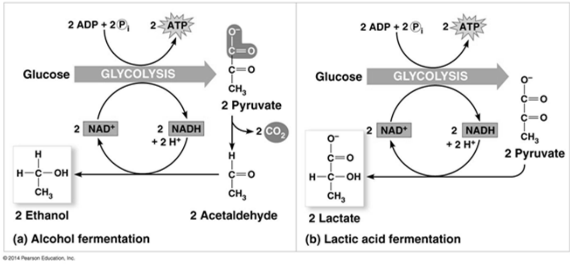

(a) Alcohol fermentation (b) Lactic acid fermentation

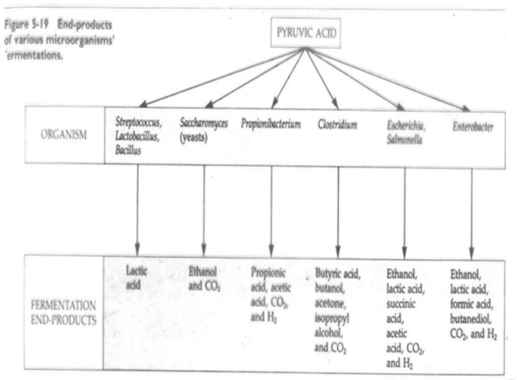

Figure 5-19 End-products of various microorganisms' 'ermentations.

Fermentation and Cellular Respiration Compared

- Both fermentation and cellular respiration use glycolysis to oxidize glucose and other organic fuels to pyruvate
- Fermentation and cellular respiration differ in their final electron acceptor
- Cellular respiration produces more ATP

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- Pyruvate represents decision point in respiratory pathway for organisms capable of carrying out either aerobic respiration or fermentation
  - strict anaerobes live in environments that lack oxygen
    - only glycolysis and fermentation
  - facultative anaerobes, e.g. yeast and certain bacteria, live in environments that either lack or contain oxygen
    - either aerobic or anaerobic respiration

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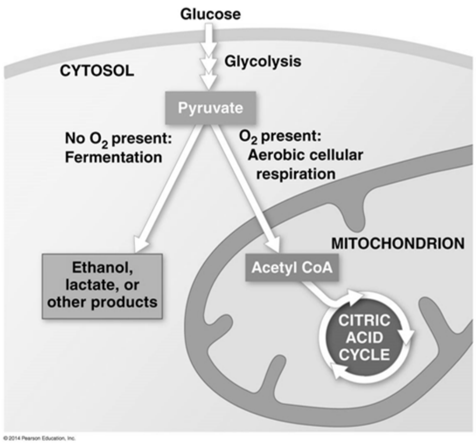

The Evolutionary Significance of Glycolysis

- Glycolysis occurs in nearly all organisms
  - it probably evolved in ancient prokaryotes before there was oxygen in the atmosphere

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The Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
  - free glucose is not common in animal diets

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- Each basic food type can be a molecular energy source
  - carbohydrates are hydrolyzed to glucose
    - this enters glycolysis
  - proteins are hydrolyzed to amino acids
    - amino group are stripped and eliminated in urine
    - carbon backbone enters glycolysis or the citric acid cycle

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- lipids are hydrolyzed to glycerol and fatty acids
  - glycerol enters glycolysis
  - fatty acids are converted to acetyl CoA which enters the citric acid cycle

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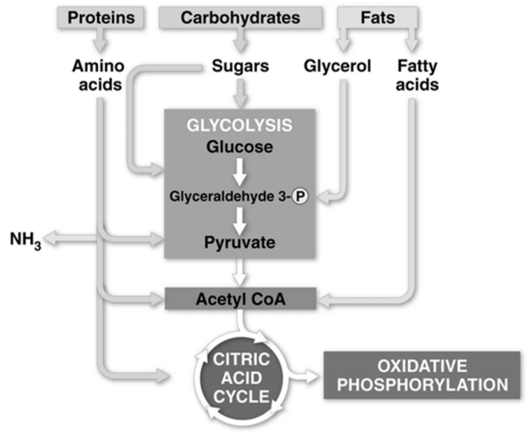

Raw Materials for Biosynthesis

- Cells obtain raw materials directly from digestion of macromolecules
- The body uses small molecules to build other substances
  - these small molecules may come directly from food or through glycolysis or the citric acid cycle

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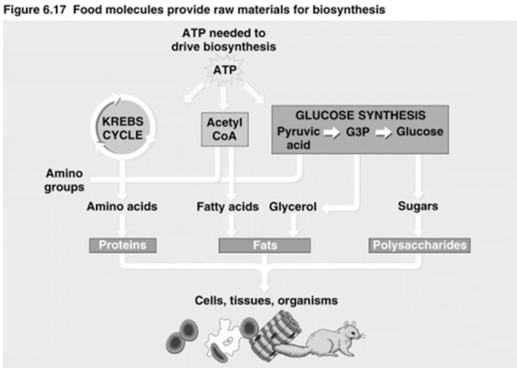
Figure 6.17 Food molecules provide raw materials for biosynthesis



Regulation of Cellular Respiration via Feedback Mechanisms

- Cellular respiration is controlled by allosteric enzymes at key points in glycolysis and the citric acid cycle
  - key regulatory point occurs at step three of glycolysis
- Conversion of fructose-6-phosphate to fructose-1,6-bisphosphate by phosphofructokinase is the first irreversible step in glycolysis

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- Regulation of this reaction allows cell to speed up and slow down cellular respiration according to the energy requirements of the cell
  - the enzyme is inhibited by both ATP and citrate
    - sensitivity to ATP regulates the overall process
    - sensitivity to citrate coordinates glycolysis and the citric acid cycle
  - the enzyme is stimulated by AMP
    - AMP is a breakdown product of ATP

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