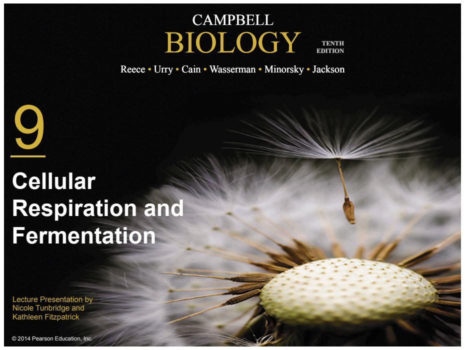

CAMPBELL
BIOLOGY
TENTH EDITION

Reece • Urry • Cain • Wasserman • Minorsky • Jackson

9
Cellular Respiration and Fermentation

Lecture Presentation by
Nicole Tunbridge and
Kathleen Fitzpatrick

Life Is Work

- Living cells require energy from outside sources
- Some animals, such as the giraffe, obtain energy by eating plants, and some animals feed on other organisms that eat plants

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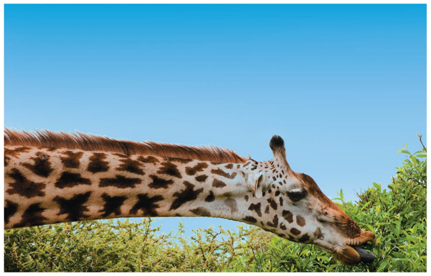
Figure 9.1



- Energy flows into an ecosystem as sunlight and leaves as heat
- Photosynthesis generates O_2 and organic molecules, which are used in cellular respiration
- Cells use chemical energy stored in organic molecules to generate ATP, which powers work

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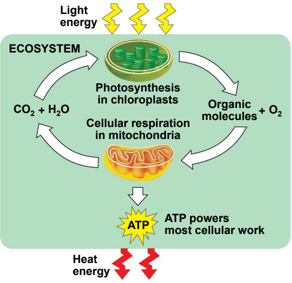
Figure 9.2



BioFlix: The Carbon Cycle

Concept 9.1: Catabolic pathways yield energy by oxidizing organic fuels

- Catabolic pathways release stored energy by breaking down complex molecules
- Electron transfer plays a major role in these pathways
- These processes are central to cellular respiration

Catabolic Pathways and Production of ATP

- The breakdown of organic molecules is exergonic
- **Fermentation** is a partial degradation of sugars that occurs without O_2
- **Aerobic respiration** consumes organic molecules and O_2 and yields ATP
- Anaerobic respiration is similar to aerobic respiration but consumes compounds other than O_2

- **Cellular respiration** includes both aerobic and anaerobic respiration but is often used to refer to aerobic respiration
- Although carbohydrates, fats, and proteins are all consumed as fuel, it is helpful to trace cellular respiration with the sugar glucose

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$ + Energy (ATP + heat)

Redox Reactions: Oxidation and Reduction

- The transfer of electrons during chemical reactions releases energy stored in organic molecules
- This released energy is ultimately used to synthesize ATP

The Principle of Redox

- Chemical reactions that transfer electrons between reactants are called oxidation-reduction reactions, or **redox reactions**
- In **oxidation**, a substance loses electrons, or is oxidized
- In **reduction**, a substance gains electrons, or is reduced (the amount of positive charge is reduced)

Figure 9.UN01

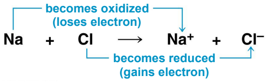
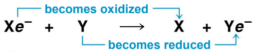
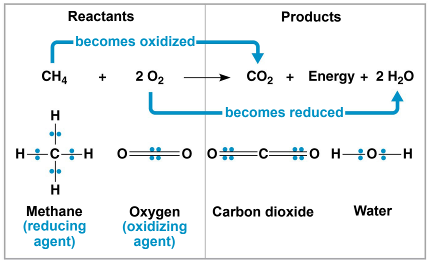


Figure 9.UN02



- The electron donor is called the **reducing agent**
- The electron receptor is called the **oxidizing agent**
- Some redox reactions do not transfer electrons but change the electron sharing in covalent bonds
- An example is the reaction between methane and O_2

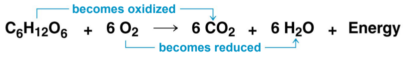
Figure 9.3



Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, the fuel (such as glucose) is oxidized, and O_2 is reduced

Figure 9.UN03



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

Stepwise Energy Harvest via NAD⁺ and the Electron Transport Chain

- In cellular respiration, glucose and other organic molecules are broken down in a series of steps
- Electrons from organic compounds are usually first transferred to **NAD^+**, a coenzyme
- As an electron acceptor, NAD^+ functions as an oxidizing agent during cellular respiration
- Each NADH (the reduced form of NAD^+) represents stored energy that is tapped to synthesize ATP

Figure 9.4

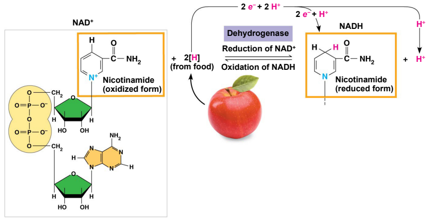


Figure 9.4a

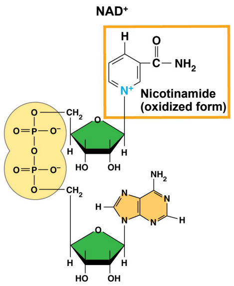
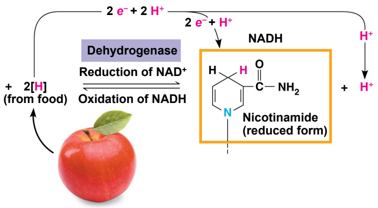


Figure 9.4b



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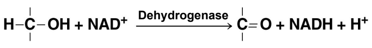
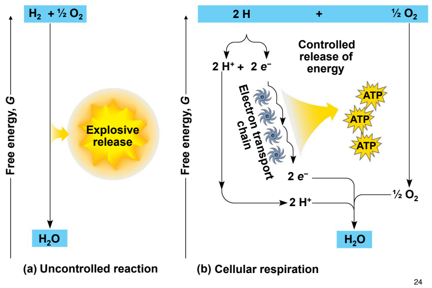


$$H{-}\overset{|}{\underset{|}{C}}{-}OH + NAD^+ \xrightarrow{\text{Dehydrogenase}} \overset{\diagdown}{\underset{\diagup}{C}}{=}O + NADH + H^+$$

- NADH passes the electrons to the **electron transport chain**
- Unlike an uncontrolled reaction, the electron transport chain passes electrons in a series of steps instead of one explosive reaction
- O_2 pulls electrons down the chain in an energy-yielding tumble
- The energy yielded is used to regenerate ATP

Figure 9.5



(a) Uncontrolled reaction

(b) Cellular respiration

The Stages of Cellular Respiration: *A Preview*

- Harvesting of energy from glucose has three stages
  - **Glycolysis** (breaks down glucose into two molecules of pyruvate)
  - The **citric acid cycle** (completes the breakdown of glucose)
  - **Oxidative phosphorylation** (accounts for most of the ATP synthesis)

Figure 9.UN05

1. GLYCOLYSIS (color-coded blue throughout the chapter)
2. PYRUVATE OXIDATION and the CITRIC ACID CYCLE (color-coded orange)
3. OXIDATIVE PHOSPHORYLATION: Electron transport and chemiosmosis (color-coded purple)

Figure 9.6-1

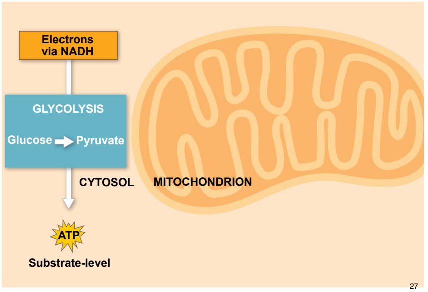


Figure 9.6-2

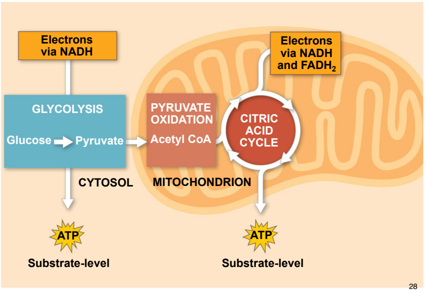
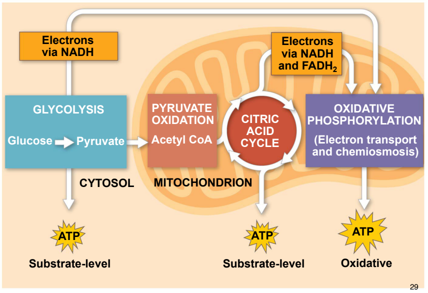
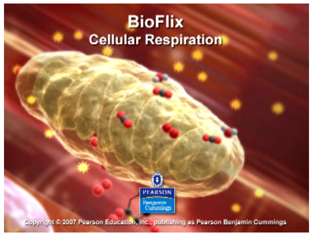


Figure 9.6-3



BioFlix: Cellular Respiration



- The process that generates most of the ATP is called oxidative phosphorylation because it is powered by redox reactions

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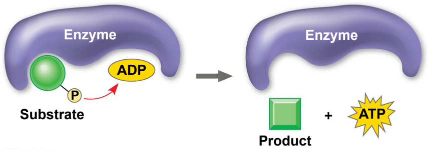
- Oxidative phosphorylation accounts for almost 90% of the ATP generated by cellular respiration
- A smaller amount of ATP is formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation**
- For each molecule of glucose degraded to CO_2 and water by respiration, the cell makes up to 32 molecules of ATP

Figure 9.7



Concept 9.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- Glycolysis (“sugar splitting”) breaks down glucose into two molecules of pyruvate
- Glycolysis occurs in the cytoplasm and has two major phases
  - Energy investment phase
  - Energy payoff phase
- Glycolysis occurs whether or not O_2 is present

Figure 9.UN06

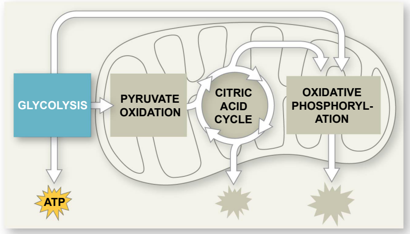
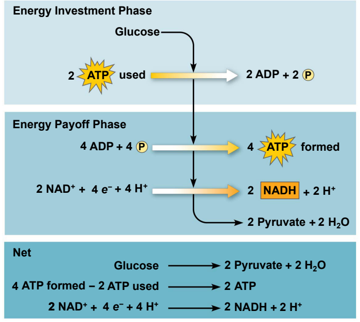


Figure 9.8



Energy Investment Phase

Glucose

2 ATP used → 2 ADP + 2 P

Energy Payoff Phase

4 ADP + 4 P → 4 ATP formed

2 NAD$^+$ + 4 e$^-$ + 4 H$^+$ → 2 NADH + 2 H$^+$

→ 2 Pyruvate + 2 H_2O

Net

Glucose → 2 Pyruvate + 2 H_2O

4 ATP formed − 2 ATP used → 2 ATP

2 NAD$^+$ + 4 e$^-$ + 4 H$^+$ → 2 NADH + 2 H$^+$

Figure 9.9a

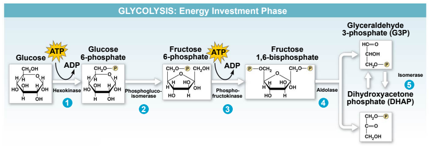
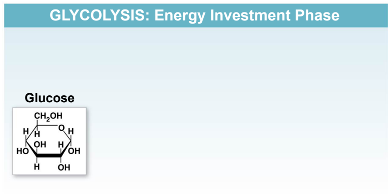


Figure 9.9aa-1



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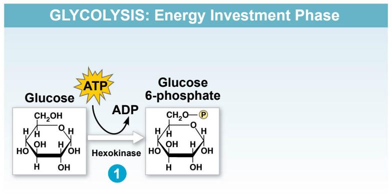

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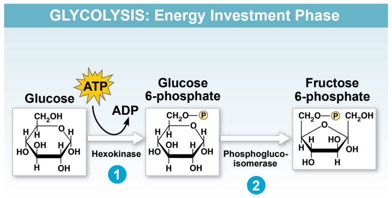

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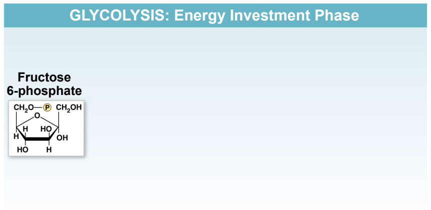

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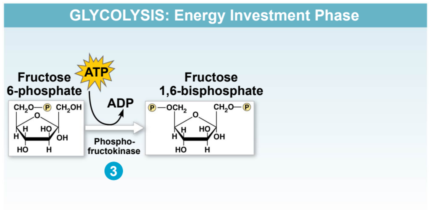

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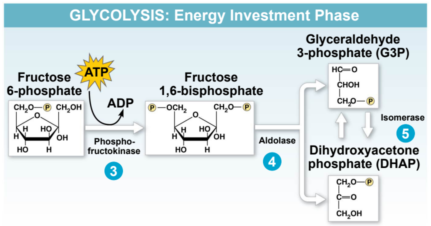

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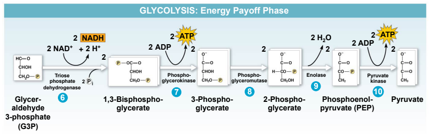

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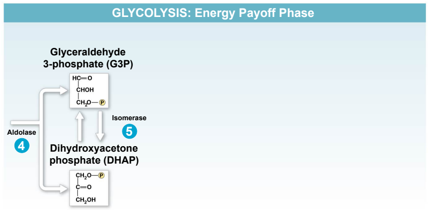
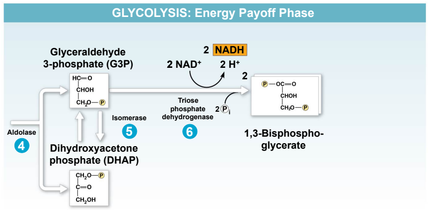


Figure 9.9ba-2



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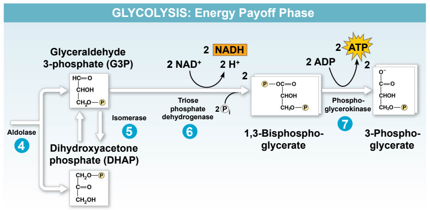
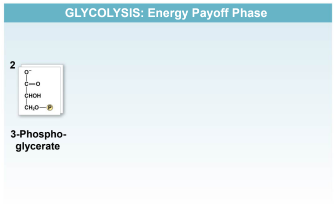


Figure 9.9bb-1



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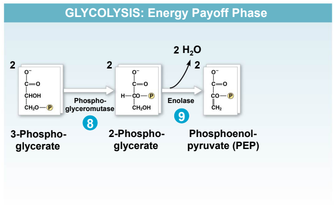
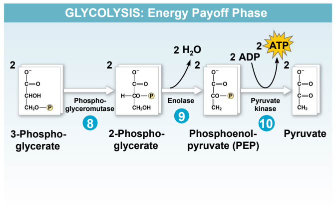


Figure 9.9bb-3



Concept 9.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

- In the presence of O_2, pyruvate enters the mitochondrion (in eukaryotic cells) where the oxidation of glucose is completed

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Oxidation of Pyruvate to Acetyl CoA

- Before the citric acid cycle can begin, pyruvate must be converted to acetyl Coenzyme A (**acetyl CoA**), which links glycolysis to the citric acid cycle
- This step is carried out by a multienzyme complex that catalyses three reactions

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Figure 9.UN07

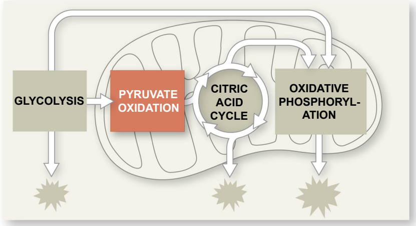
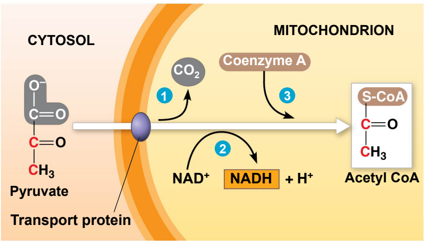


Figure 9.10



The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, completes the break down of pyruvate to CO_2
- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn

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Figure 9.11

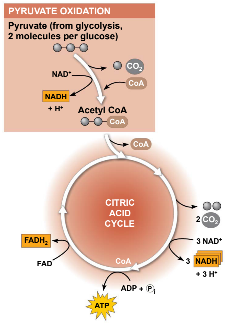


Figure 9.11a

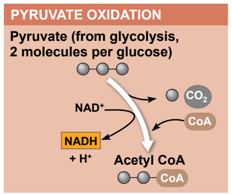
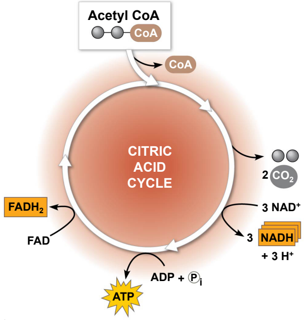


Figure 9.11b



- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- The acetyl group of acetyl CoA joins the cycle by combining with oxaloacetate, forming citrate
- The next seven steps decompose the citrate back to oxaloacetate, making the process a cycle
- The NADH and $FADH_2$ produced by the cycle relay electrons extracted from food to the electron transport chain

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Figure 9.UN08

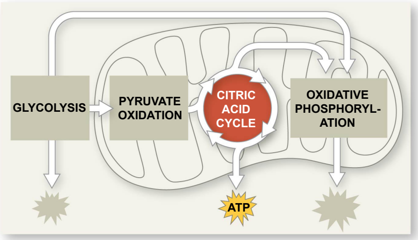
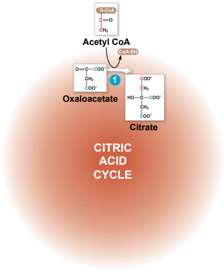


Figure 9.12-1



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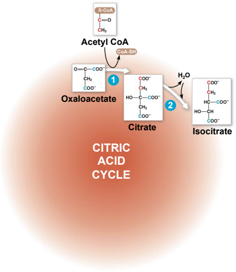

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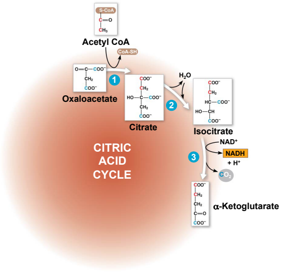

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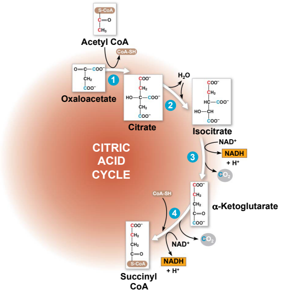

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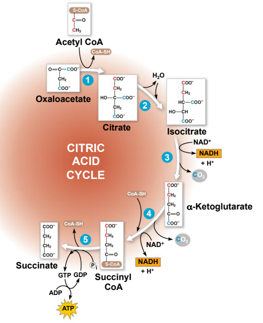

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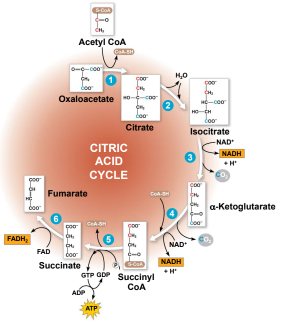

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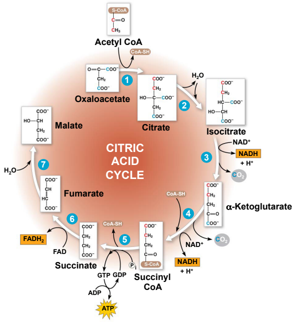

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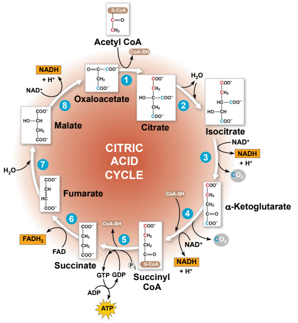


Figure 9.12a

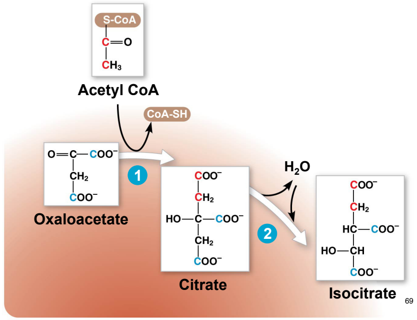
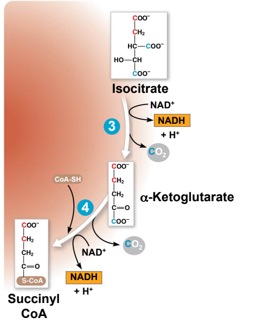


Figure 9.12b



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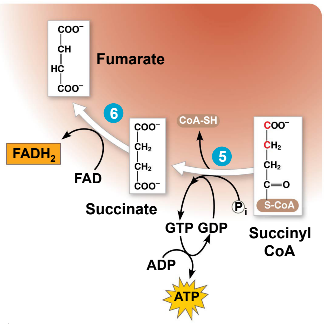

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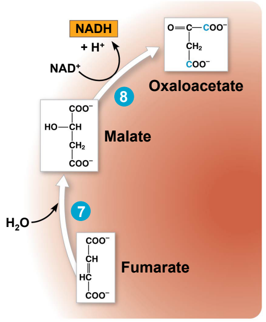


Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- Following glycolysis and the citric acid cycle, NADH and $FADH_2$ account for most of the energy extracted from food
- These two electron carriers donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation

---

The Pathway of Electron Transport

- The electron transport chain is in the inner membrane (cristae) of the mitochondrion
- Most of the chain's components are proteins, which exist in multiprotein complexes
- The carriers alternate reduced and oxidized states as they accept and donate electrons
- Electrons drop in free energy as they go down the chain and are finally passed to O_2, forming H_2O

Figure 9.UN09

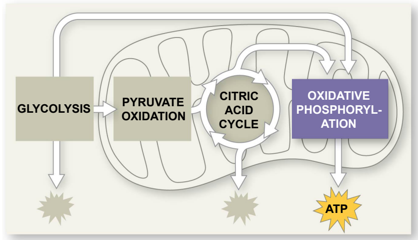


Figure 9.13

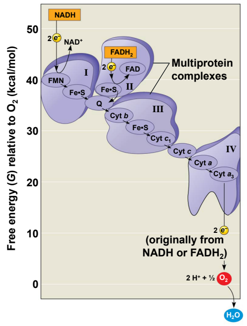


Figure 9.13a

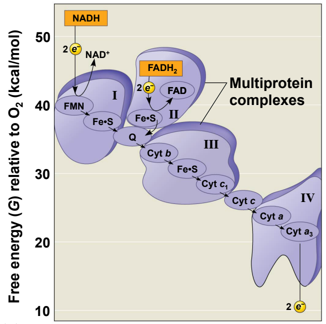
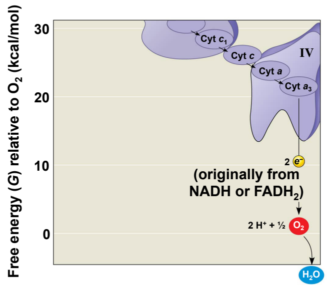


Figure 9.13b



- Electrons are transferred from NADH or $FADH_2$ to the electron transport chain
- Electrons are passed through a number of proteins including **cytochromes** (each with an iron atom) to O_2
- The electron transport chain generates no ATP directly
- It breaks the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts

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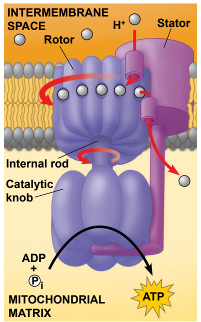
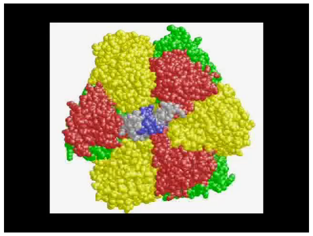
Chemiosmosis: The Energy-Coupling Mechanism

- Electron transfer in the electron transport chain causes proteins to pump H^+ from the mitochondrial matrix to the intermembrane space
- H+ then moves back across the membrane, passing through the protein complex, **ATP synthase**
- ATP synthase uses the exergonic flow of H^+ to drive phosphorylation of ATP
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive cellular work

Figure 9.14



Video: ATP Synthase 3-D Structure, Top View



Video: ATP Synthase 3-D Structure, Side View

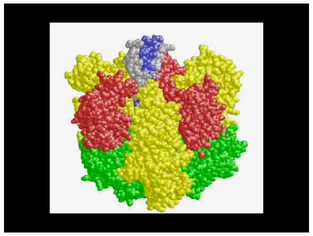


Figure 9.15

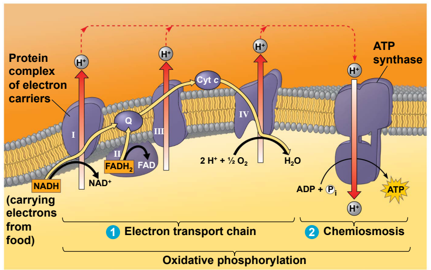


Figure 9.15a

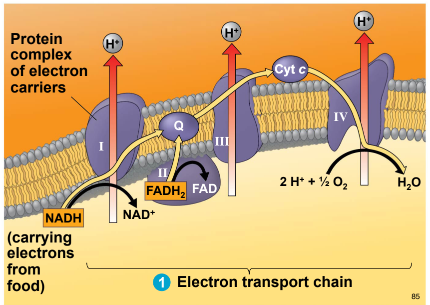
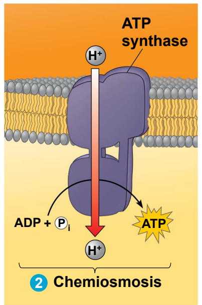


Figure 9.15b



- The energy stored in a H^+ gradient across a membrane couples the redox reactions of the electron transport chain to ATP synthesis
- The H+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

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An Accounting of ATP Production by Cellular Respiration

- During cellular respiration, most energy flows in this sequence:

  glucose → NADH → electron transport chain → proton-motive force → ATP
- About 34% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making about 32 ATP
- There are several reasons why the number of ATP is not known exactly

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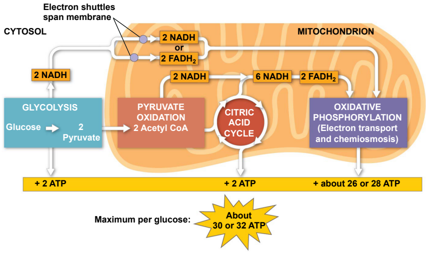
Figure 9.16



Electron shuttles span membrane

CYTOSOL

MITOCHONDRION

2 NADH or 2 $FADH_2$

2 NADH

2 NADH

6 NADH

2 $FADH_2$

GLYCOLYSIS

Glucose → 2 Pyruvate

PYRUVATE OXIDATION

2 Acetyl CoA

CITRIC ACID CYCLE

OXIDATIVE PHOSPHORYLATION (Electron transport and chemiosmosis)

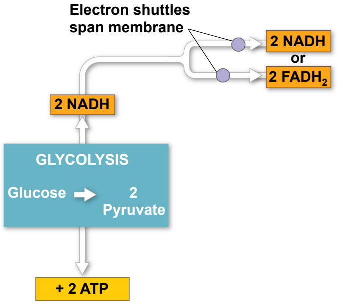
+ 2 ATP

+ 2 ATP

+ about 26 or 28 ATP

Maximum per glucose: About 30 or 32 ATP

Figure 9.16a



Electron shuttles span membrane

2 NADH or 2 $FADH_2$

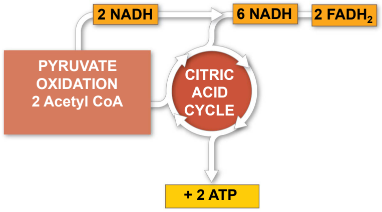
2 NADH

GLYCOLYSIS

Glucose → 2 Pyruvate

+ 2 ATP

Figure 9.16b



2 NADH

6 NADH

2 $FADH_2$

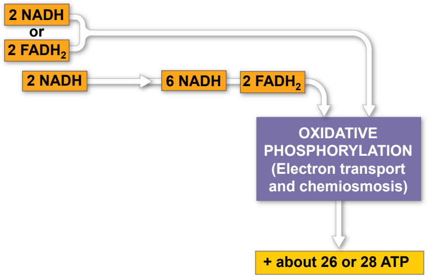
PYRUVATE OXIDATION

2 Acetyl CoA

CITRIC ACID CYCLE

+ 2 ATP

Figure 9.16c



2 NADH or 2 $FADH_2$

2 NADH

6 NADH

2 $FADH_2$

OXIDATIVE PHOSPHORYLATION (Electron transport and chemiosmosis)

+ about 26 or 28 ATP

Figure 9.16d

Maximum per glucose: About 30 or 32 ATP

Concept 9.5: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- Most cellular respiration requires O_2 to produce ATP
- Without O_2, the electron transport chain will cease to operate
- In that case, glycolysis couples with anaerobic respiration or fermentation to produce ATP

- Anaerobic respiration uses an electron transport chain with a final electron acceptor other than O_2, for example sulfate
- Fermentation uses substrate-level phosphorylation instead of an electron transport chain to generate ATP

Types of Fermentation

- Fermentation consists of glycolysis plus reactions that regenerate NAD^+, which can be reused by glycolysis
- Two common types are alcohol fermentation and lactic acid fermentation

- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps
  - The first step releases CO_2
  - The second step produces ethanol
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking

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Figure 9.17

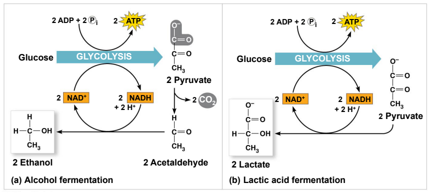
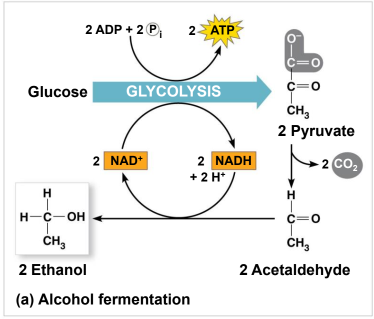
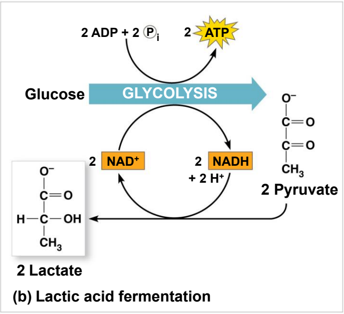


Figure 9.17a



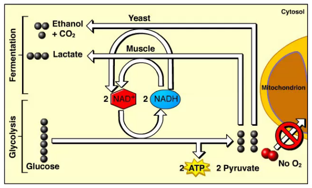
(a) Alcohol fermentation

Figure 9.17b



(b) Lactic acid fermentation

Animation: Fermentation Overview



- In **lactic acid fermentation**, pyruvate is reduced by NADH, forming lactate as an end product, with no release of CO_2
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
- Human muscle cells use lactic acid fermentation to generate ATP when O_2 is scarce

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Comparing Fermentation with Anaerobic and Aerobic Respiration

- All use glycolysis (net ATP = 2) to oxidize glucose and harvest chemical energy of food
- In all three, NAD^+ is the oxidizing agent that accepts electrons during glycolysis

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- The processes have different mechanisms for oxidizing NADH:
  - In fermentation, an organic molecule (such as pyruvate or acetaldehyde) acts as a final electron acceptor
  - In cellular respiration electrons are transferred to the electron transport chain
- Cellular respiration produces 32 ATP per glucose molecule; fermentation produces 2 ATP per glucose molecule

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- **Obligate anaerobes** carry out fermentation or anaerobic respiration and cannot survive in the presence of O_2
- Yeast and many bacteria are **facultative anaerobes**, meaning that they can survive using either fermentation or cellular respiration
- In a facultative anaerobe, pyruvate is a fork in the metabolic road that leads to two alternative catabolic routes

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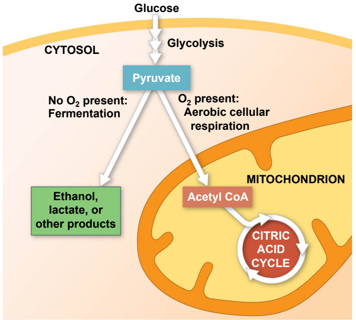
Figure 9.18



The Evolutionary Significance of Glycolysis

- Ancient prokaryotes are thought to have used glycolysis long before there was oxygen in the atmosphere
- Very little O_2 was available in the atmosphere until about 2.7 billion years ago, so early prokaryotes likely used only glycolysis to generate ATP
- Glycolysis is a very ancient process

Concept 9.6: Glycolysis and the citric acid cycle connect to many other metabolic pathways

- Gycolysis and the citric acid cycle are major intersections to various catabolic and anabolic pathways

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The Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
- Glycolysis accepts a wide range of carbohydrates
- Proteins must be digested to amino acids; amino groups can feed glycolysis or the citric acid cycle

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- Fats are digested to glycerol (used in glycolysis) and fatty acids (used in generating acetyl CoA)
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA
- An oxidized gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate

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Figure 9.19-1

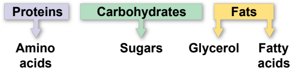


Figure 9.19-2

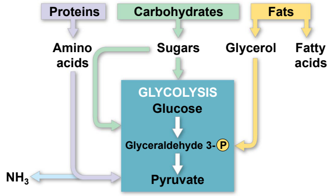


Figure 9.19-3

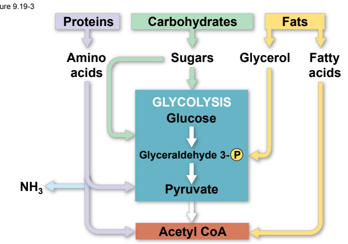


Figure 9.19-4

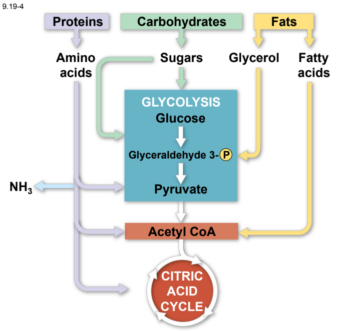
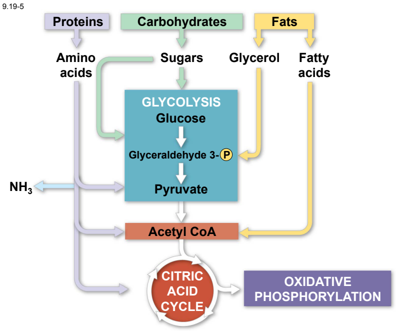


Figure 9.19-5



Biosynthesis (Anabolic Pathways)

- The body uses small molecules to build other substances
- These small molecules may come directly from food, from glycolysis, or from the citric acid cycle

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Regulation of Cellular Respiration via Feedback Mechanisms

- Feedback inhibition is the most common mechanism for metabolic control
- If ATP concentration begins to drop, respiration speeds up; when there is plenty of ATP, respiration slows down
- Control of catabolism is based mainly on regulating the activity of enzymes at strategic points in the catabolic pathway

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Figure 9.20

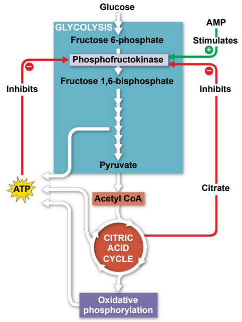


Figure 9.UN10a

Thyroid Hormone Level	Oxygen Consumption Rate (nmol O_2/min · mg cells)
Low	4.3
Normal	4.8
Elevated	8.7

Figure 9.UN10b

Figure 9.UN11

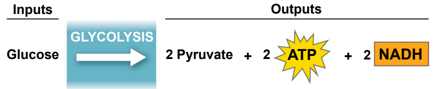


Figure 9.UN12

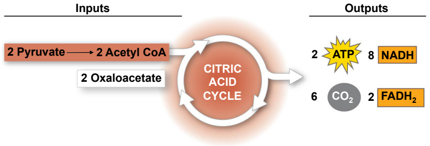


Figure 9.UN13

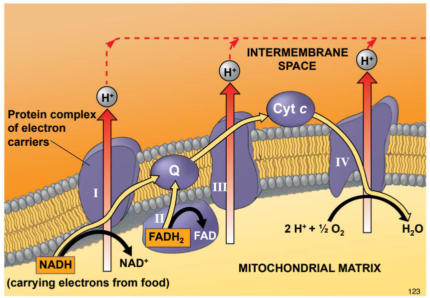
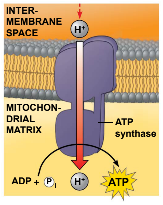


Figure 9.UN14



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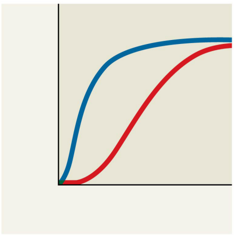

Figure 9.UN16

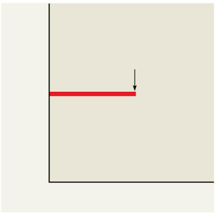

Figure 9.UN17