

LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

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Chapter 9

Cellular Respiration and Fermentation



Lectures by
Erin Barley
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Overview: Life Is Work

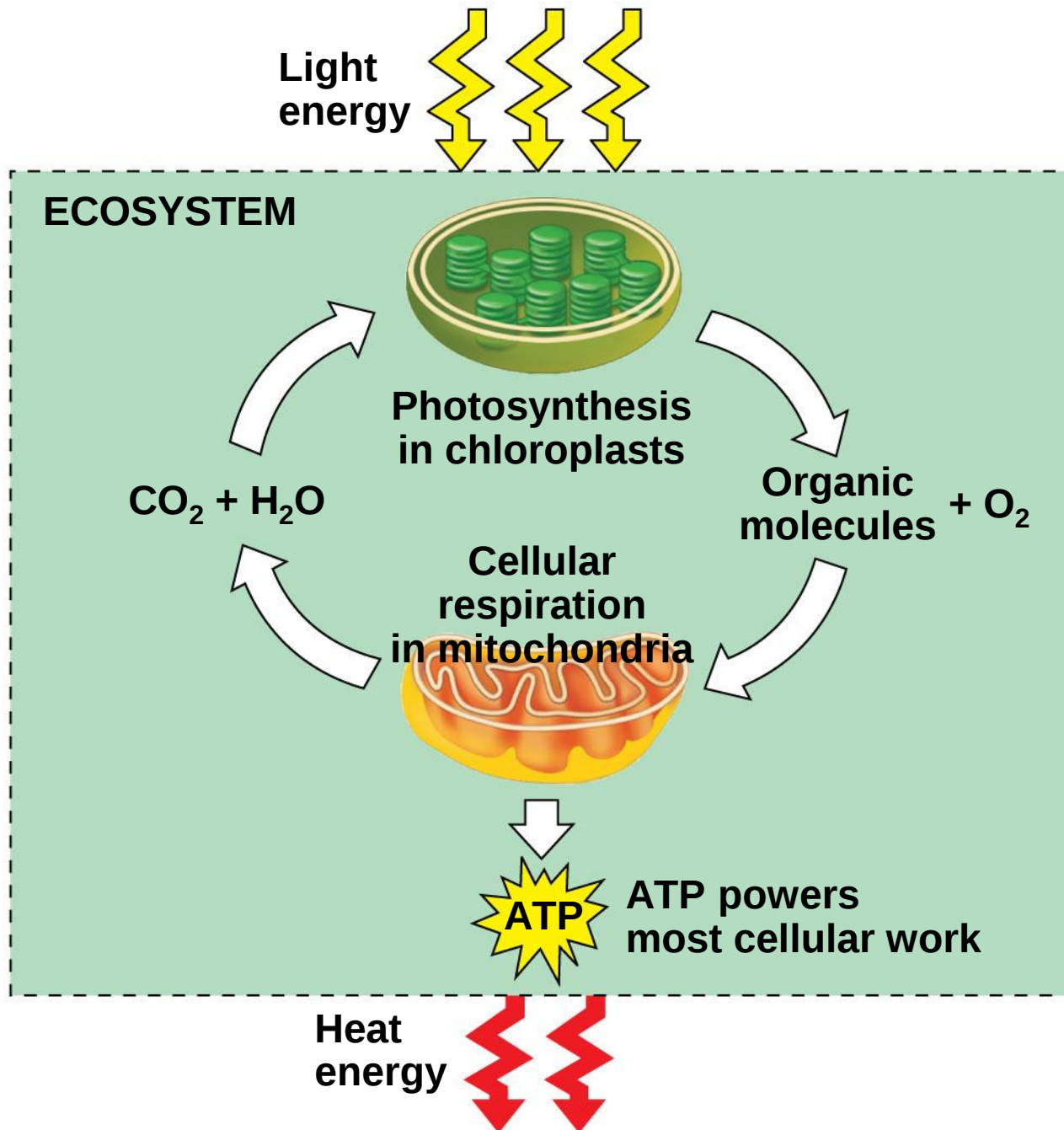
- Living cells **require energy** from outside sources
- Some animals, such as the giant panda, **obtain energy by eating plants**, and **some animals feed on other organisms that eat plants**

Figure 9.1



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- 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 O₂**

- **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**:



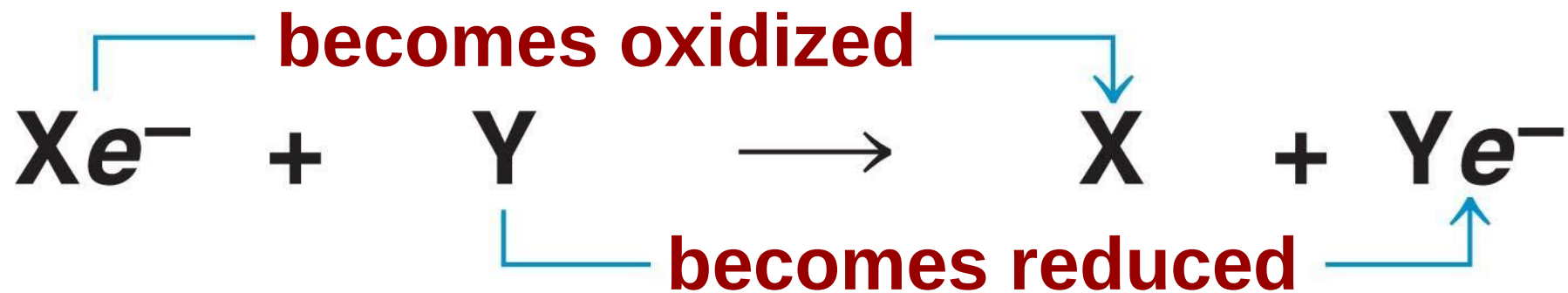
Redox Reactions:

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*)



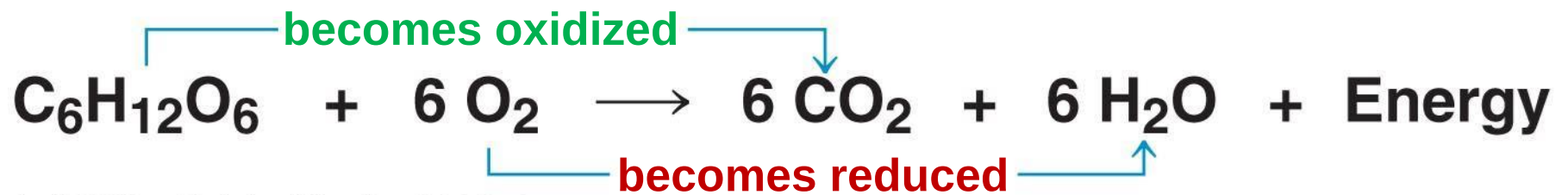
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The **electron donor** is called the
reducing agent

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 **O₂** is **reduced**:



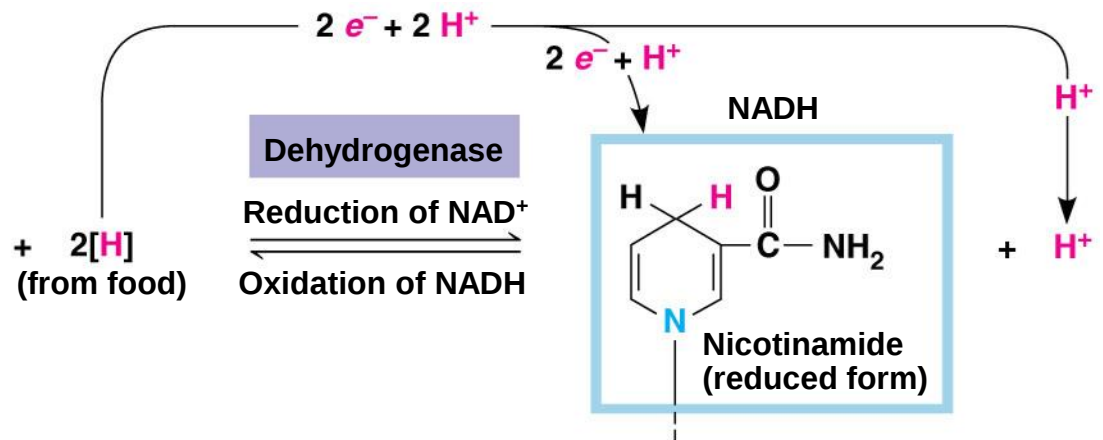
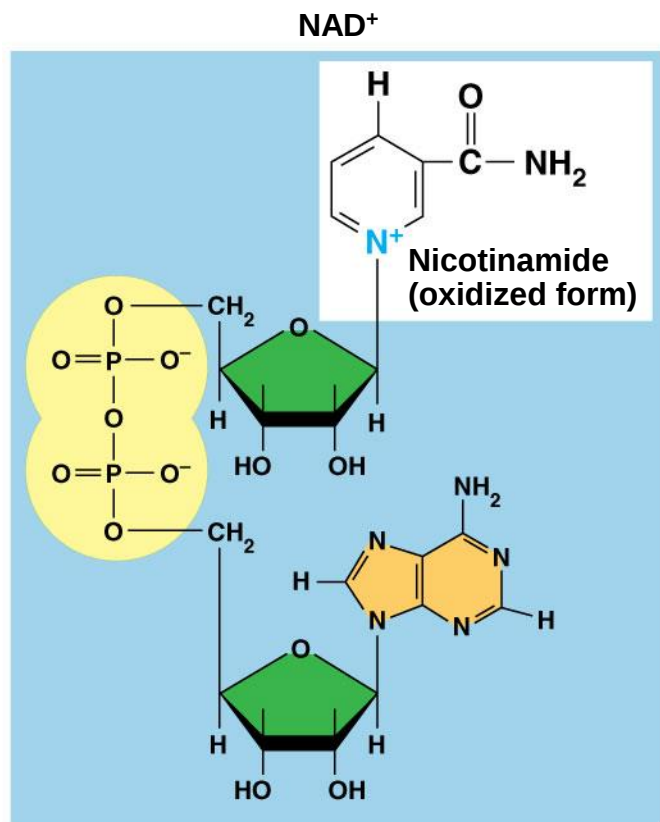
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Stepwise Energy Harvest via NAD^+ and the *Electron Transport Chain*

- 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

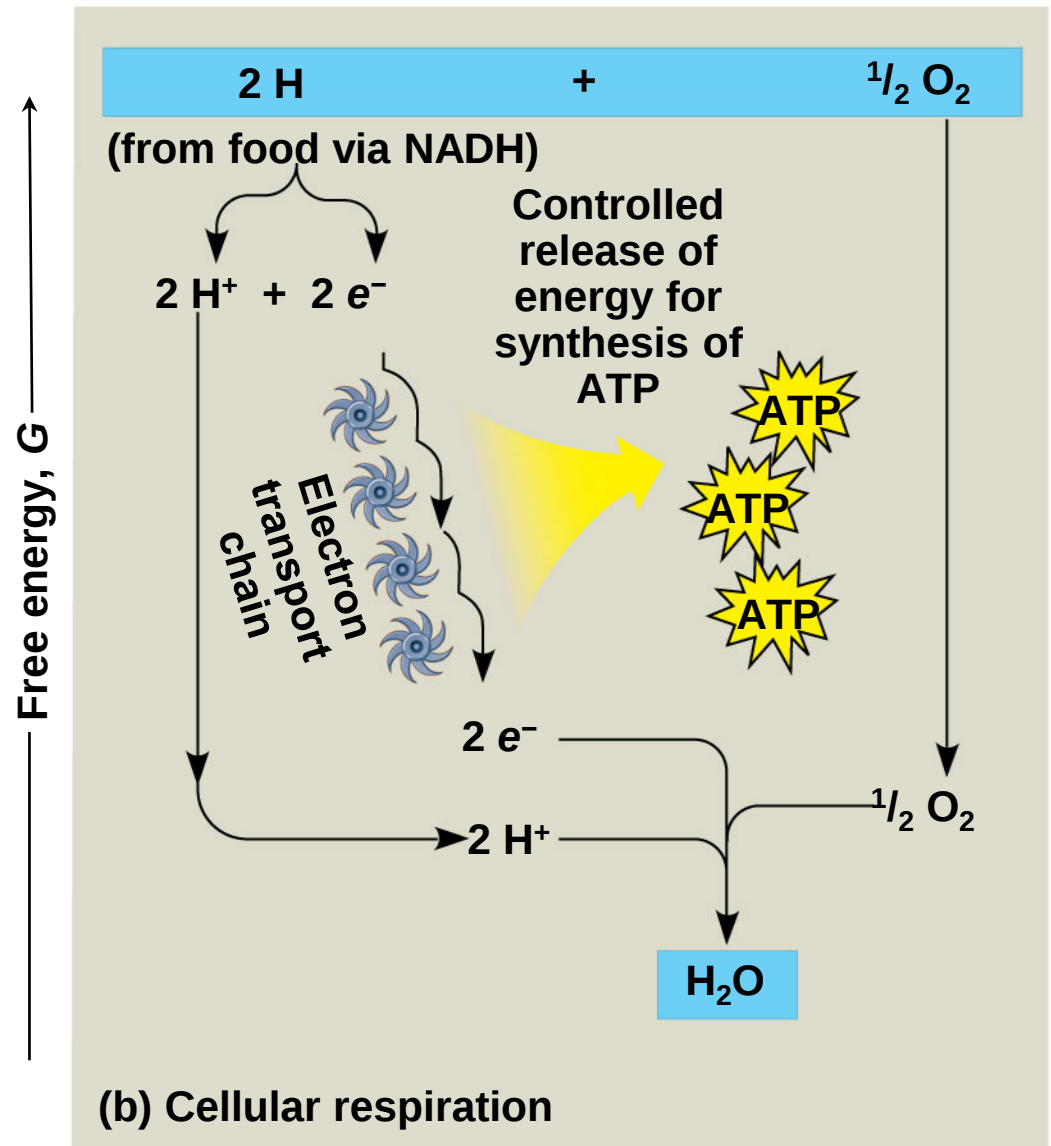
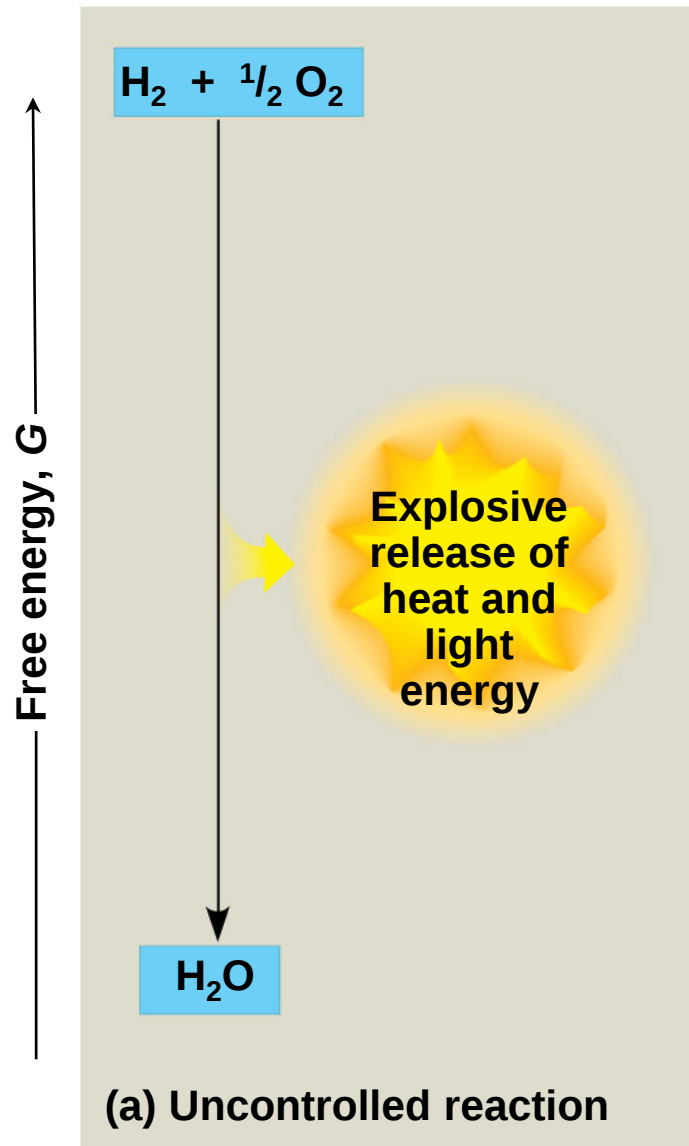
Figure 9.4



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- **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***

- O₂ pulls electrons down the chain in an energy-yielding **tumble**
- The energy yielded is used to **regenerate ATP**

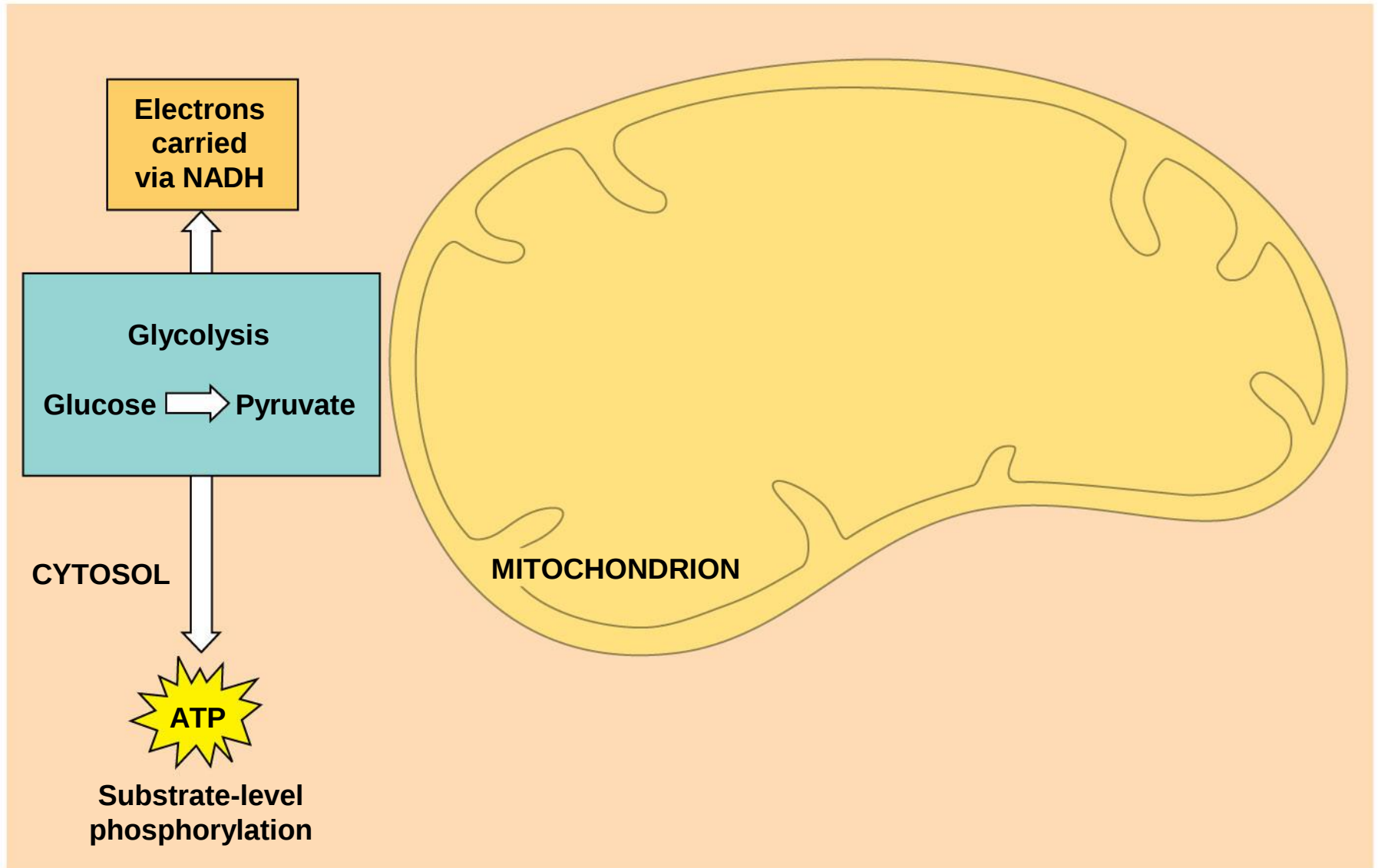
Figure 9.5



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 9.6-1



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Figure 9.6-2

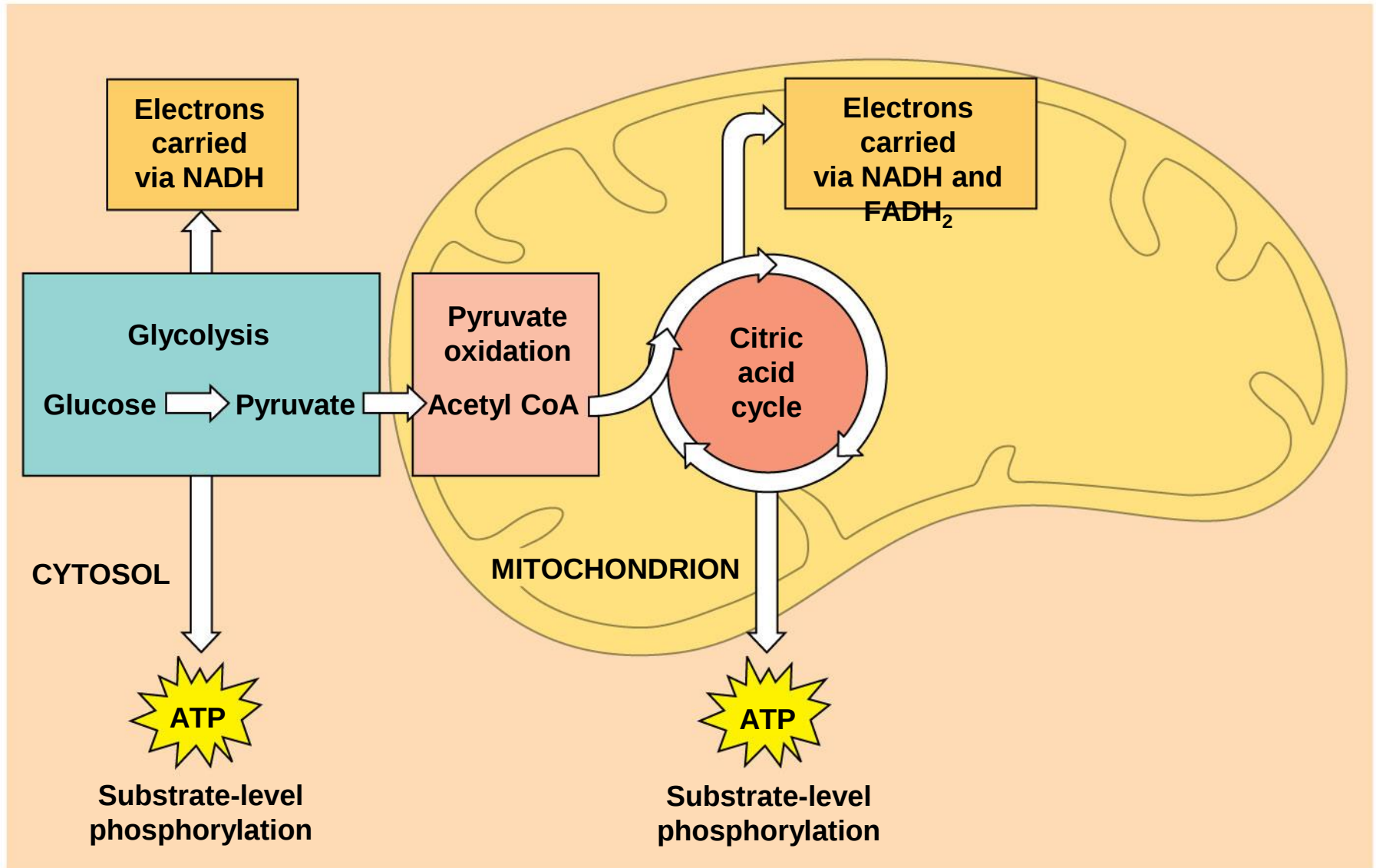
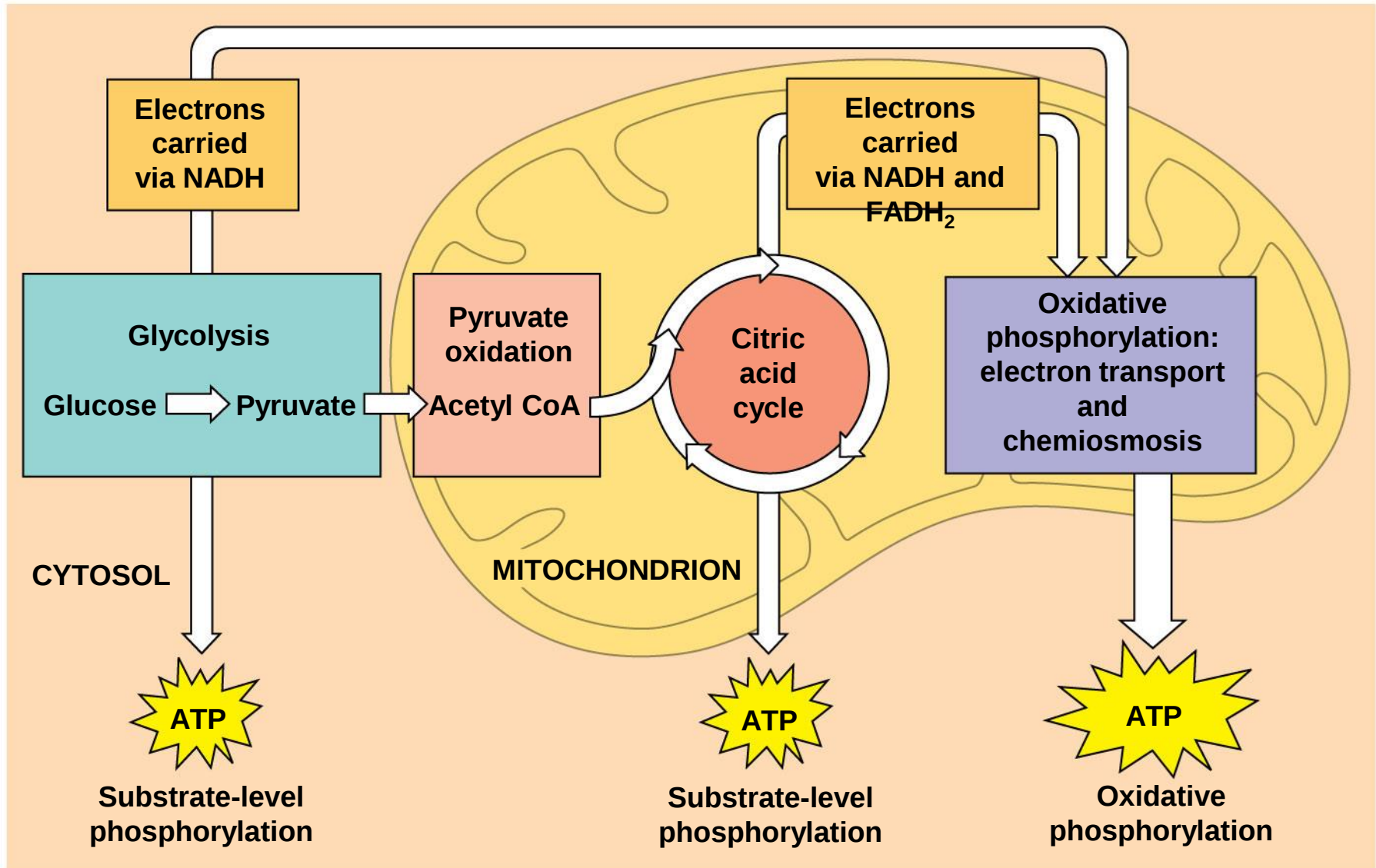


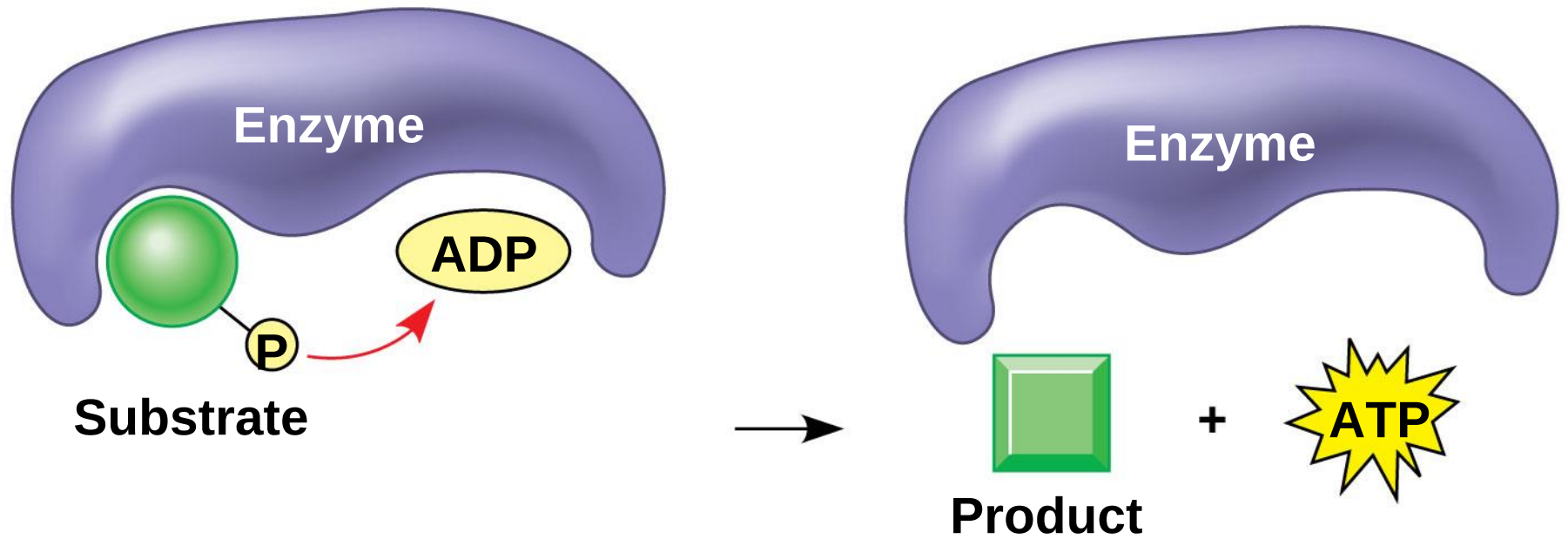
Figure 9.6-3



- 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



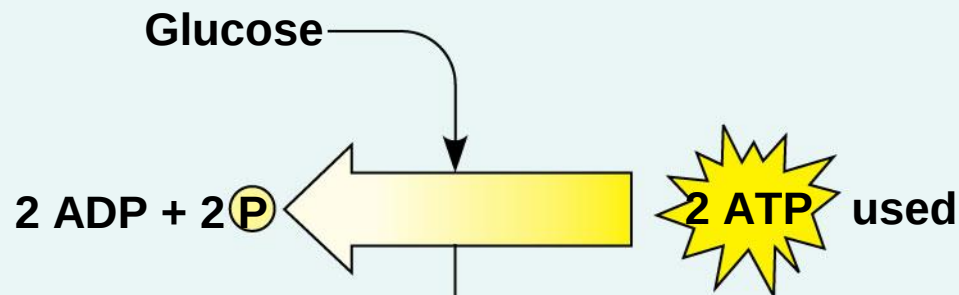
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Concept 9.2: **Glycolysis** harvests chemical energy by oxidizing glucose to pyruvate

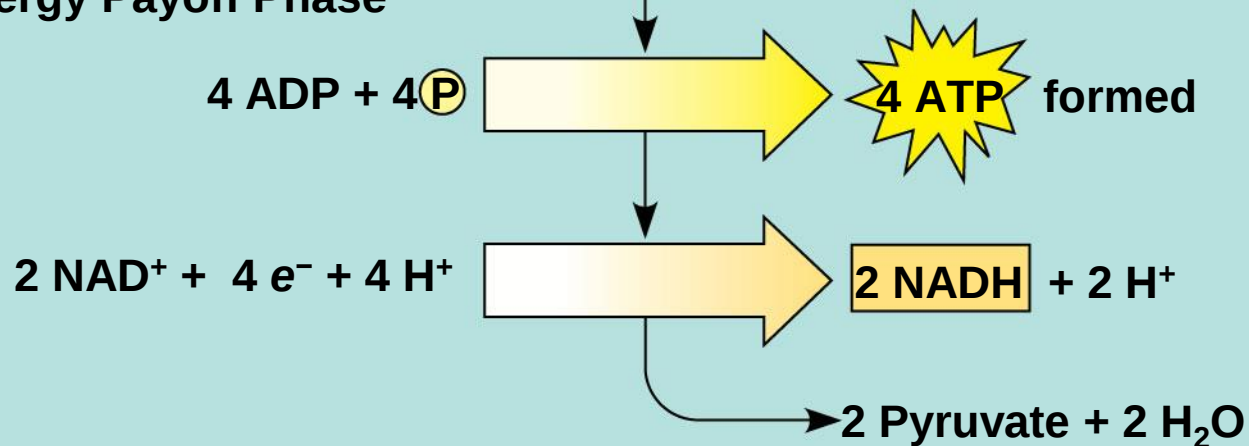
- **Glycolysis** (“splitting of sugar”) breaks down **glucose** into **two molecules of pyruvate**
- **Glycolysis occurs in the cytoplasm** and has **two major phases**:
 - **Energy investment phase**
 - **Energy payoff phase**

Figure 9.8

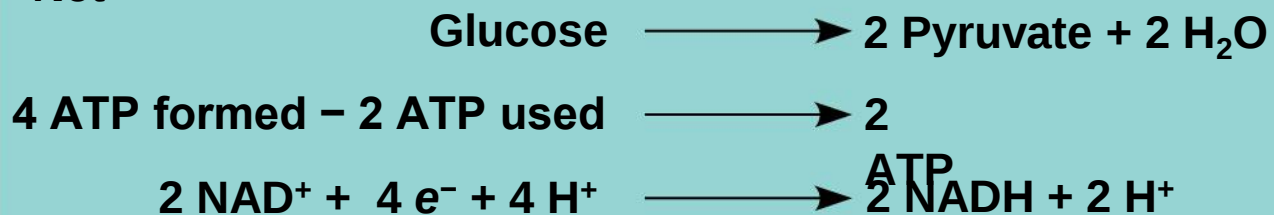
Energy Investment Phase



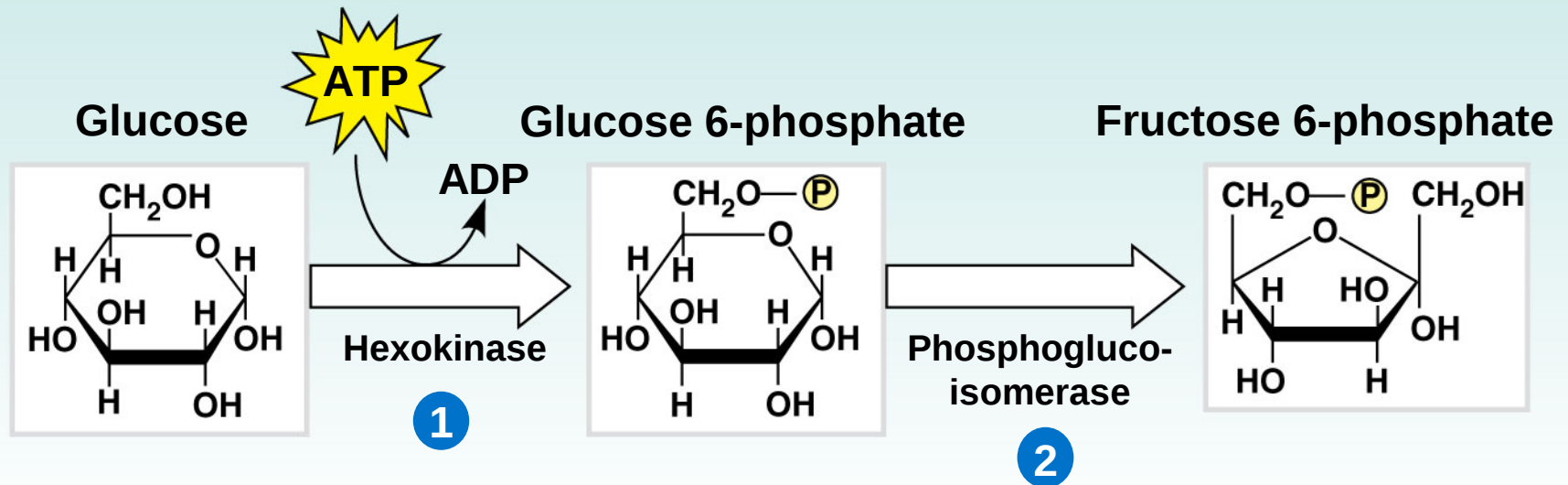
Energy Payoff Phase



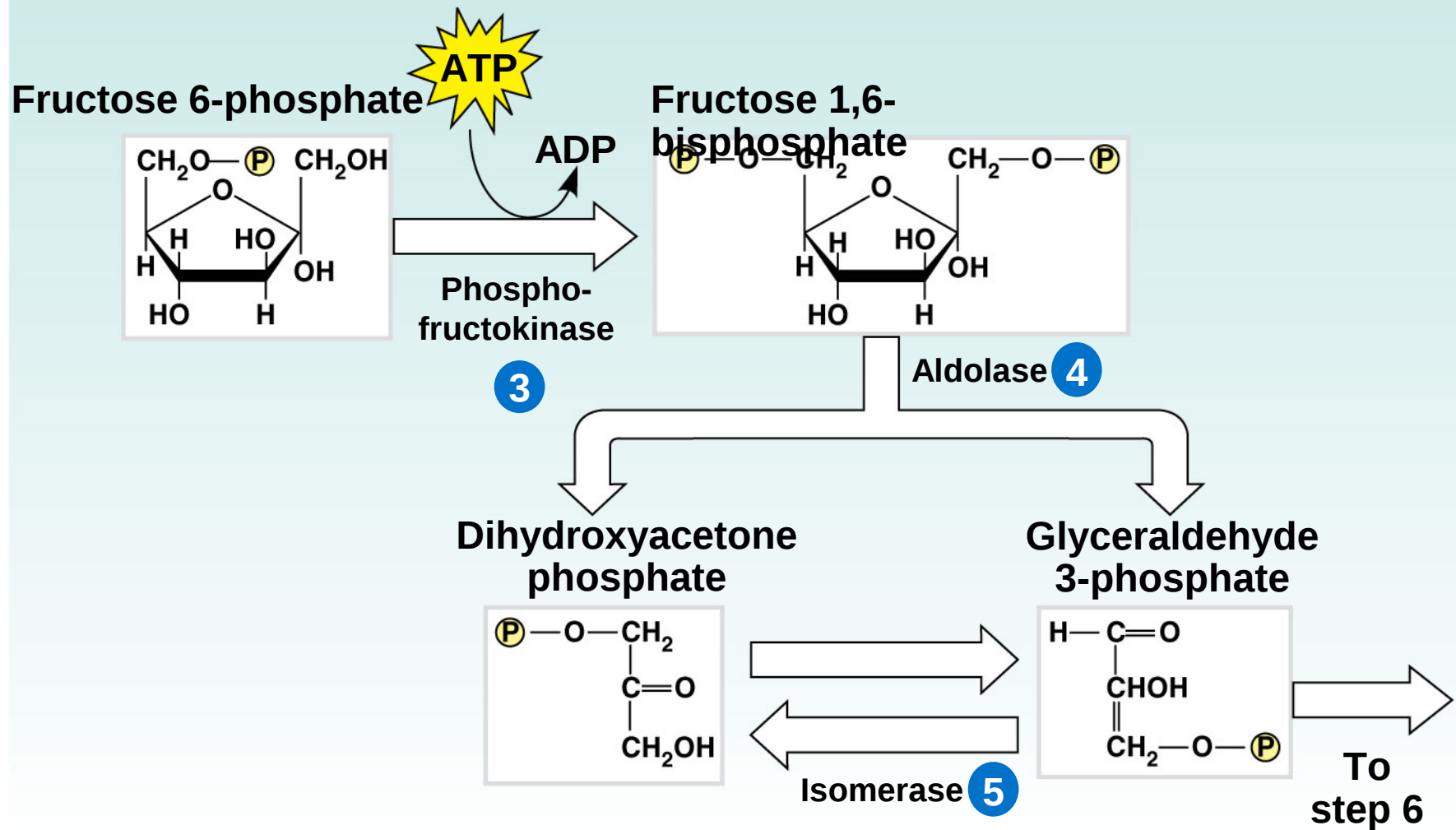
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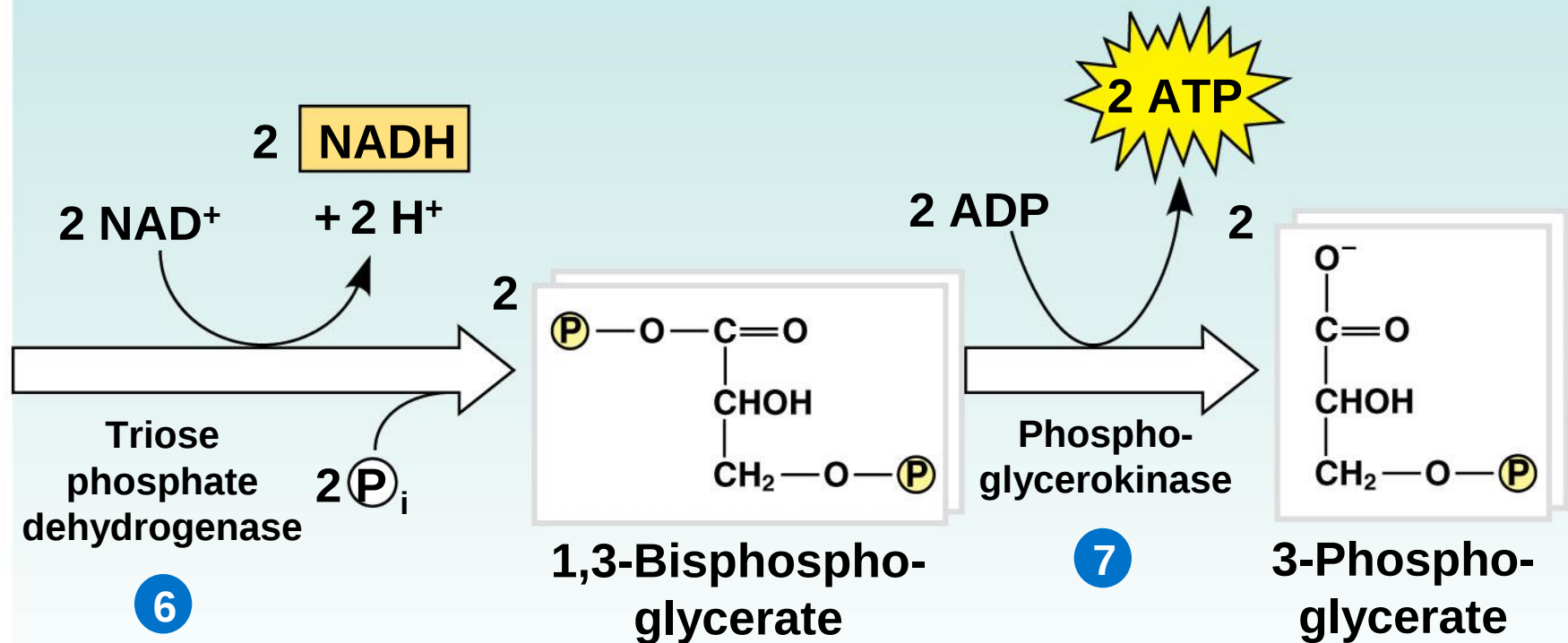
Glycolysis: Energy Investment Phase



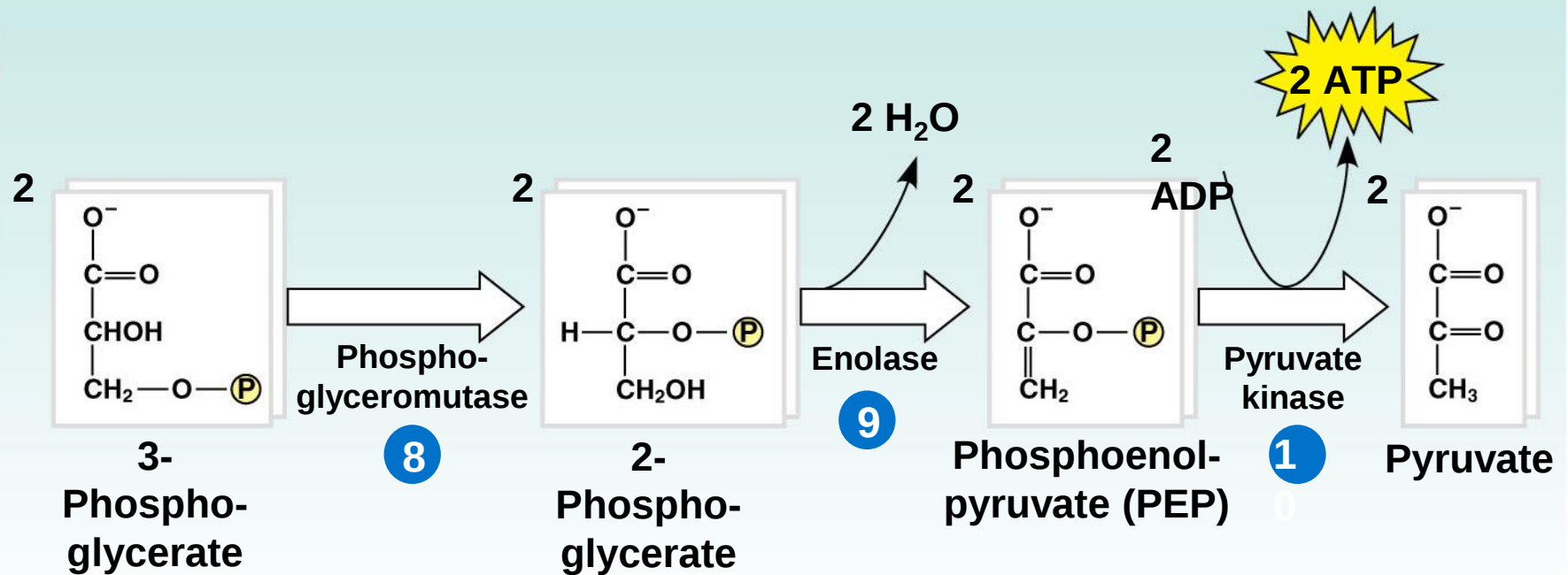
Glycolysis: Energy Investment Phase



Glycolysis: Energy Payoff Phase



Glycolysis: Energy Payoff Phase



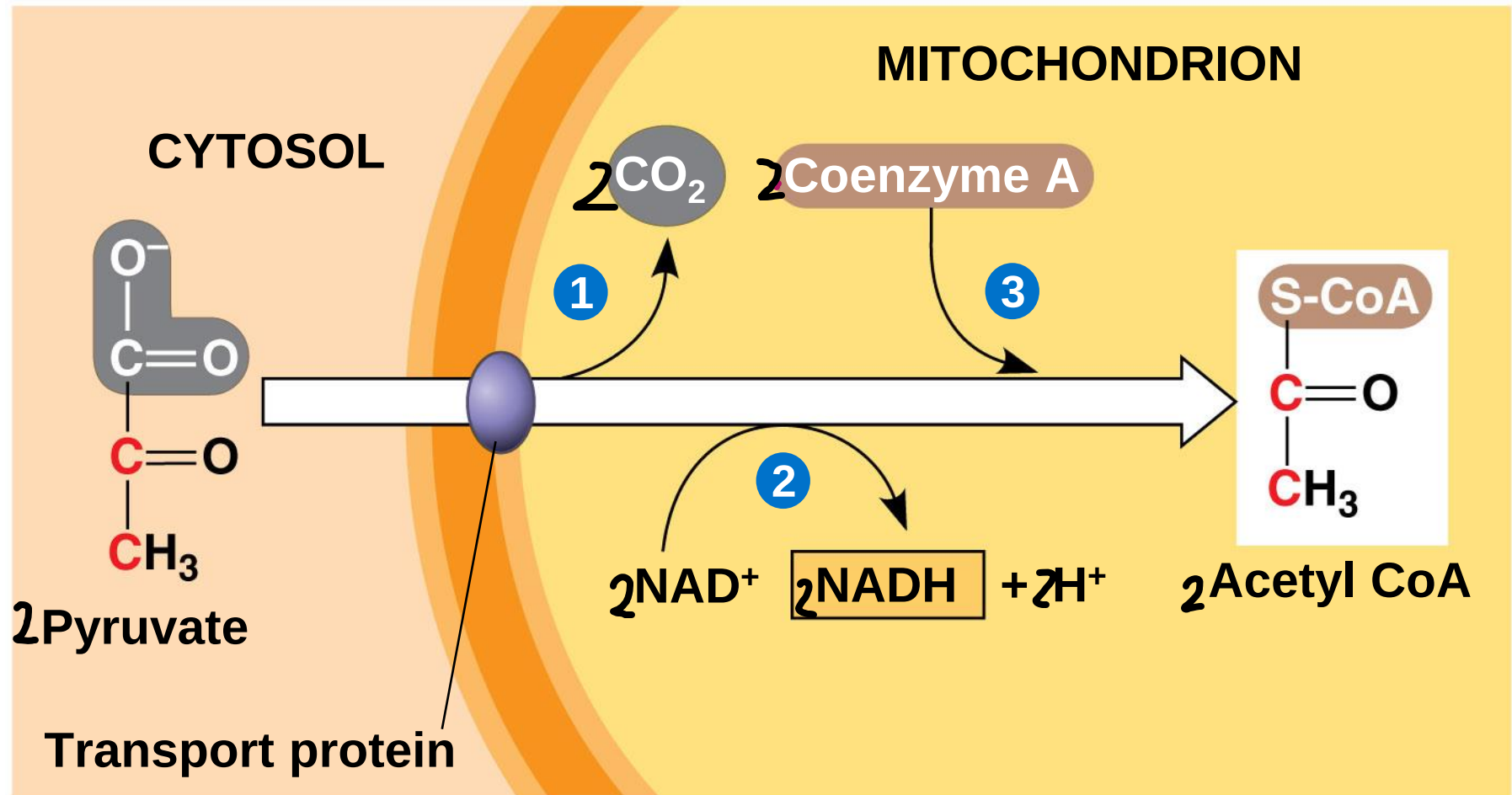
Concept 9.3: The **citric acid cycle** completes the energy-yielding oxidation of organic molecules

- **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 its 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

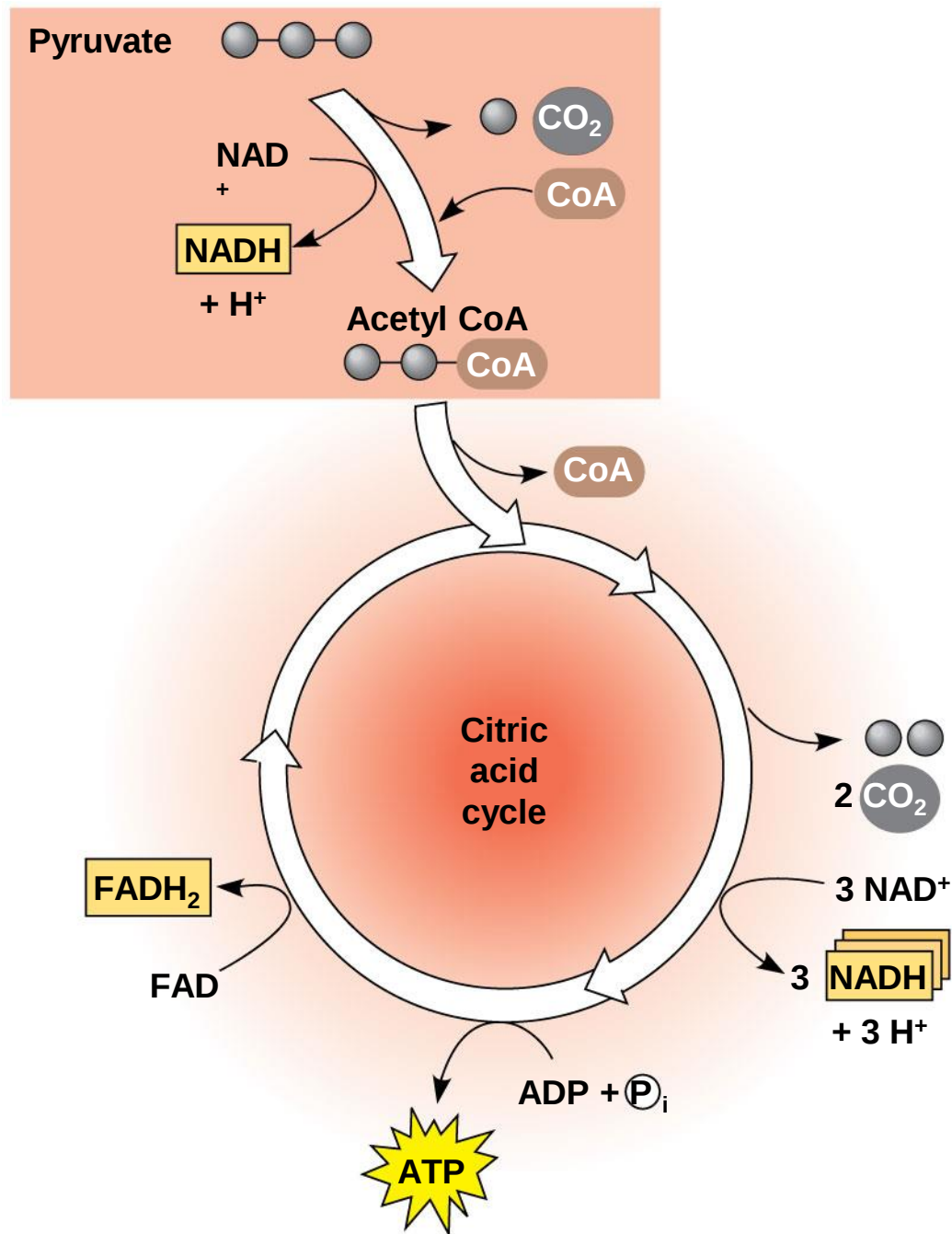


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The Citric Acid Cycle

- 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 FADH₂ 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 FADH₂ produced by the cycle relay **electrons** extracted from food to the electron transport chain

Figure 9.12-1

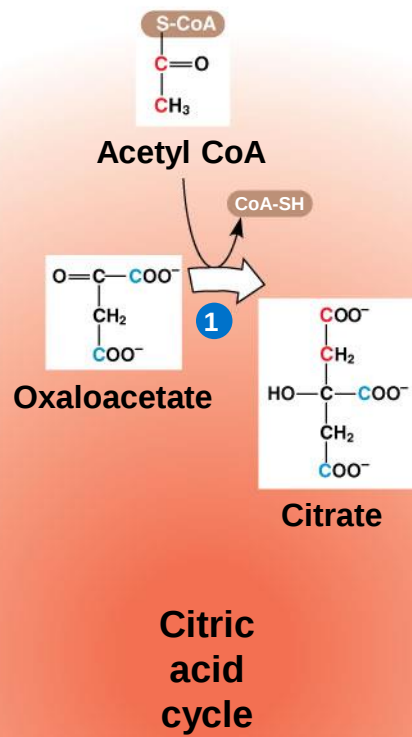
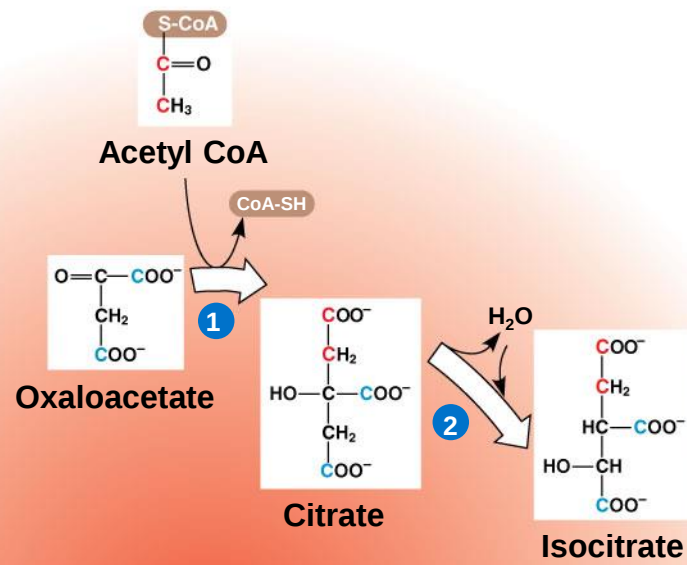


Figure 9.12-2



**Citric
acid
cycle**

Figure 9.12-3

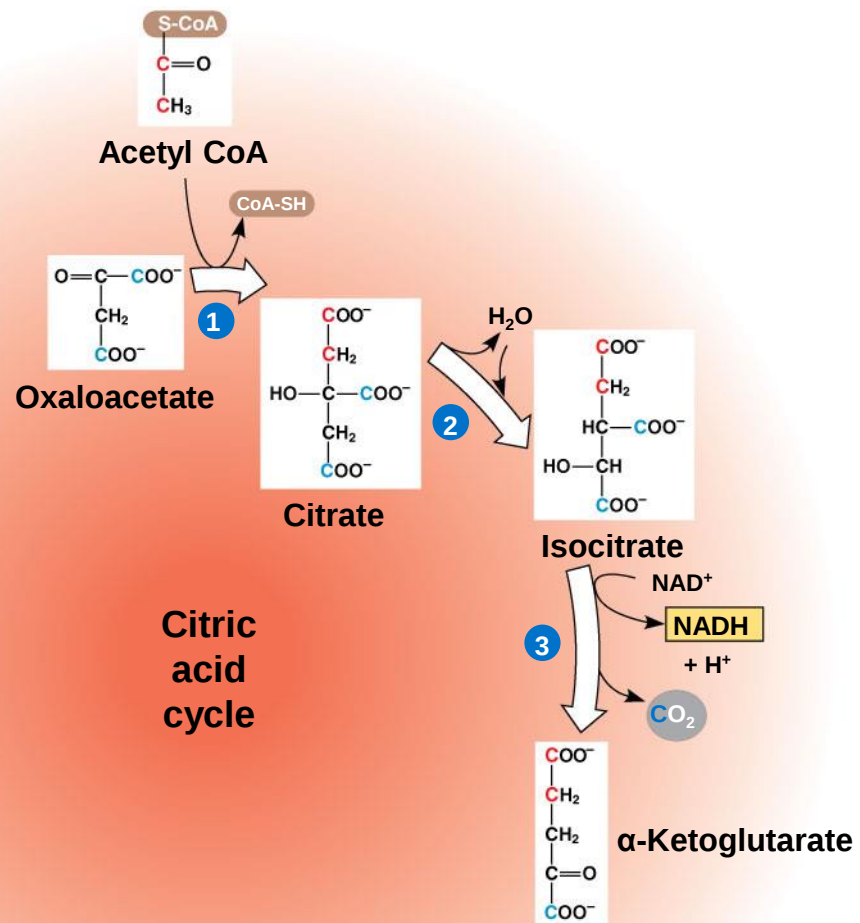


Figure 9.12-4

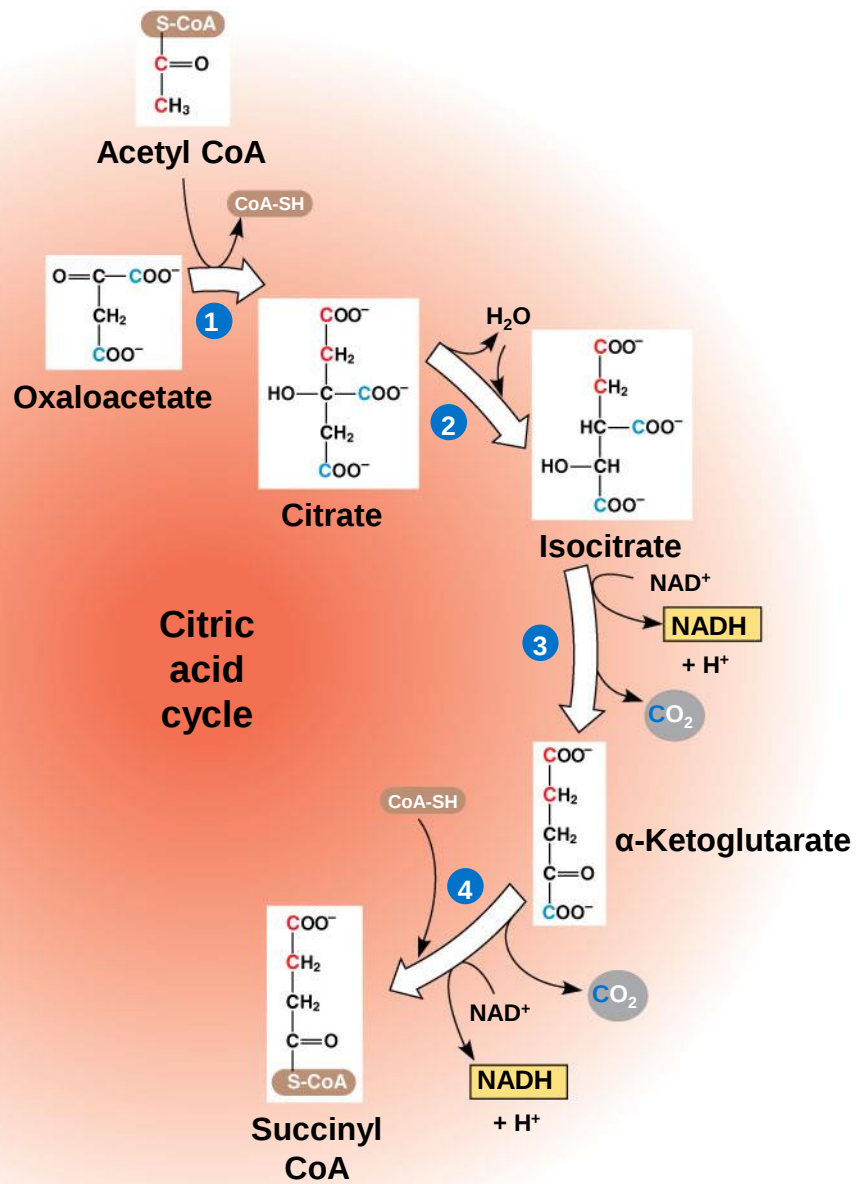


Figure 9.12-5

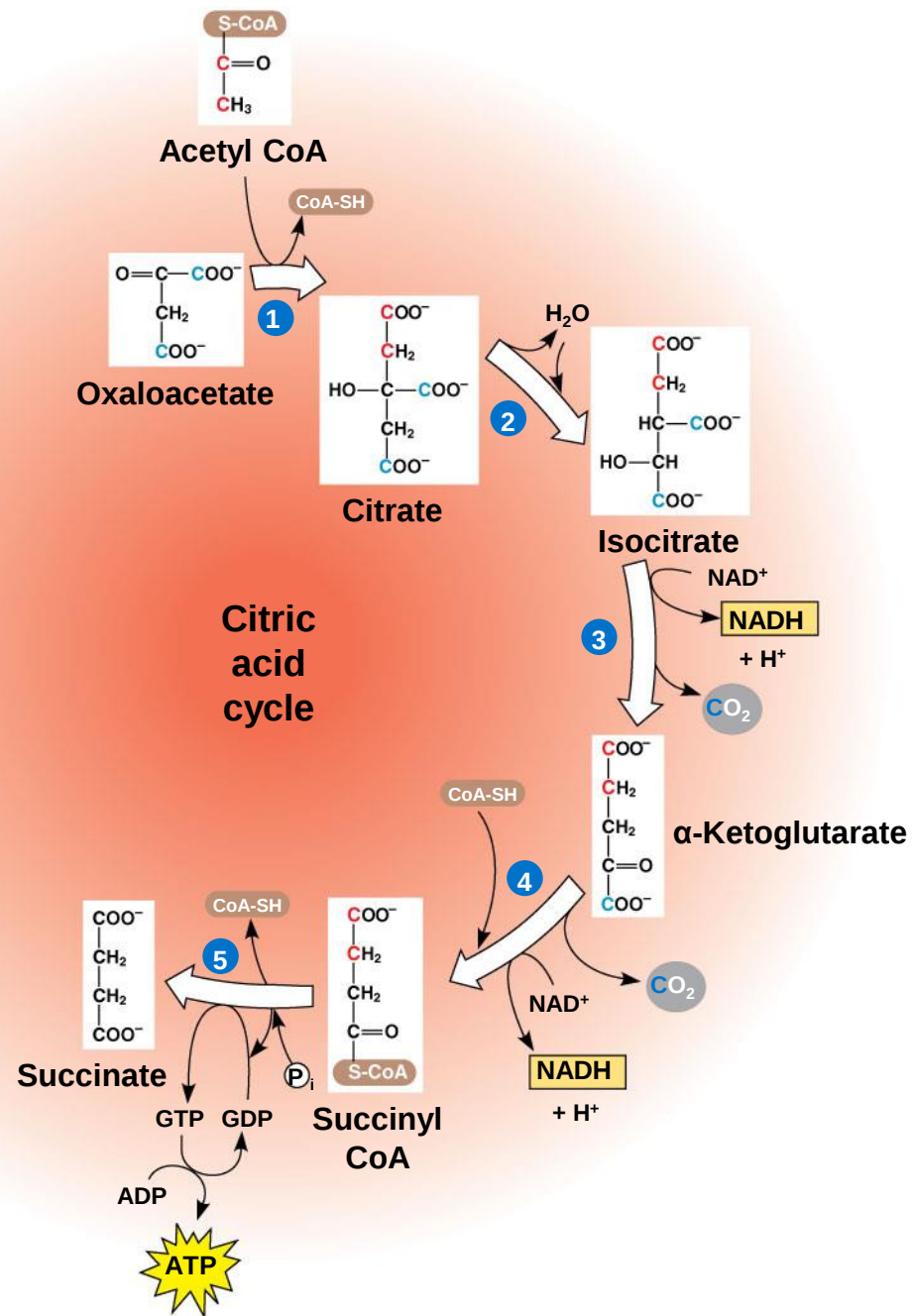


Figure 9.12-6

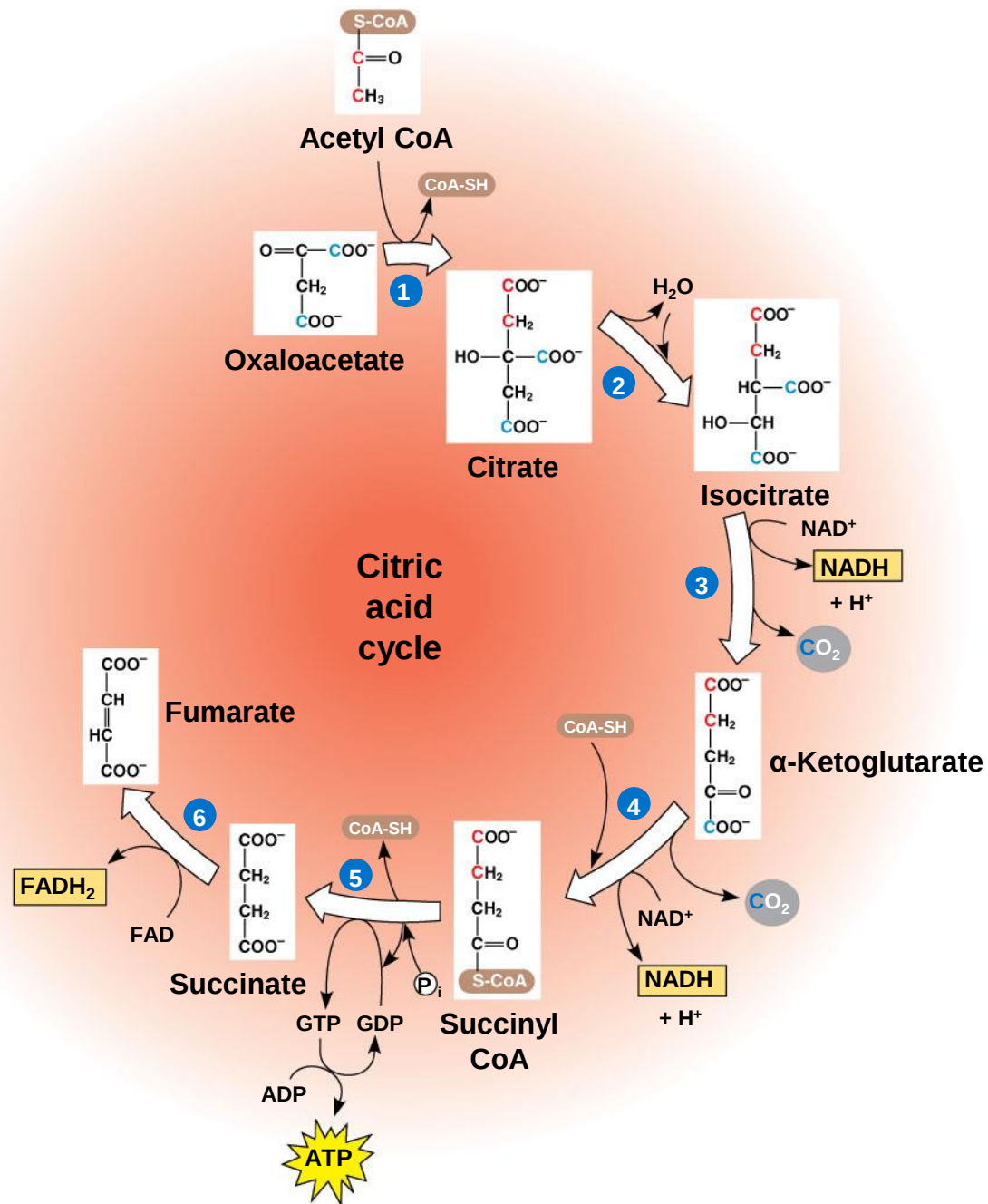


Figure 9.12-7

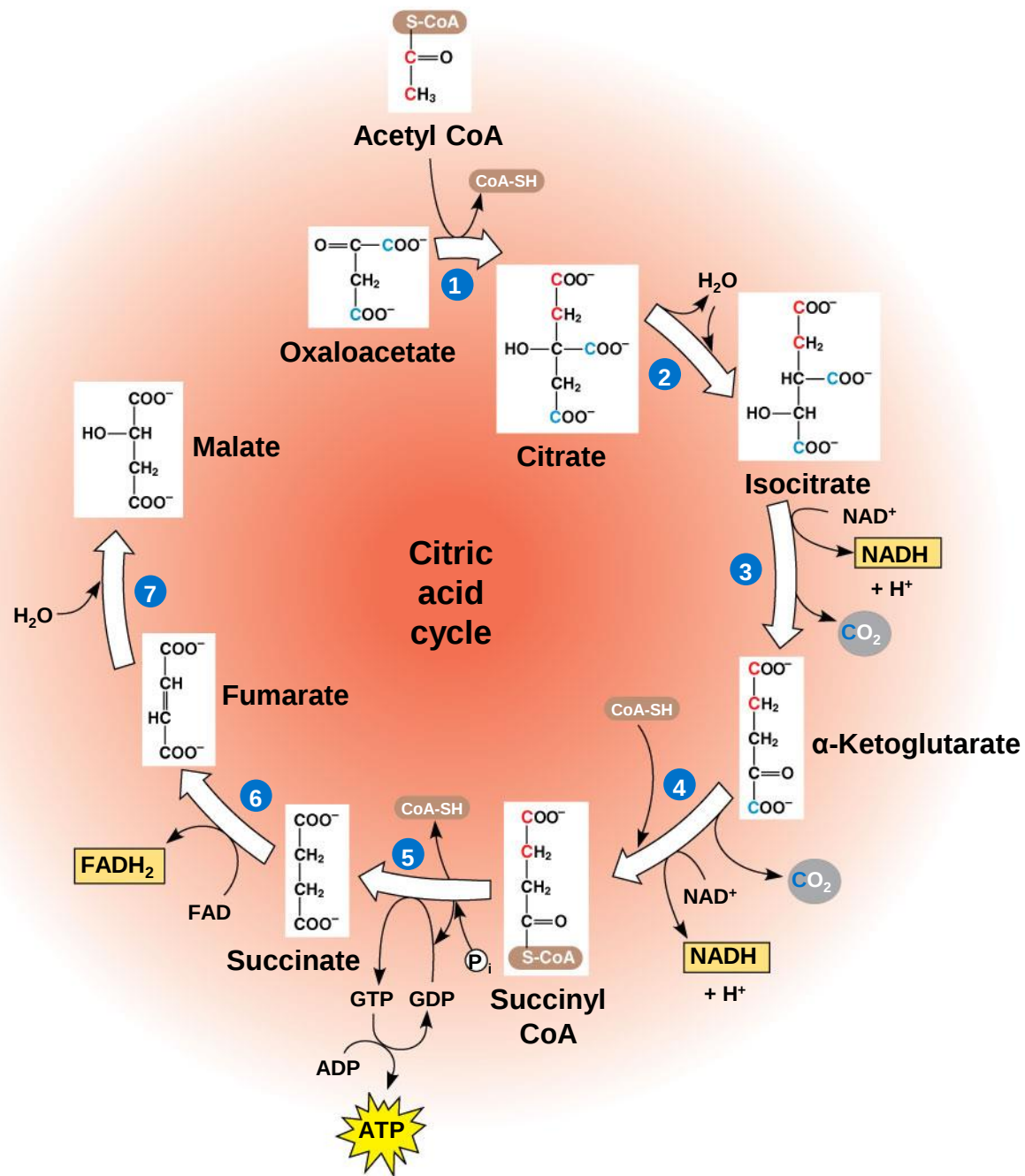
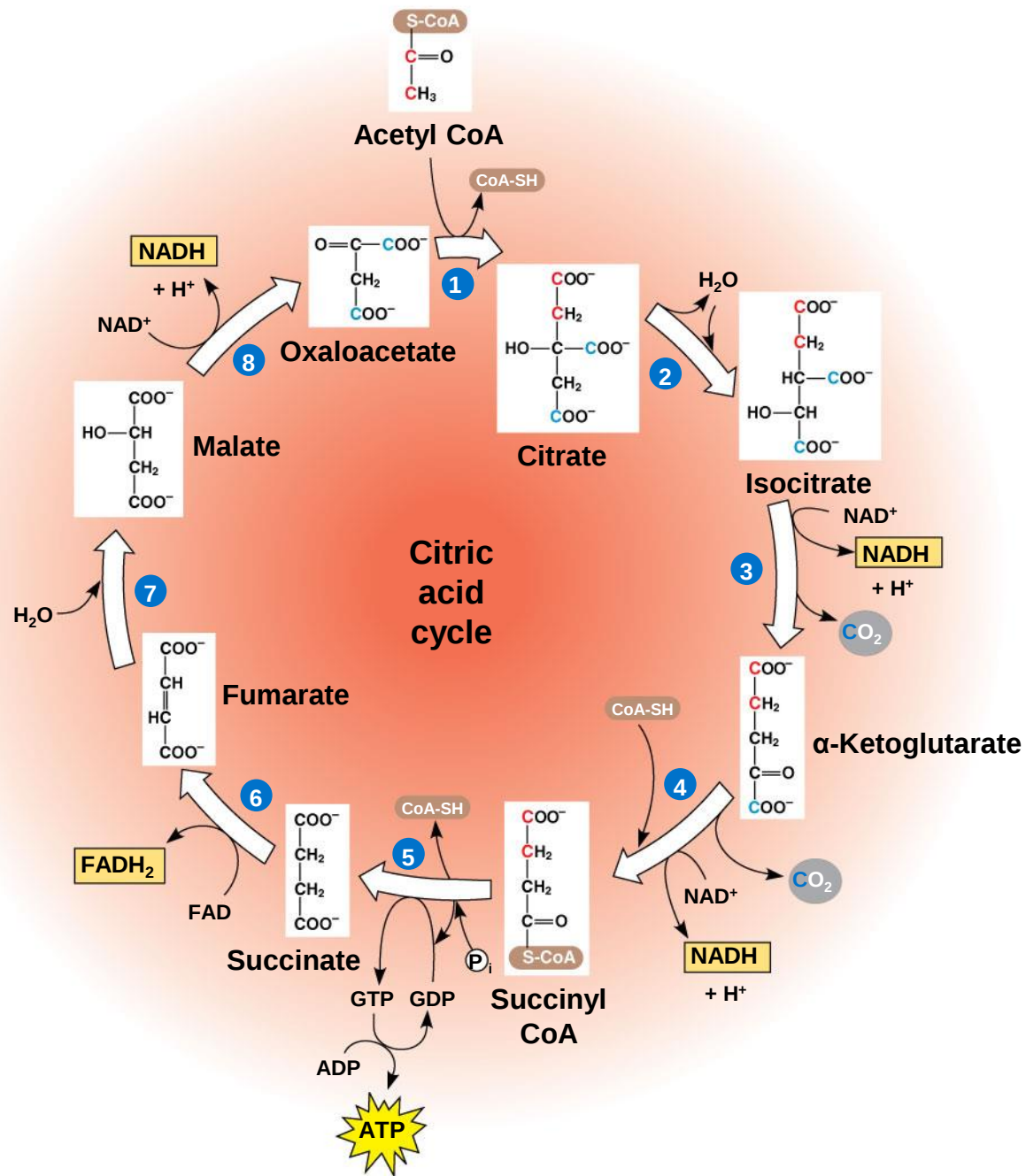


Figure 9.12-8

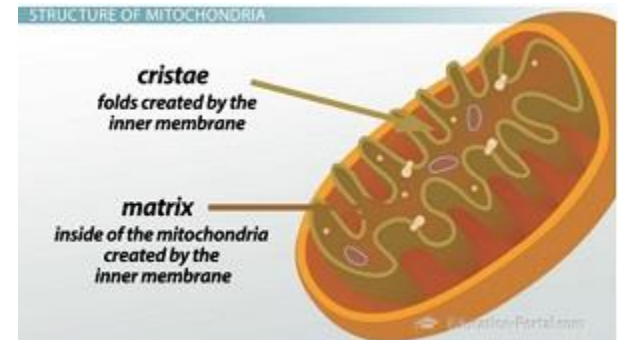


Concept 9.4: During **oxidative phosphorylation**, chemiosmosis couples electron transport to ATP synthesis

- Following glycolysis and the citric acid cycle, **NADH** and **FADH₂** 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 generates no ATP***
- **Electrons drop** in free energy as they go down the chain and are **finally passed to O₂, forming H₂O**

Figure 9.13

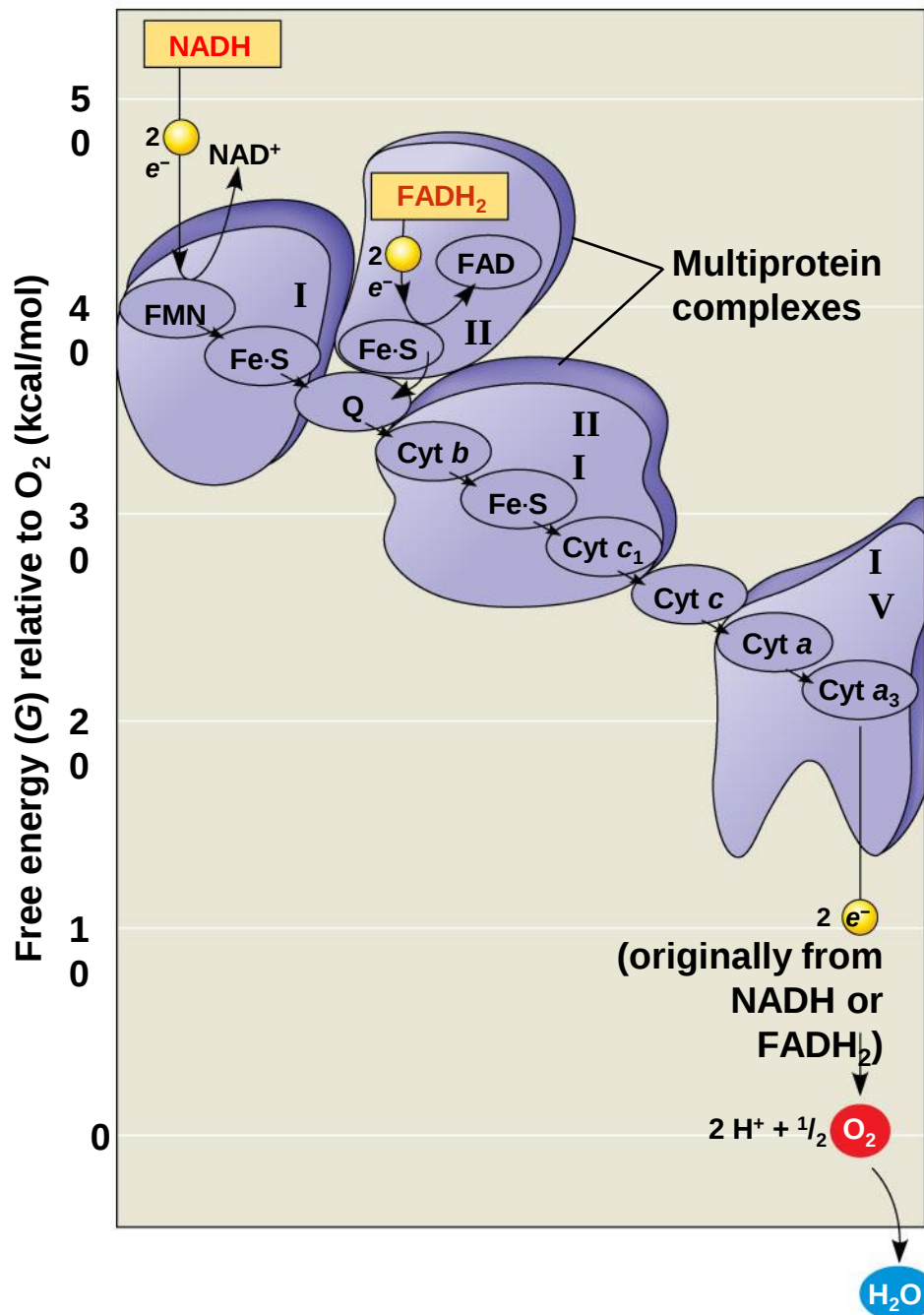
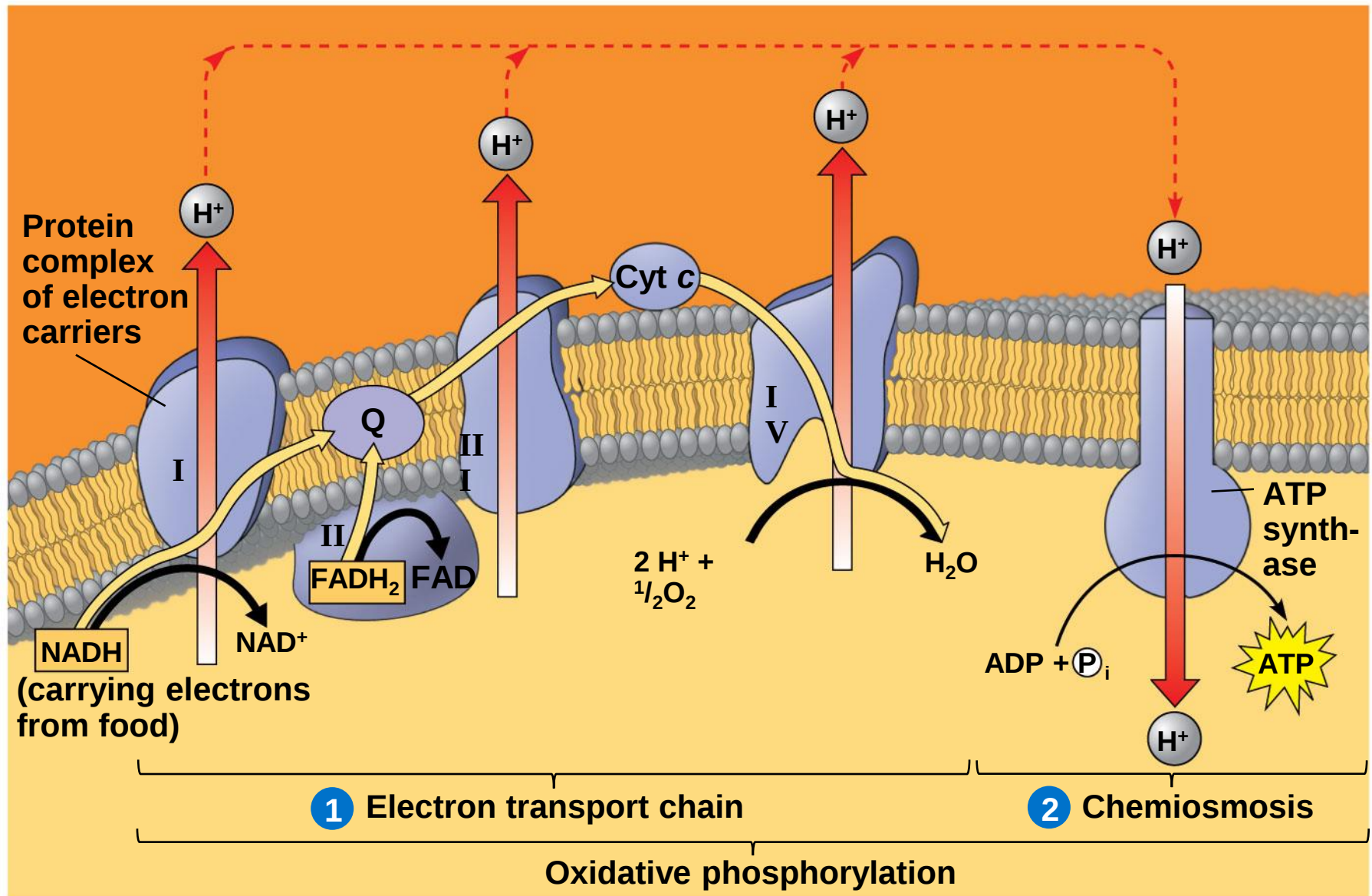


Figure 9.15



- 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**
- 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

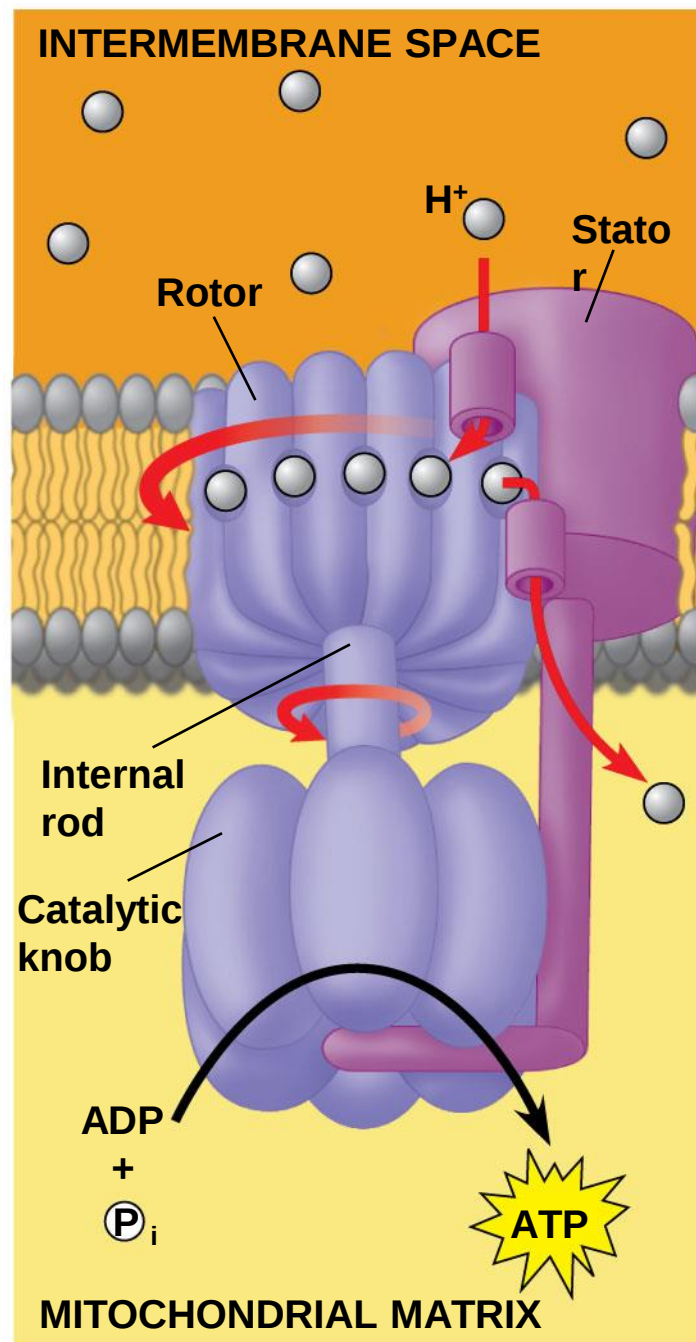
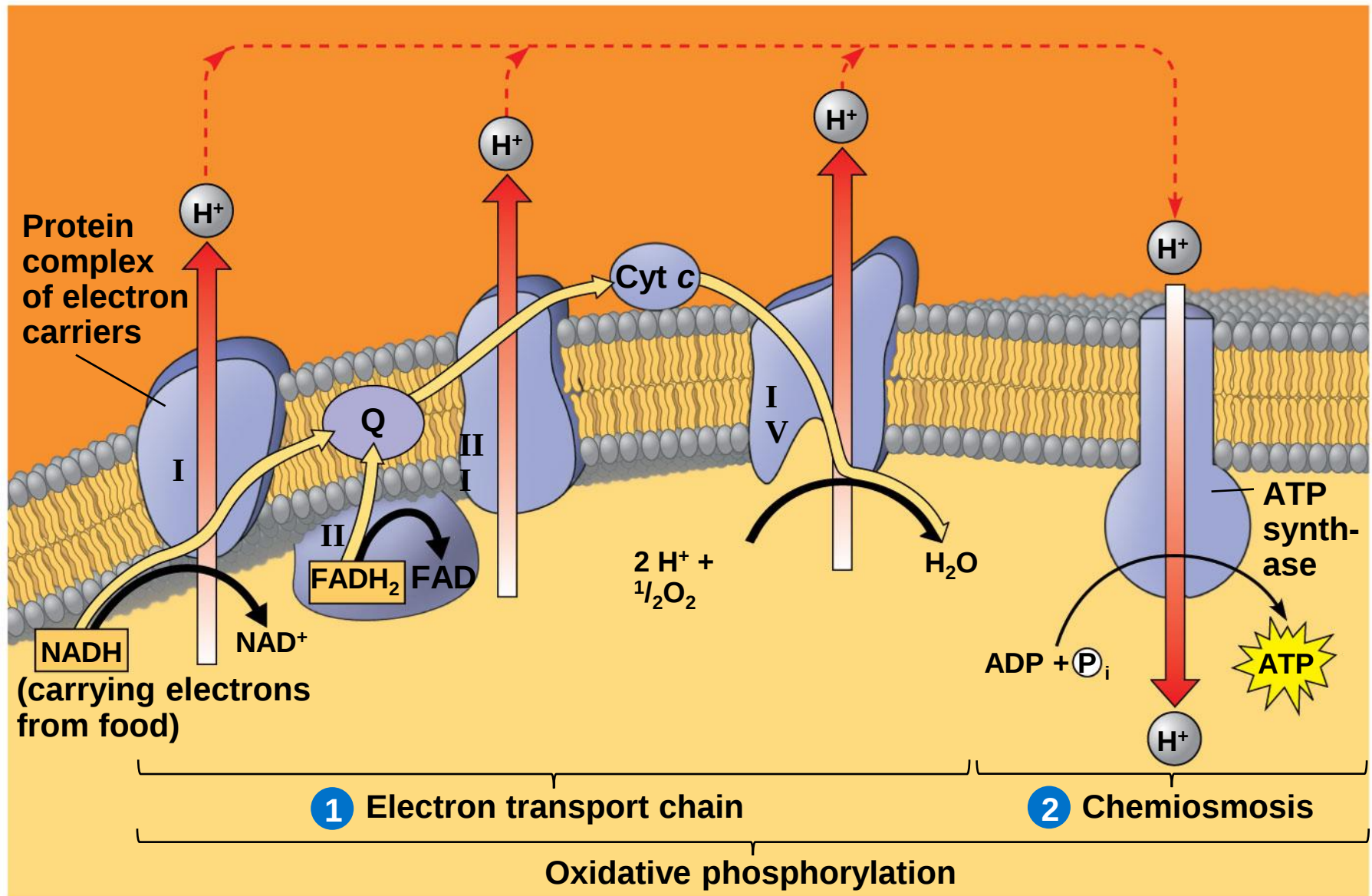


Figure 9.15



- 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

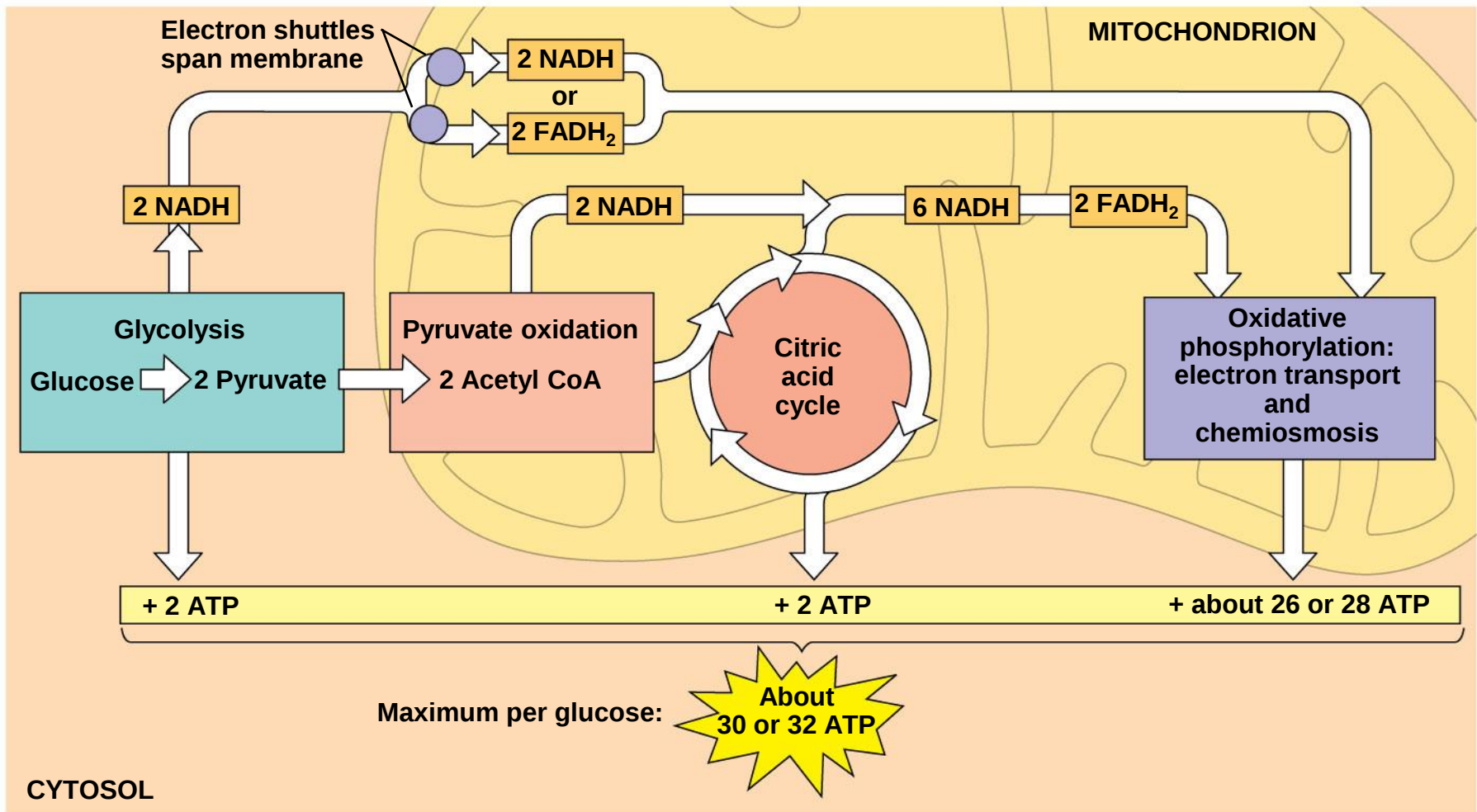
An Accounting of ATP Production by Cellular Respiration

- 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



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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)

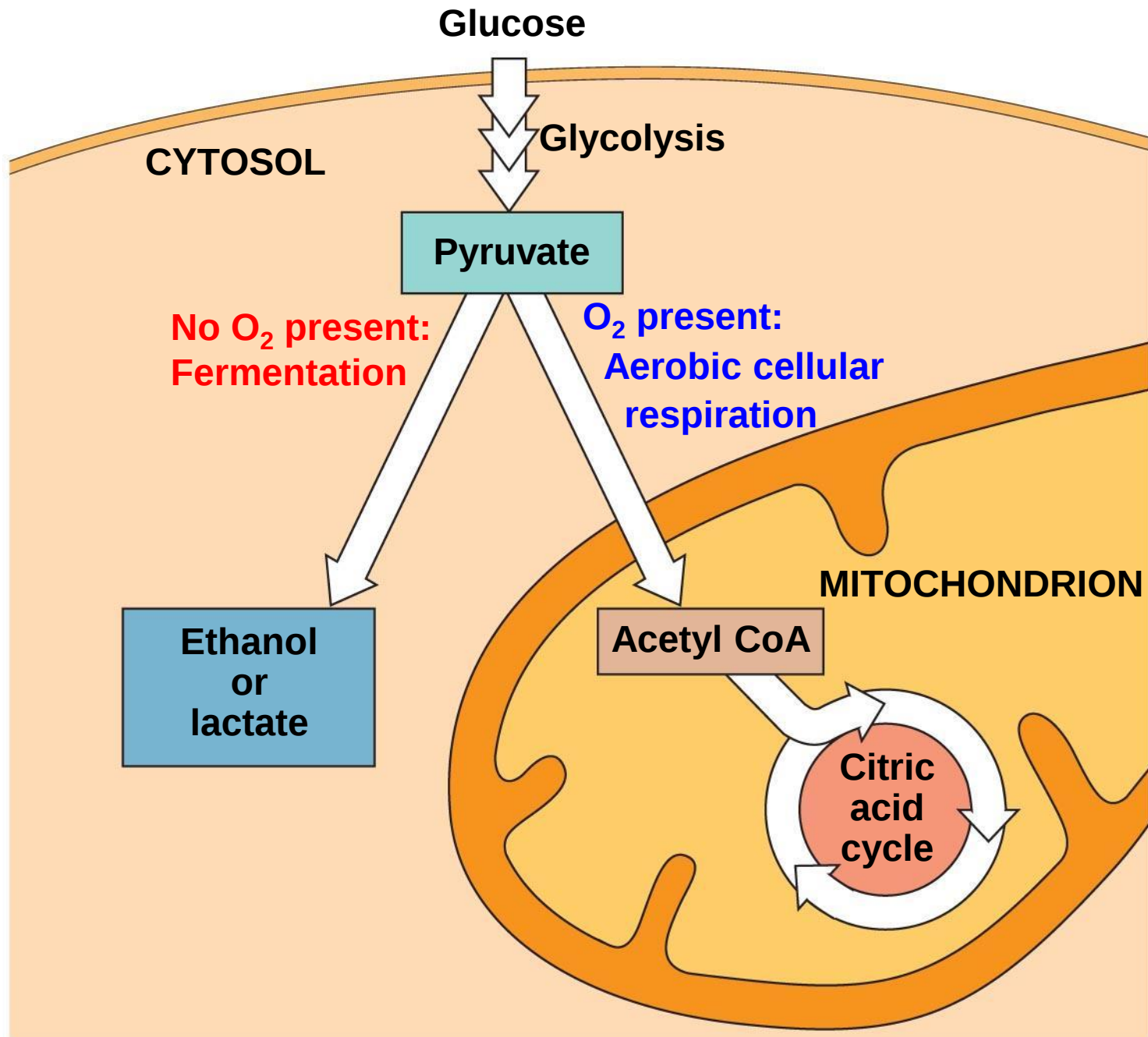
- In the absence of O_2 , glycolysis couples with fermentation or anaerobic respiration to produce ATP

- Anaerobic respiration uses an electron transport chain with **a final electron acceptor other than O₂** (e.g. sulfate)
- Fermentation uses **substrate-level phosphorylation** instead of an electron transport chain to generate ATP

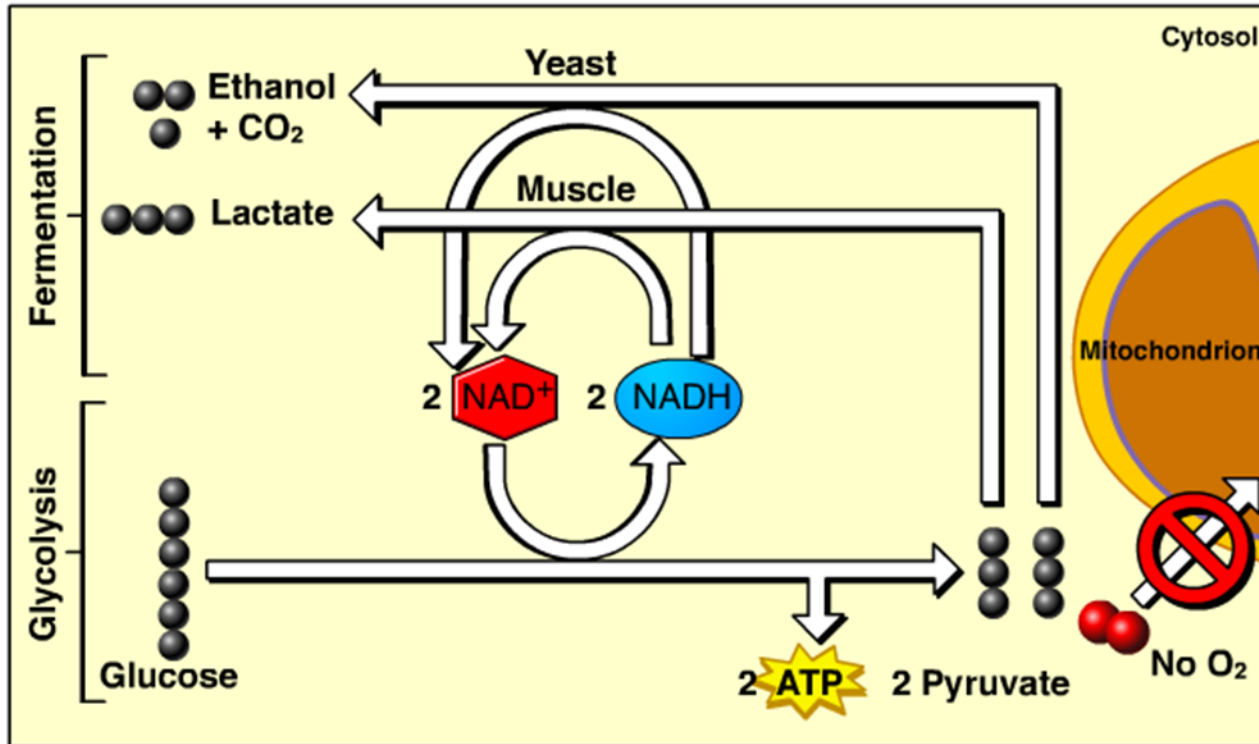
Types of Fermentation

- 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

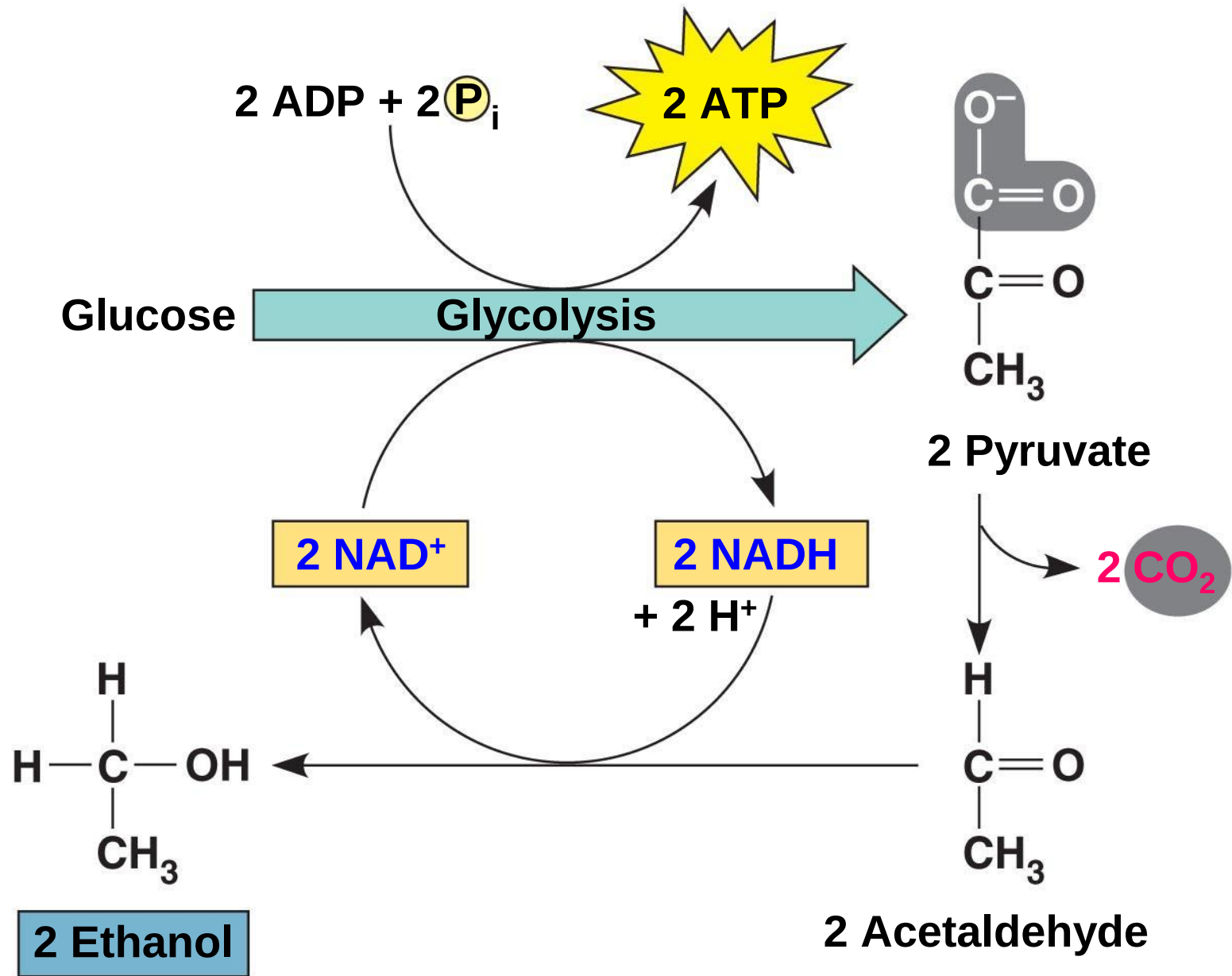
Fig. 9-19



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- In alcohol fermentation, pyruvate is converted to ethanol in two steps, with the first releasing CO₂
 - Alcohol fermentation by yeast is used in **brewing**, winemaking, and baking

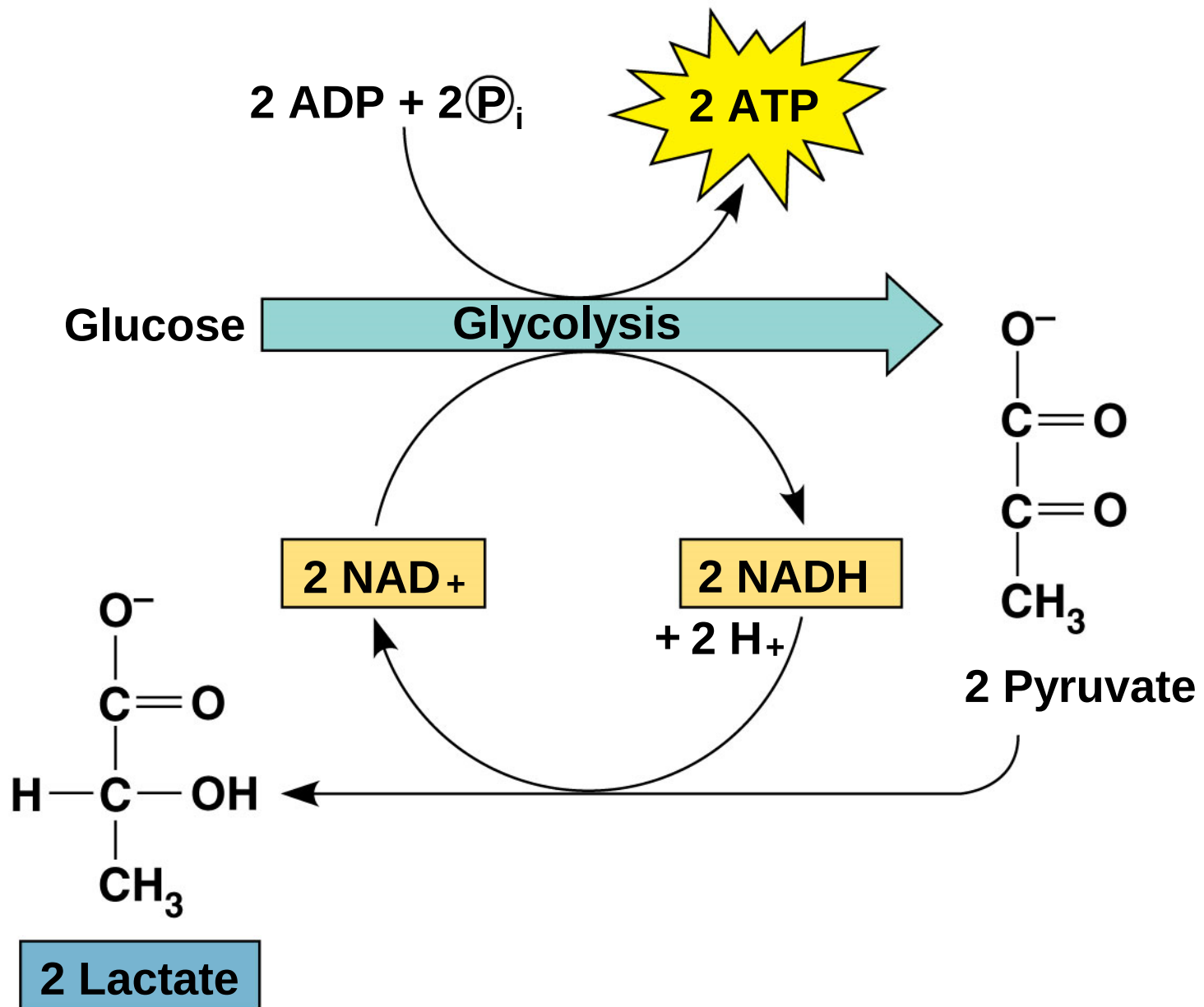


Animation: Fermentation Overview
Right-click slide / select "Play"



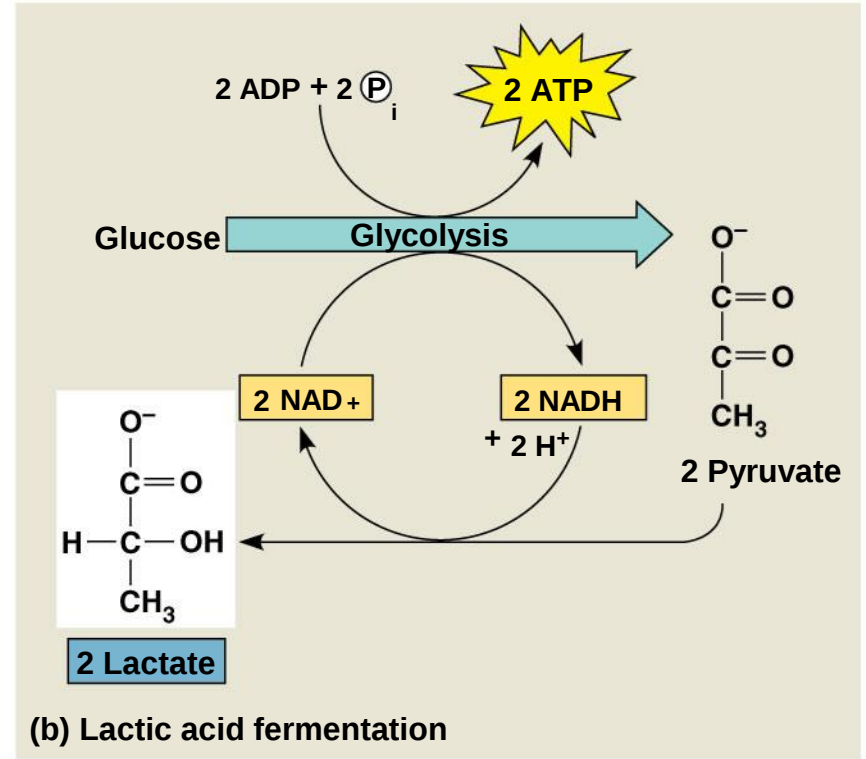
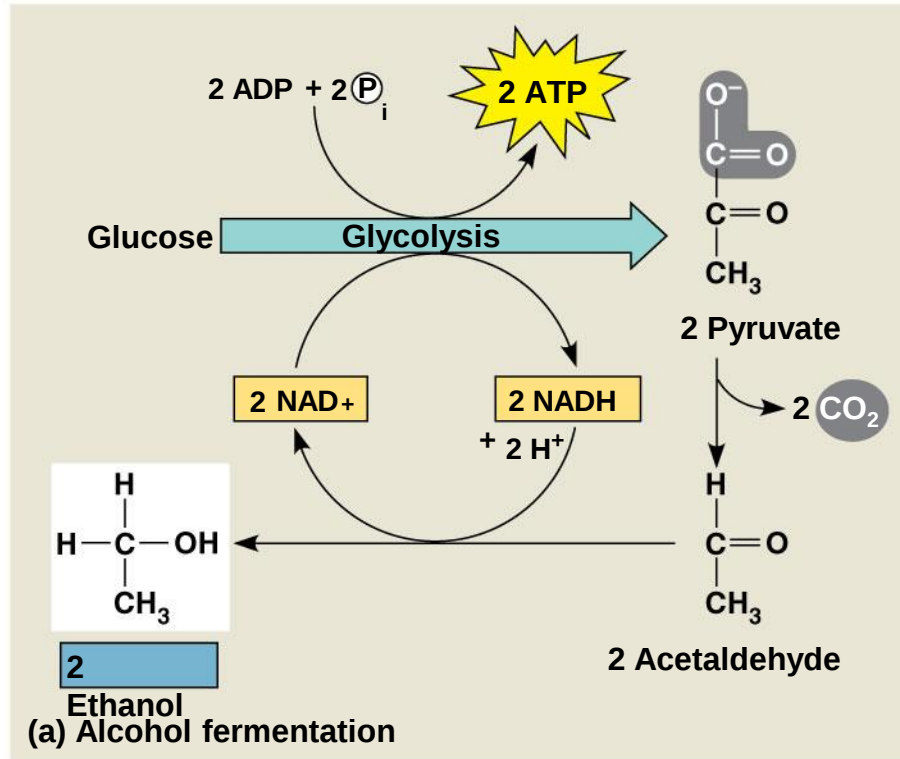
(a) Alcohol fermentation

- In **lactic acid fermentation**, pyruvate is **reduced to NADH**, forming **lactate** as an end product, **with no release of CO₂**
- 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 O₂ is scarce**



(b) Lactic acid fermentation

Figure 9.17



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

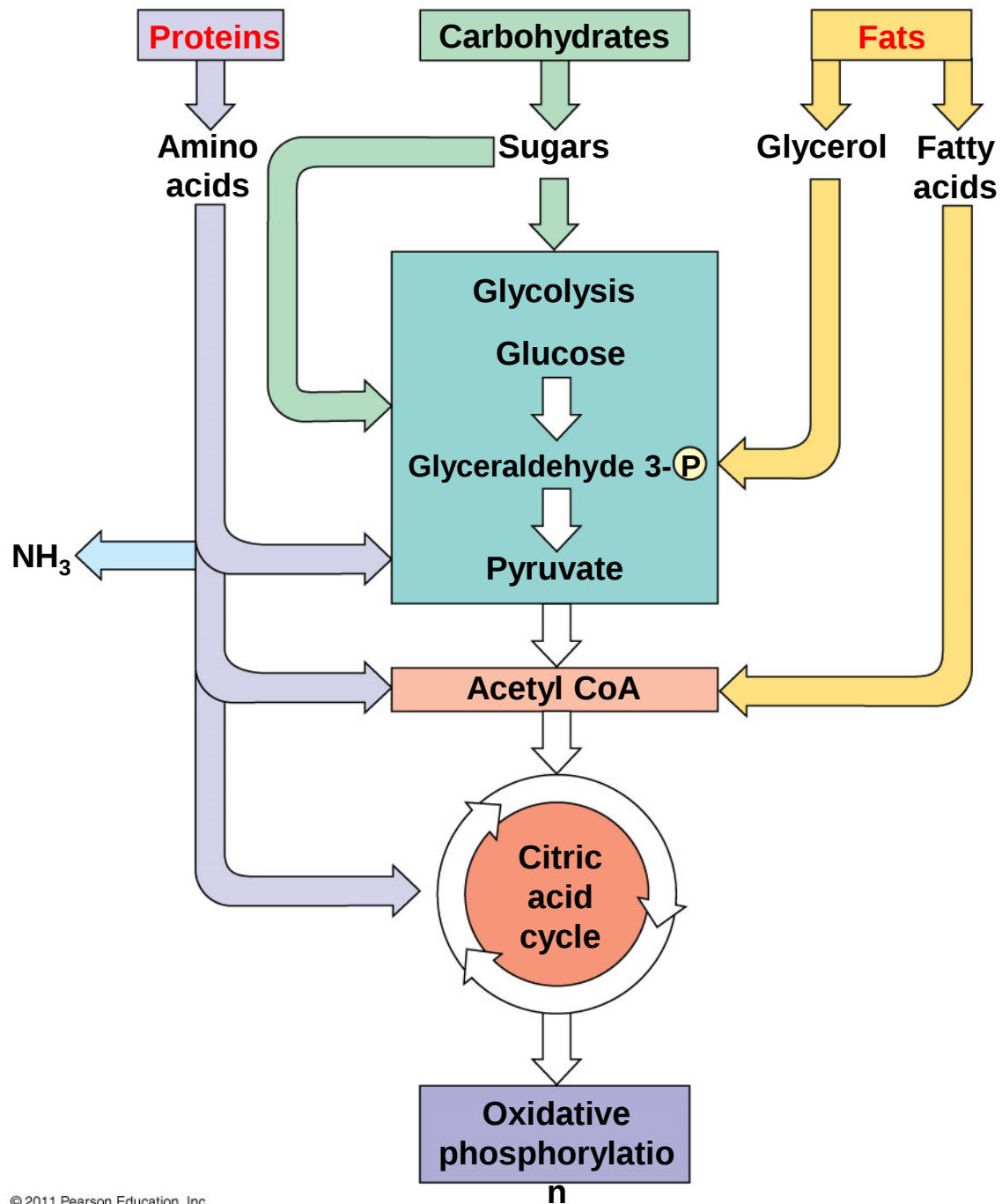
- **Glycolysis and the citric acid cycle are major intersections** to various catabolic and anabolic pathways

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** (able to adapt) **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

