LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
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Chapter 9

Cellular Respiration and Fermentation

Lectures by
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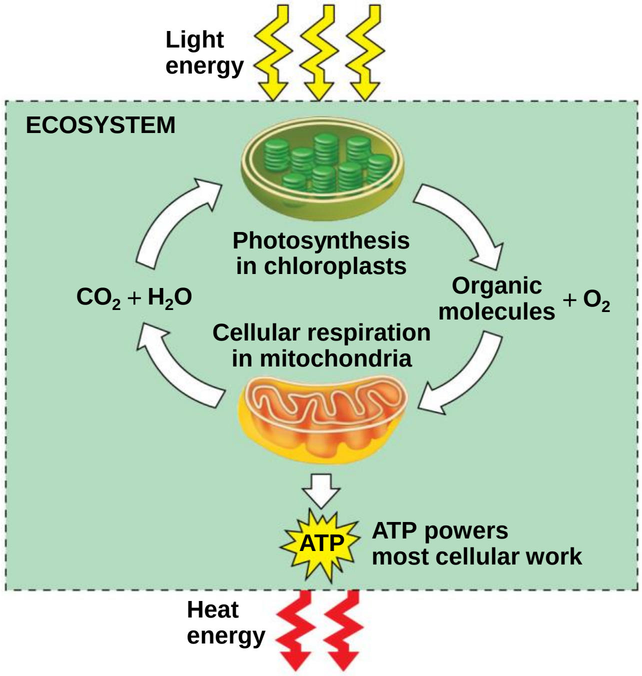
Overview: Life Is Work

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

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 regenerate ATP, which powers work

Figure 9.2



Concept 9.1: Catabolic pathways yield energy by oxidizing organic fuels

- 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

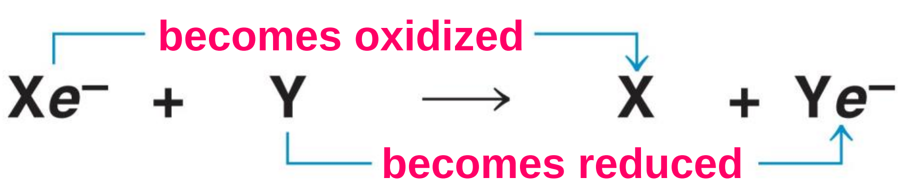
- The transfer of electrons during chemical reactions releases energy stored in organic molecules
- This released energy is ultimately used to synthesize ATP

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*)

Fig. 9-UN2

Example: Na + Cl → Na^+ + Cl^-



The electron donor is called the **reducing agent**
The electron receptor is called the **oxidizing agent**

Oxidation of Organic Fuel ***Molecules During*** *Cellular Respiration*

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

Fig. 9-UN3

becomes oxidized

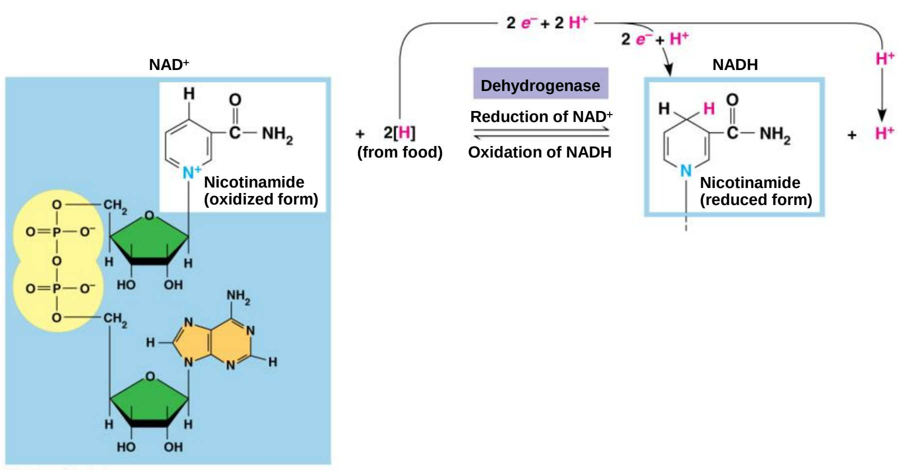
$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{Energy}$$

becomes reduced

Stepwise Energy Harvest via NAD⁺ and the Electron Transport Chain

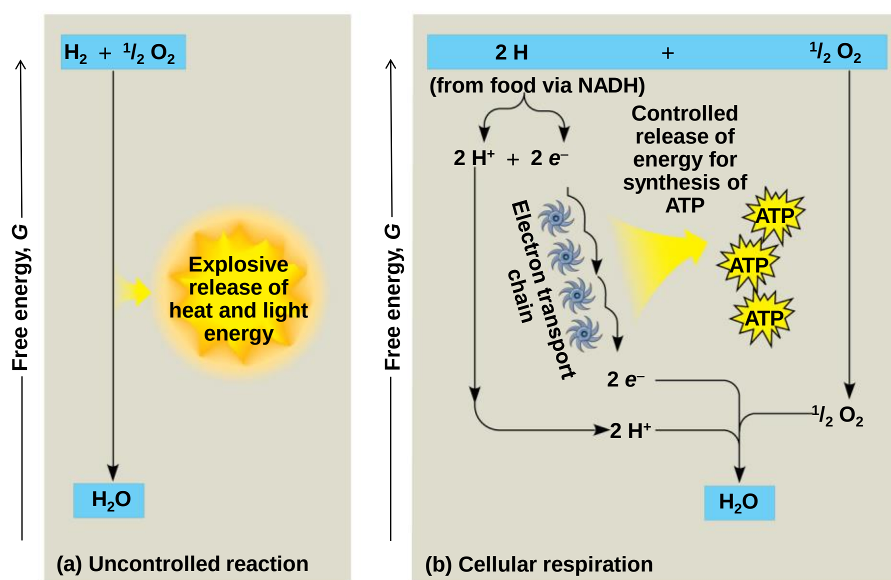
- In cellular respiration, glucose and other organic molecules are broken down in a series of steps
- Electrons from organic compounds are usually first transferred to **NAD⁺**, a coenzyme
- As an electron acceptor, NAD⁺ functions as an oxidizing agent during cellular respiration
- Each NADH (the reduced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

Figure 9.4



- 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



The Stages of Cellular Respiration: *A Preview*

- Cellular respiration 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 teal throughout the chapter)**
2. **Pyruvate oxidation and the citric acid cycle (color-coded salmon)**
3. **Oxidative phosphorylation: electron transport and chemiosmosis (color-coded violet)**

Figure 9.6-1

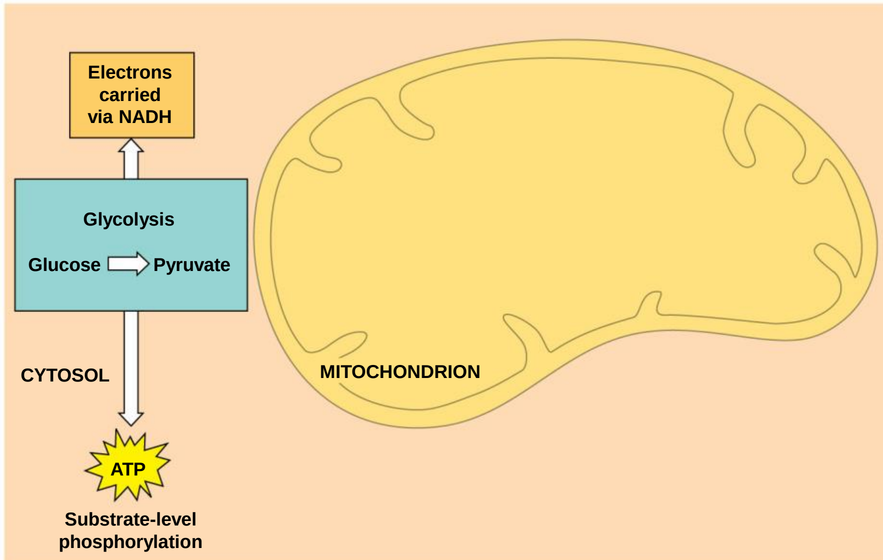


Figure 9.6-2

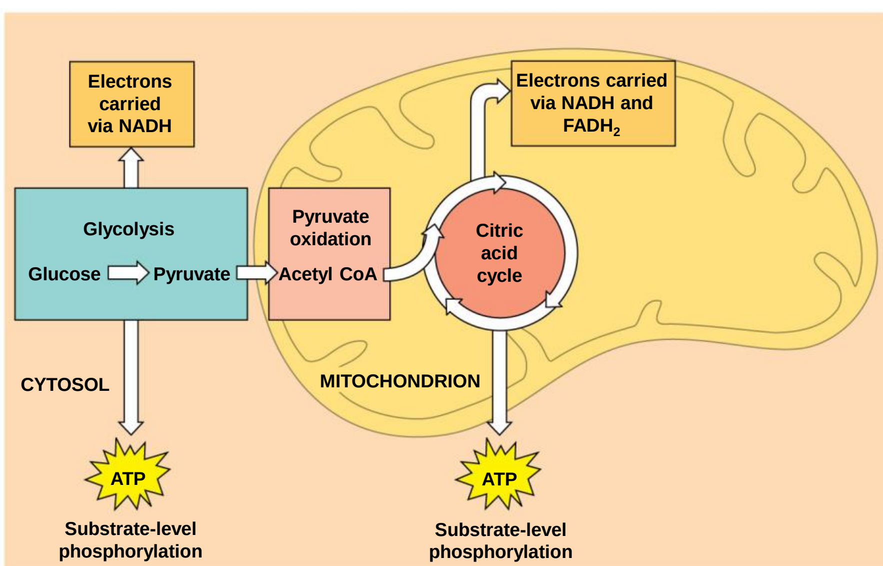
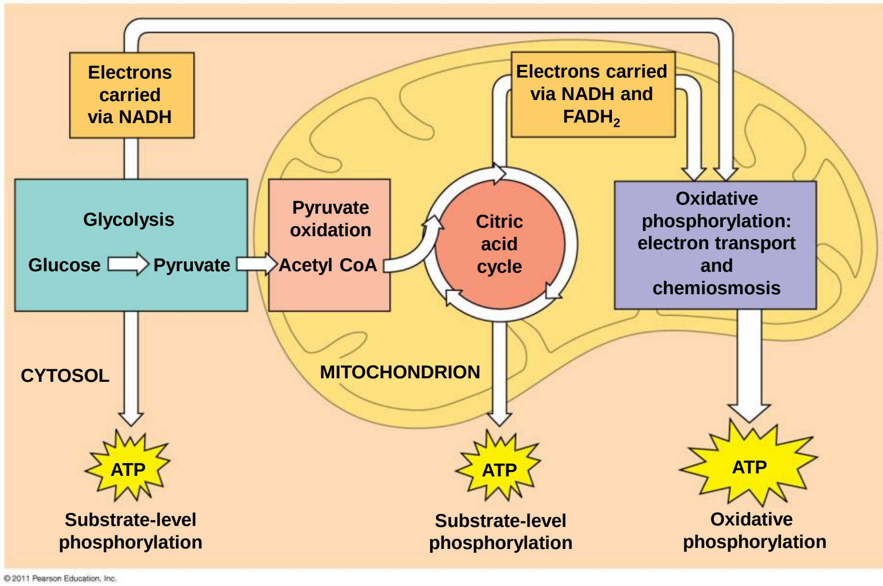
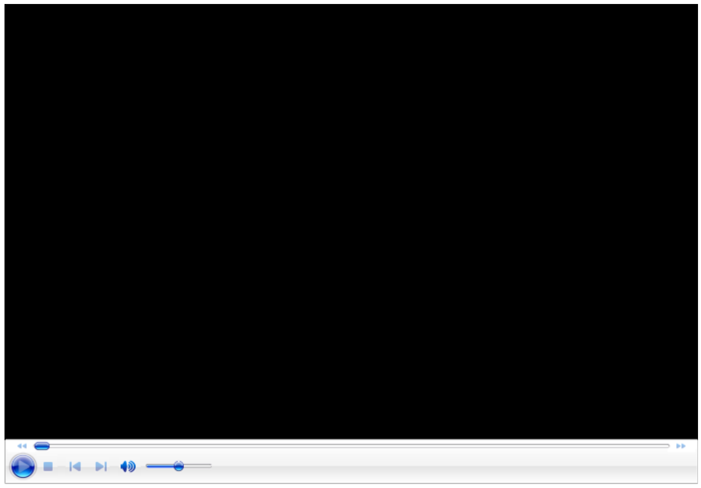


Figure 9.6-3



- The process that generates most of the ATP is called **oxidative phosphorylation.**

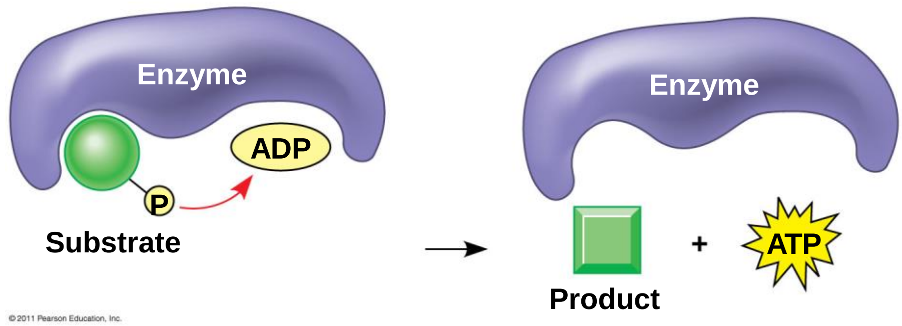


BioFlix: Cellular Respiration

Right-clickslide/ select"Play"

- The process that generates most of the ATP is called **oxidative phosphorylation.**
- 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 ("splitting of sugar") breaks down glucose into two molecules of pyruvate
- Glycolysis occurs in the cytoplasm and has two major phases:
  - Energy investment phase
  - Energy payoff phase

Figure 9.8

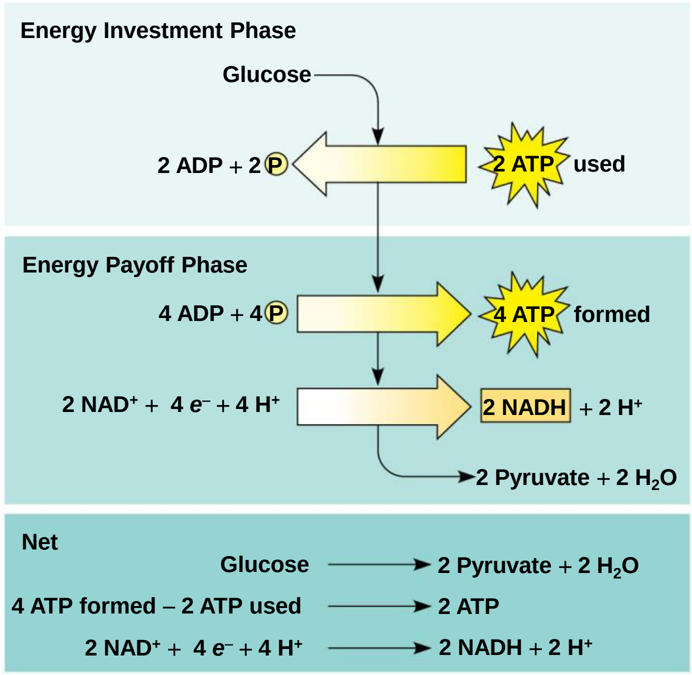


Figure 9.9a

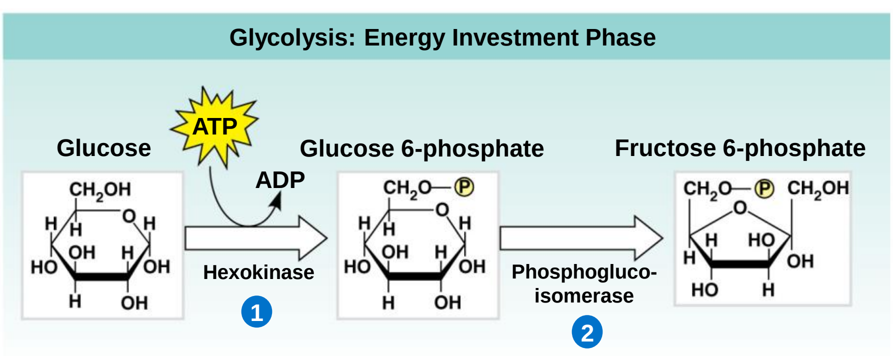


Figure 9.9b

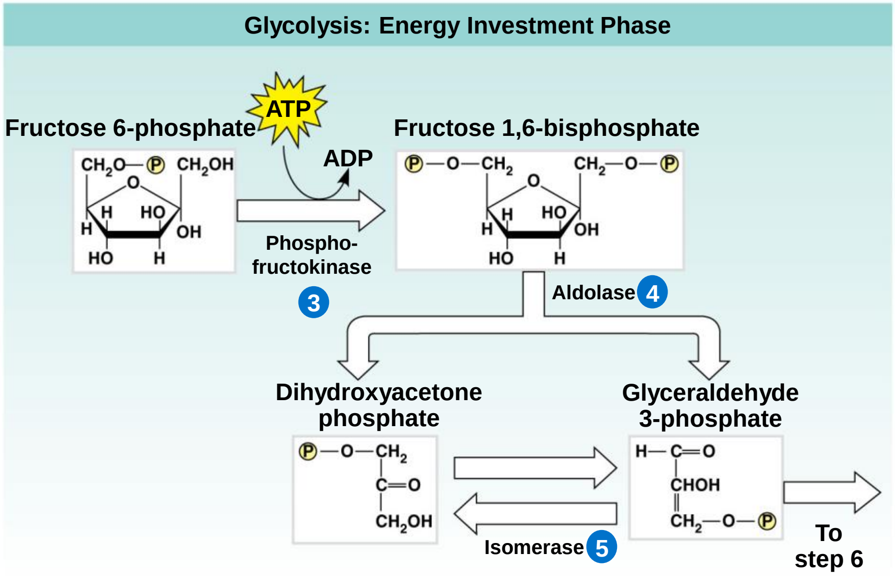


Figure 9.9c

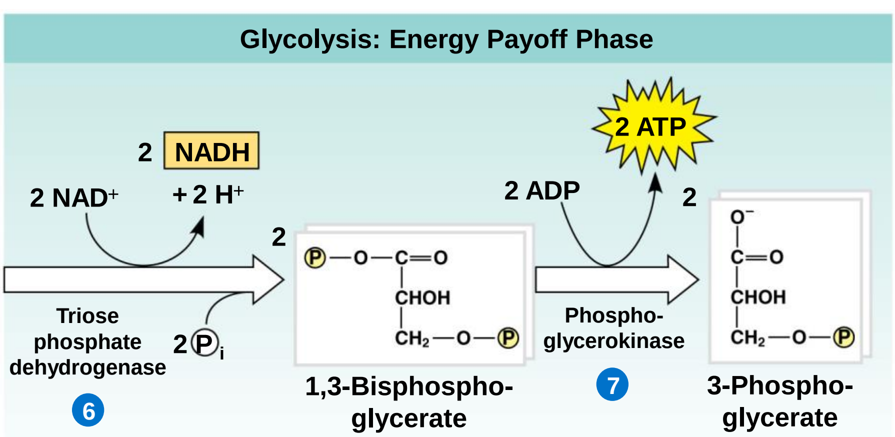
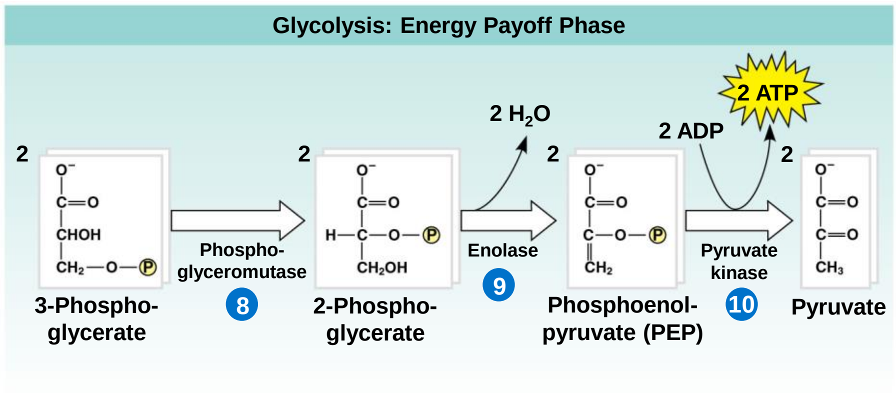


Figure 9.9d



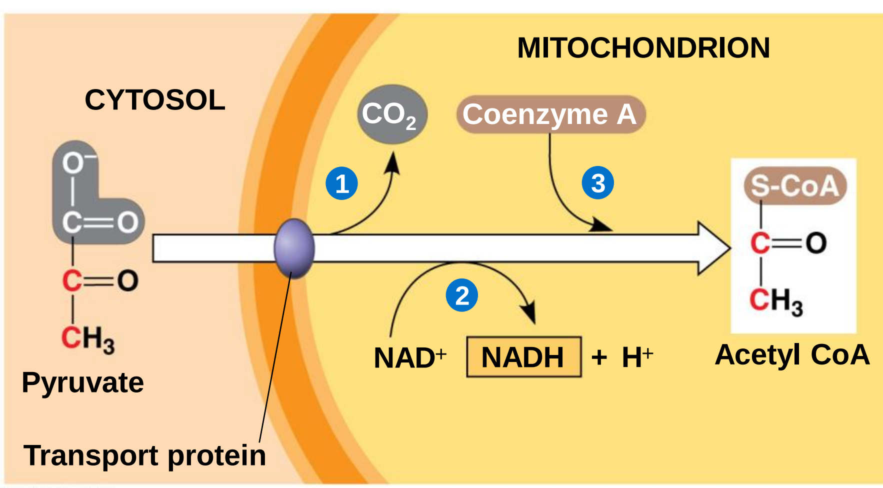
Concept 9.3: The citric acid cycle completes the energy-yielding oxidation of organic molecules

- In the presence of O_2, pyruvate enters the mitochondrion

Oxidation of Pyruvate to Acetyl CoA

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

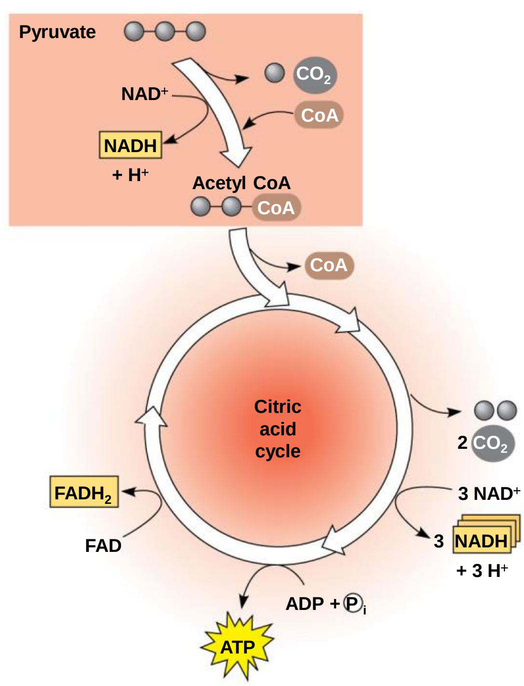
Figure 9.10



The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, takes place within the mitochondrial matrix
- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn (*Each glucose makes 2 turns*)

Figure 9.11



- In the first step, 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**

Figure 9.12-1

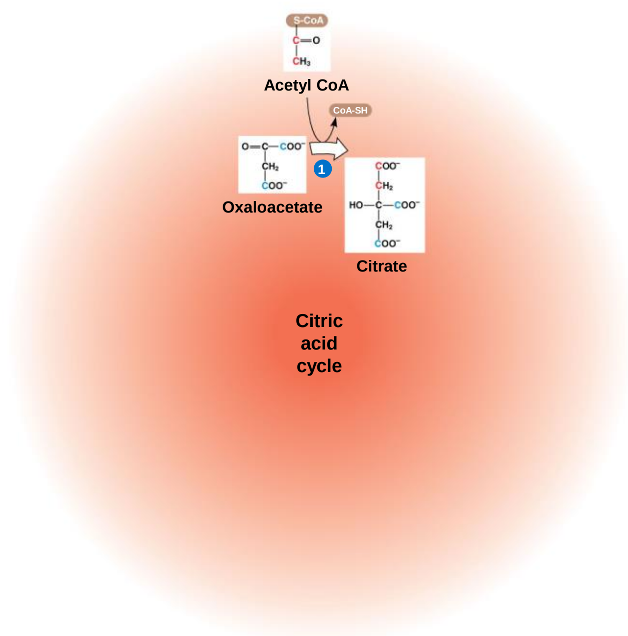


Figure 9.12-2

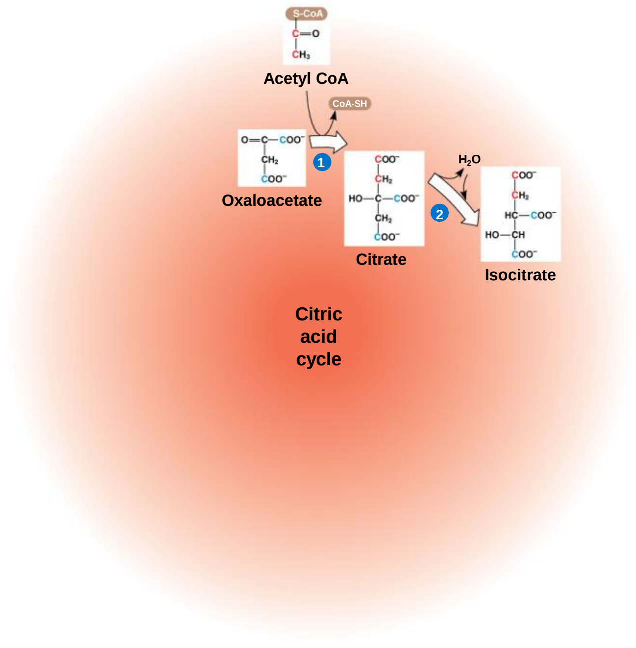


Figure 9.12-3

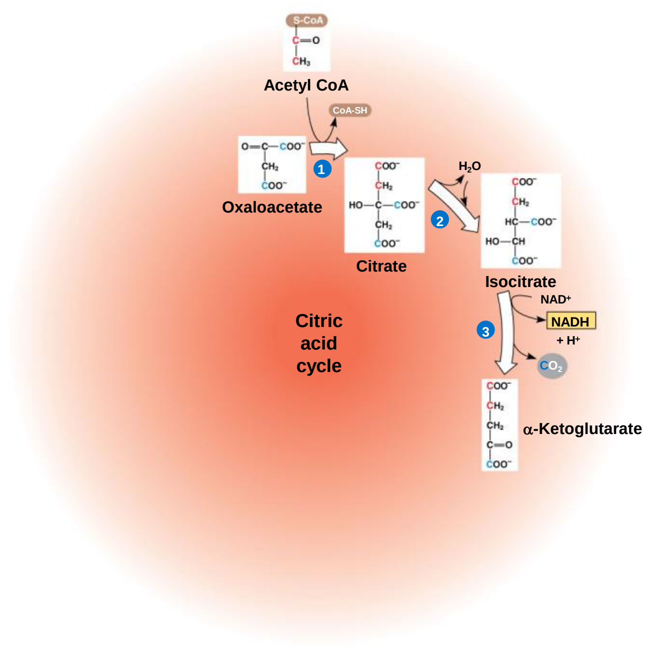


Figure 9.12-4

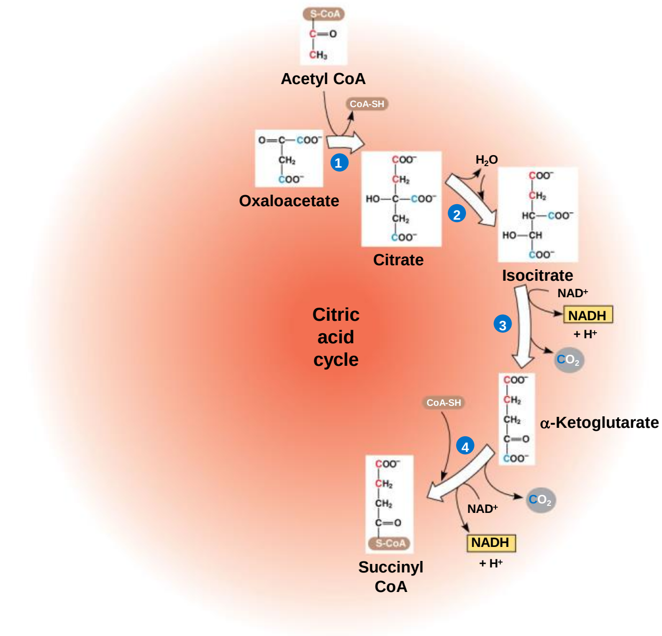


Figure 9.12-5

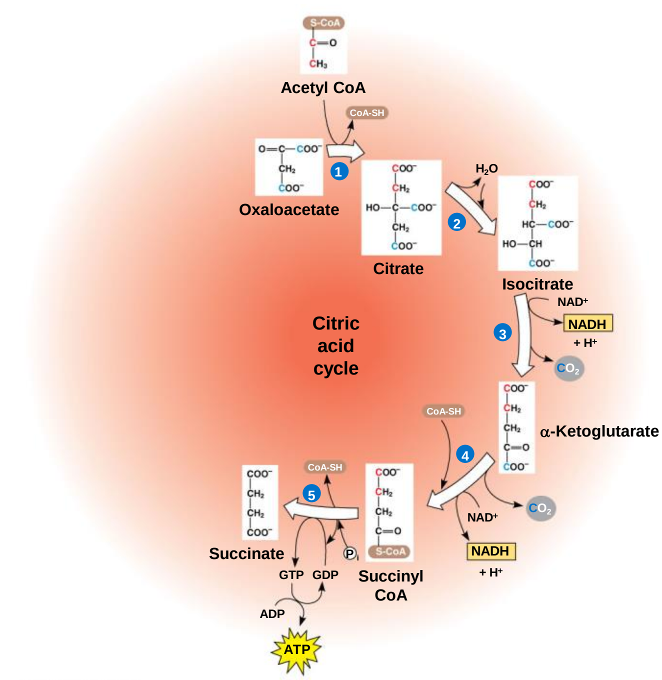


Figure 9.12-6

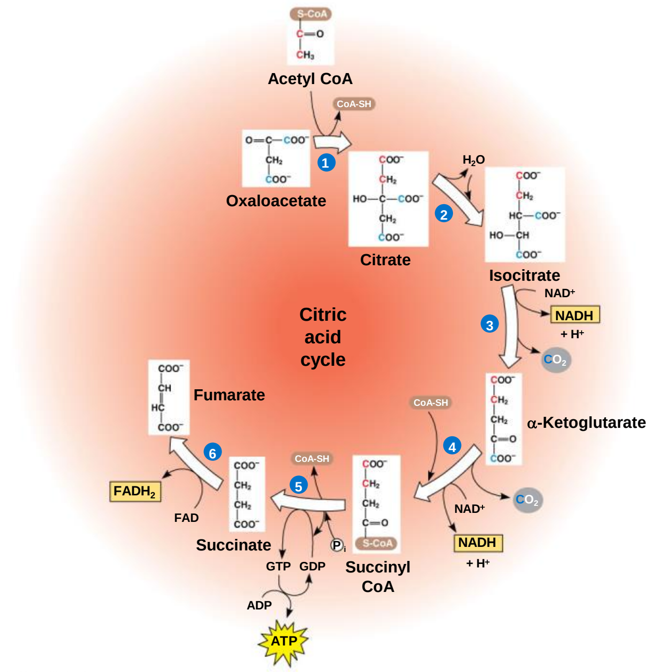


Figure 9.12-7

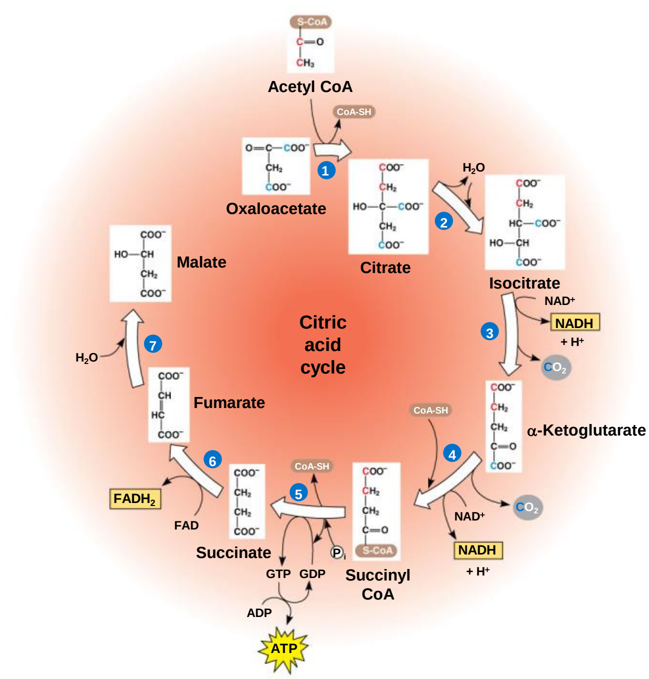
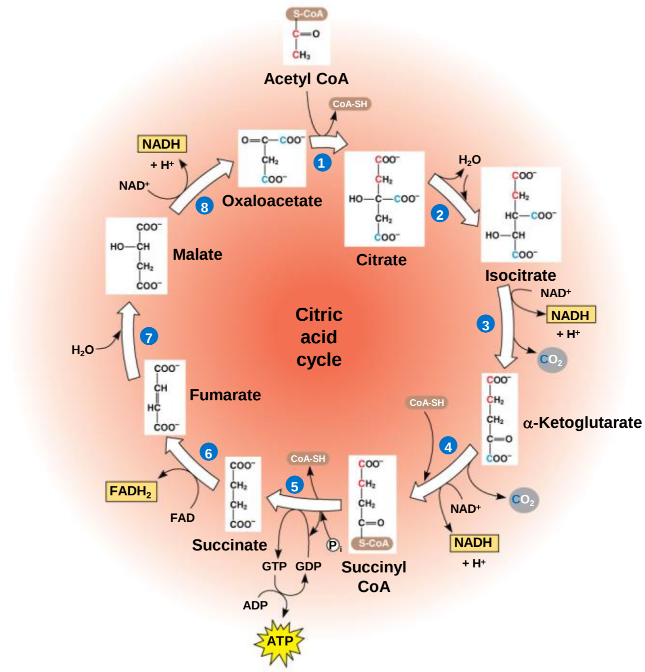


Figure 9.12-8



Class activity!

- Why Glucose is oxidized stepwise in a long process and not concentrated into few steps??
- What is the net ATP production in the first 2 steps –Glycolysis & Citric acid cycle? By which mechanism?
- What other forms of energy were produced?

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 cristae of the mitochondrion
- Most of the chain's components are proteins, which exist in multiprotein complexes
- The electron transport chain <u>generates no ATP</u>
- Electrons drop in free energy as they go down the chain and are finally passed to O_2, forming H_2O

Figure 9.13

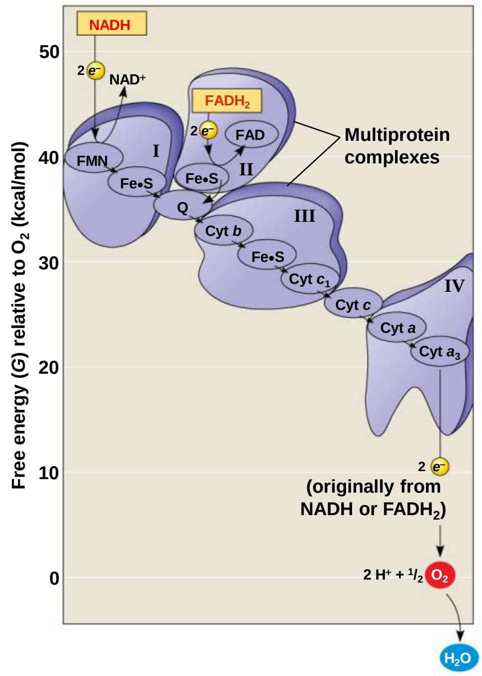
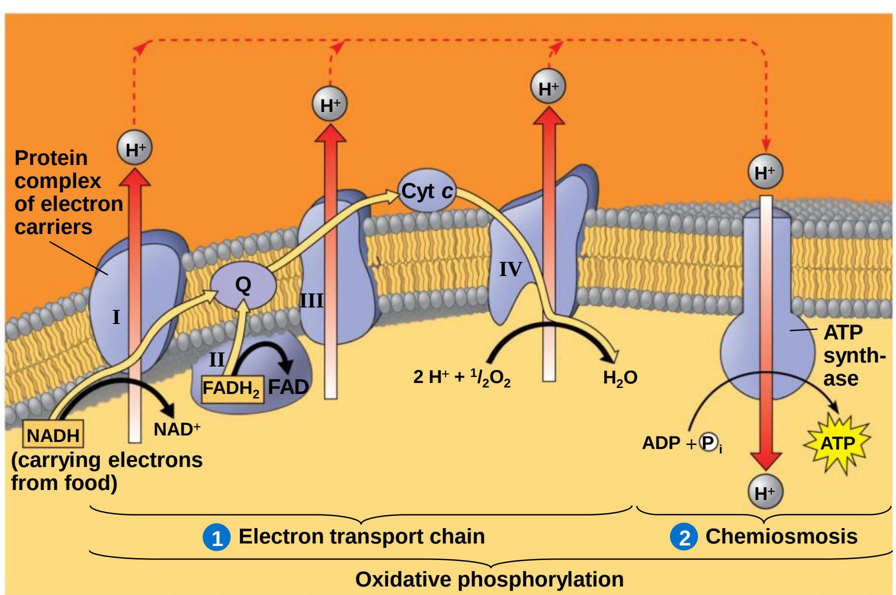


Figure 9.15



- 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

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 channels in **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

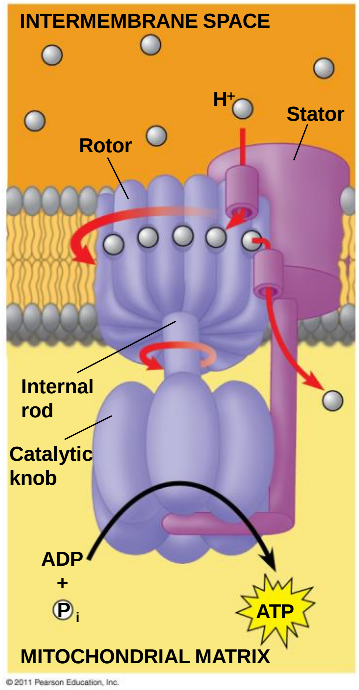
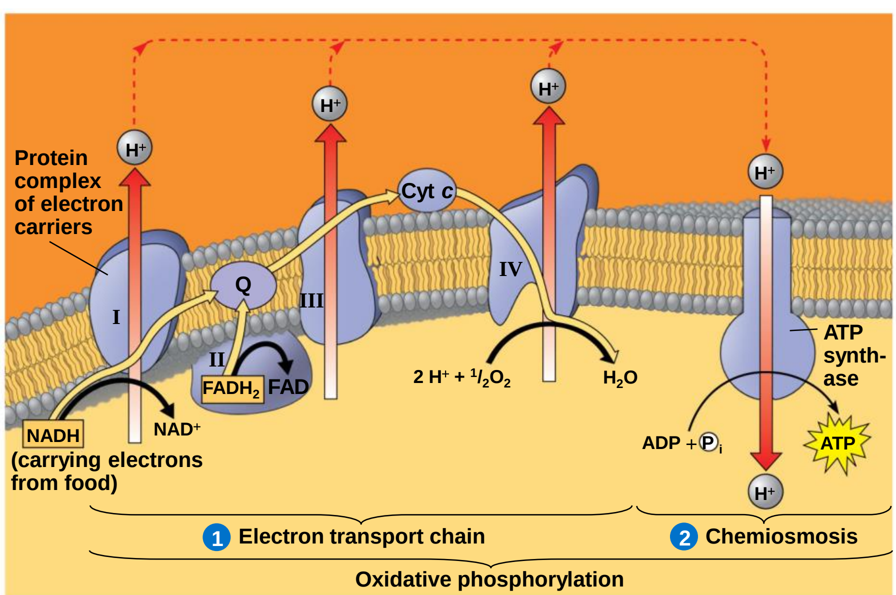


Figure 9.15



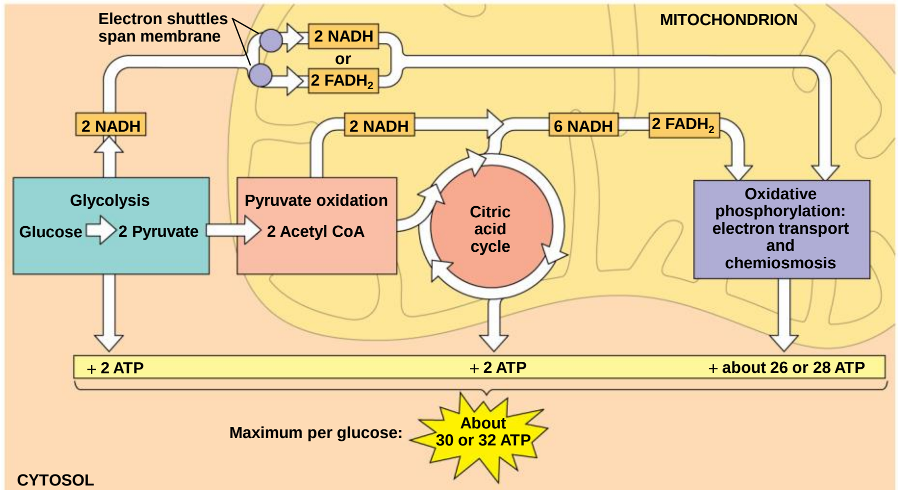
- The **energy stored in a H^+ gradient** across a membrane **couples the redox reactions of the electron transport chain to ATP synthesis**
- The H^+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

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**

Figure 9.16



Class activity!

- Why is the number of ATP produced per Glucose molecule is not known exactly?
  >> 30-32 ATPs per Glucose molecule

- How efficient is the oxidation of glucose compared to automobiles??

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

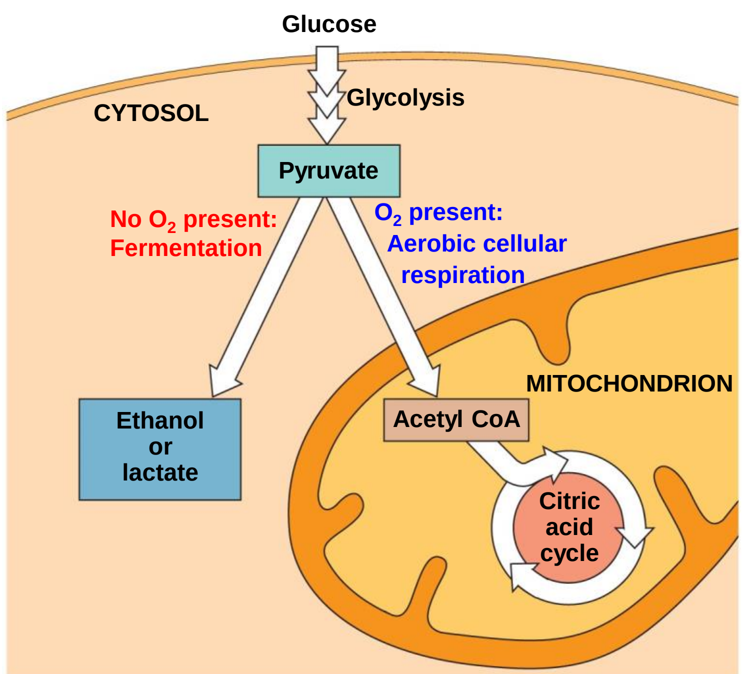
- Most cellular respiration requires O_2 to produce ATP
- Glycolysis can produce ATP with or without O_2 (in aerobic or anaerobic conditions)
- In the absence of O_2, glycolysis couples with fermentation or anaerobic respiration to produce ATP

- **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

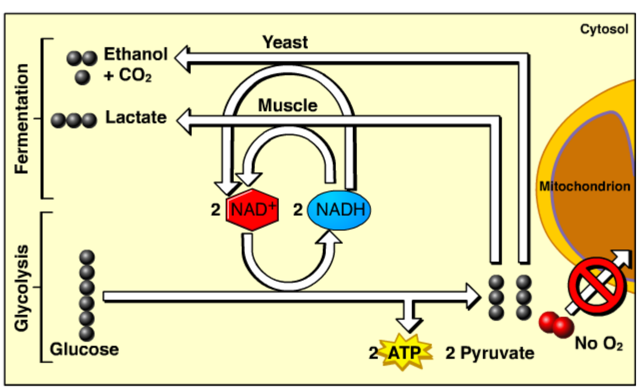
Types of Fermentation

- 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**

Fig. 9-19

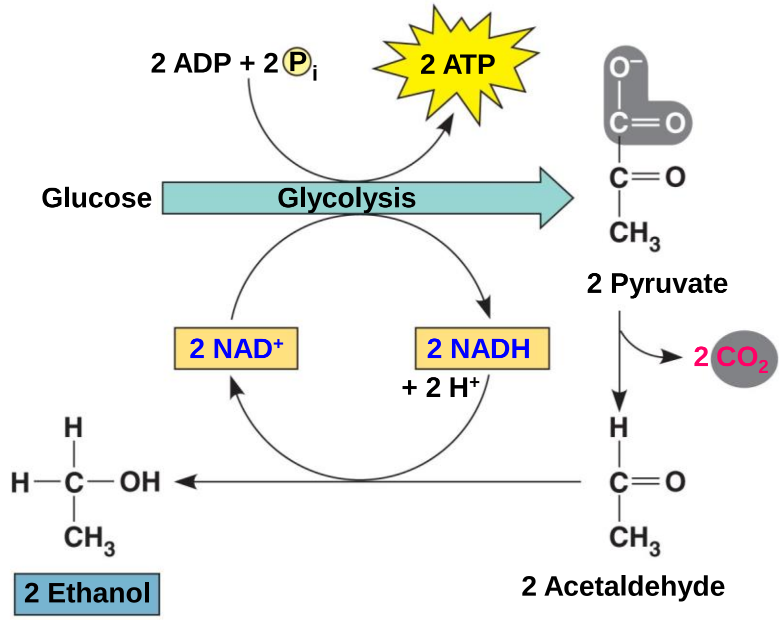


- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps, with the **first releasing CO_2**
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking



Animation: Fermentation Overview
Right-click slide / select "Play"

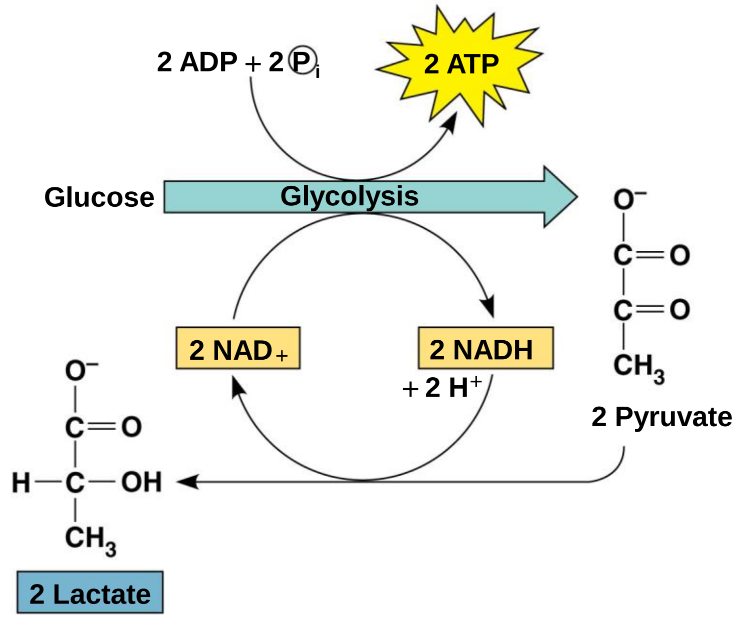
Fig. 9-18a



(a) Alcohol fermentation

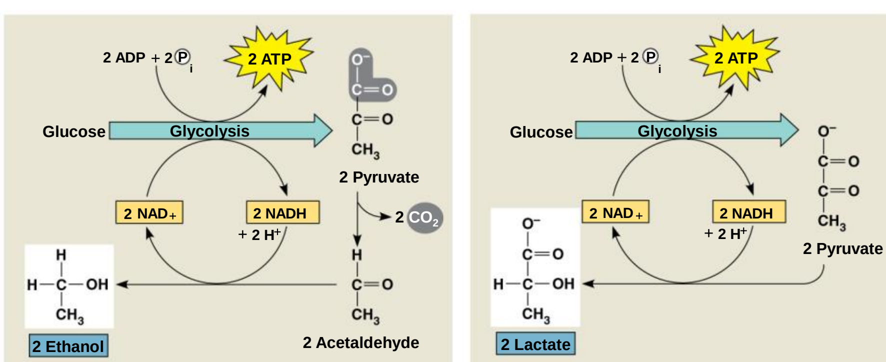
- In **lactic acid fermentation**, pyruvate is reduced to NADH, forming lactate as an end product, **with no release of CO_2**
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
- Human muscle cells use lactic acid fermentation to generate ATP when O_2 is scarce

Figure 9.17b



(b) Lactic acid fermentation

Figure 9.17



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

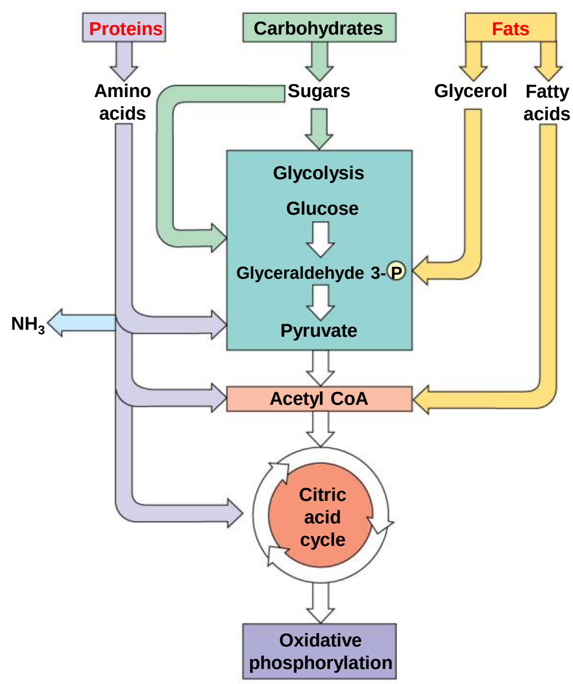
- Gycolysis and the citric acid cycle **are major intersections to various catabolic and anabolic pathways**

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

- 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**

Figure 9.19



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**
- **Humans can make more than half of the 20 amino acids by modifying compounds siphoned away from citric acid cycle**
- **Glucose can be synthesized from pyruvate**
- **Fats can be synthesized from Acetyl-CoA**

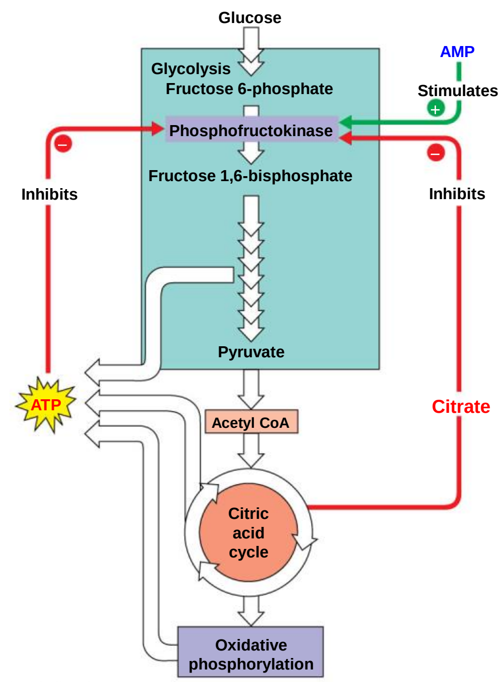
Metabolism

- Metabolism is remarkably versatile and adaptable!!

Regulation of Cellular Respiration via Feedback Mechanisms

- Feedback inhibition is the most common mechanism for 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

Figure 9.20



Class activity!

- What makes fats a much better fuel than carbohydrates??
- Under what circumstances might your body synthesize fat molecules?

Class activity!

- What will happen in a muscle cell that has used up its supply of oxygen and ATP?
- During intense exercise, can a muscle cell use fat as a concentrated source of chemical energy? Explain?