Chapter 9

Cellular Respiration: Harvesting Chemical Energy

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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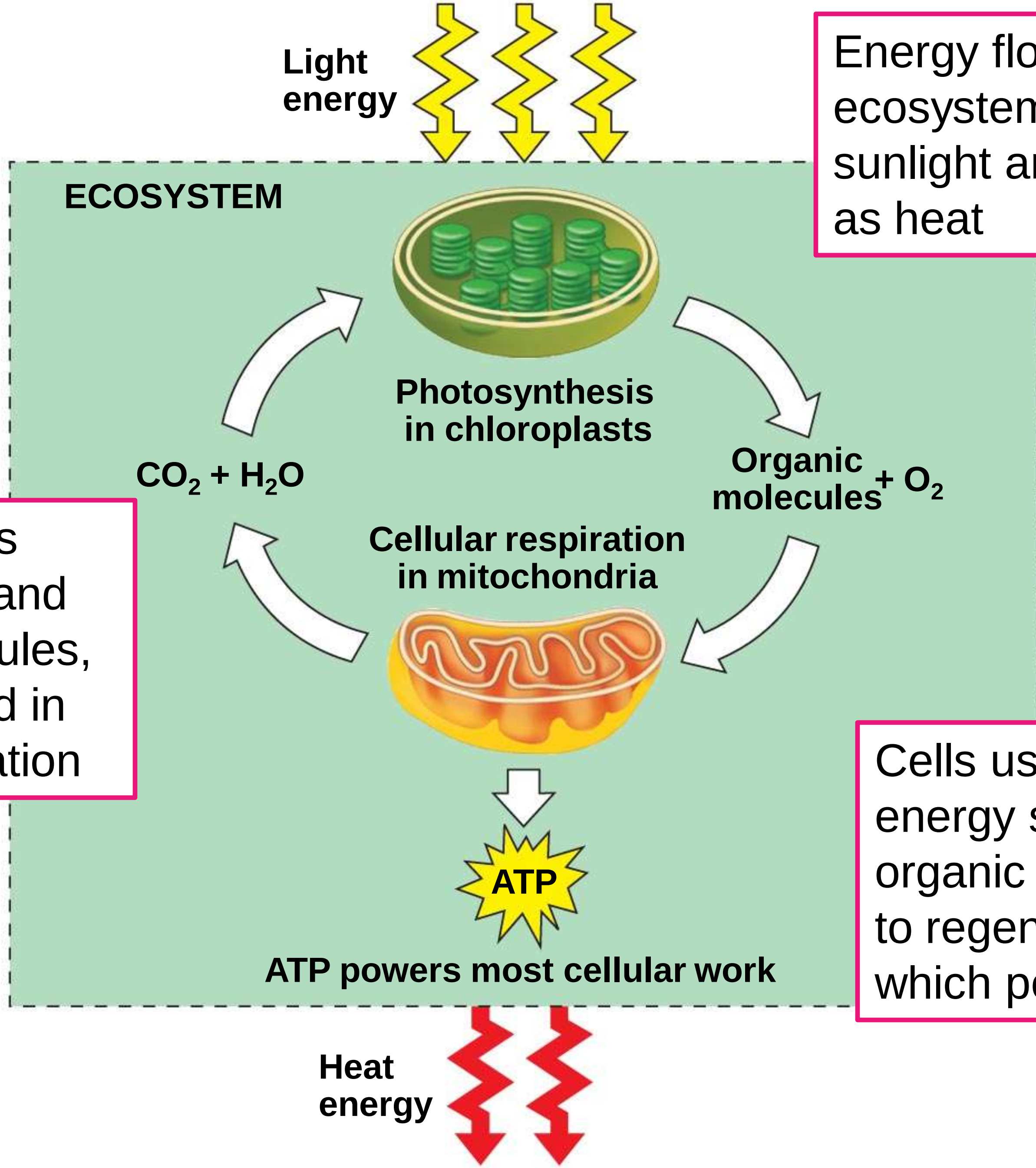
Living cells require energy from outside sources

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

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**:

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

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 cell's energy currency.

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)

Oxidation of Organic Fuel Molecules During Cellular Respiration

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

becomes oxidized ($C_6H_{12}O_6 \rightarrow 6\,CO_2$)

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

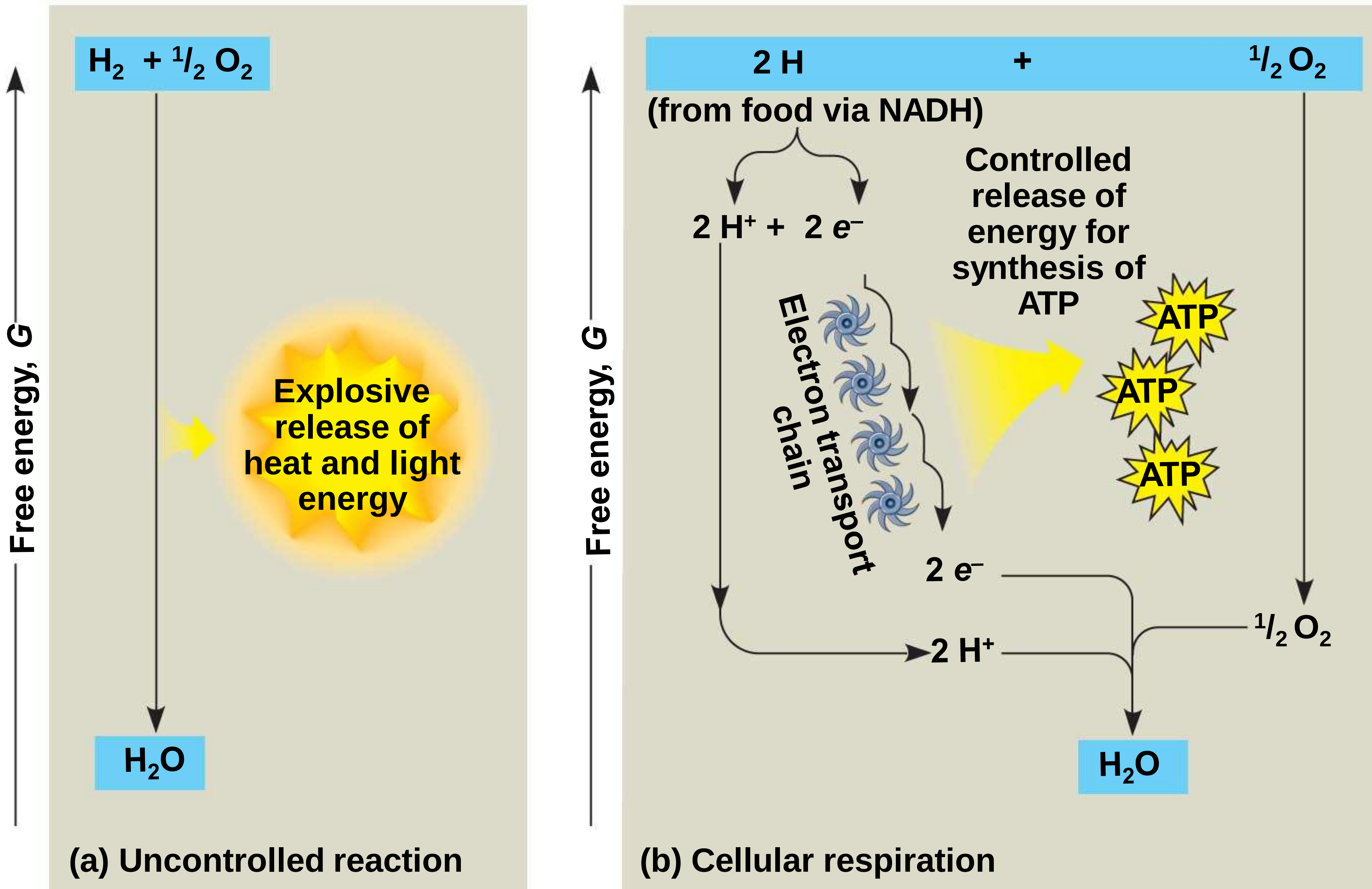
becomes reduced ($6\,O_2 \rightarrow 6\,H_2O$)

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**
- Each **NADH** (the reduced form of NAD^+) represents stored energy that is tapped to synthesize ATP

- 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**



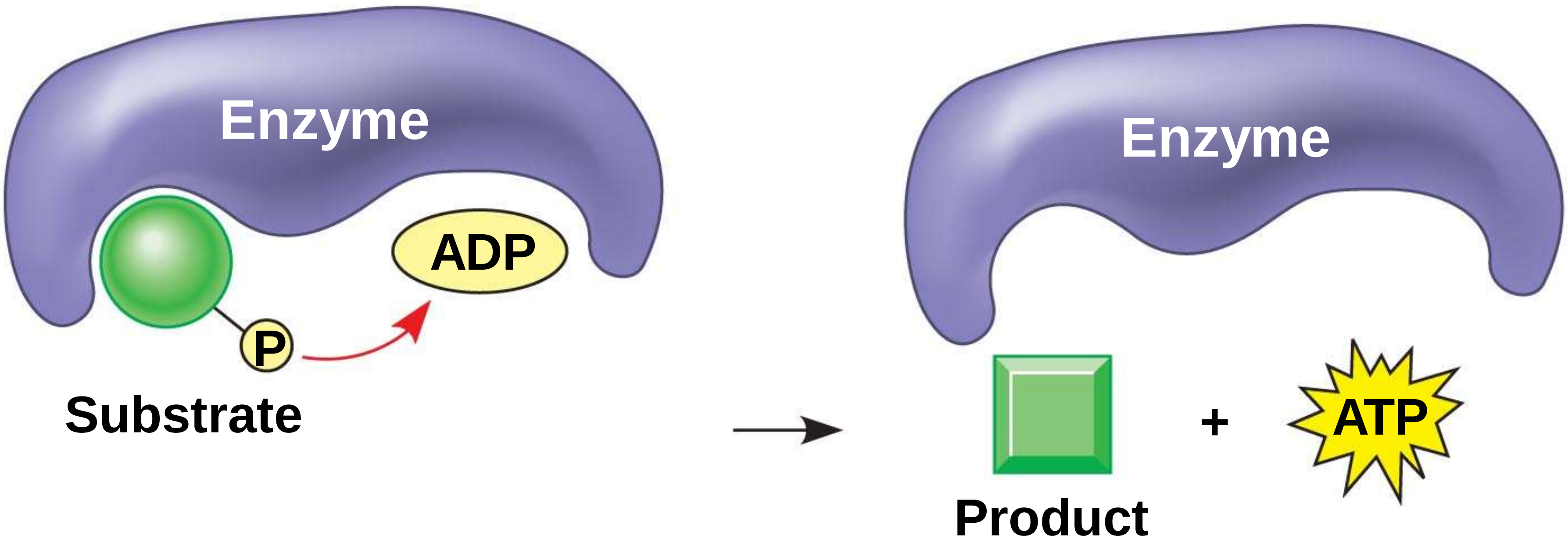
$H_2 + {}^1/_2 O_2$
Free energy, G
Explosive release of heat and light energy
H_2O
(a) Uncontrolled reaction
2 H
+
$^1/_2 O_2$
(from food via NADH)
$2 H^+ + 2 e^-$
Controlled release of energy for synthesis of ATP
ATP
ATP
ATP
Electron transport chain
$2 e^-$
$^1/_2 O_2$
$2 H^+$
H_2O
Free energy, G
(b) Cellular respiration

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 **almost 90% of the ATP synthesis**)

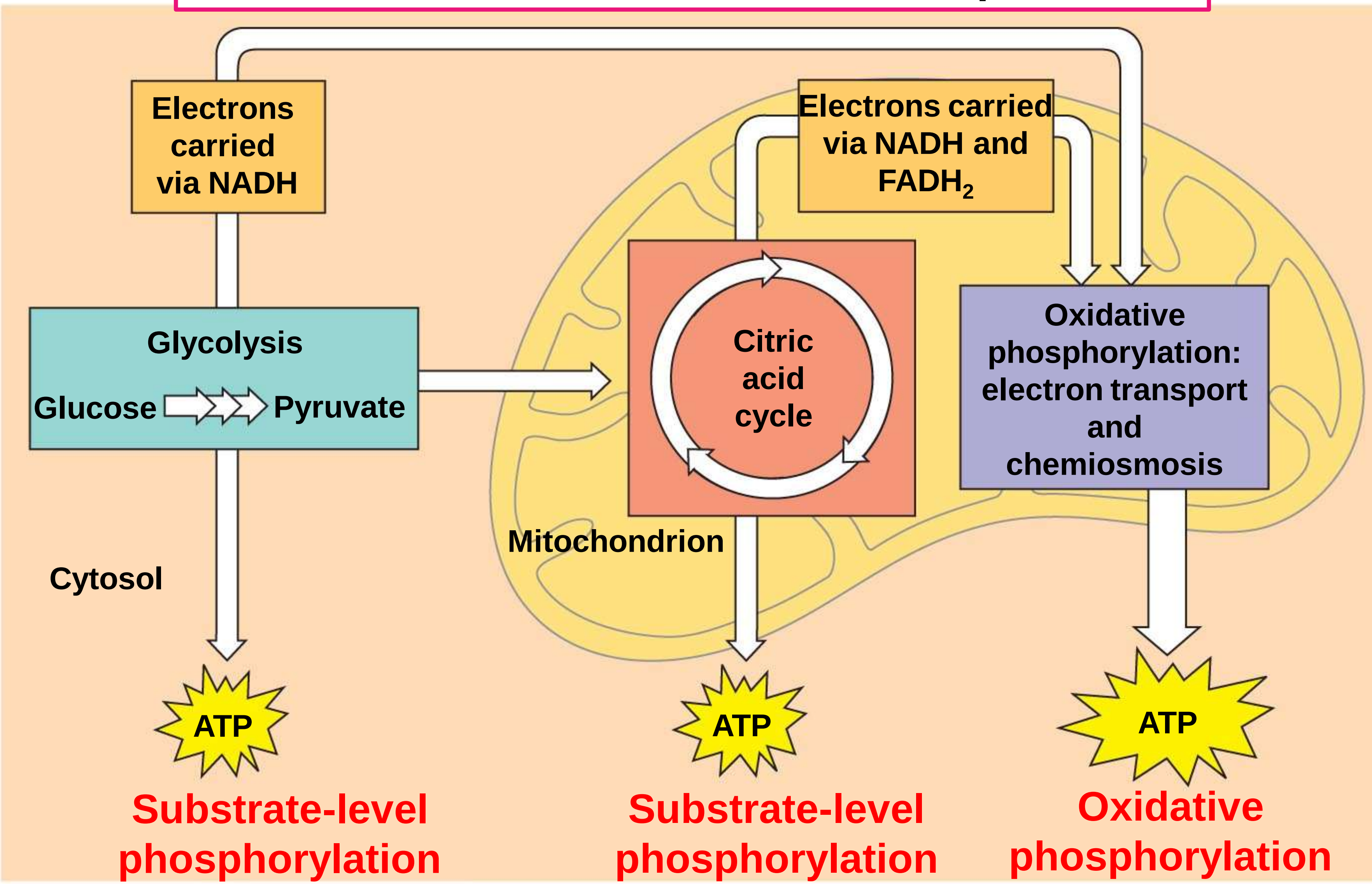
PLAY BioFlix: Cellular Respiration

Substrate-level phosphorylation



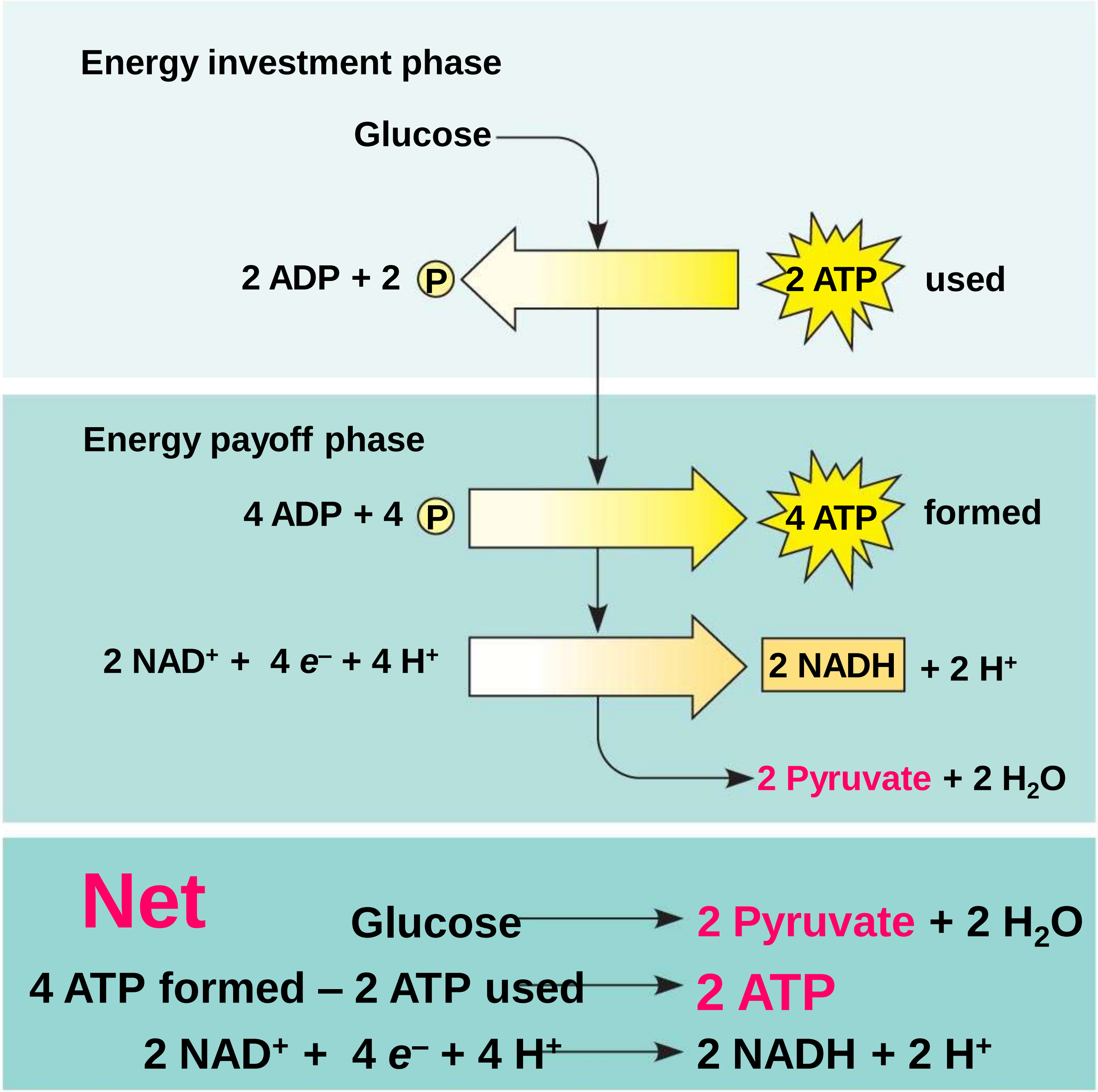
A **smaller amount of ATP** is formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation**

An overview of cellular respiration



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**

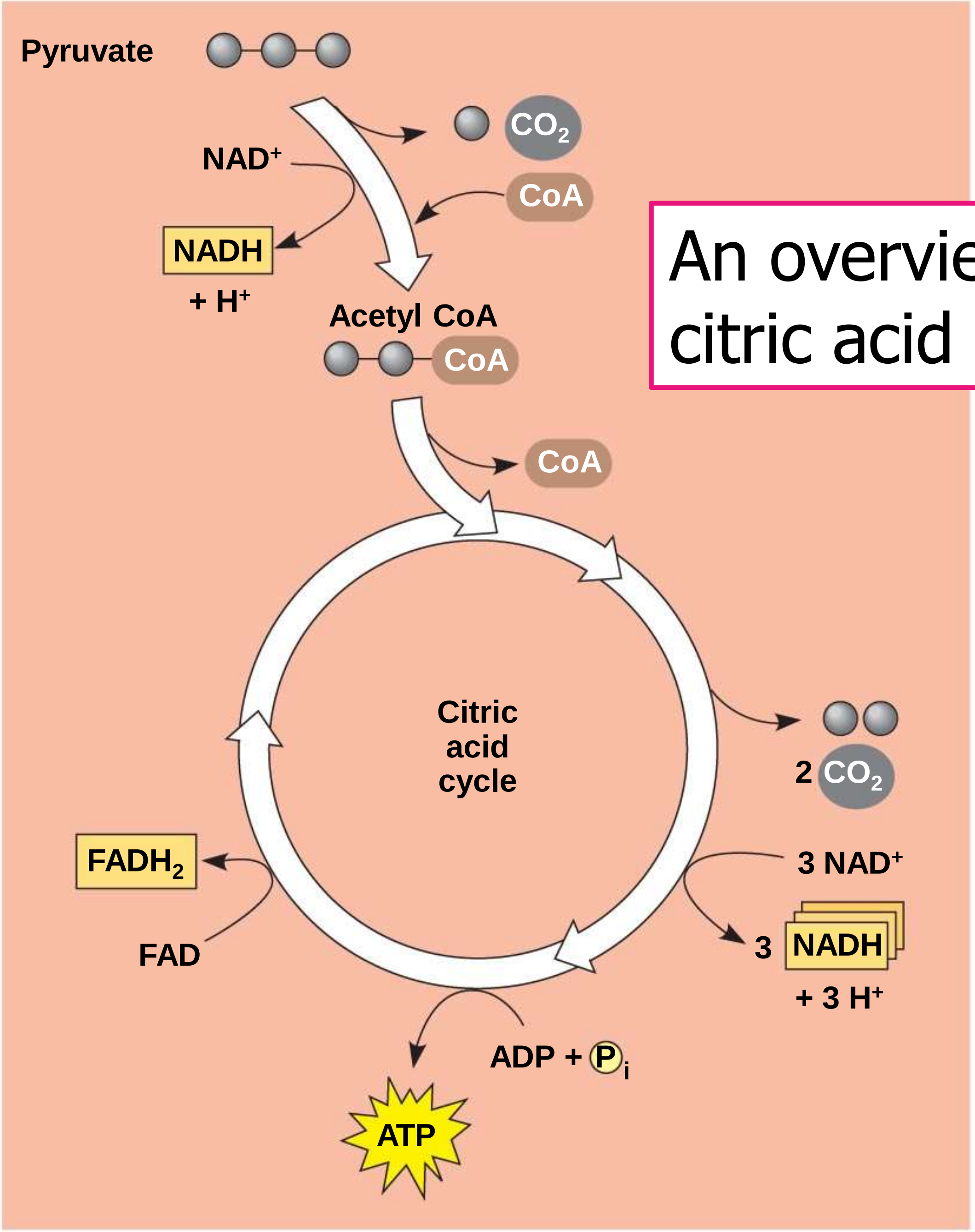


The energy input and output of glycolysis

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

- In the presence of O_2, **pyruvate enters the mitochondrion**
- Before the citric acid cycle can begin, pyruvate must be converted to **acetyl CoA**, which **links the cycle to glycolysis**

- The **citric acid cycle**, also called **Krebs cycle**, takes place **within the mitochondrial matrix**
- The cycle **oxidizes organic fuel** derived from pyruvate, generating **1 ATP**, 3 NADH, and 1 $FADH_2$ **per turn**



An overview of the citric acid cycle

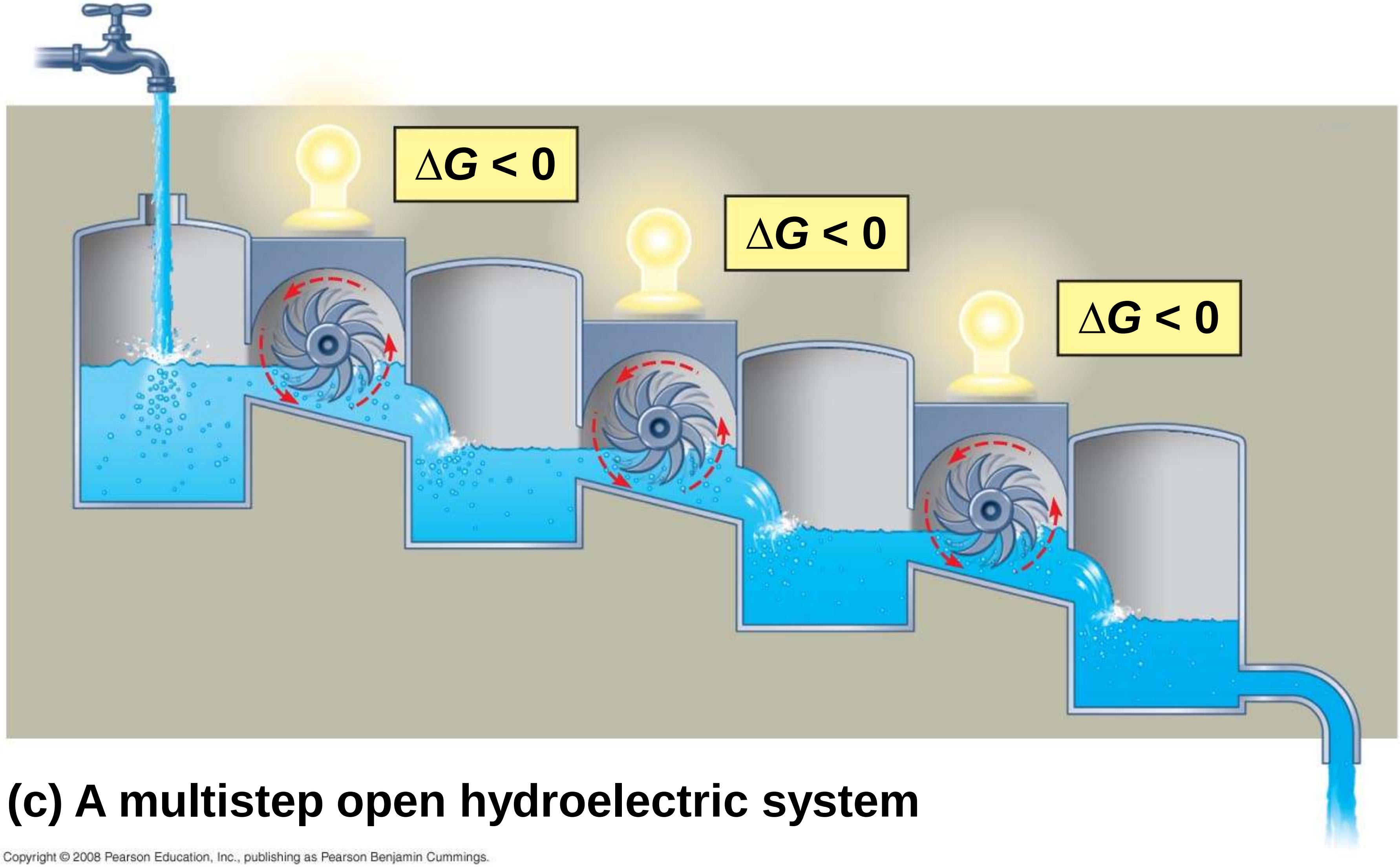
- The **citric acid cycle** has **eight steps**, **each catalyzed by a specific enzyme**
- The NADH and $FADH_2$ produced by the cycle **relay electrons** extracted from food to the **electron transport chain**

During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

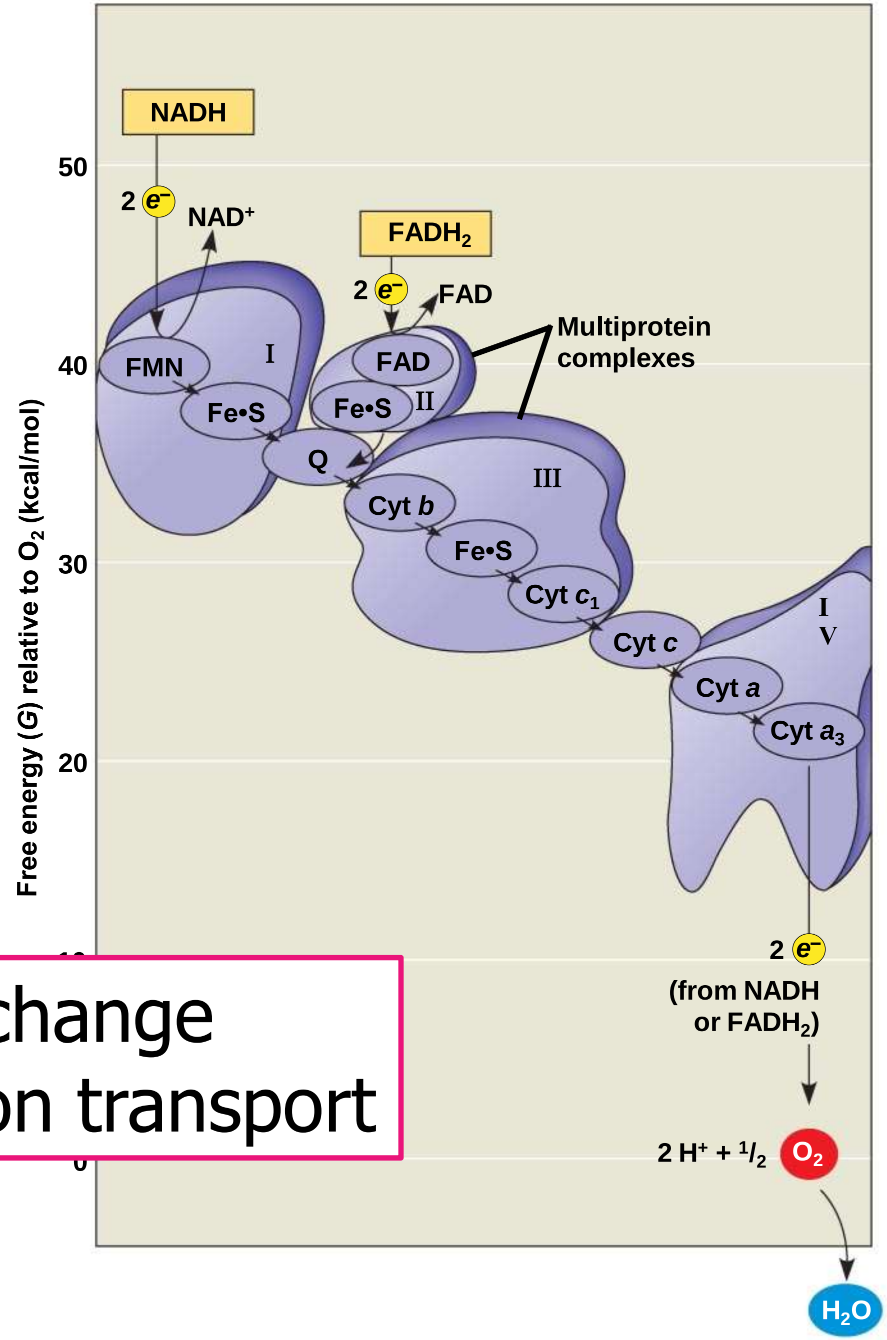
- Following glycolysis and the citric acid cycle, NADH and $FADH_2$ account for most of the energy extracted from food
- **These two electron carriers donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation**

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 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
- The electron transport chain **generates no ATP**



(c) A multistep open hydroelectric system

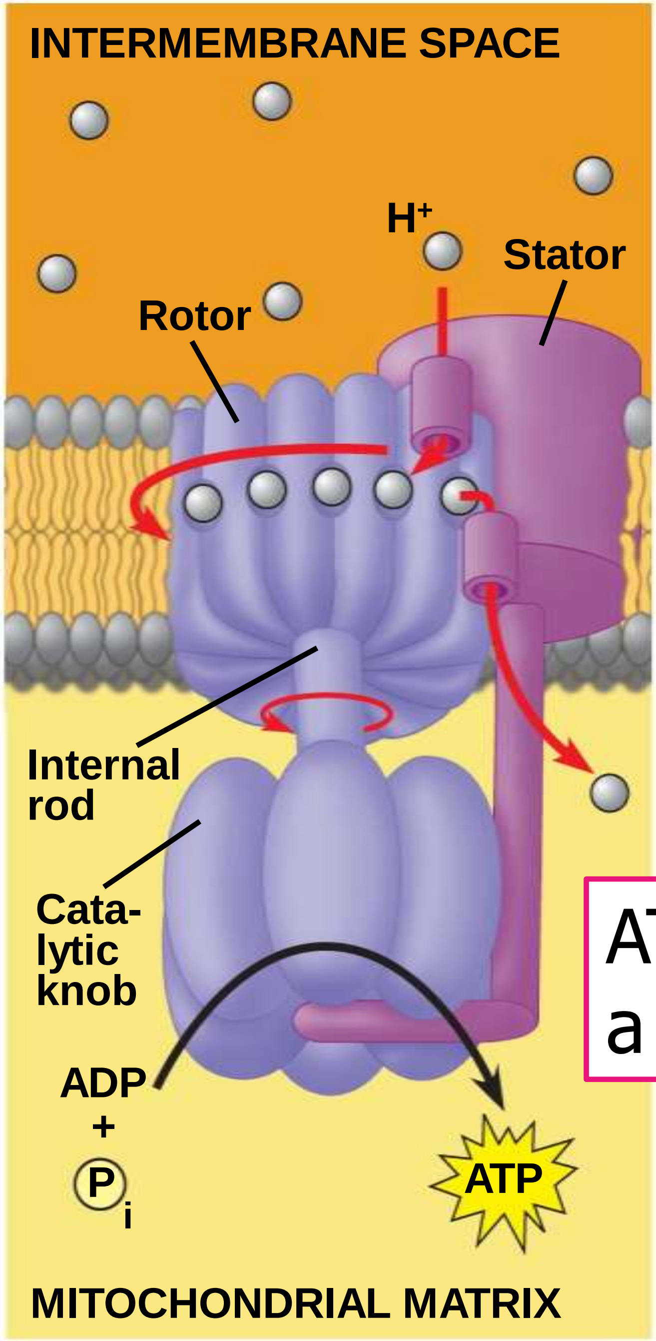


Free-energy change during electron transport

The chain's **function** is to break the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts

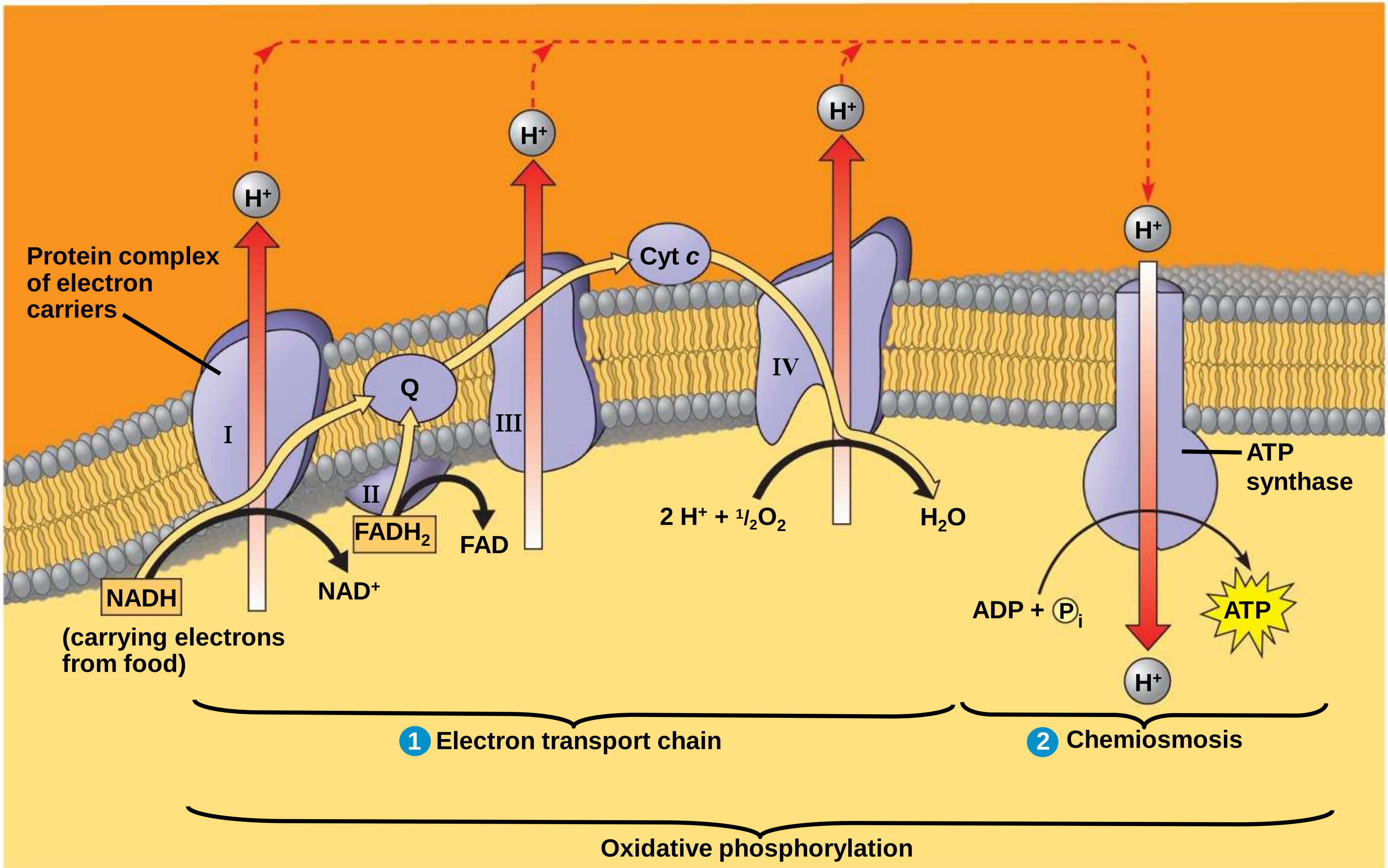
Chemiosmosis: The Energy-Coupling Mechanism

- As electrons are being transferred into the electron transport chain, proteins 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



ATP synthase, a molecular mill

Chemiosmosis couples the electron transport chain to ATP synthesis



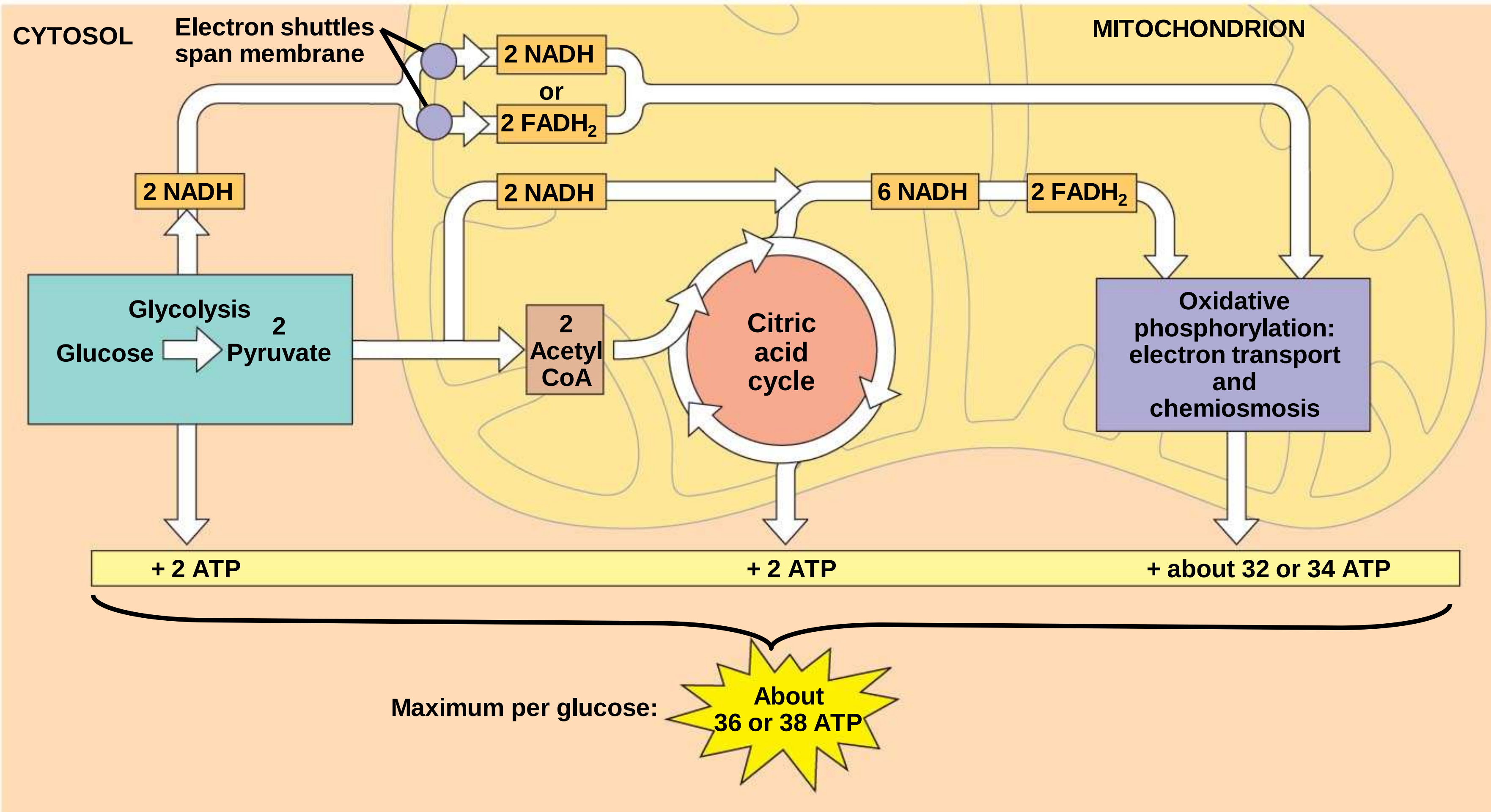
An Accounting of ATP Production by Cellular Respiration

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

glucose → NADH → electron transport chain → H^+ gradient → ATP

- About **40% of the energy** in a glucose molecule is transferred to ATP during cellular respiration, making **about 38 ATP**

ATP yield per molecule of glucose at each stage of cellular respiration



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

Glycolysis accepts a wide range of carbohydrates

- **Anaerobic respiration** uses an electron transport chain **with an electron acceptor other than O_2, for example sulfate**

- Fermentation uses **phosphorylation instead of an electron transport chain to generate ATP**

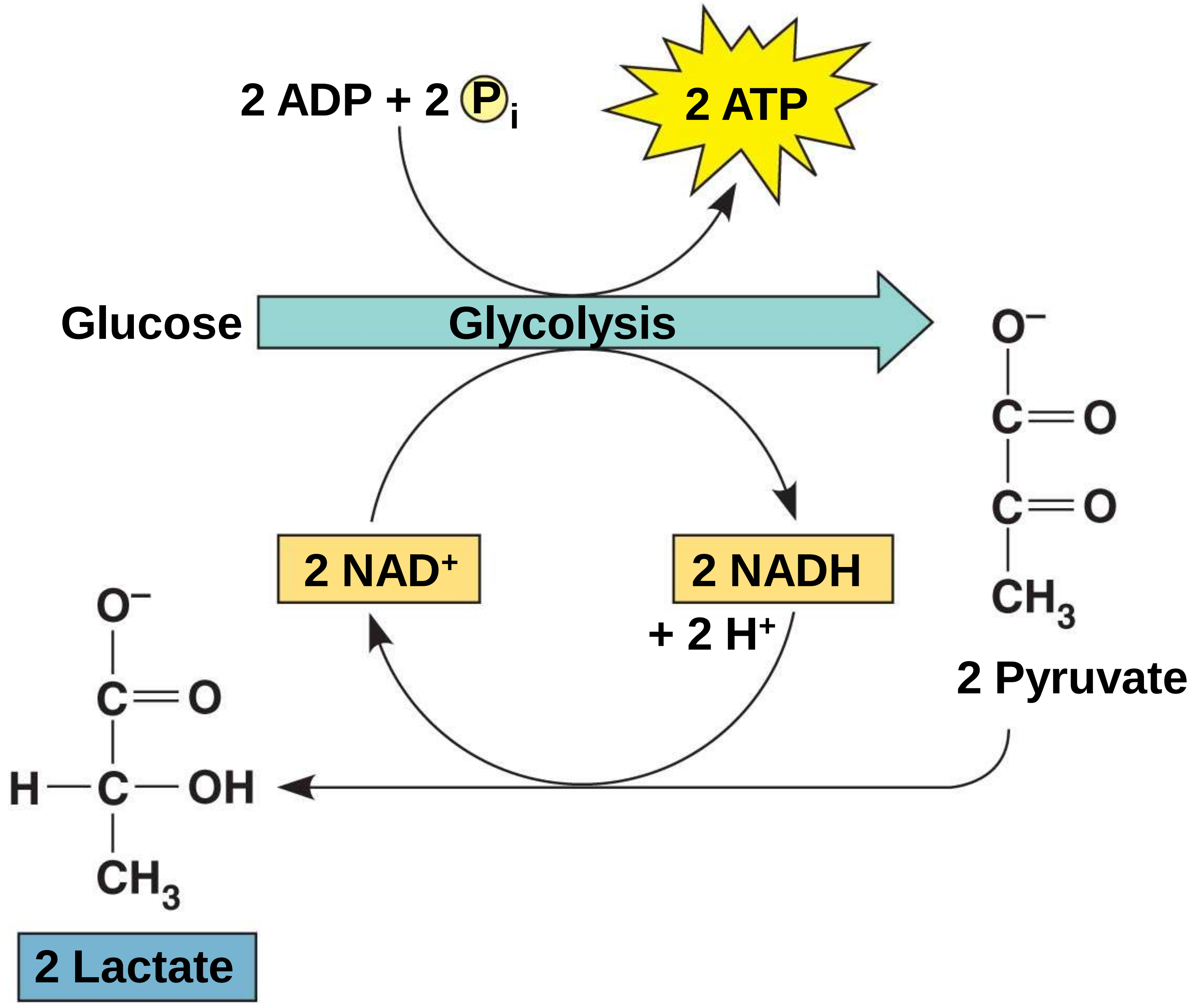
- Fermentation consists of glycolysis plus reactions that regenerate NAD^+, which can be reused by glycolysis

- 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

PLAY Animation: Fermentation Overview

- 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**

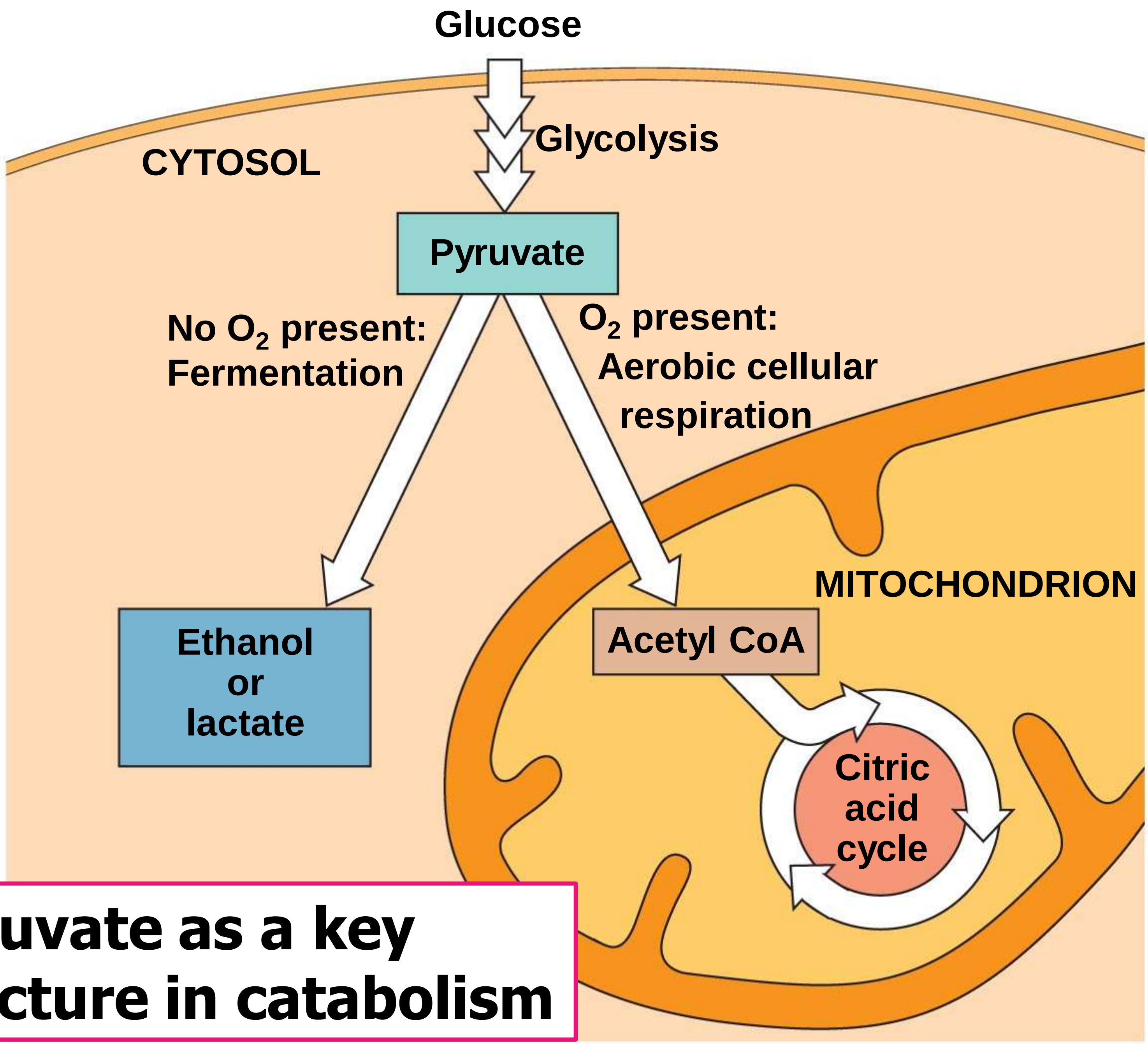


(b) Lactic acid fermentation

Fermentation and Aerobic Respiration Compared

- Both processes use **glycolysis** to oxidize glucose and other organic fuels to pyruvate
- 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 **38 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



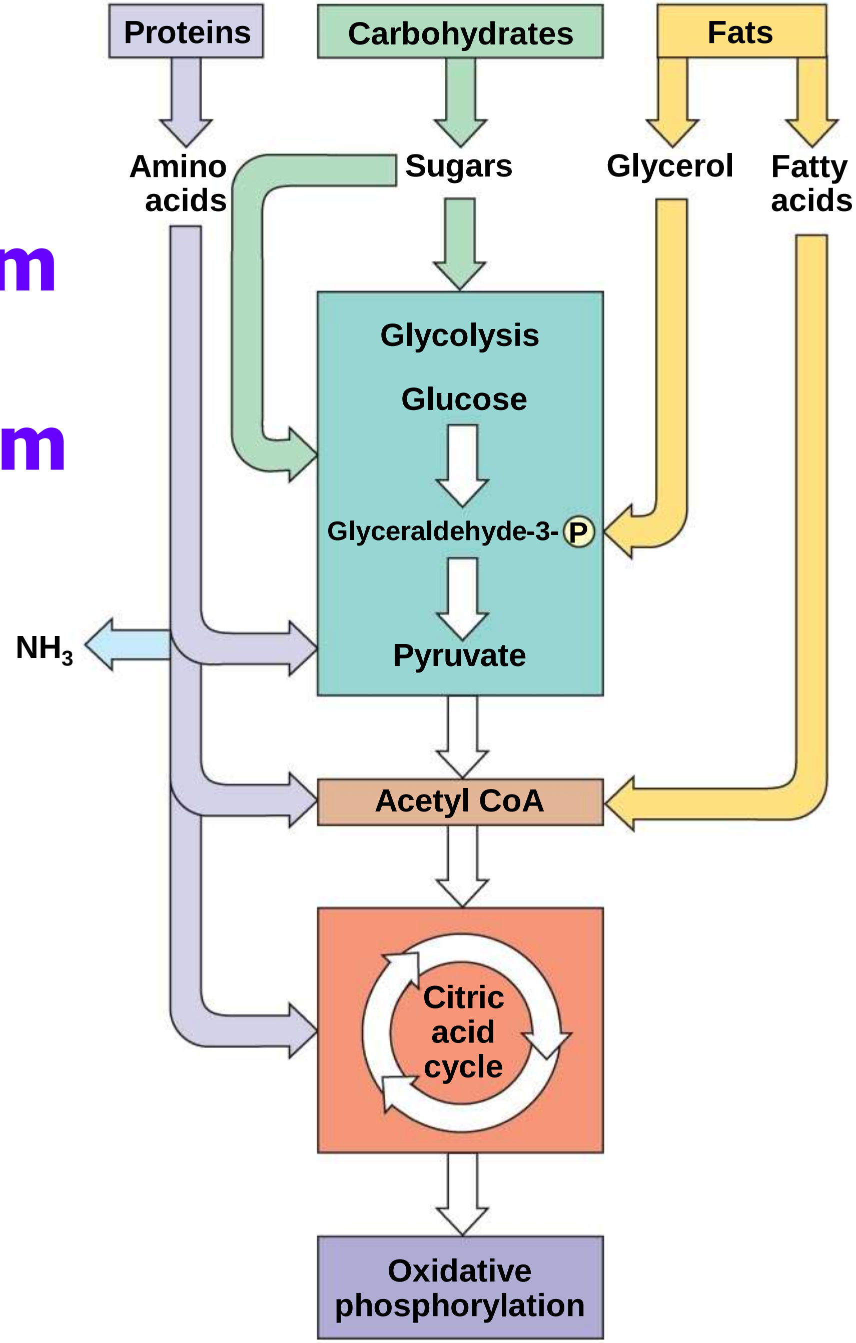
Pyruvate as a key juncture in catabolism

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**

The catabolism of various molecules from food



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

Questions ?

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