

Overview: Life Is Work

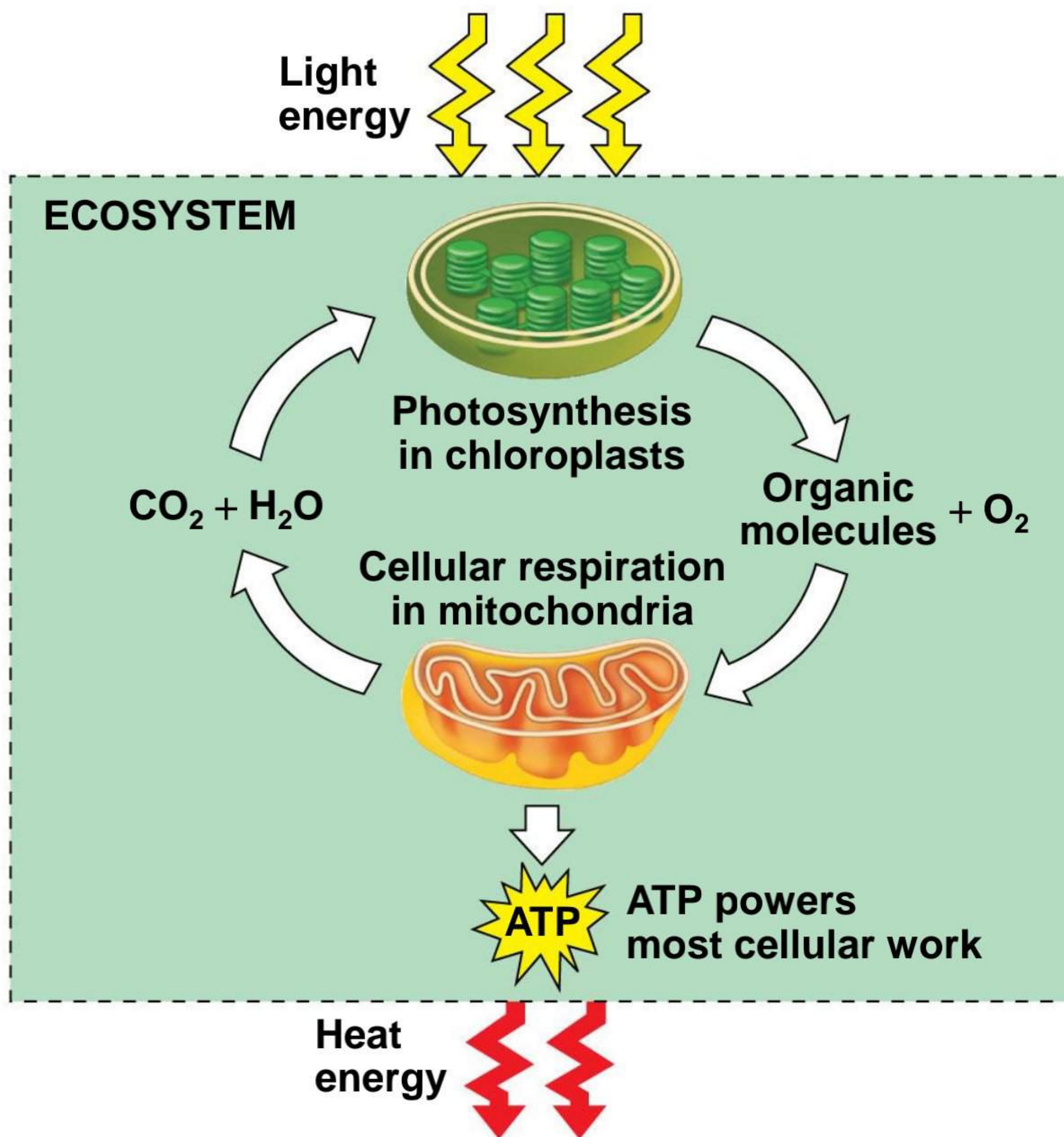
- Living cells require energy from outside sources
- Some animals, such as the chimpanzee, obtain energy by eating plants, and some animals feed on other organisms that eat plants

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

- Several processes are central to cellular respiration and related pathways

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

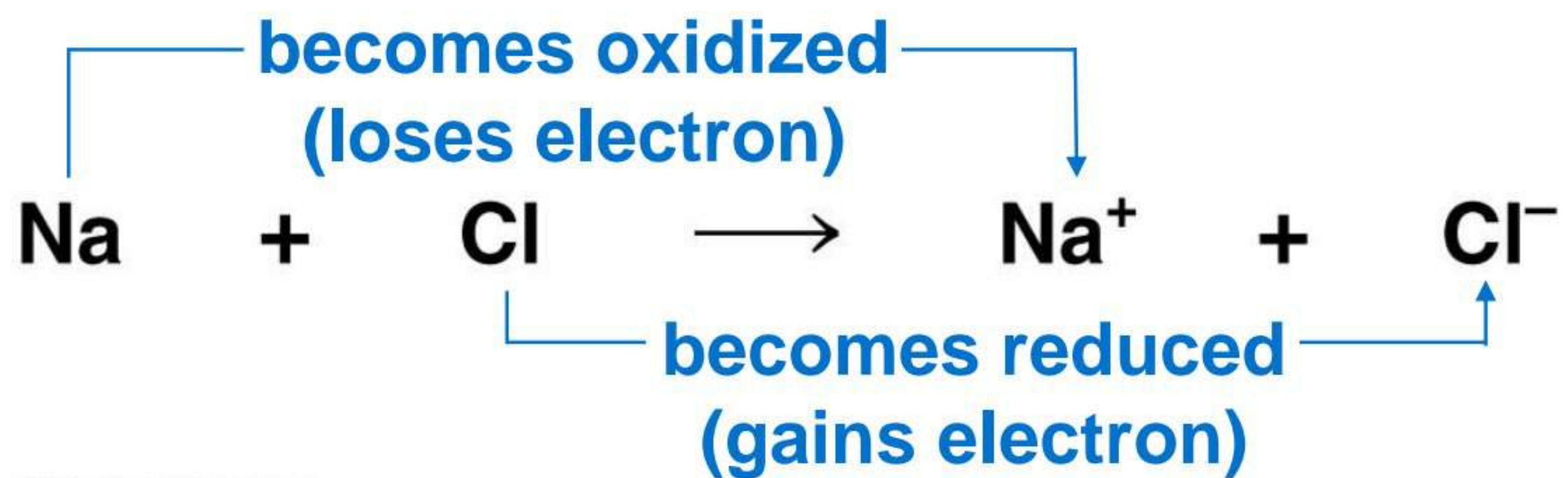


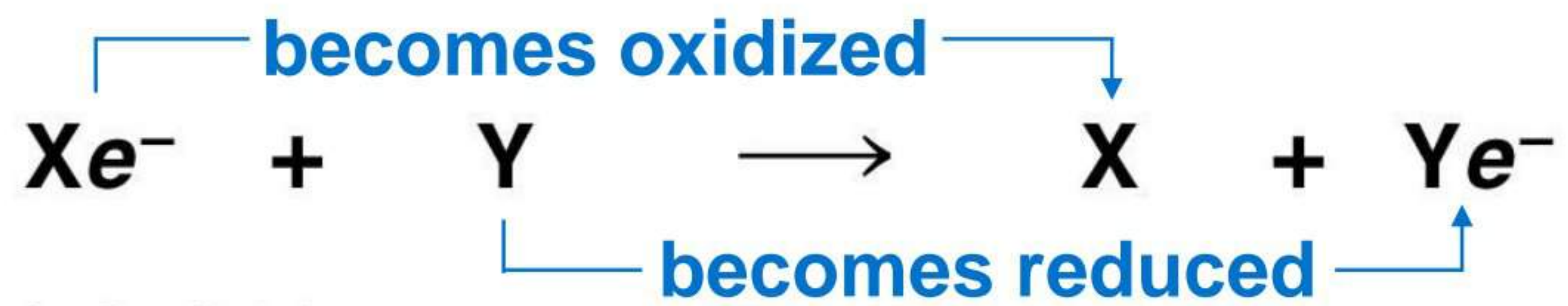
Redox Reactions: Oxidation and Reduction

- 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

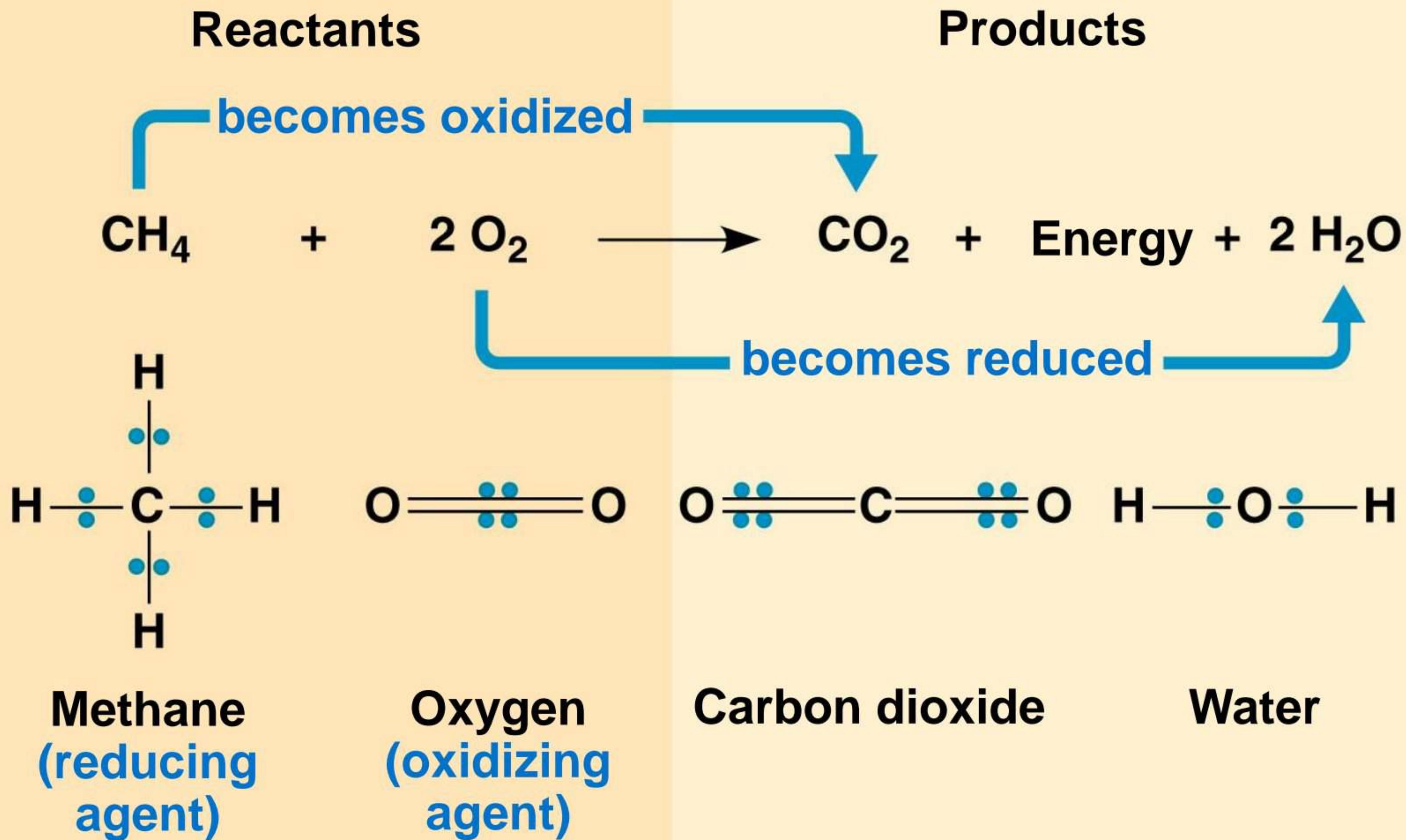
- Chemical reactions that transfer electrons between reactants are called oxidation-reduction reactions, or **redox reactions**
- In **oxidation**, a substance loses electrons, or is oxidized
- In **reduction**, a substance gains electrons, or is reduced (the amount of positive charge is reduced)





- 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

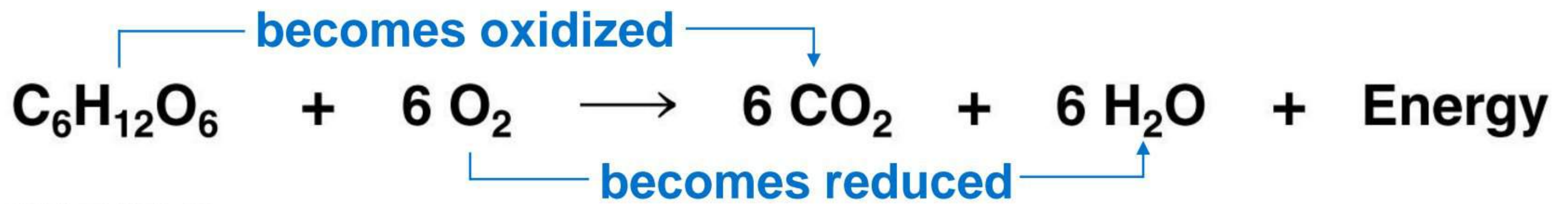
Figure 9.3



Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, the fuel (such as glucose) is oxidized, and O₂ is reduced

Figure 9.UN03



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

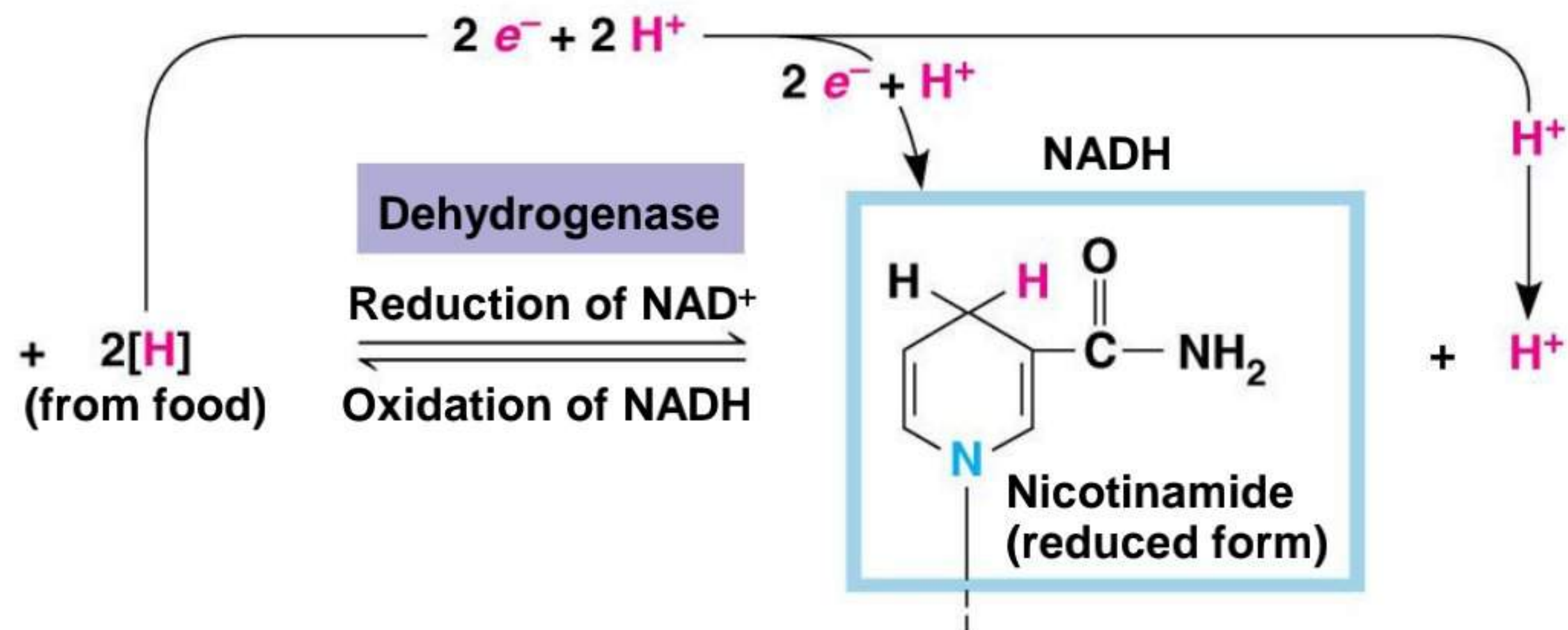
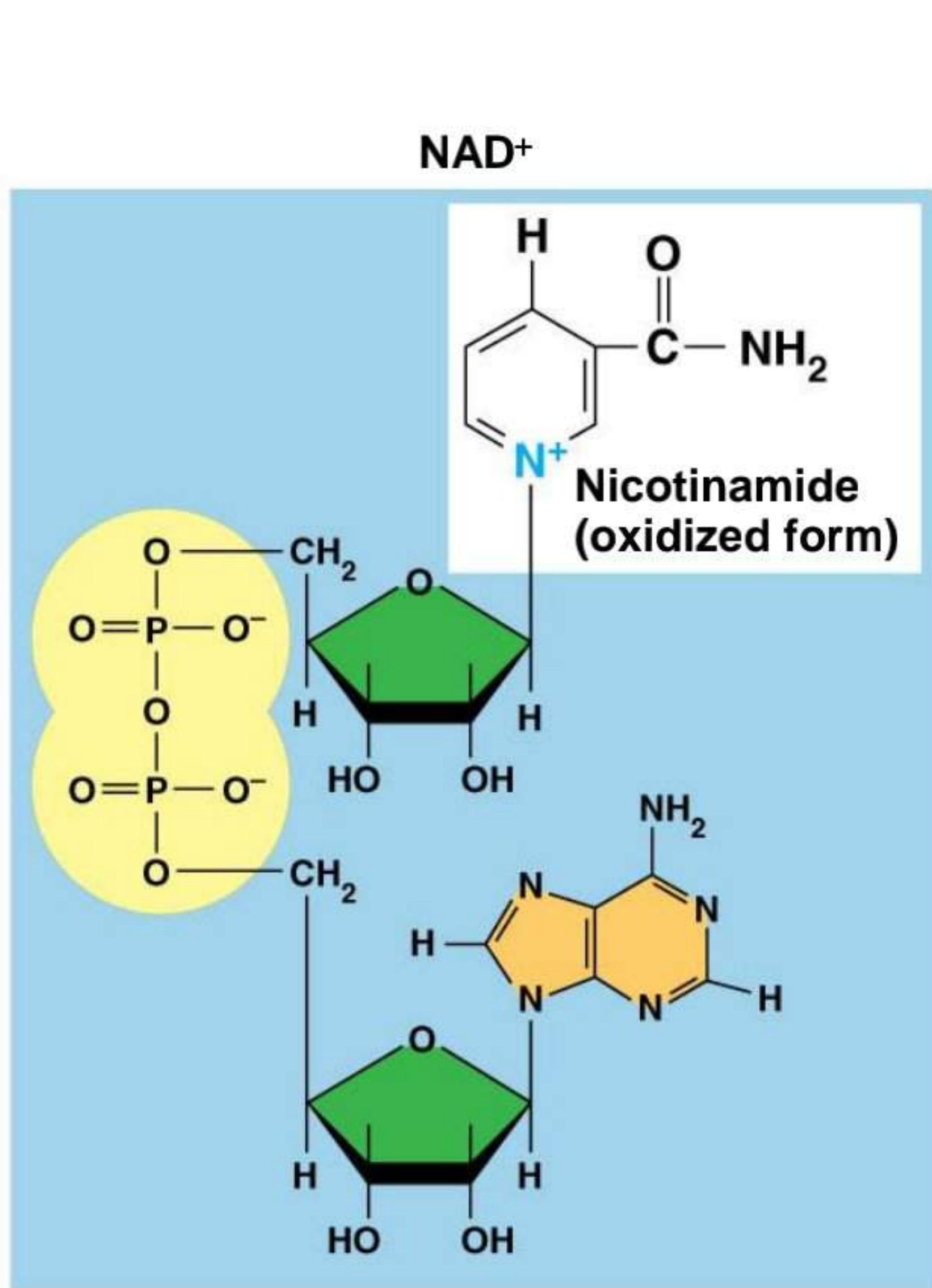
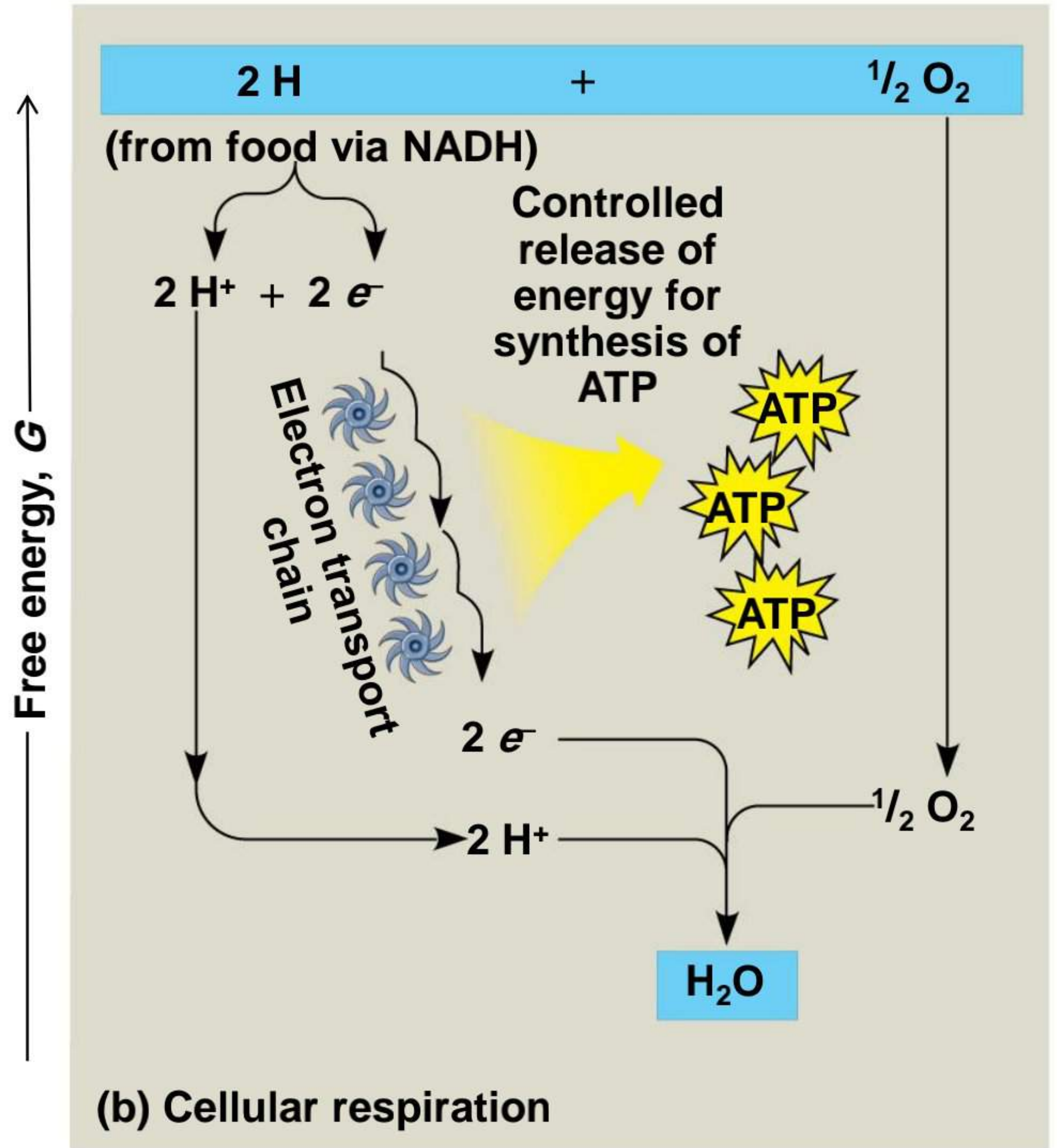
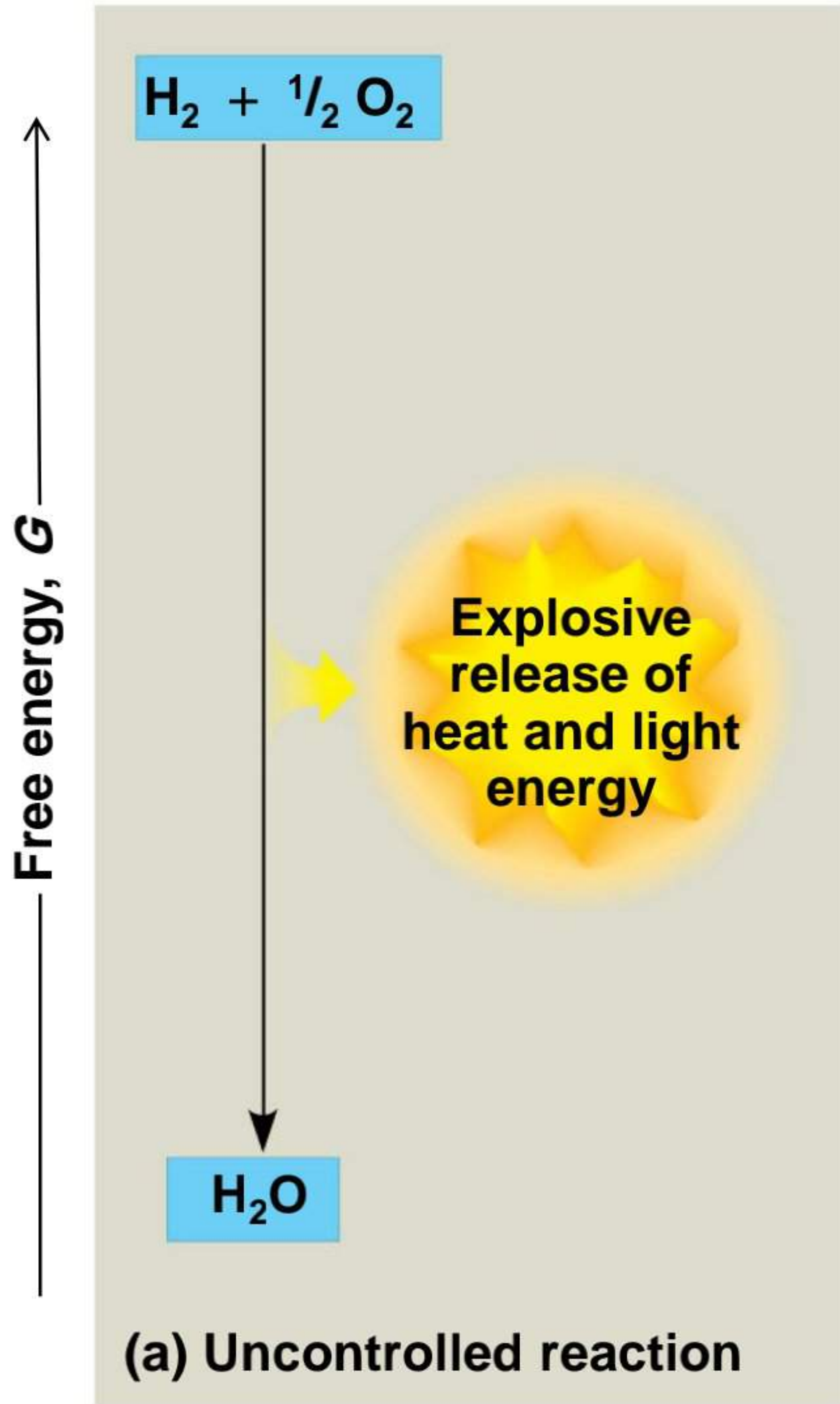


Figure 9.UN04



- 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

- 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)

- 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

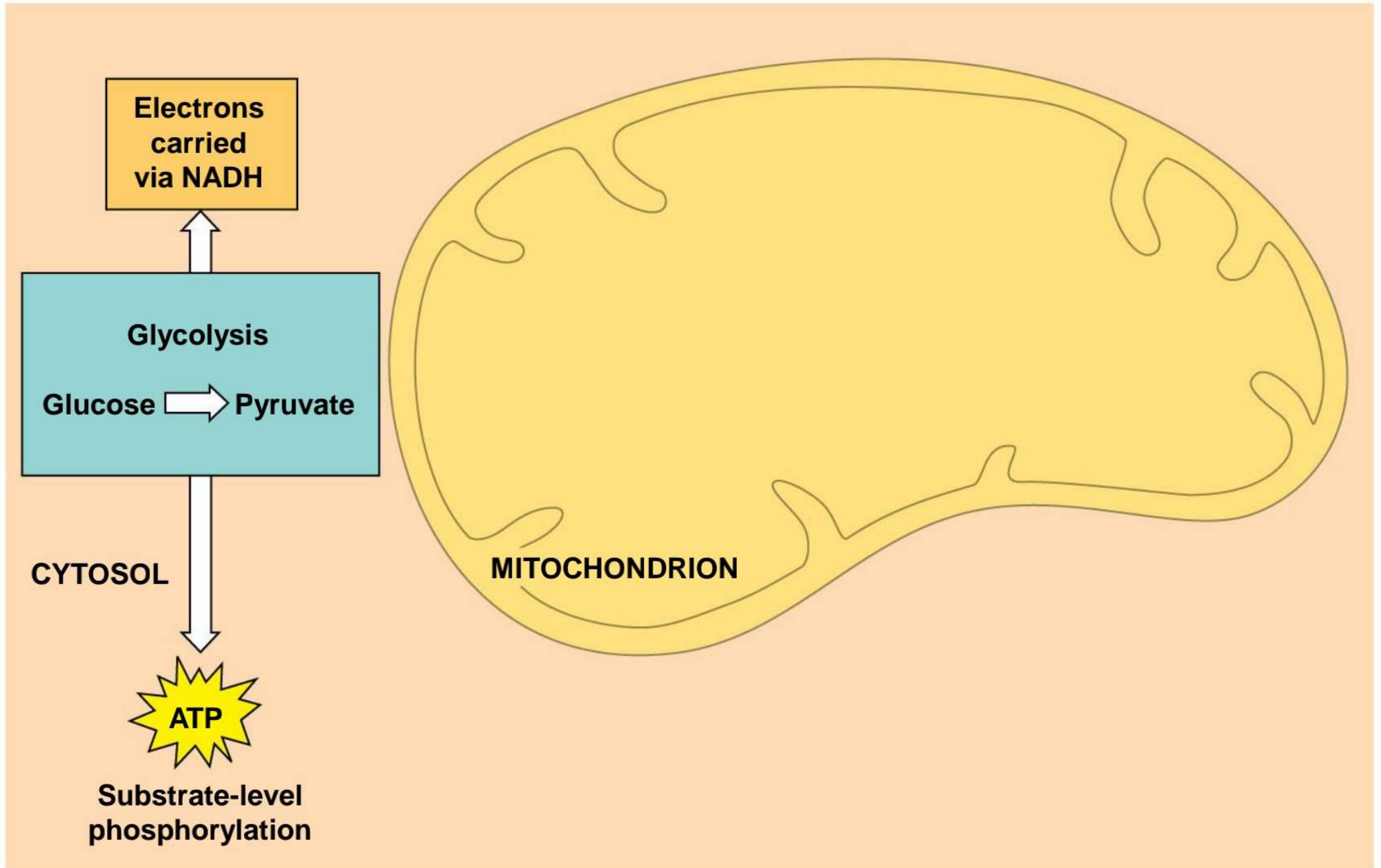


Figure 9.6-2

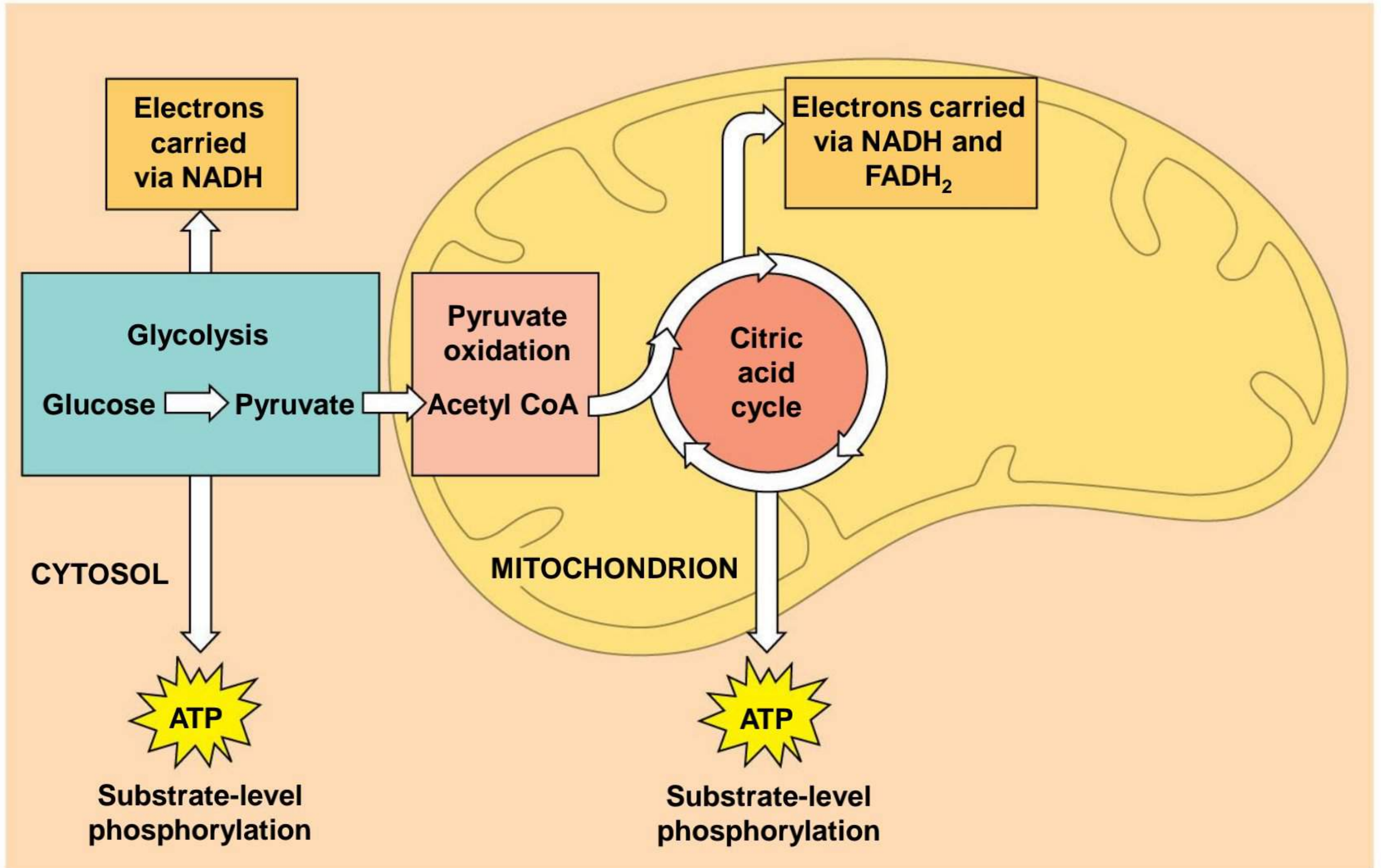
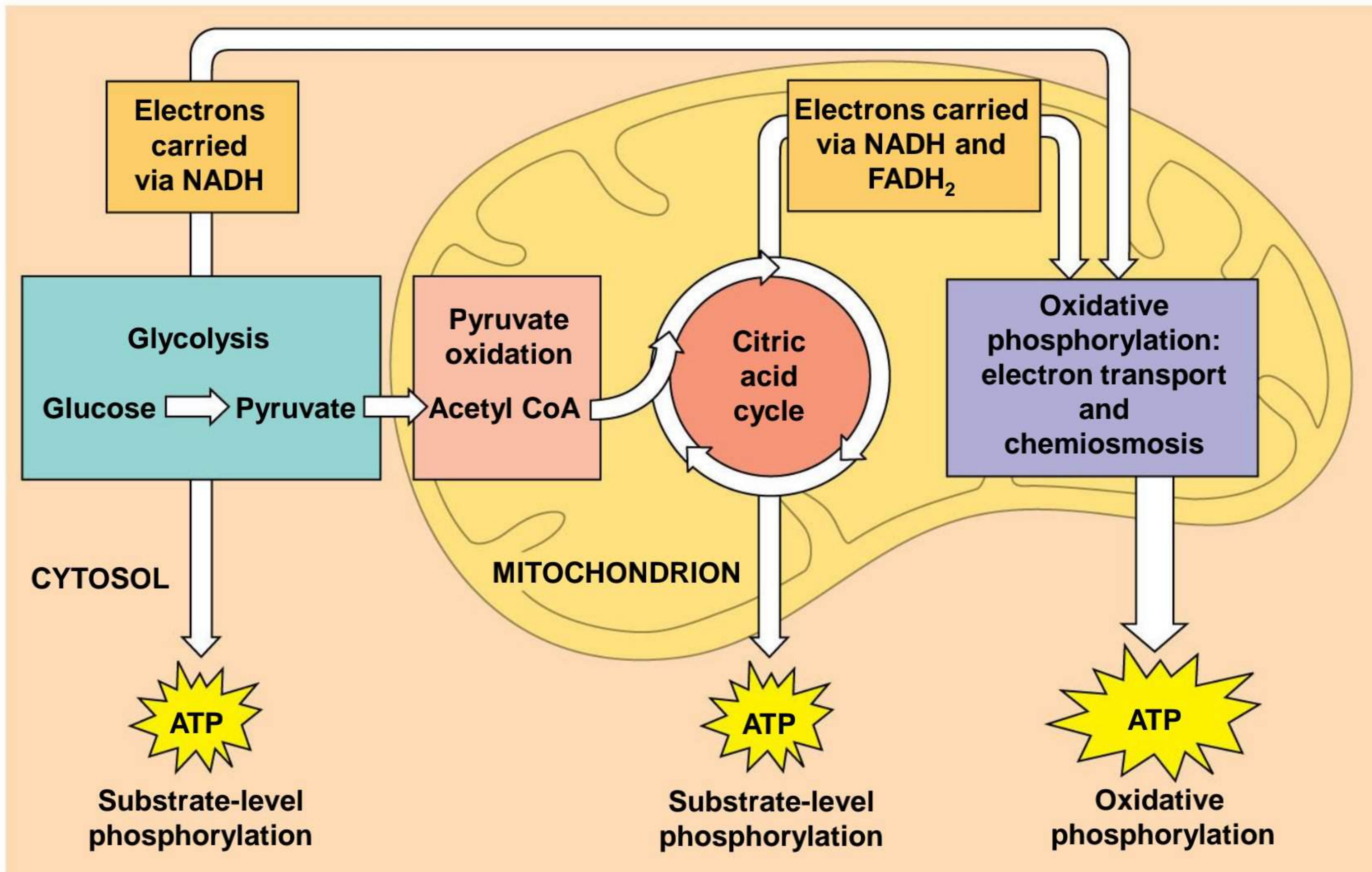


Figure 9.6-3



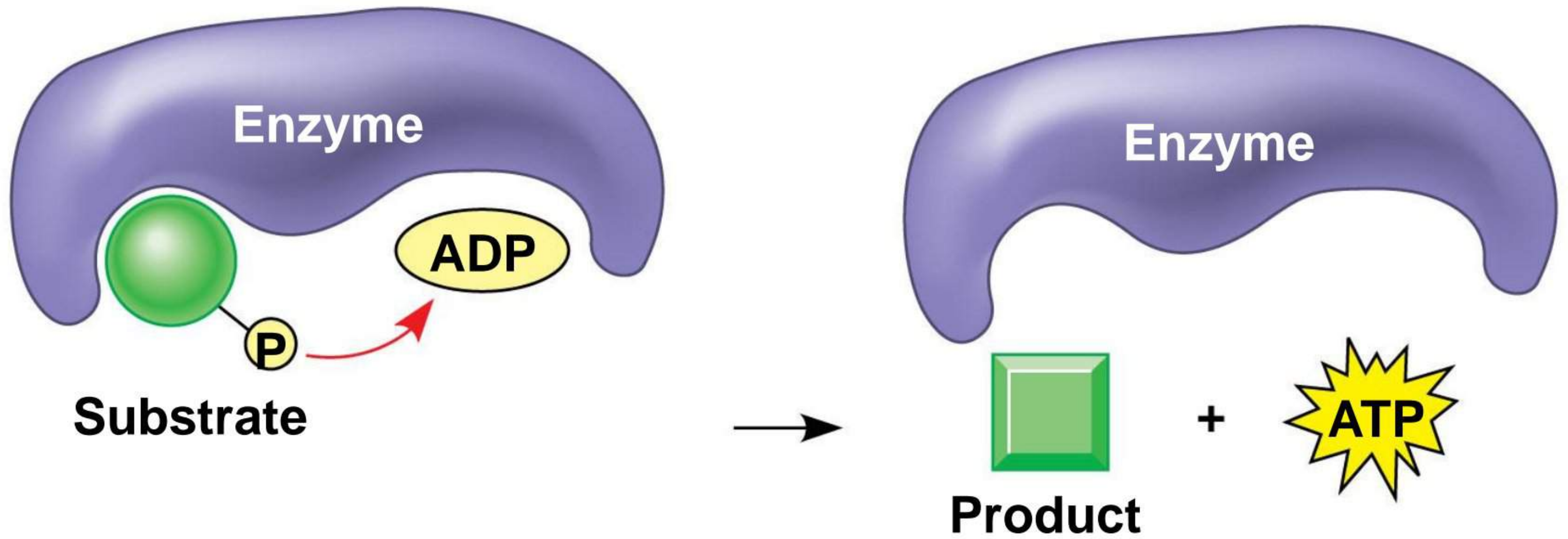
- The process that generates most of the ATP is called oxidative phosphorylation because it is powered by redox reactions



BioFlix: Cellular Respiration

- 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
- Glycolysis occurs whether or not O_2 is present

Figure 9.8

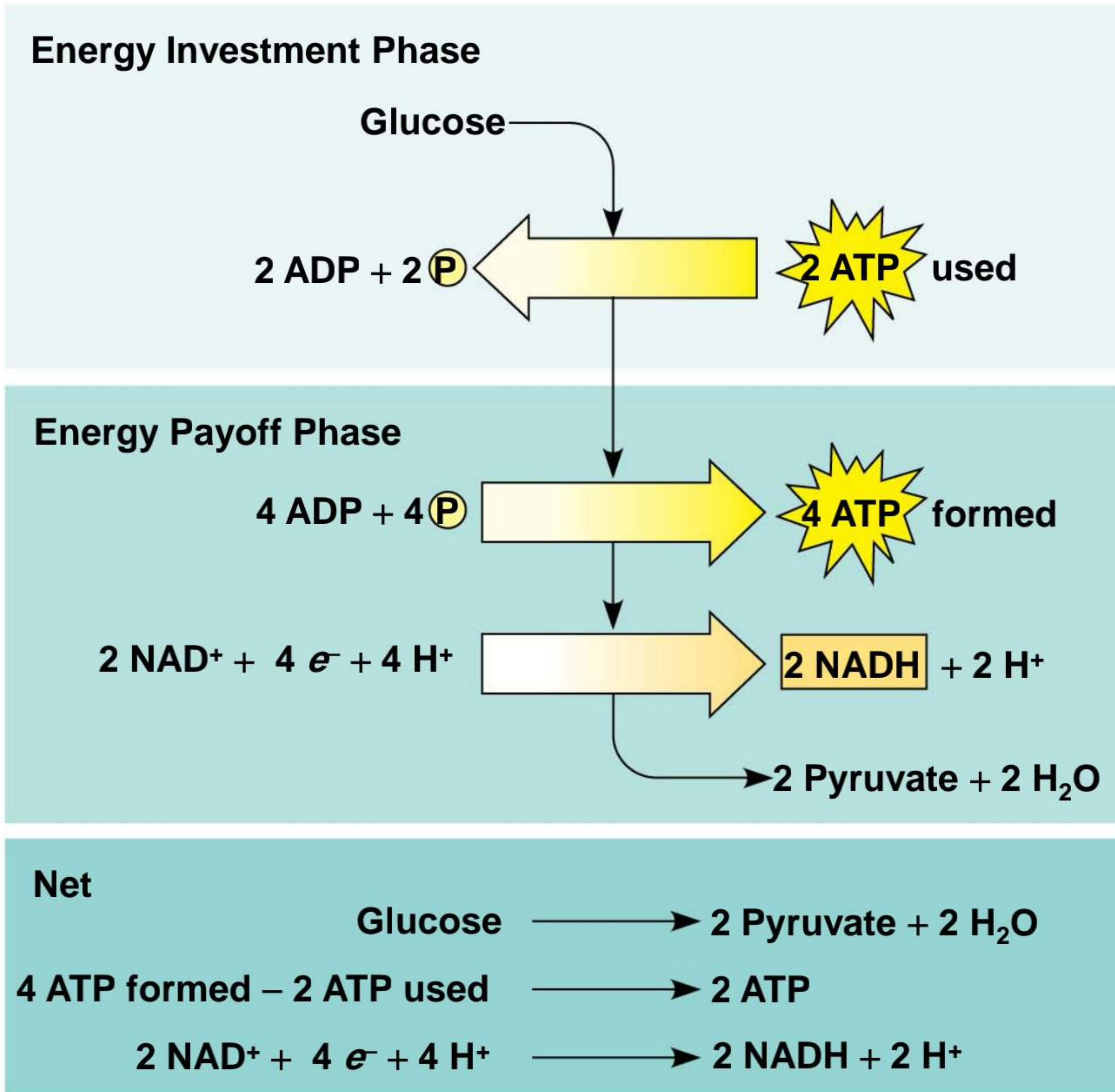


Figure 9.9-1

Glycolysis: Energy Investment Phase

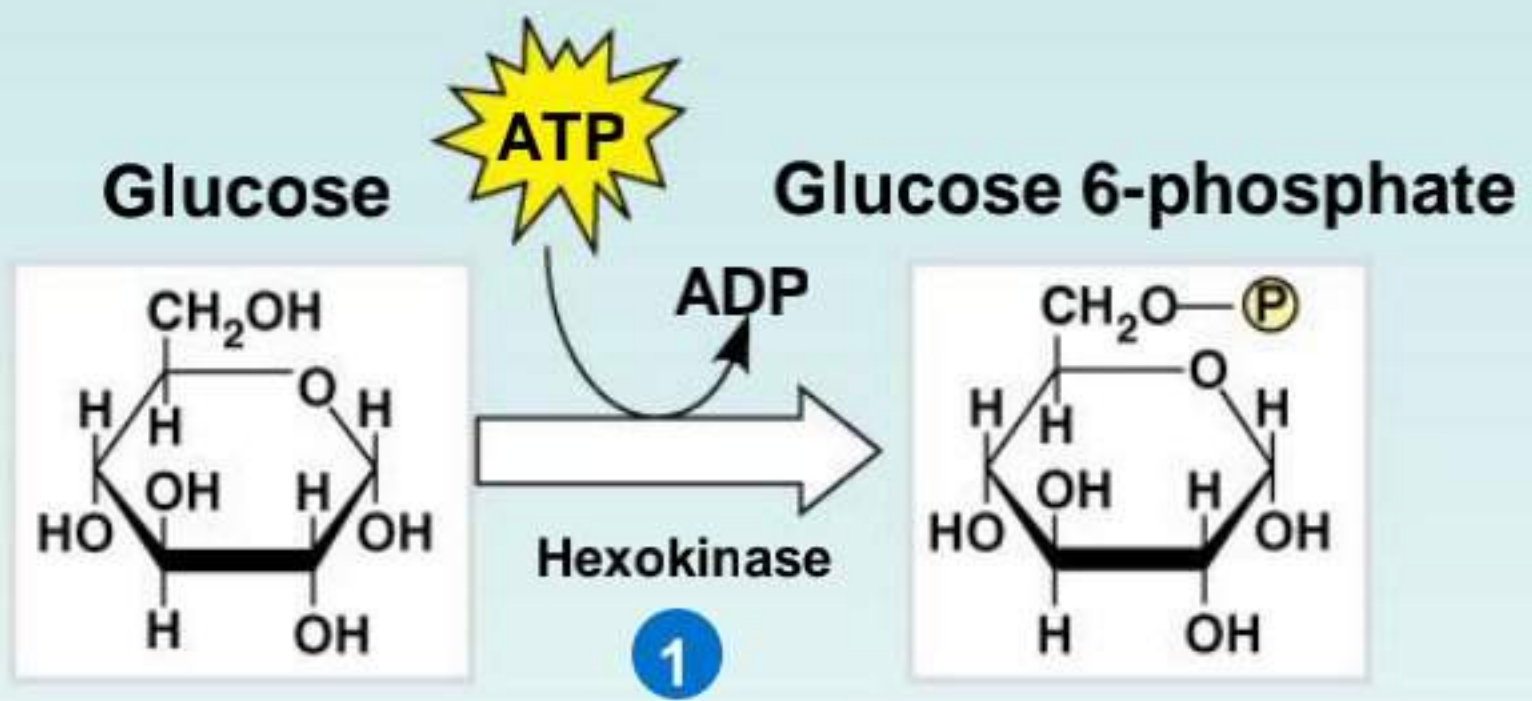


Figure 9.9-2

Glycolysis: Energy Investment Phase

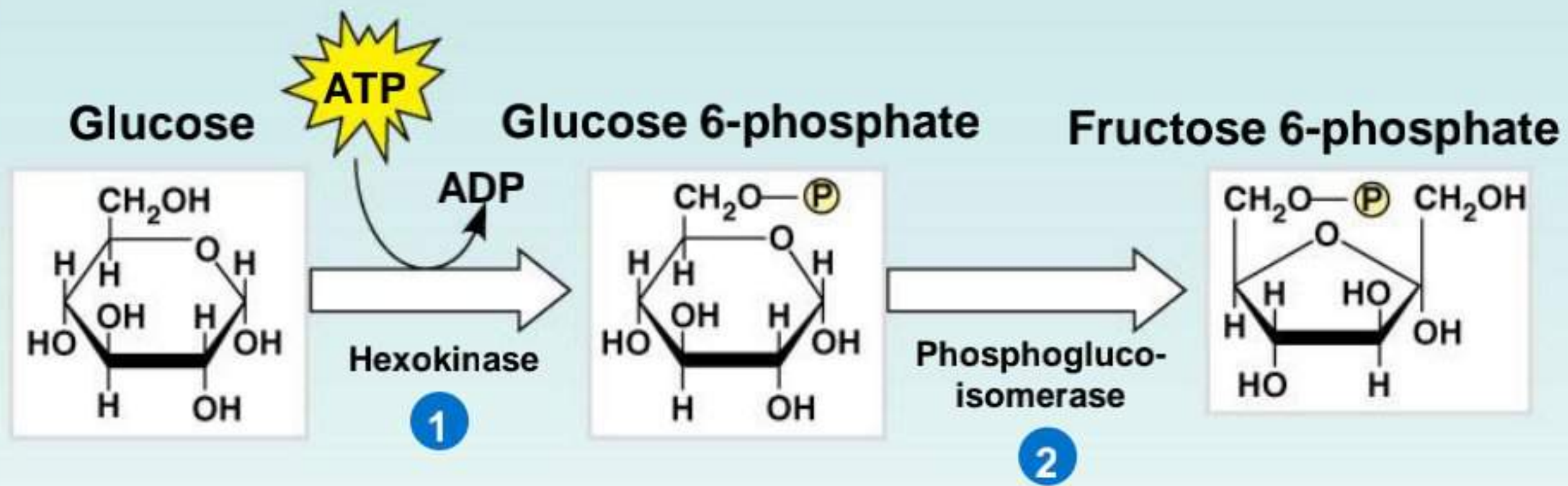


Figure 9.9-3

Glycolysis: Energy Investment Phase

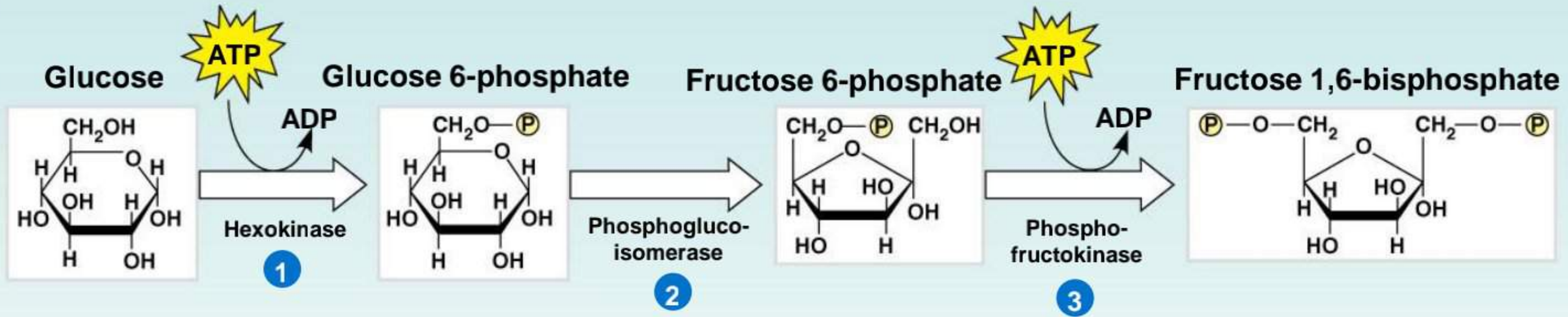


Figure 9.9-4

Glycolysis: Energy Investment Phase

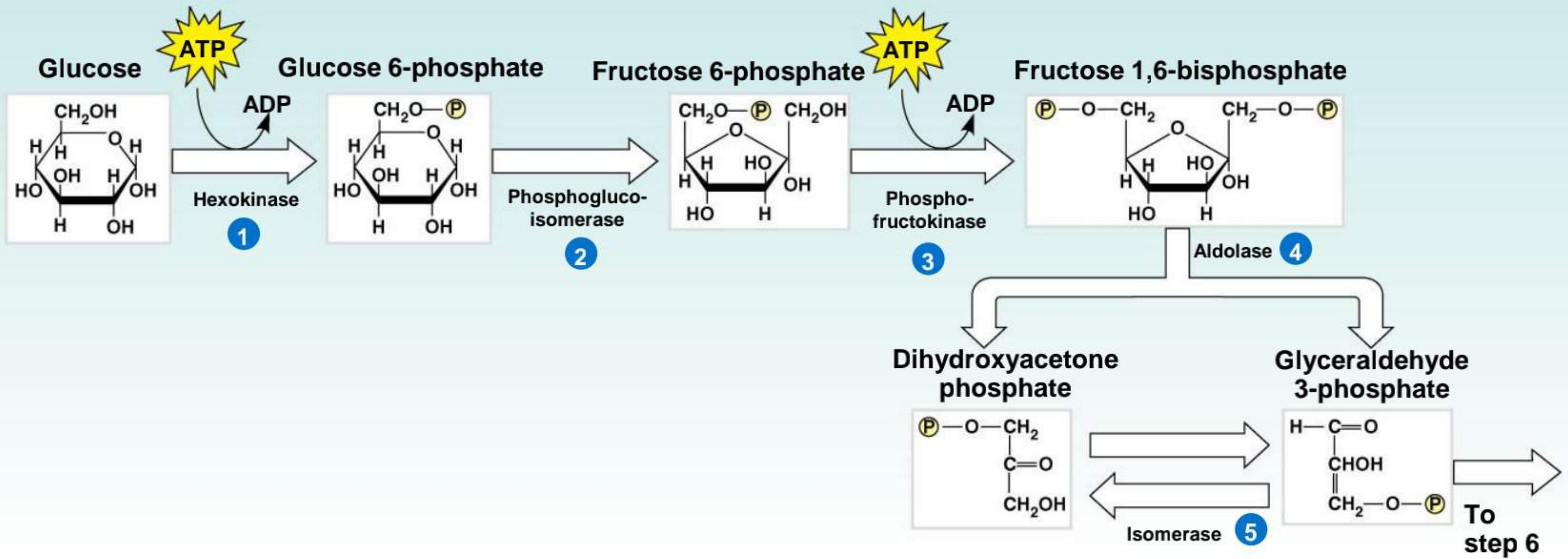


Figure 9.9-5

Glycolysis: Energy Payoff Phase

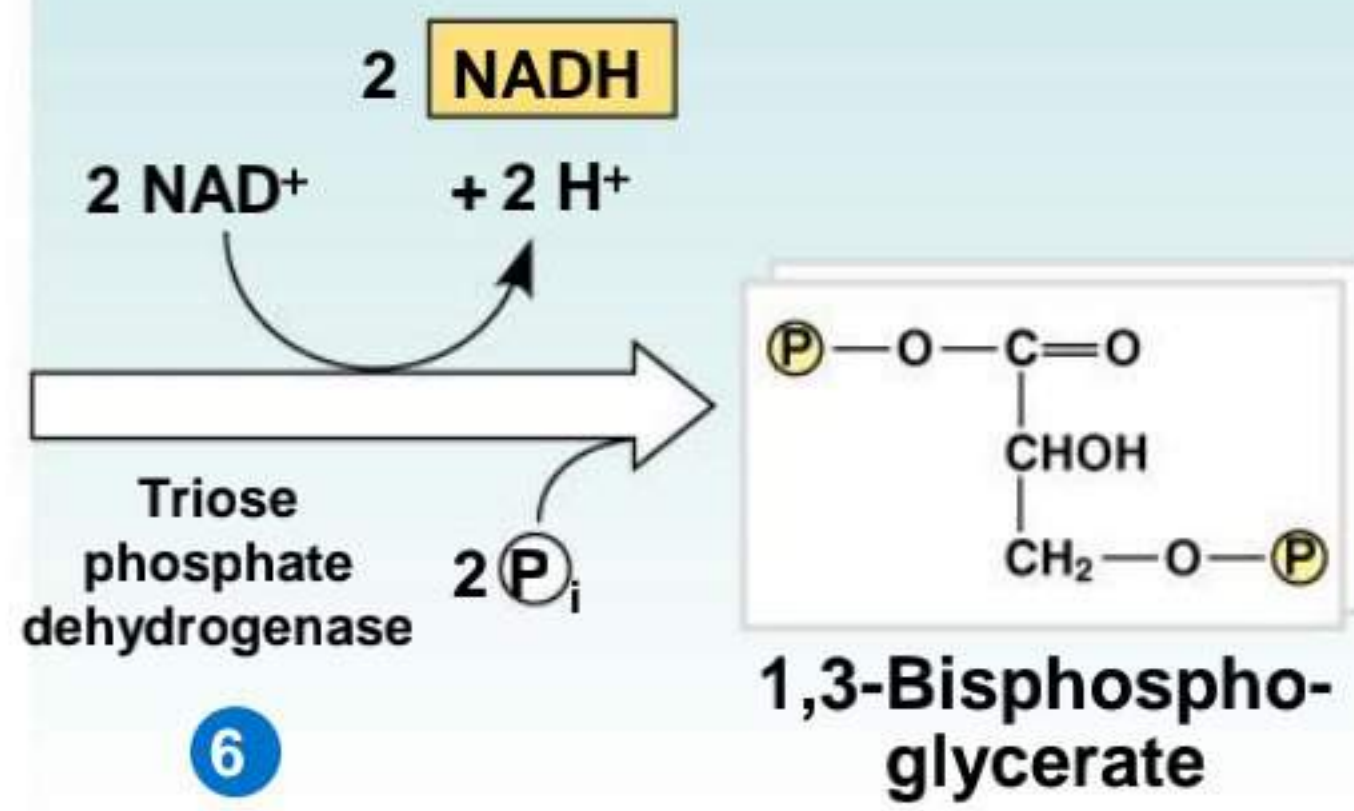


Figure 9.9-6

Glycolysis: Energy Payoff Phase

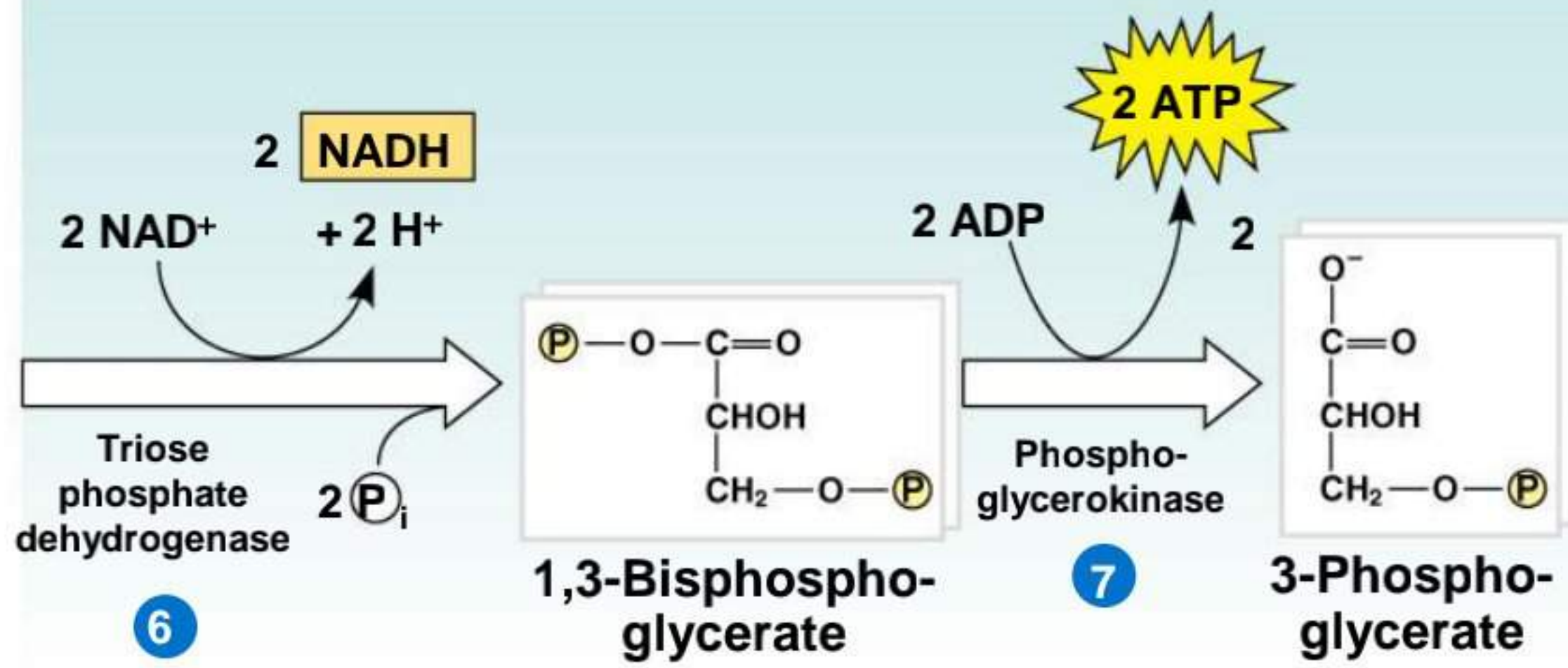


Figure 9.9-7

Glycolysis: Energy Payoff Phase

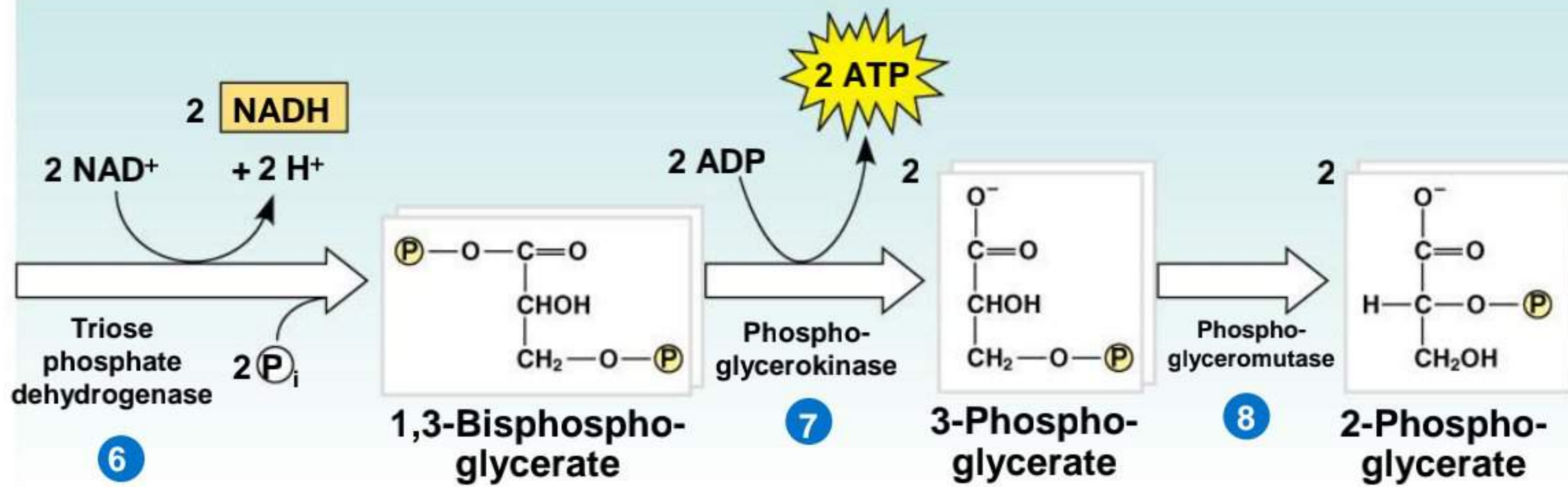


Figure 9.9-8

Glycolysis: Energy Payoff Phase

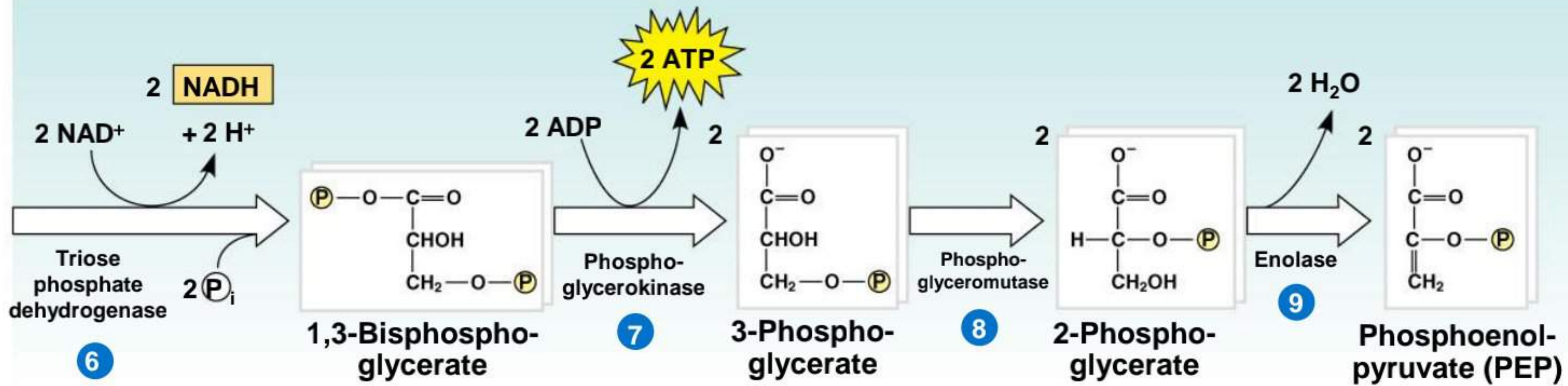


Figure 9.9-9

Glycolysis: Energy Payoff Phase

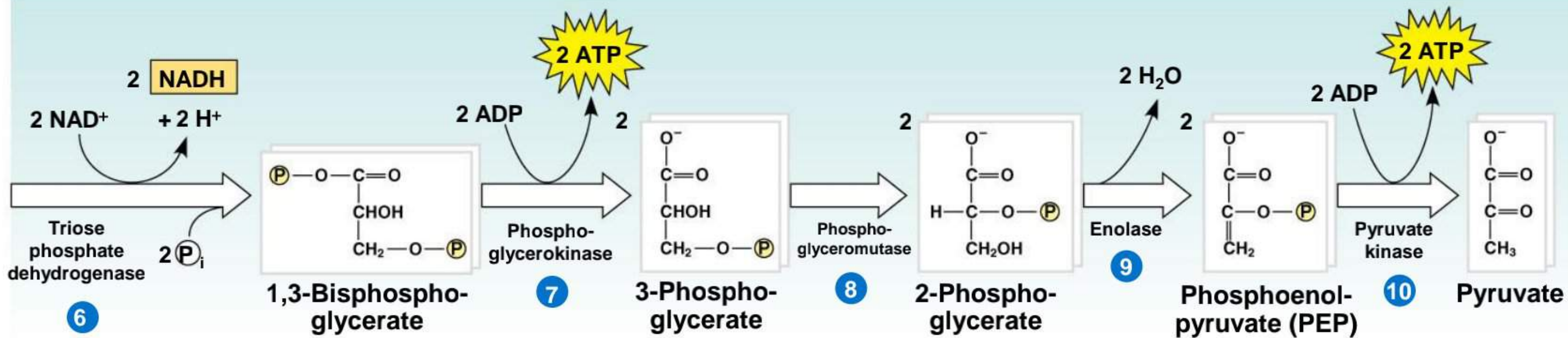


Figure 9.9a

Glycolysis: Energy Investment Phase

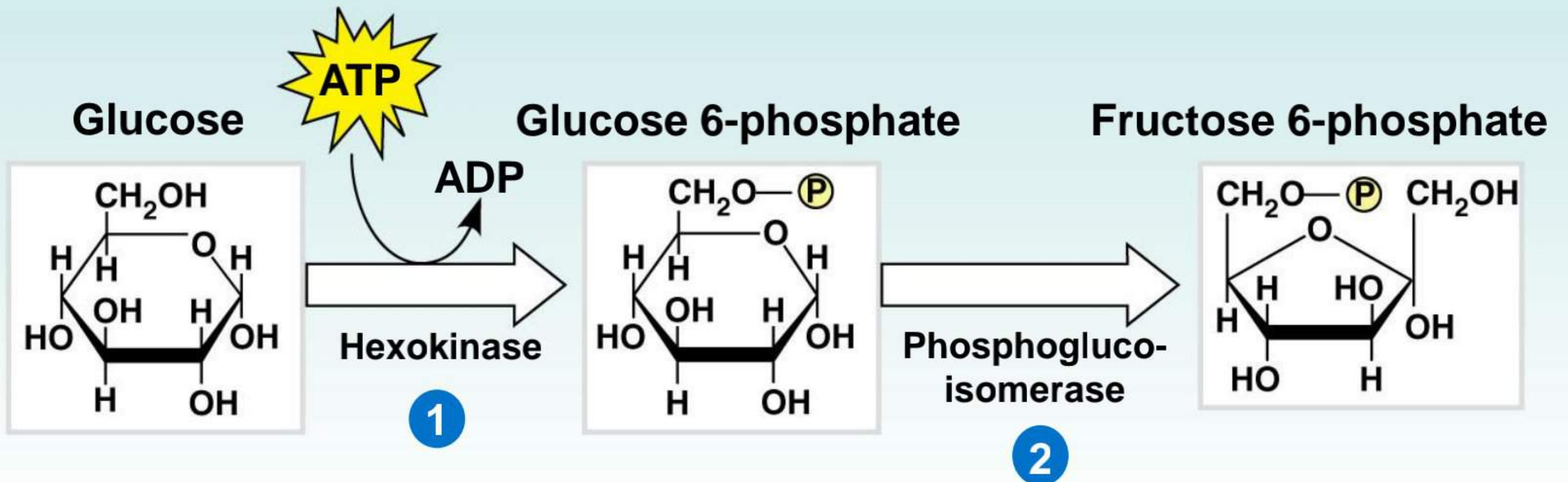


Figure 9.9b

Glycolysis: Energy Investment Phase

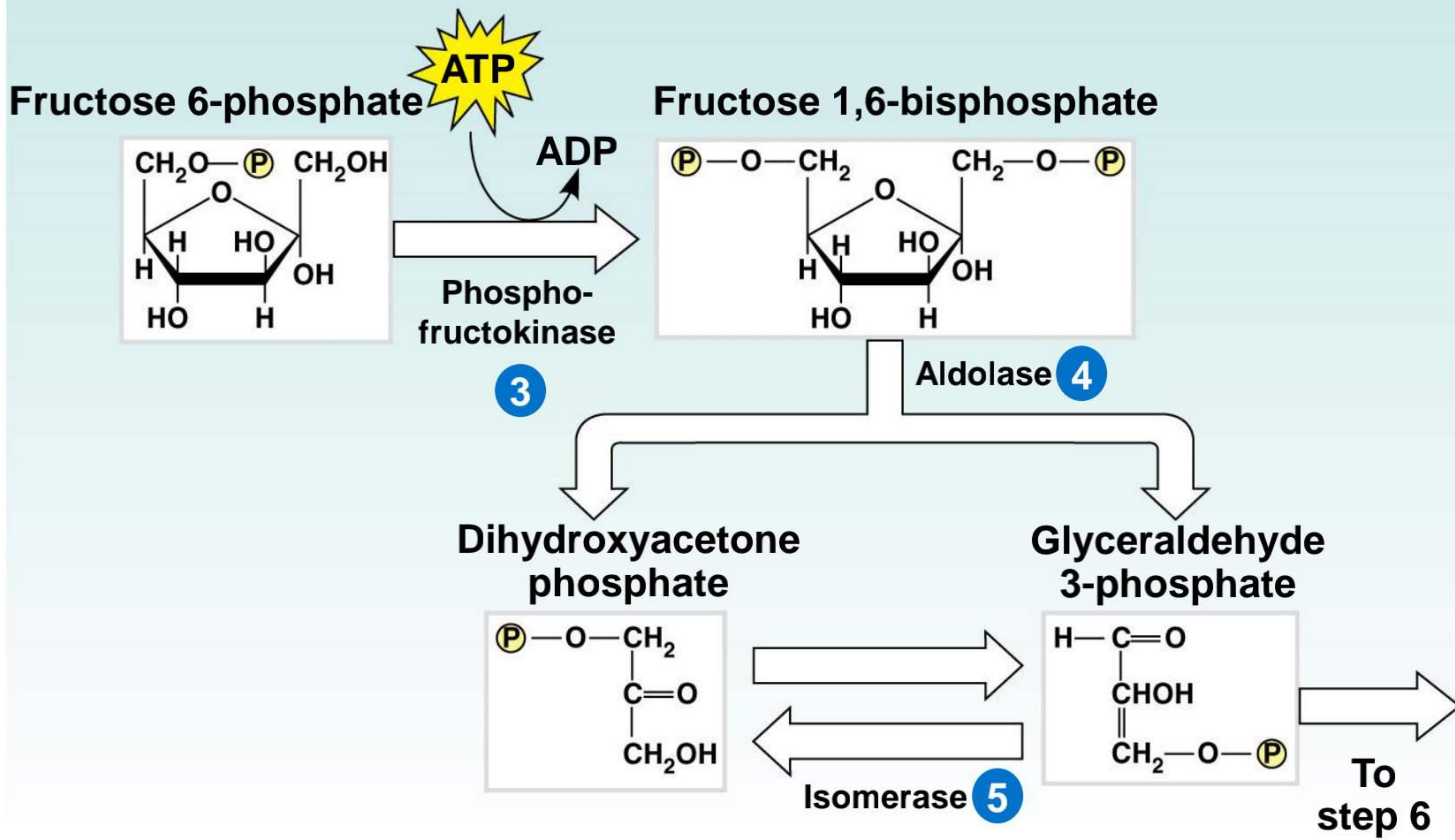


Figure 9.9c

Glycolysis: Energy Payoff Phase

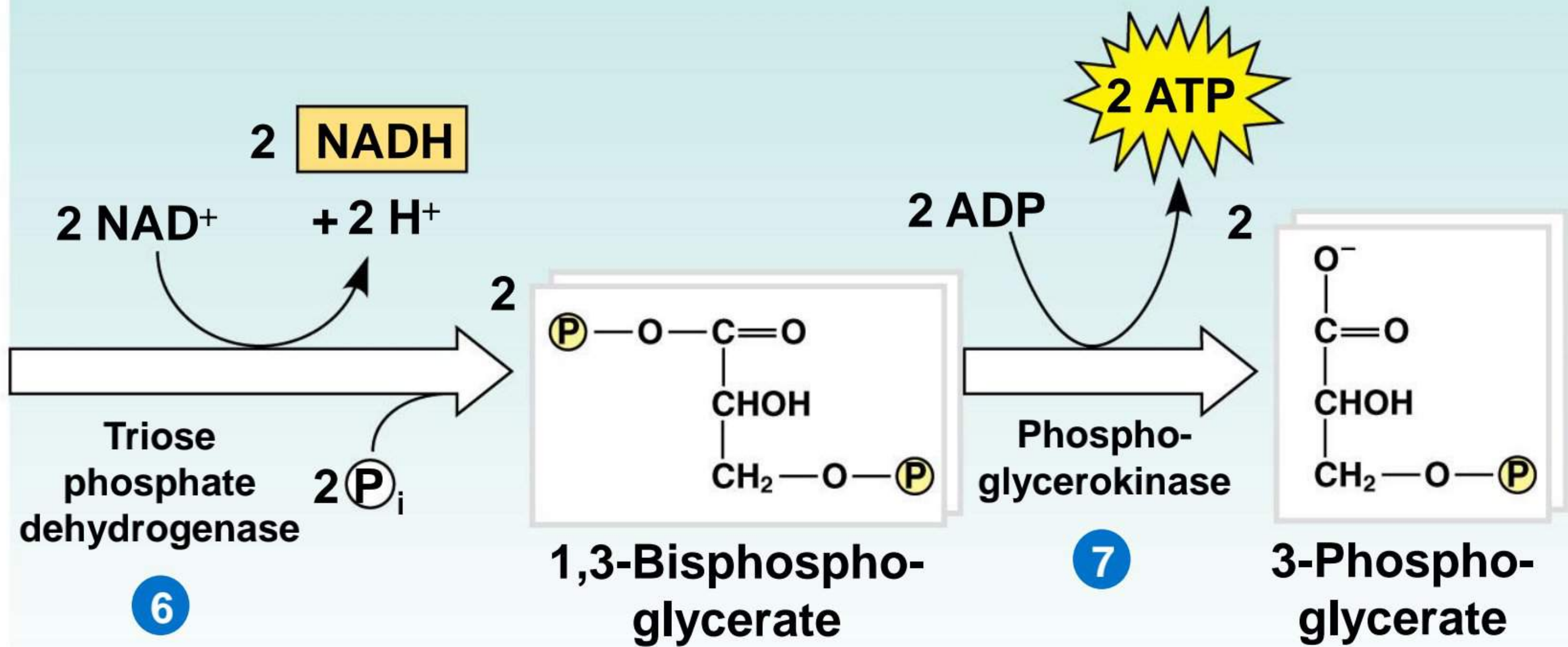
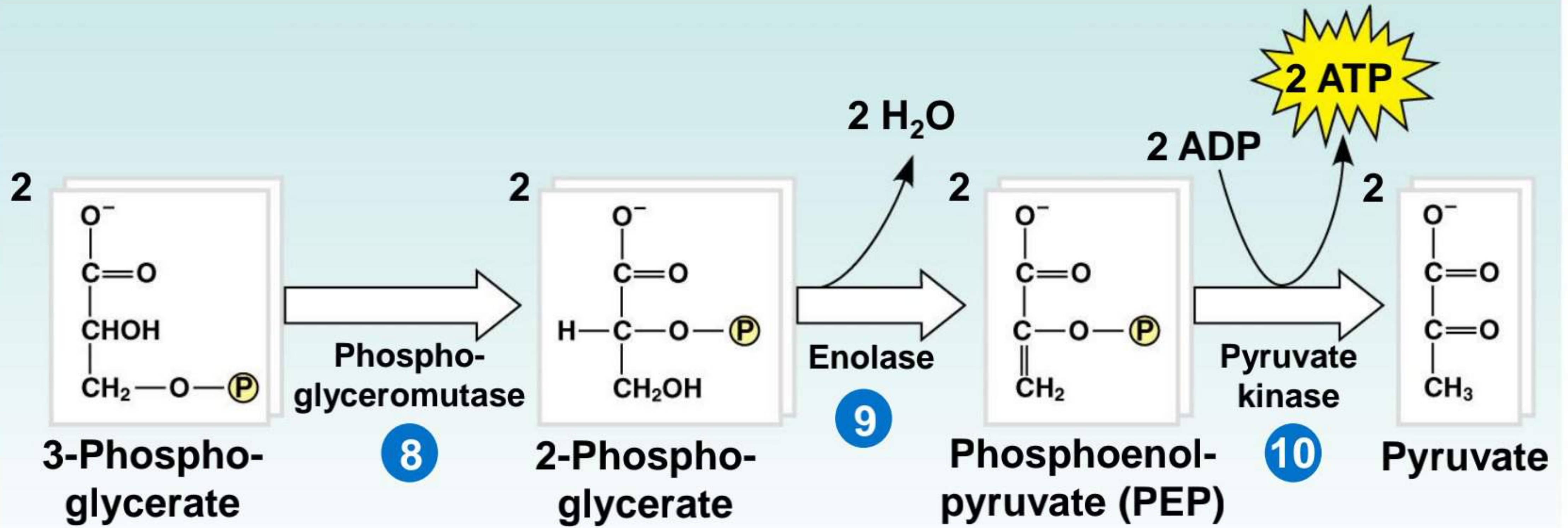


Figure 9.9d

Glycolysis: Energy Payoff Phase



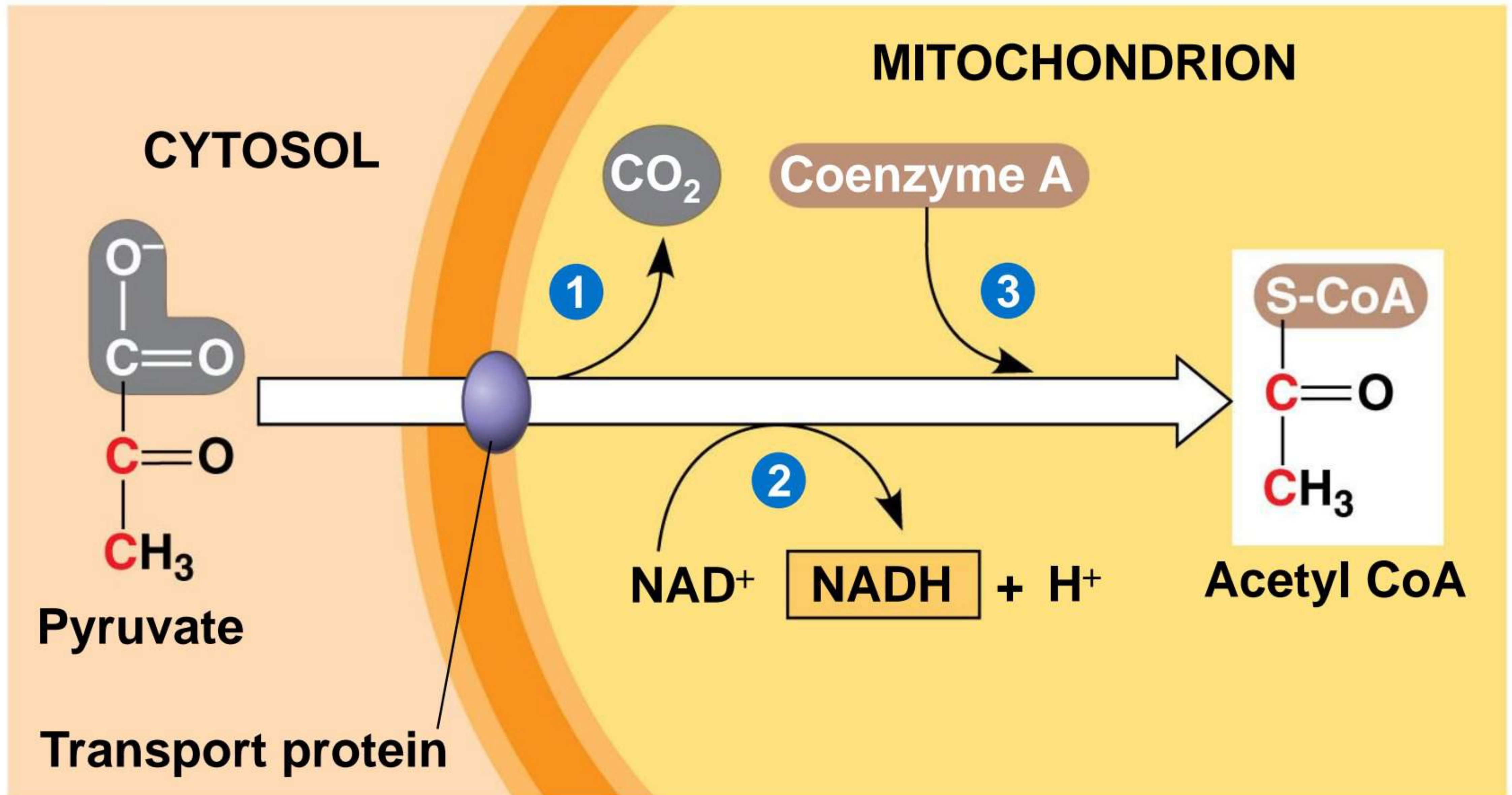
Concept 9.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

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

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

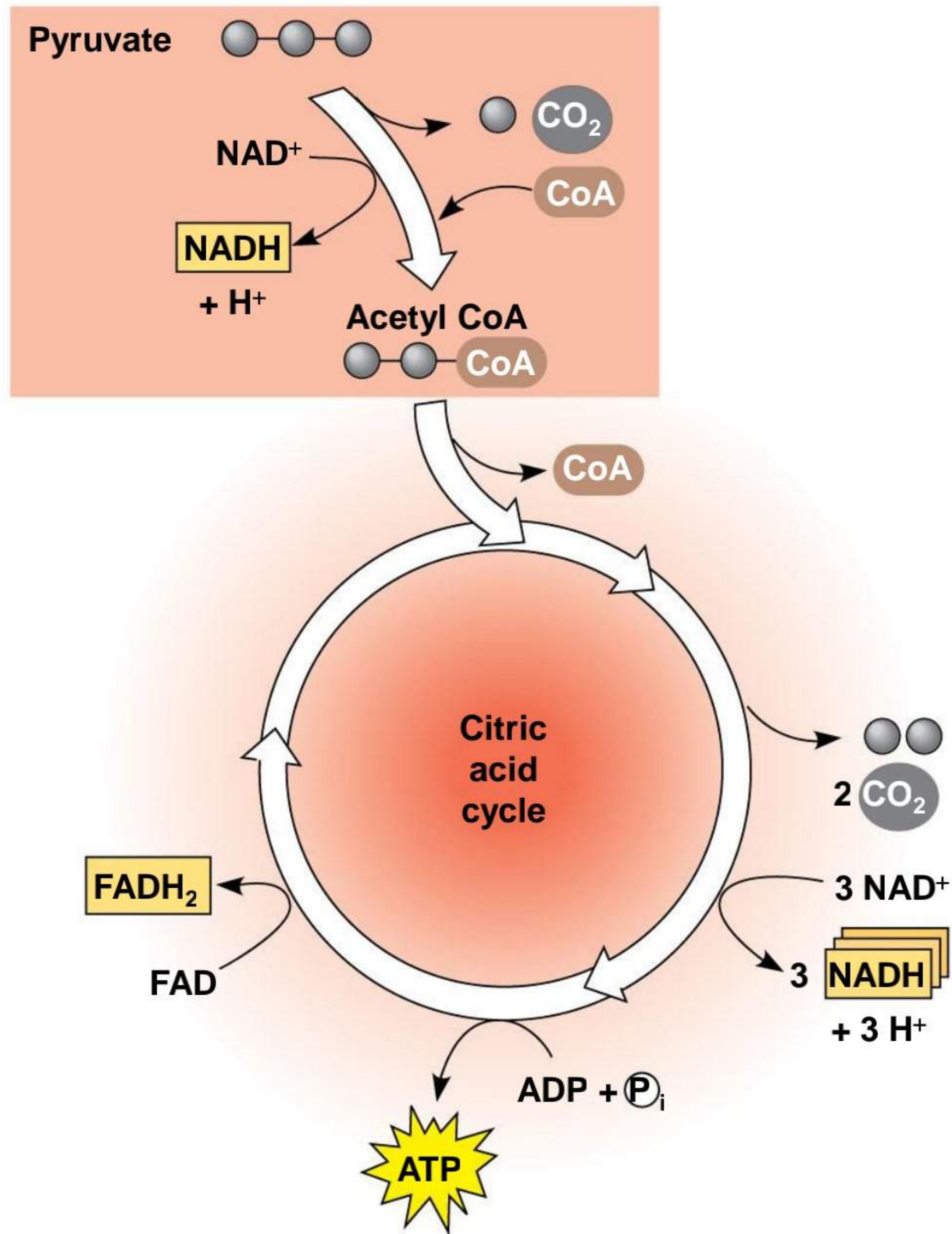
Figure 9.10



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

Figure 9.11



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

Figure 9.12-1

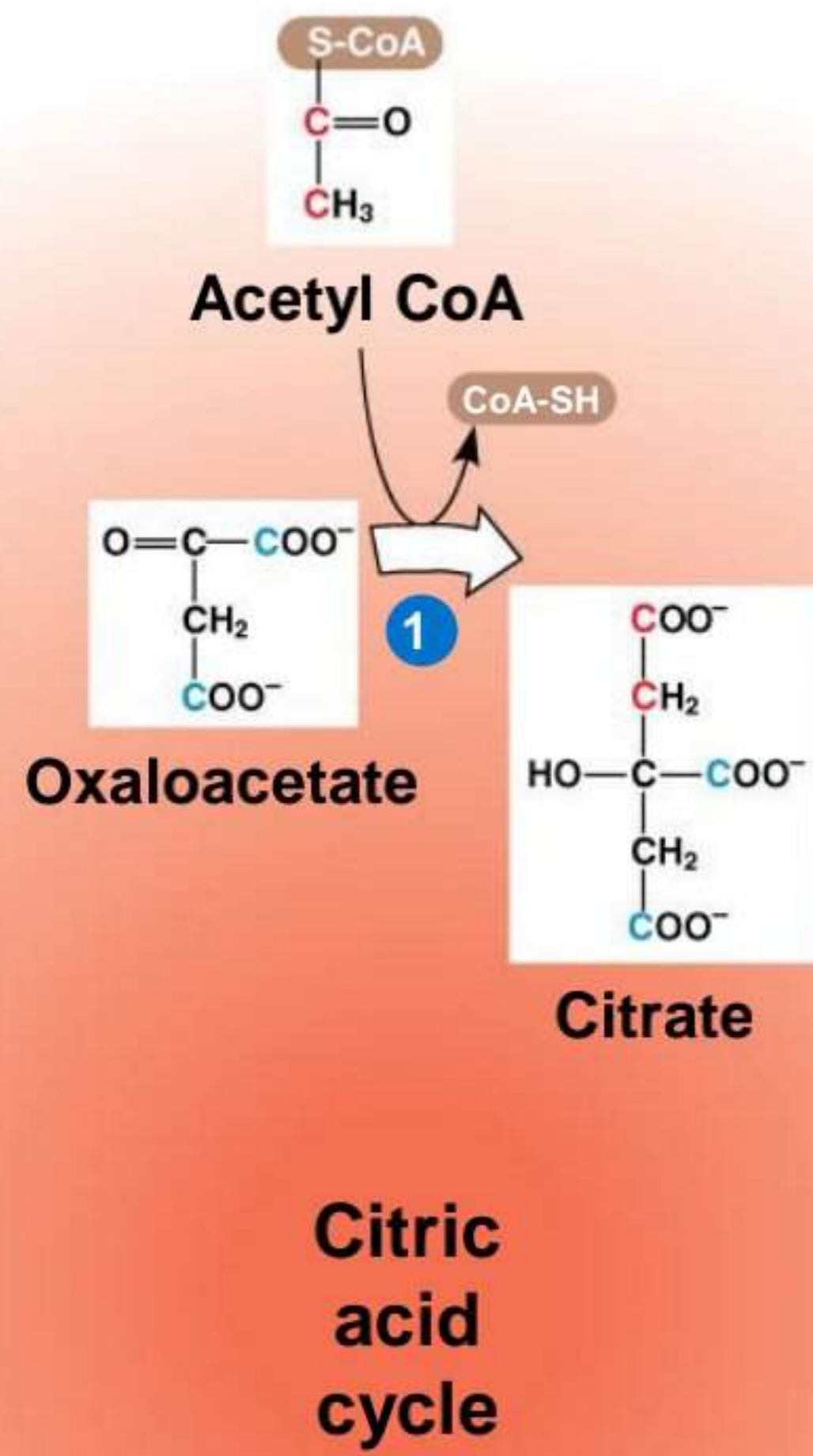
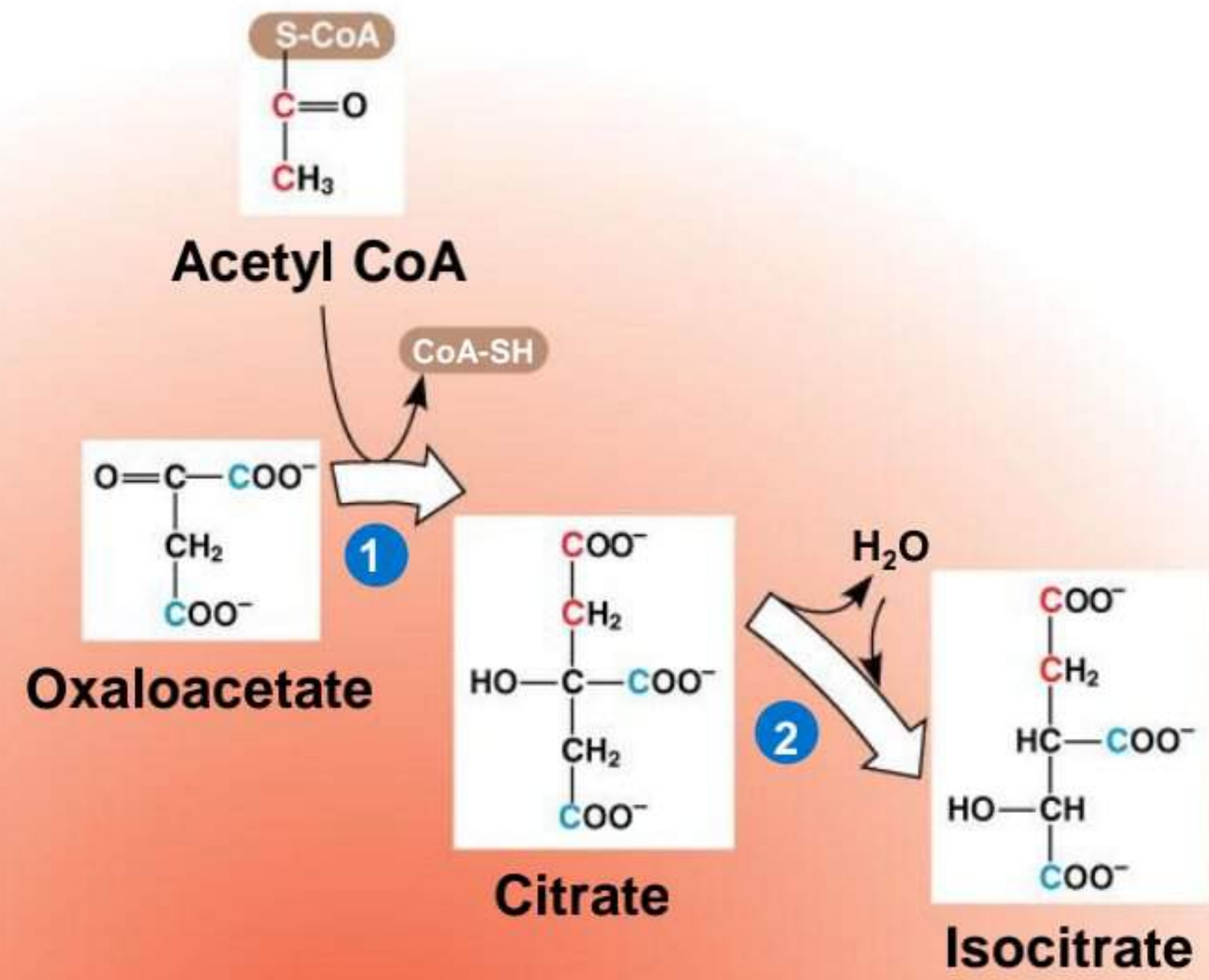


Figure 9.12-2



**Citric
acid
cycle**

Figure 9.12-3

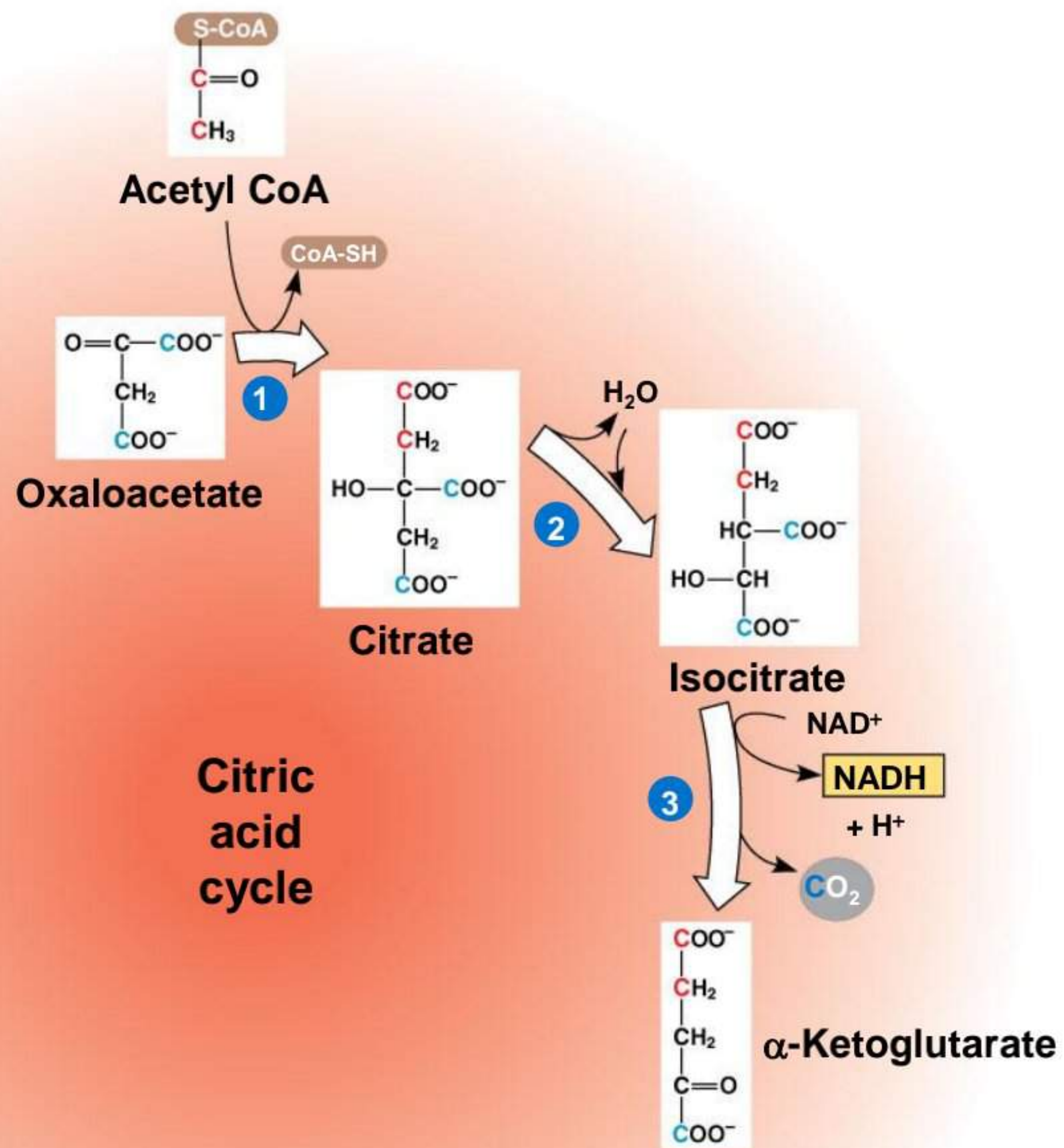


Figure 9.12-4

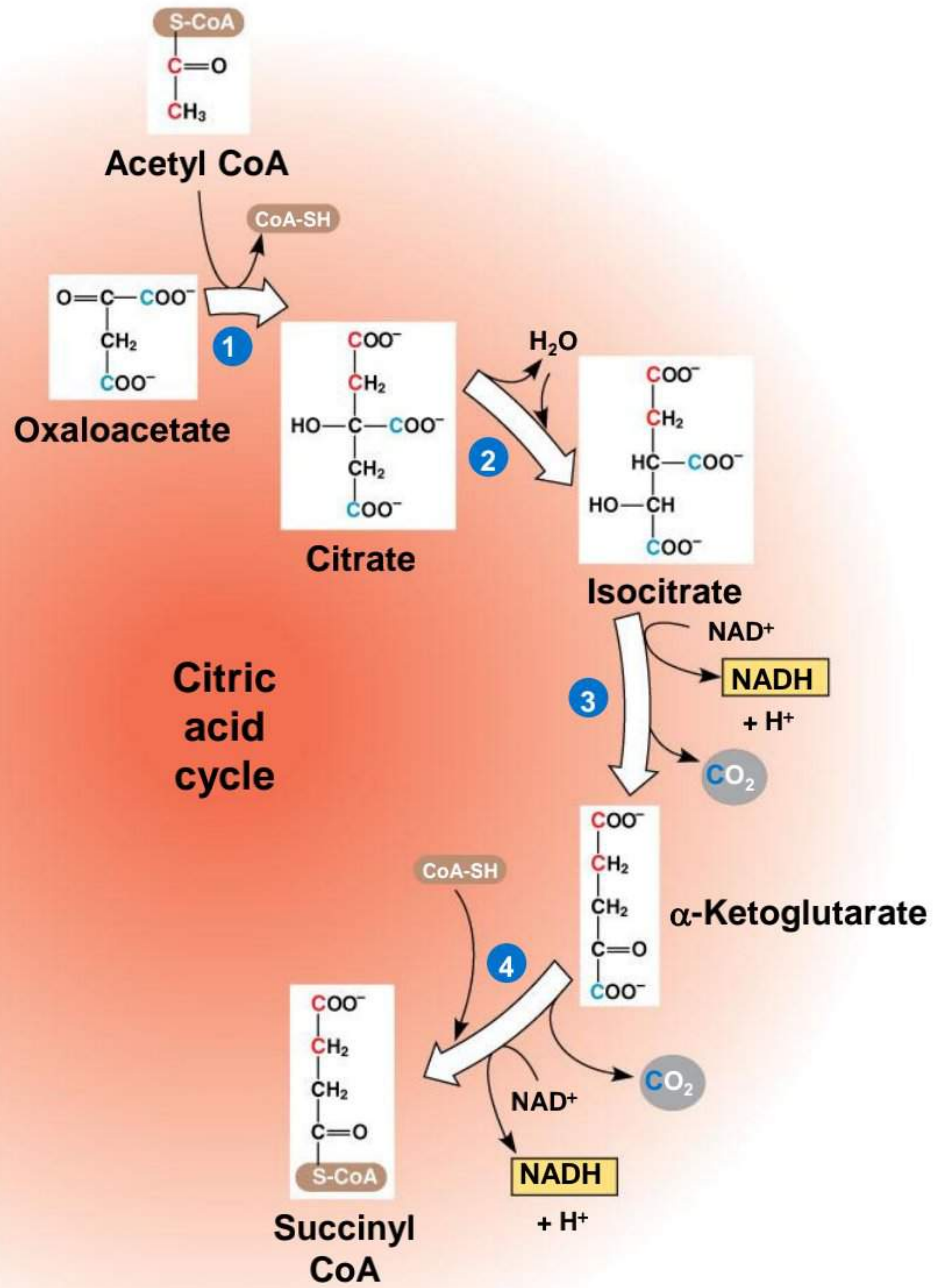


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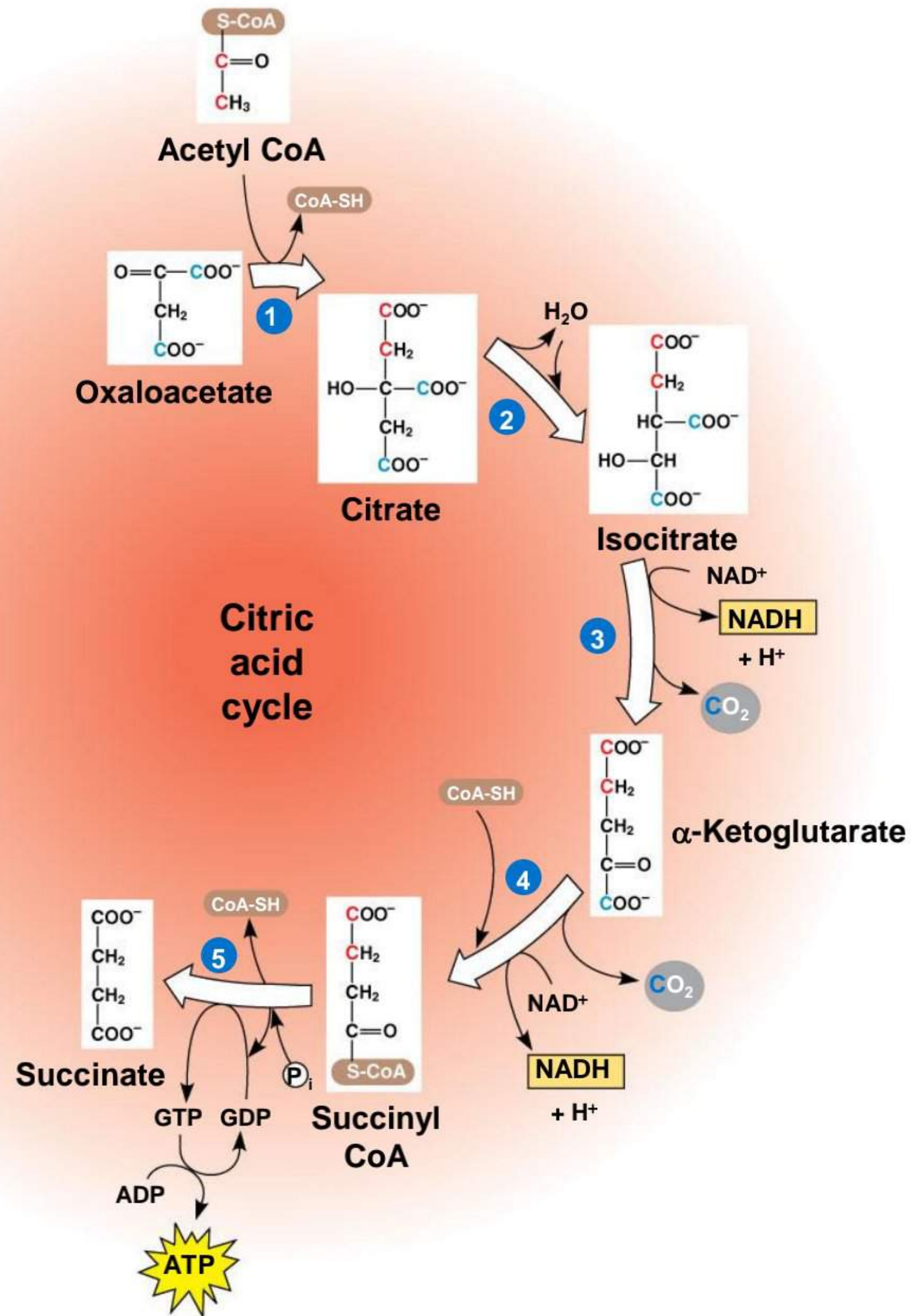


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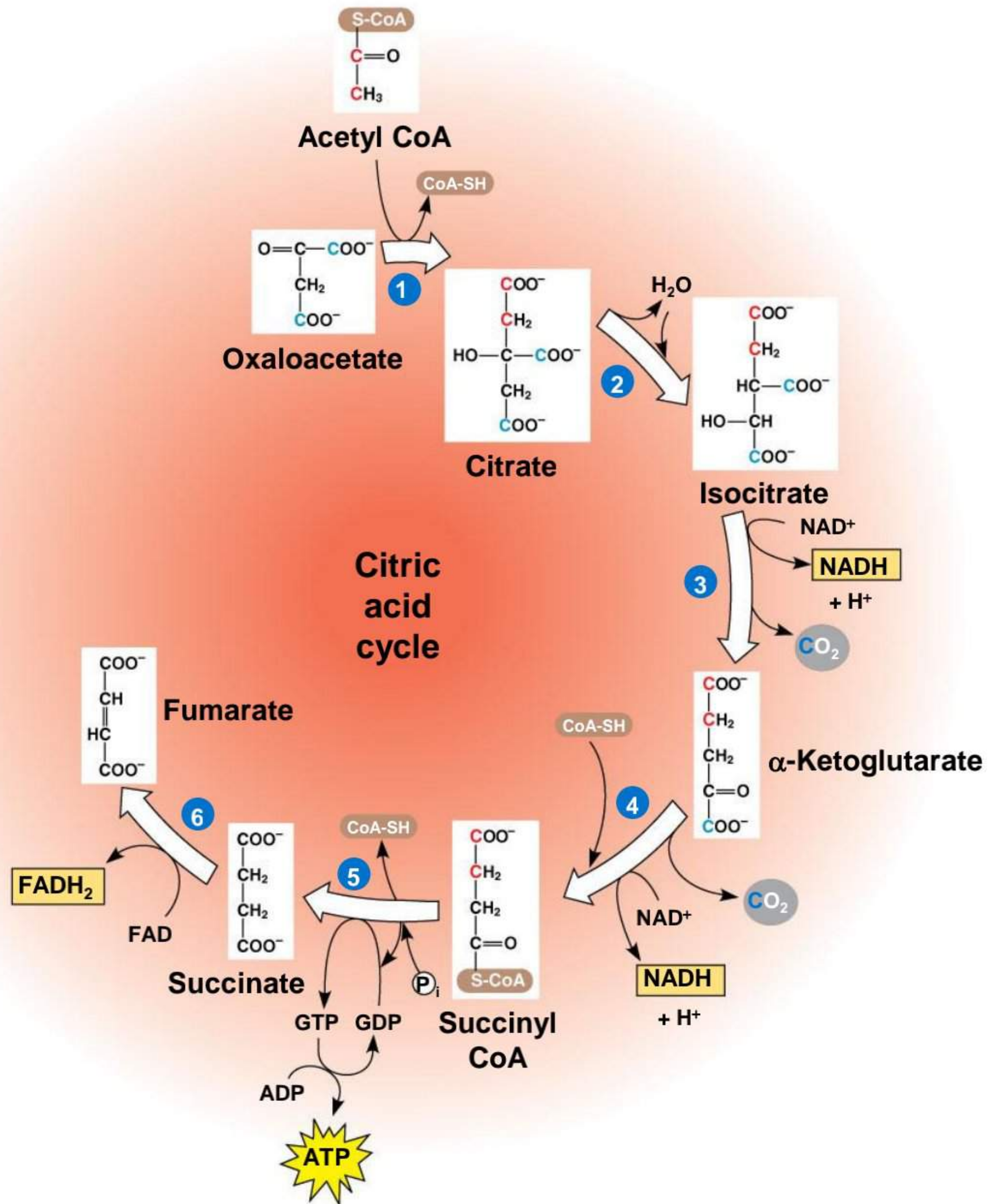


Figure 9.12-7

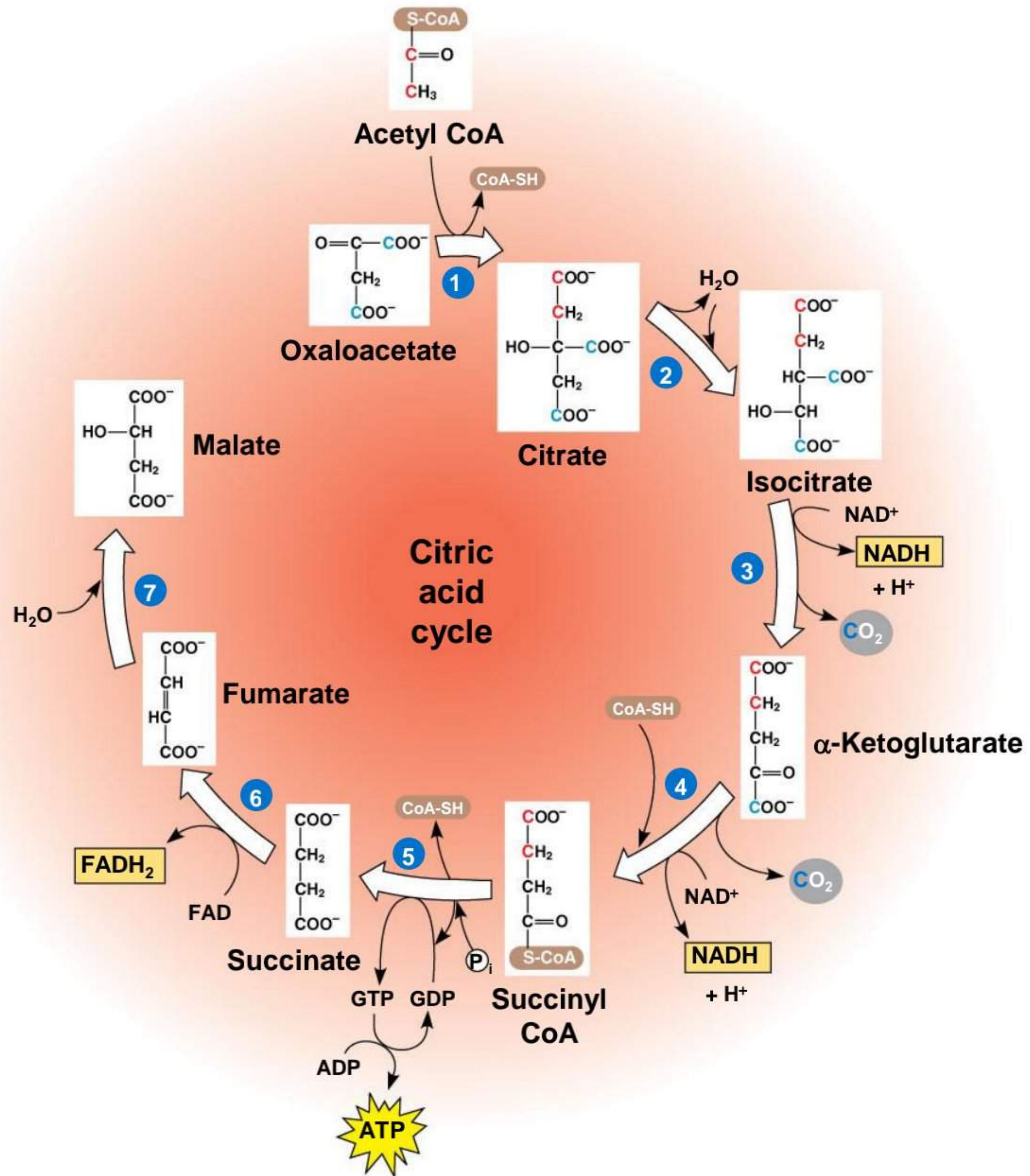


Figure 9.12-8

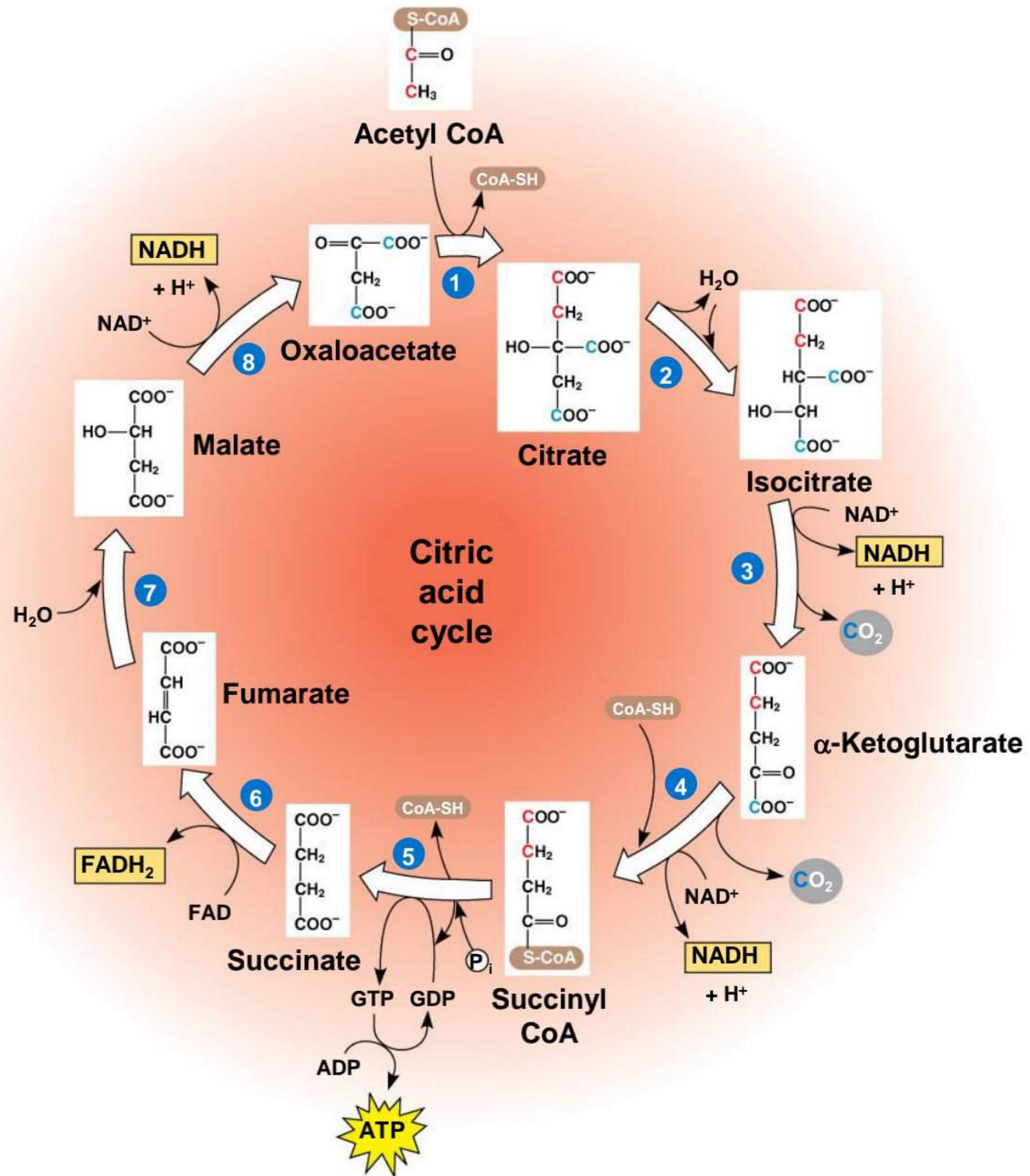


Figure 9.12a

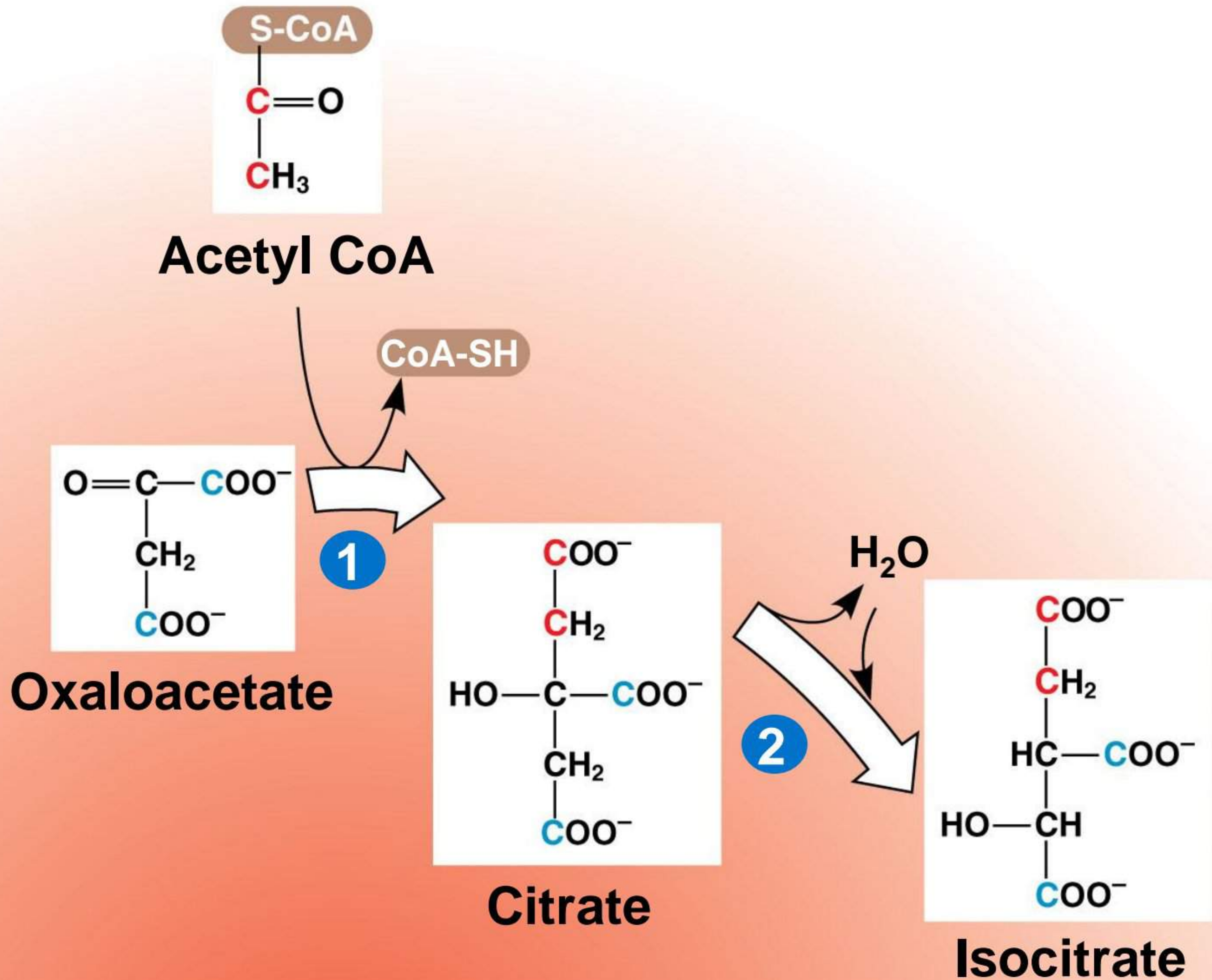


Figure 9.12b

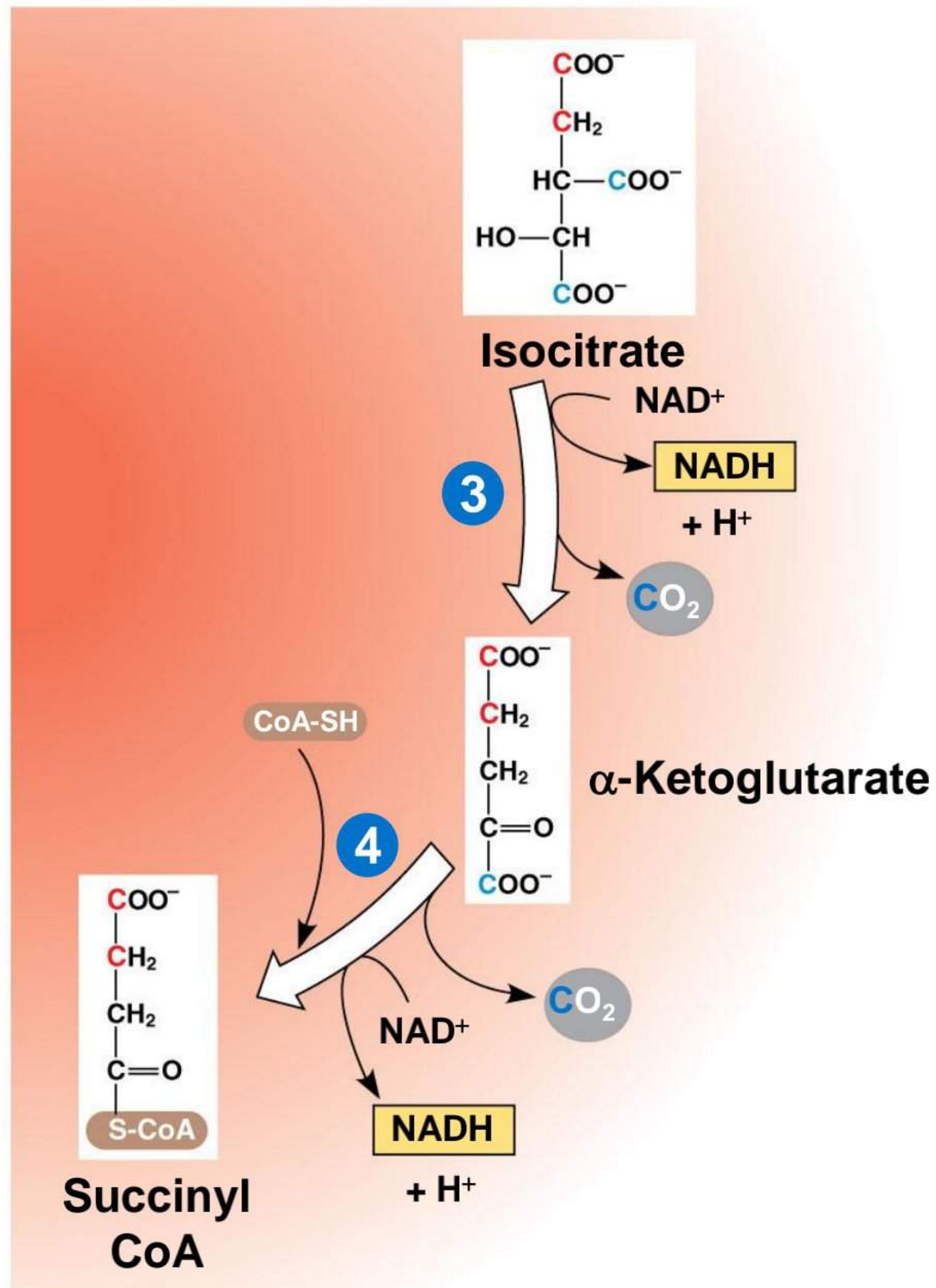


Figure 9.12c

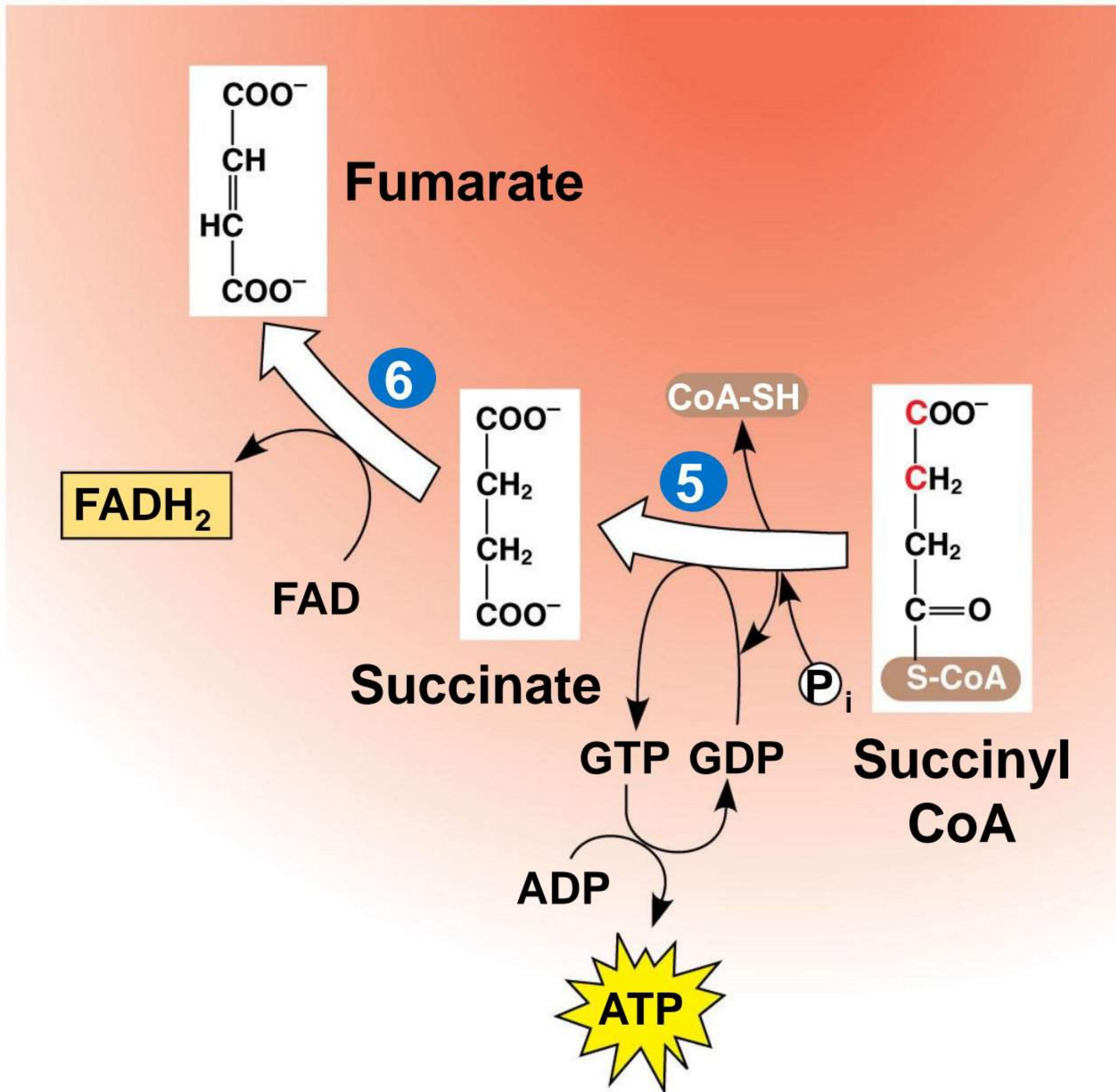
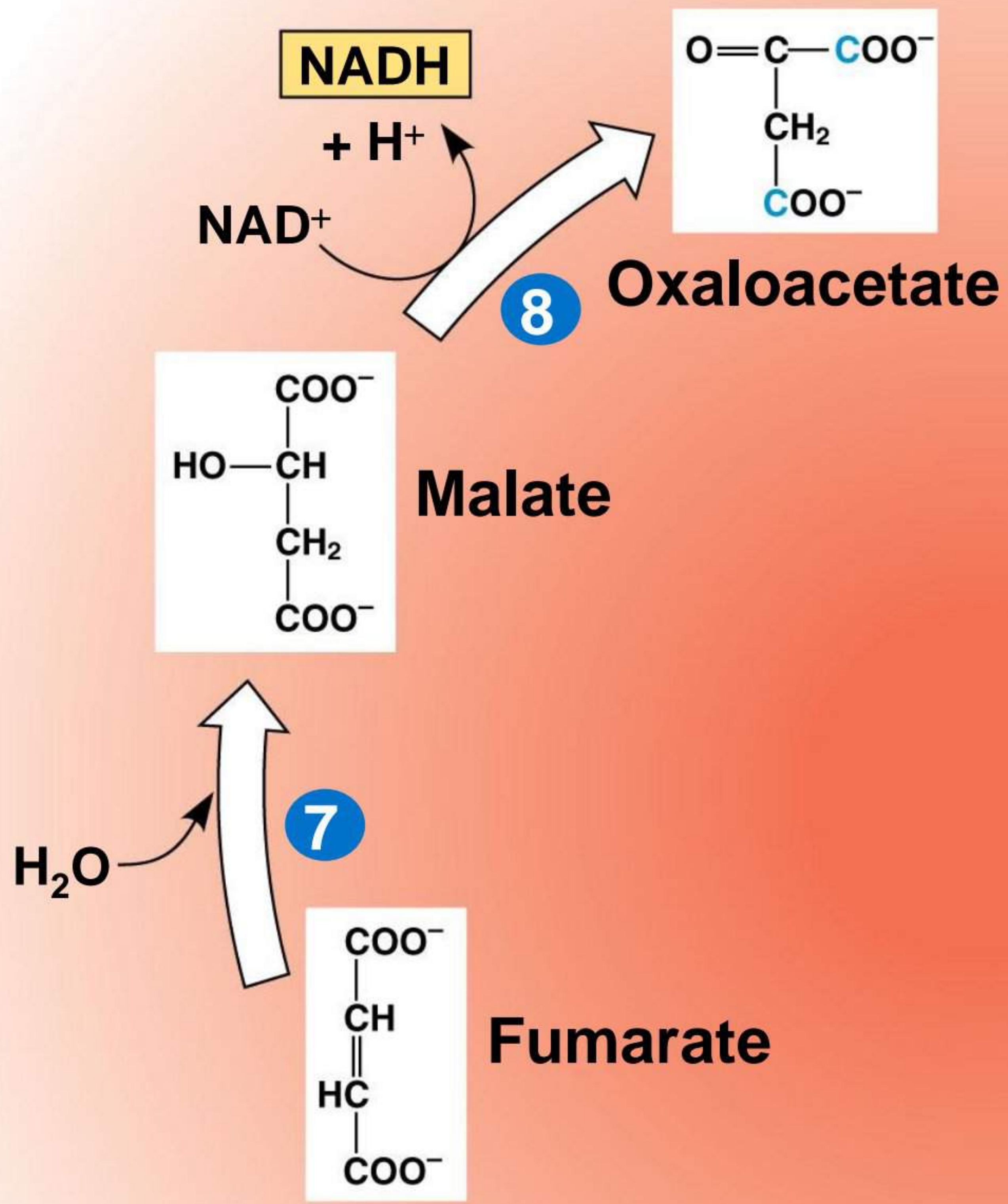


Figure 9.12d



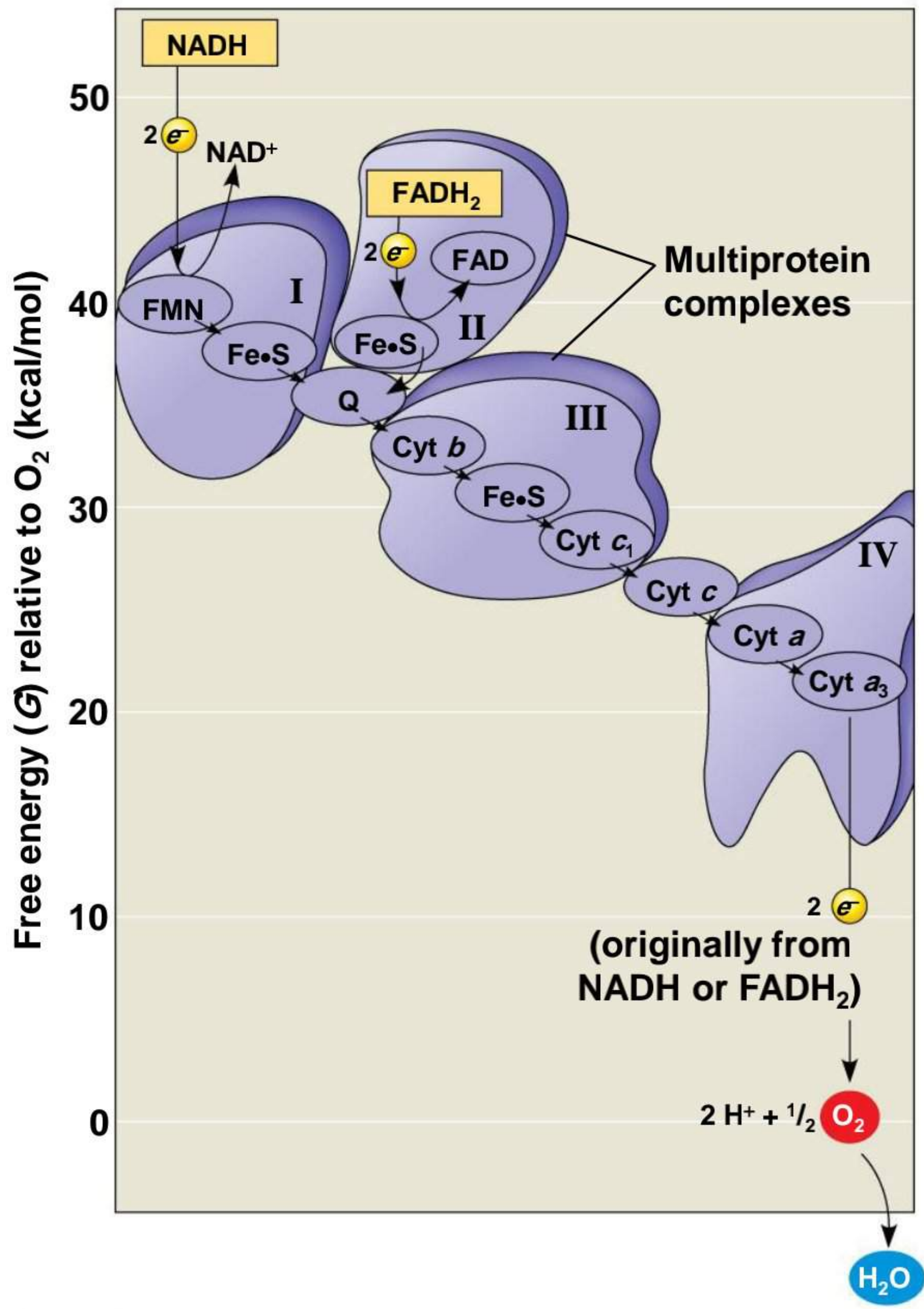
Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- 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 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 9.13



- Electrons are transferred from NADH or FADH₂ to the electron transport chain
- Electrons are passed through a number of proteins including **cytochromes** (each with an iron atom) to O₂
- The electron transport chain generates no ATP directly
- It breaks the large free-energy drop from food to O₂ 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 the proton, **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

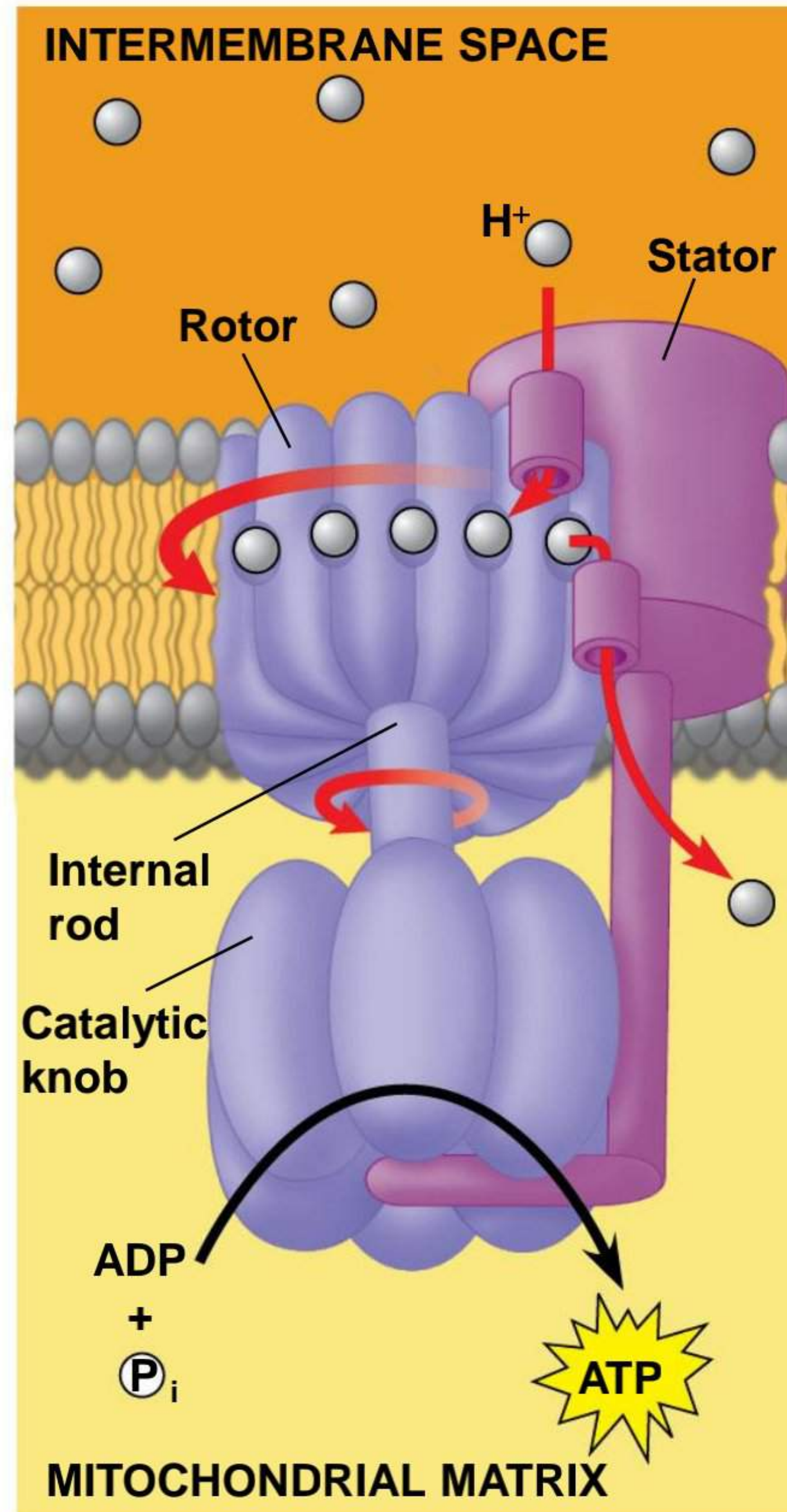
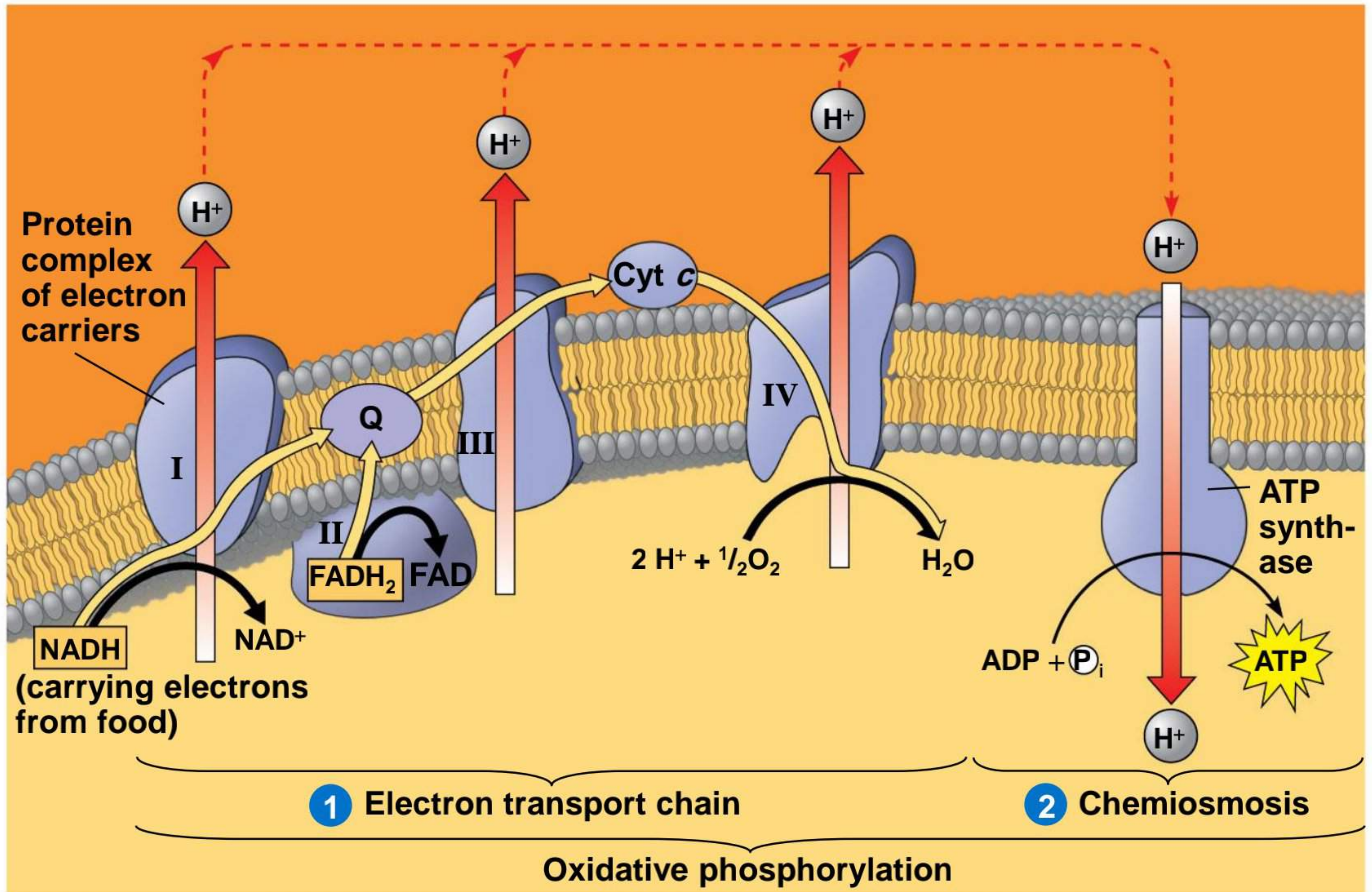


Figure 9.15

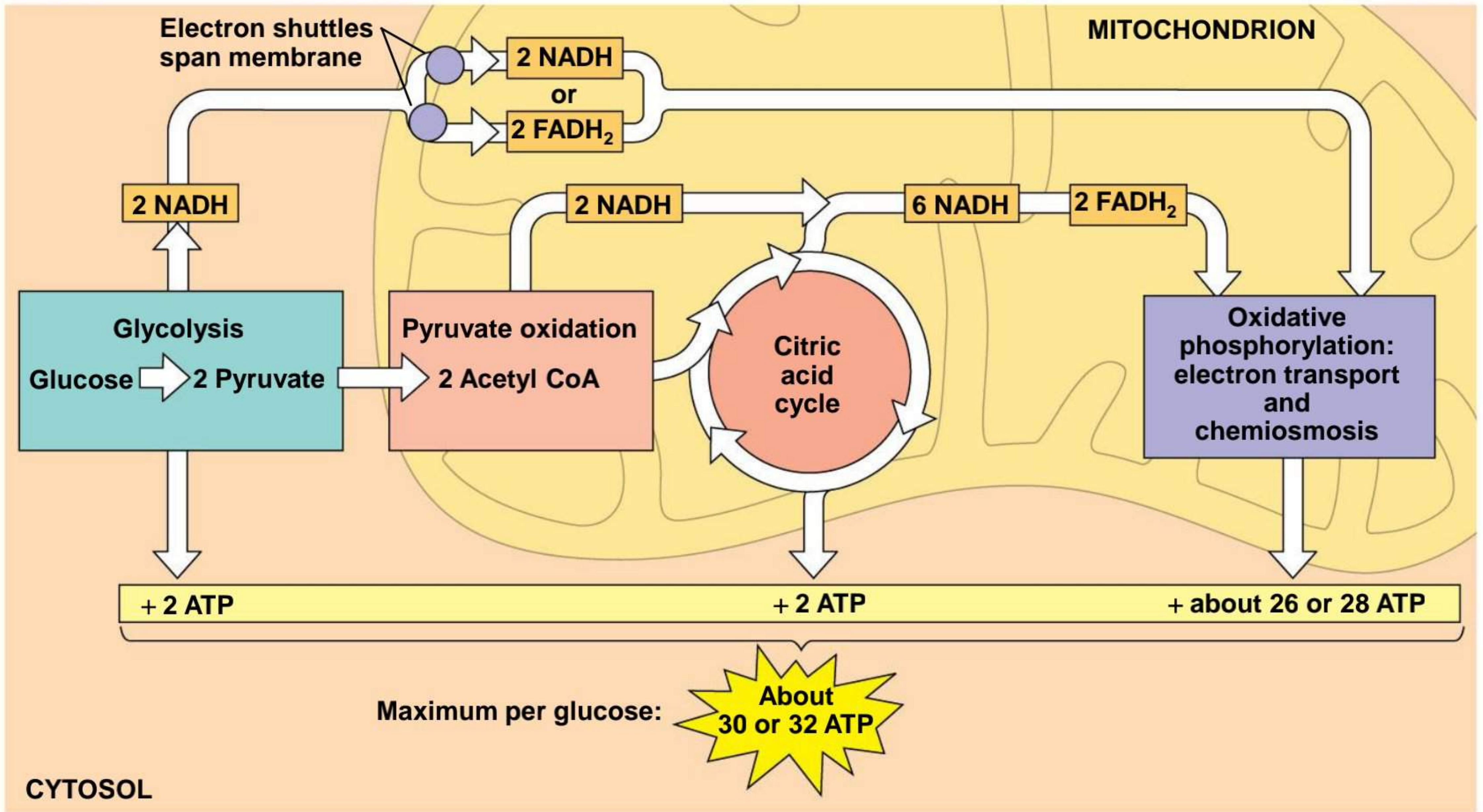


- The energy stored in a H^+ gradient across a membrane couples the redox reactions of the electron transport chain to ATP synthesis
- The H^+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

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



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 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**

- 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

Figure 9.17

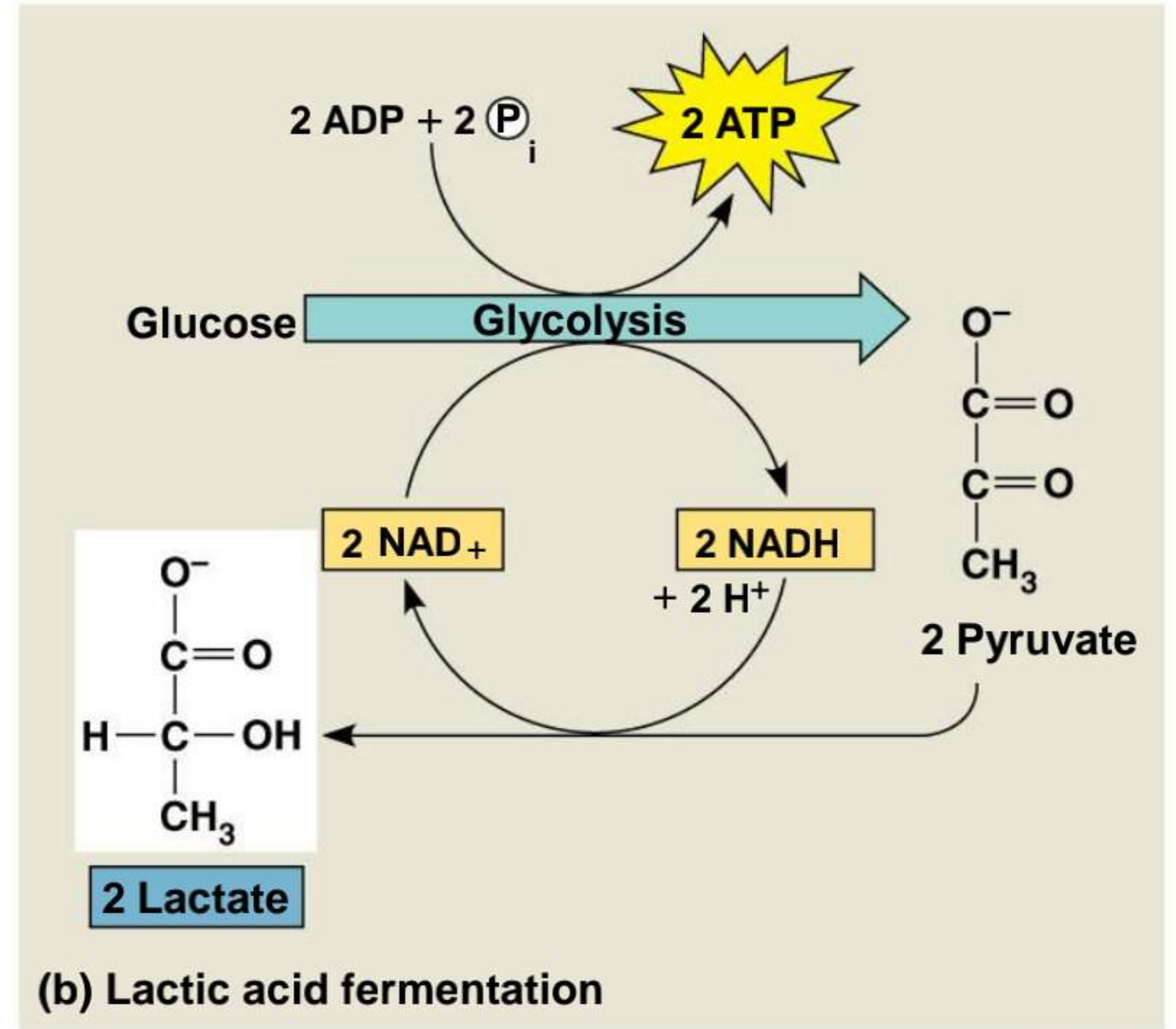
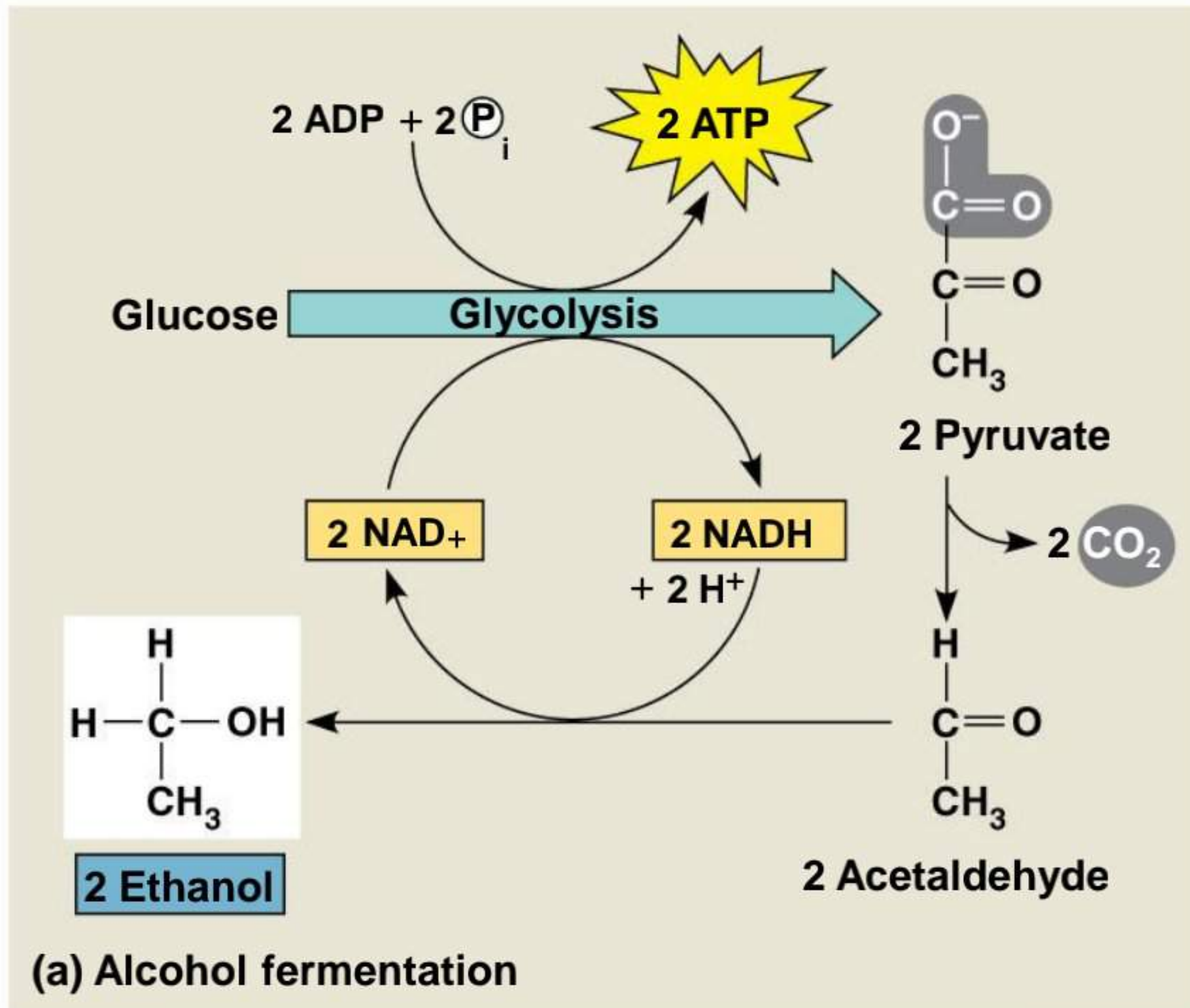
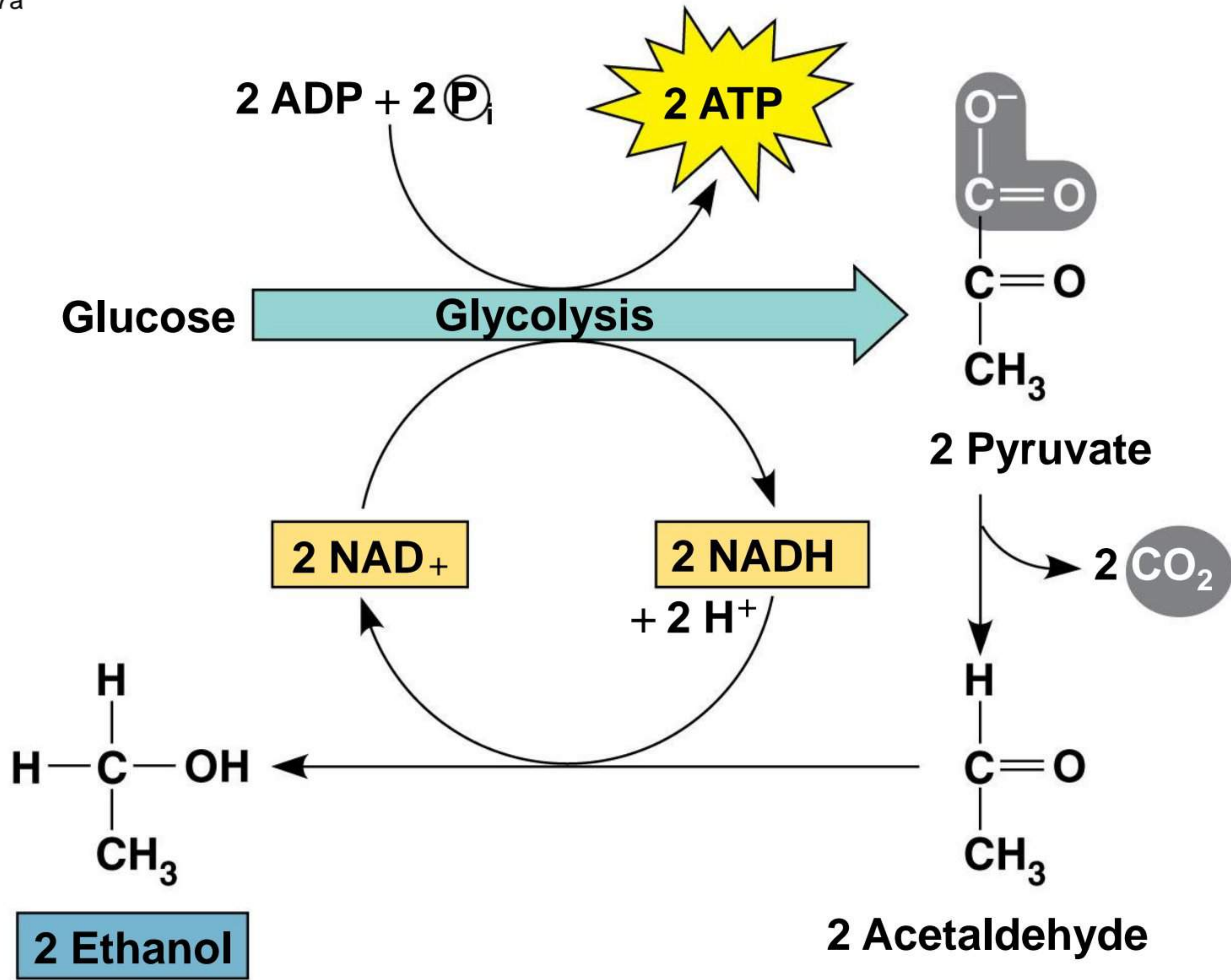
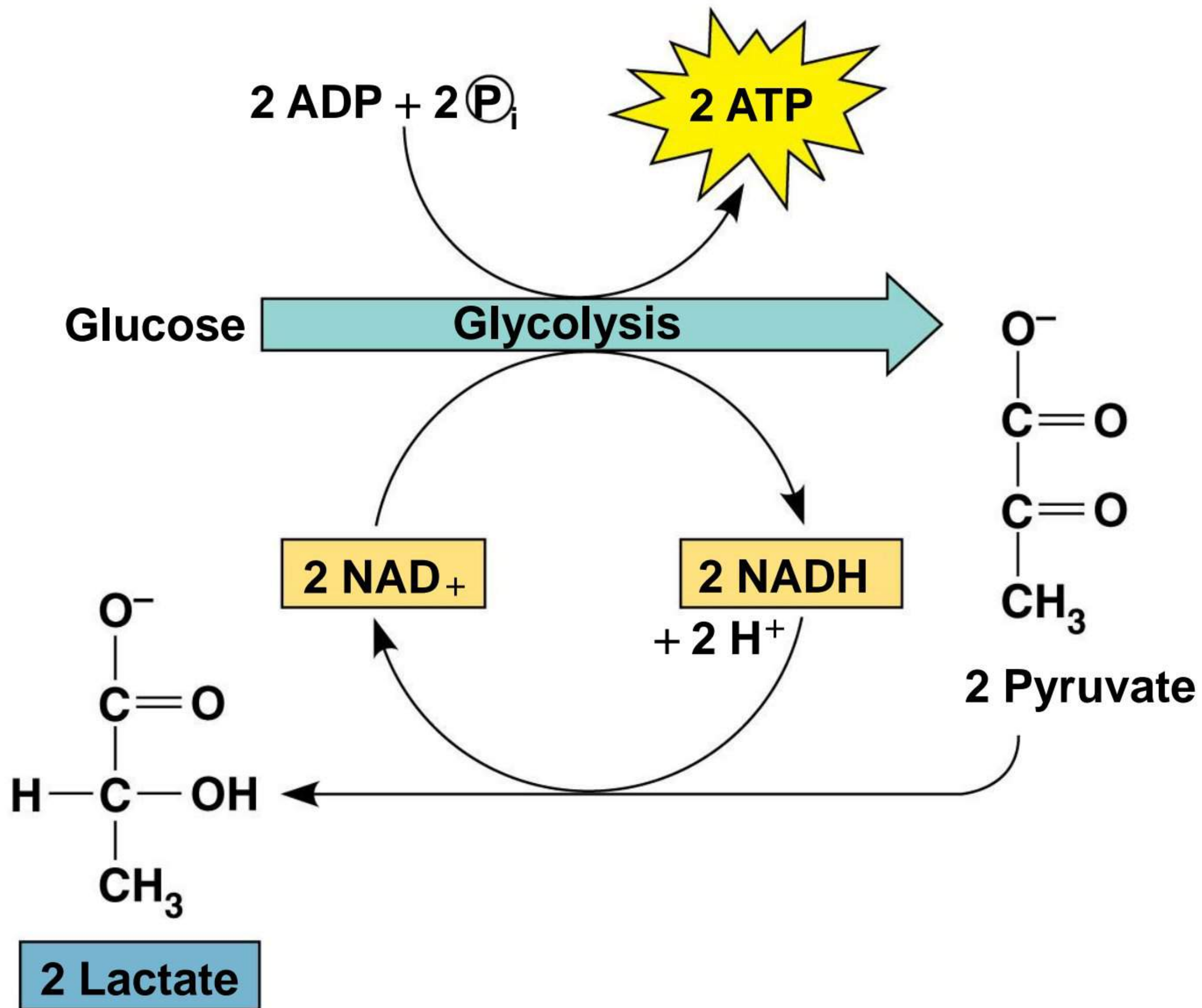


Figure 9.17a



(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



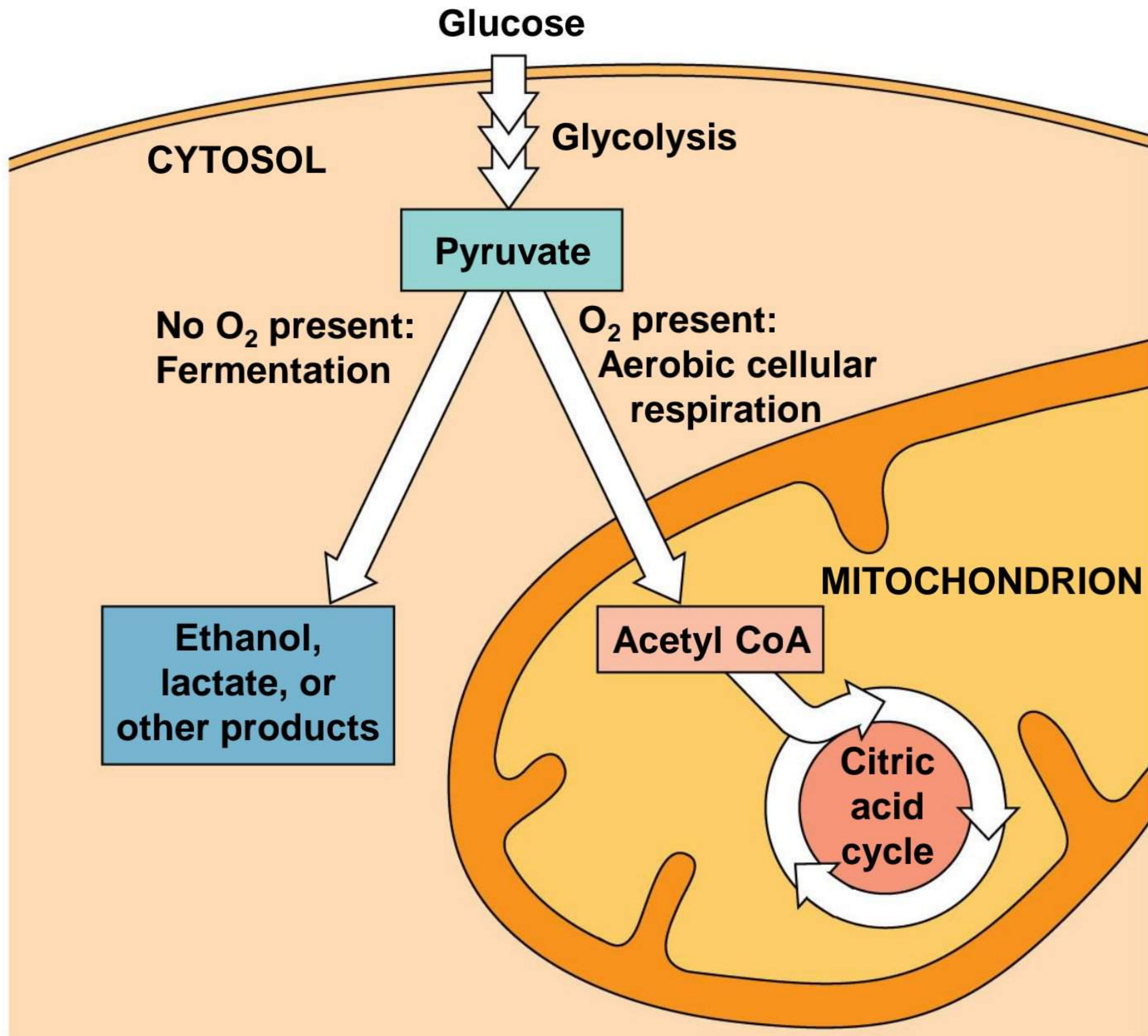
(b) Lactic acid fermentation

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
- The processes have different final electron acceptors: an organic molecule (such as pyruvate or acetaldehyde) in fermentation and O_2 in cellular respiration
- Cellular respiration produces 32 ATP per glucose molecule; fermentation produces 2 ATP per glucose molecule

- **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

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 O₂ 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

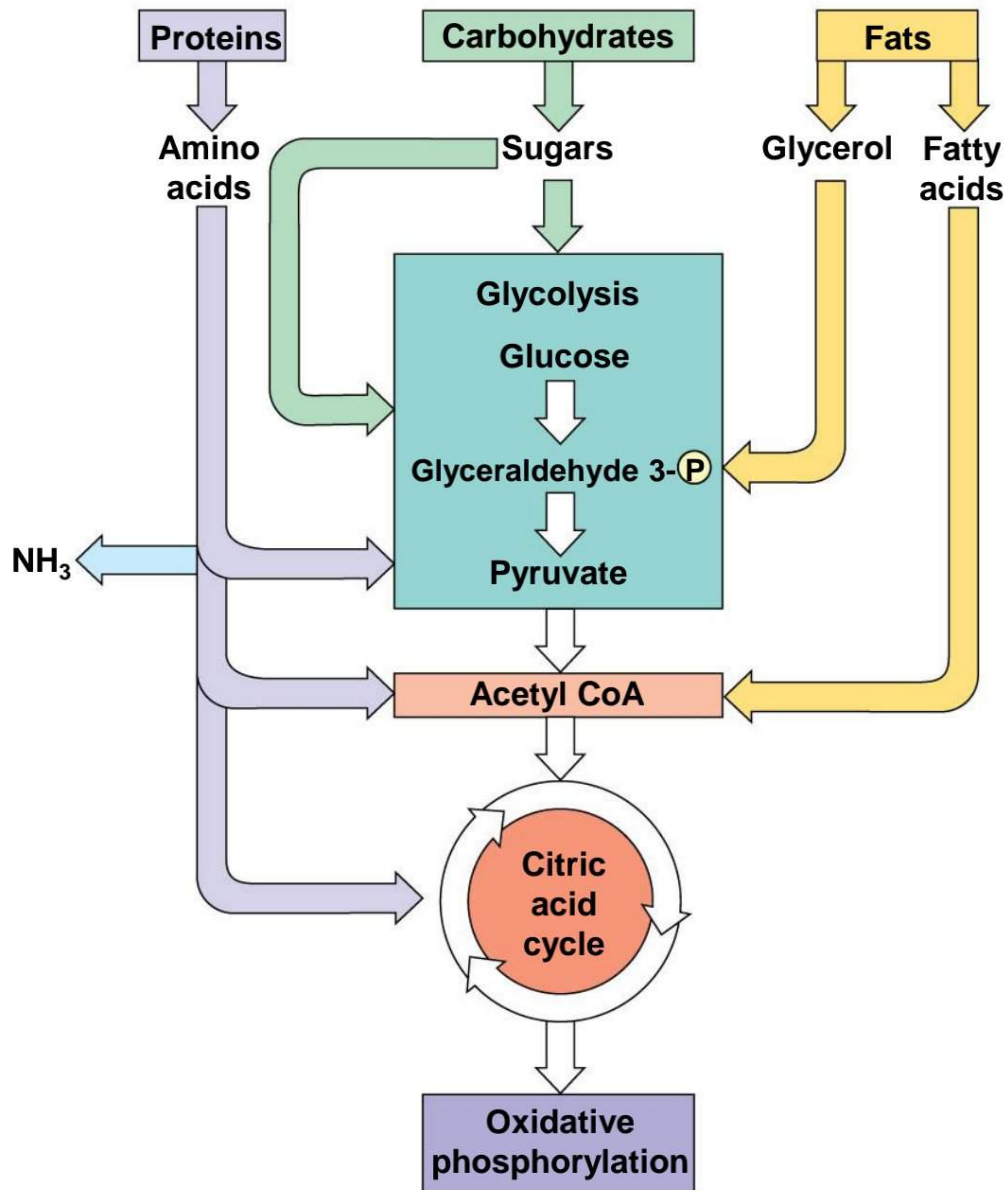
- Glycolysis and the citric acid cycle are major intersections to various catabolic and anabolic pathways

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



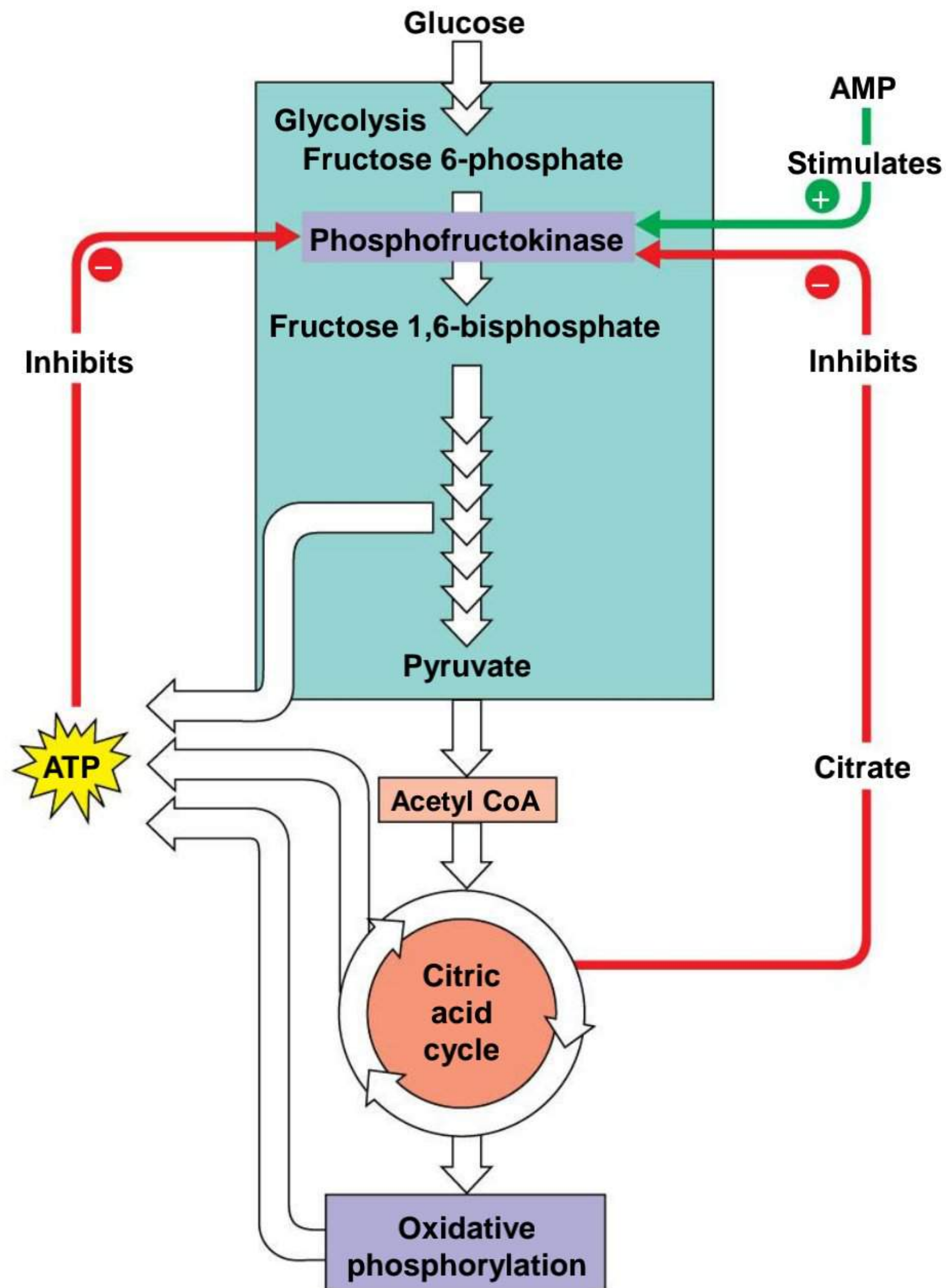
Biosynthesis (Anabolic Pathways)

- 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

Regulation of Cellular Respiration via Feedback Mechanisms

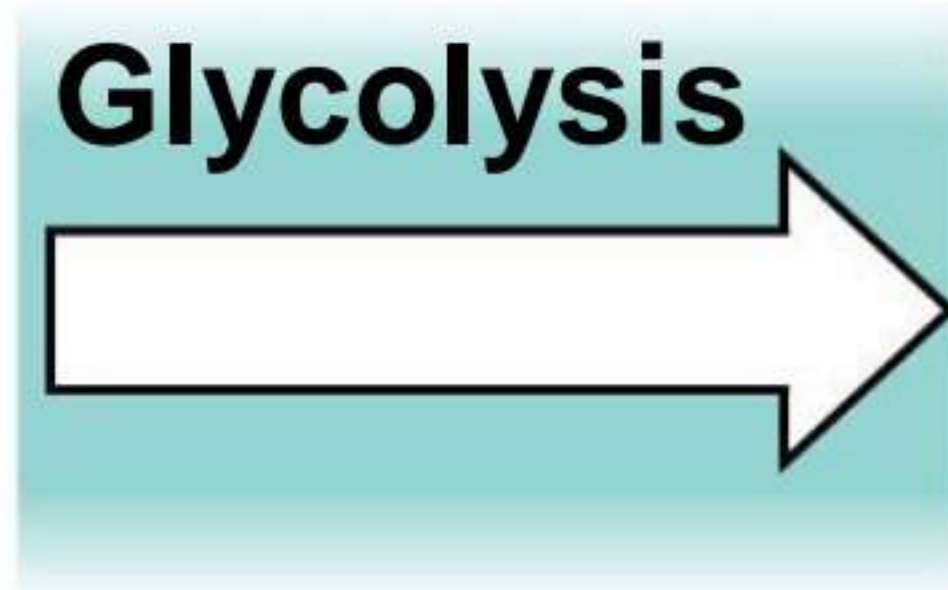
- Feedback inhibition is the most common mechanism for control
- If ATP concentration begins to drop, respiration speeds up; when there is plenty of ATP, respiration slows down
- Control of catabolism is based mainly on regulating the activity of enzymes at strategic points in the catabolic pathway

Figure 9.20



Inputs

Glucose

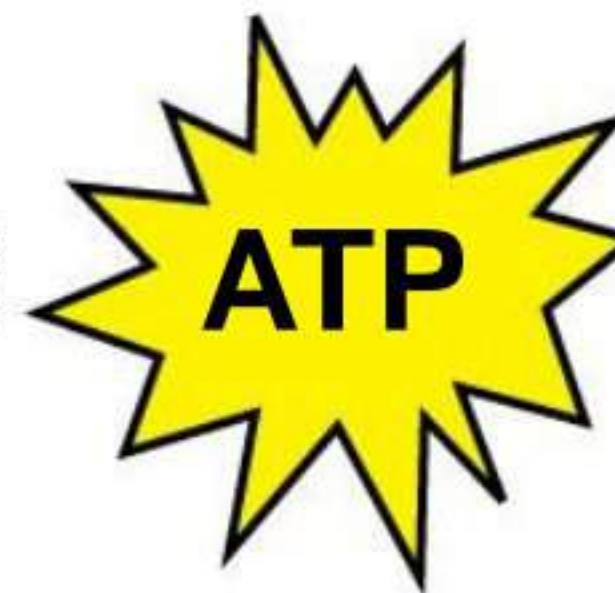


Outputs

2 Pyruvate

+

2



+

2



Figure 9.UN07

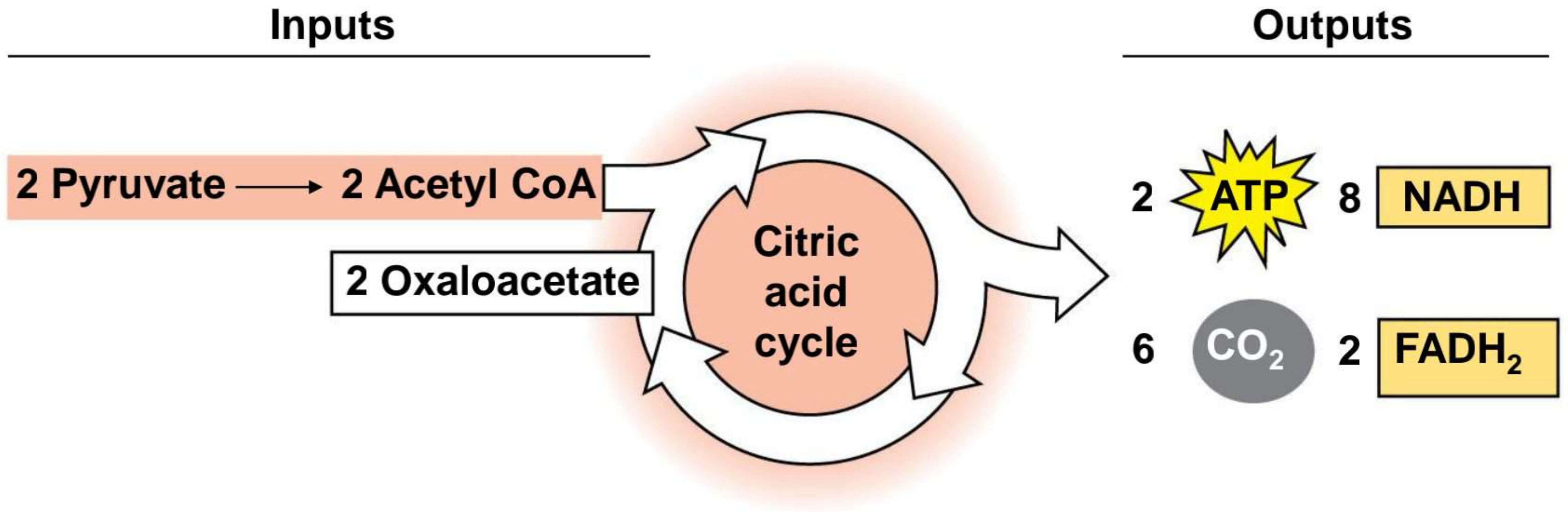


Figure 9.UN08

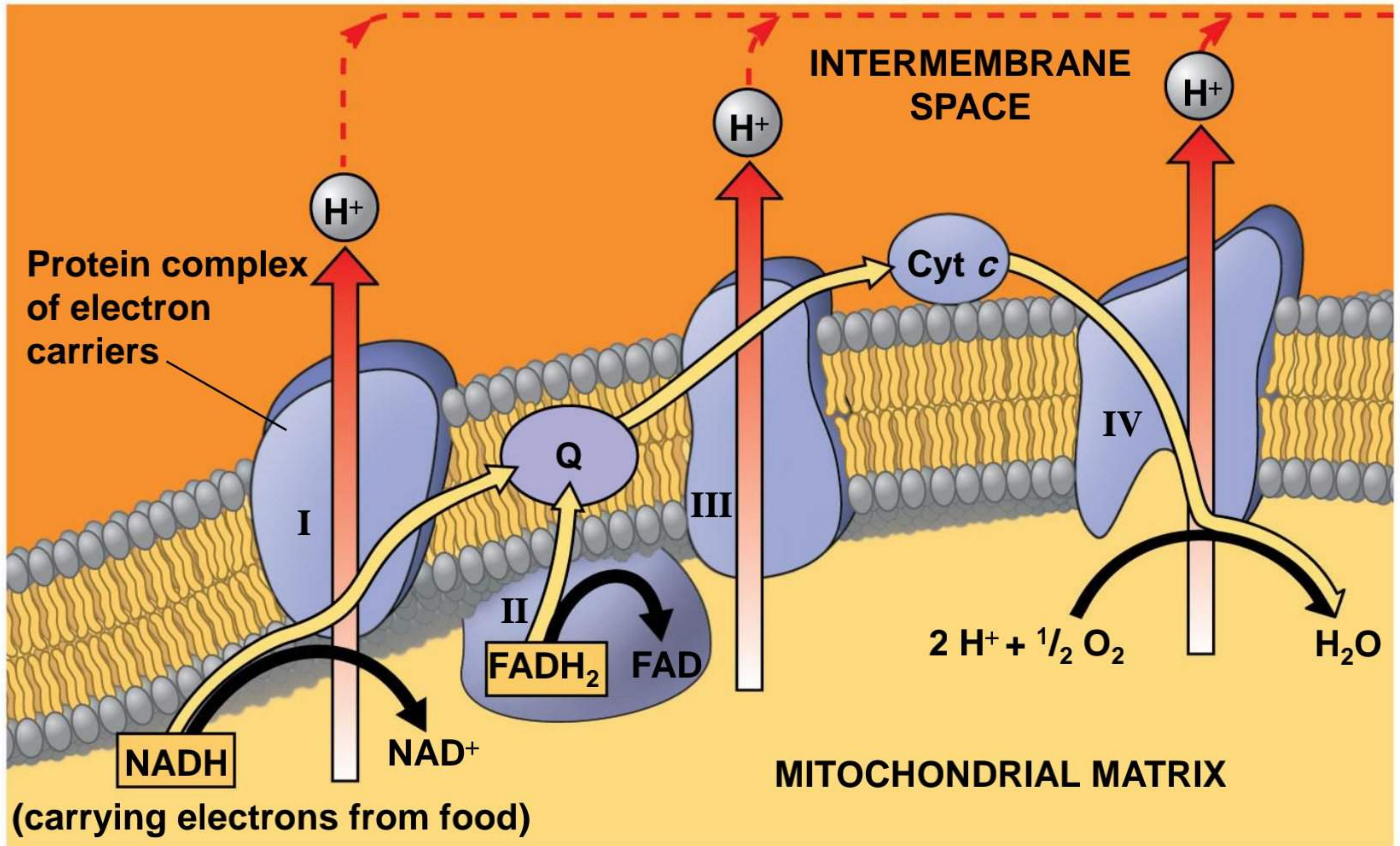
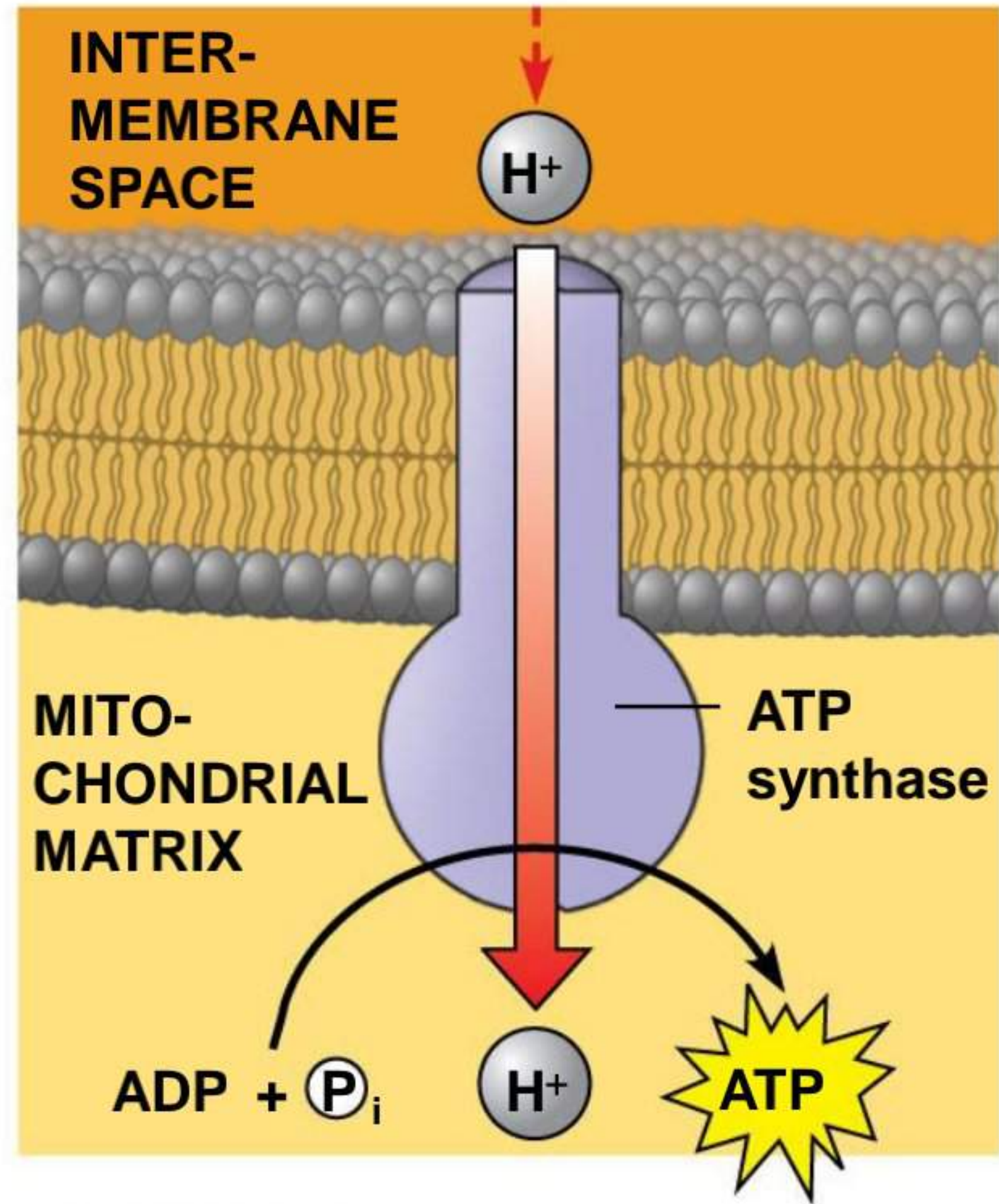


Figure 9.UN09



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Figure 9.UN10

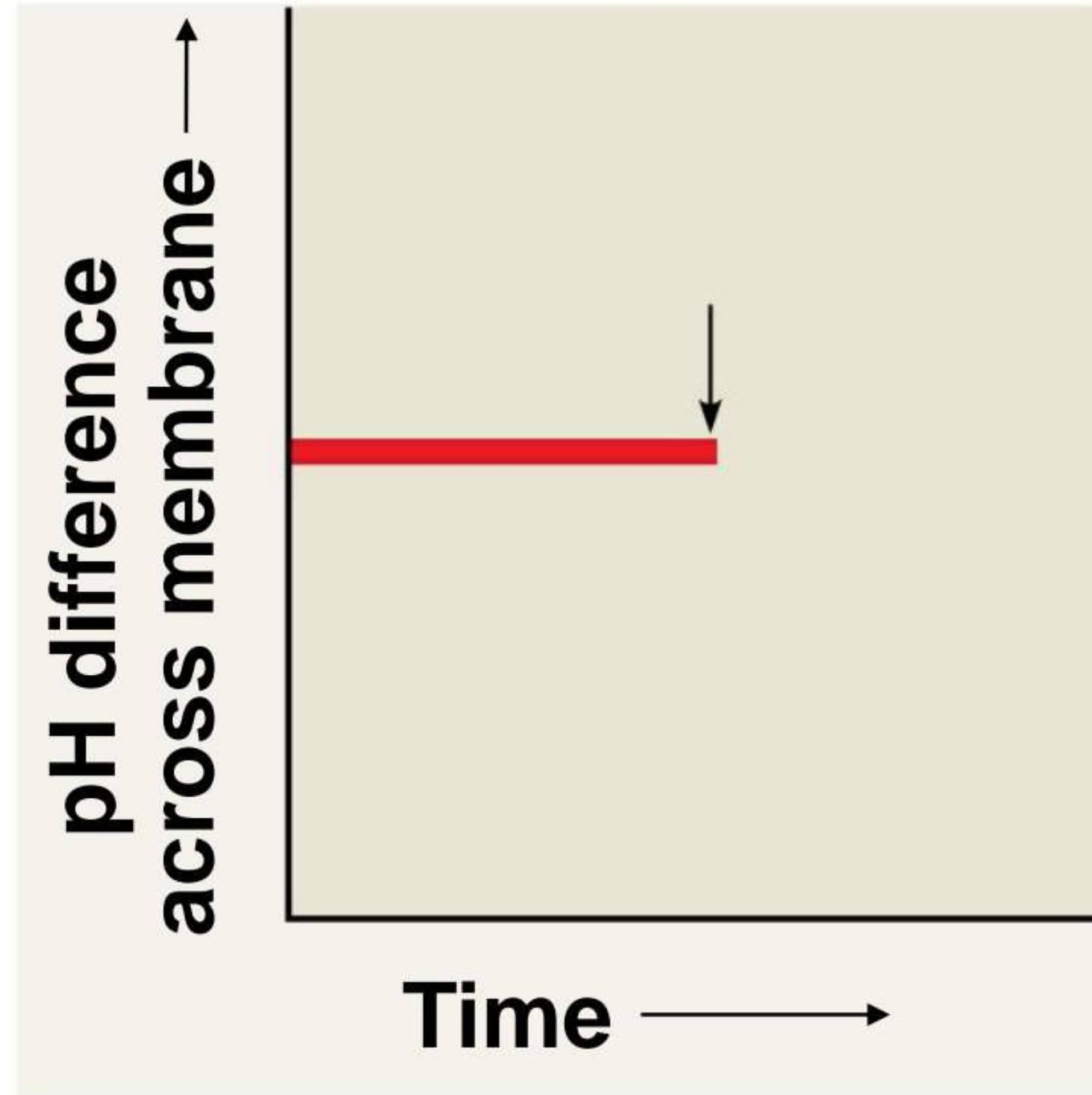


Figure 9.UN11

