How cells harvest chemical energy

生科系李鳳鳴

Overview: Life Is Work

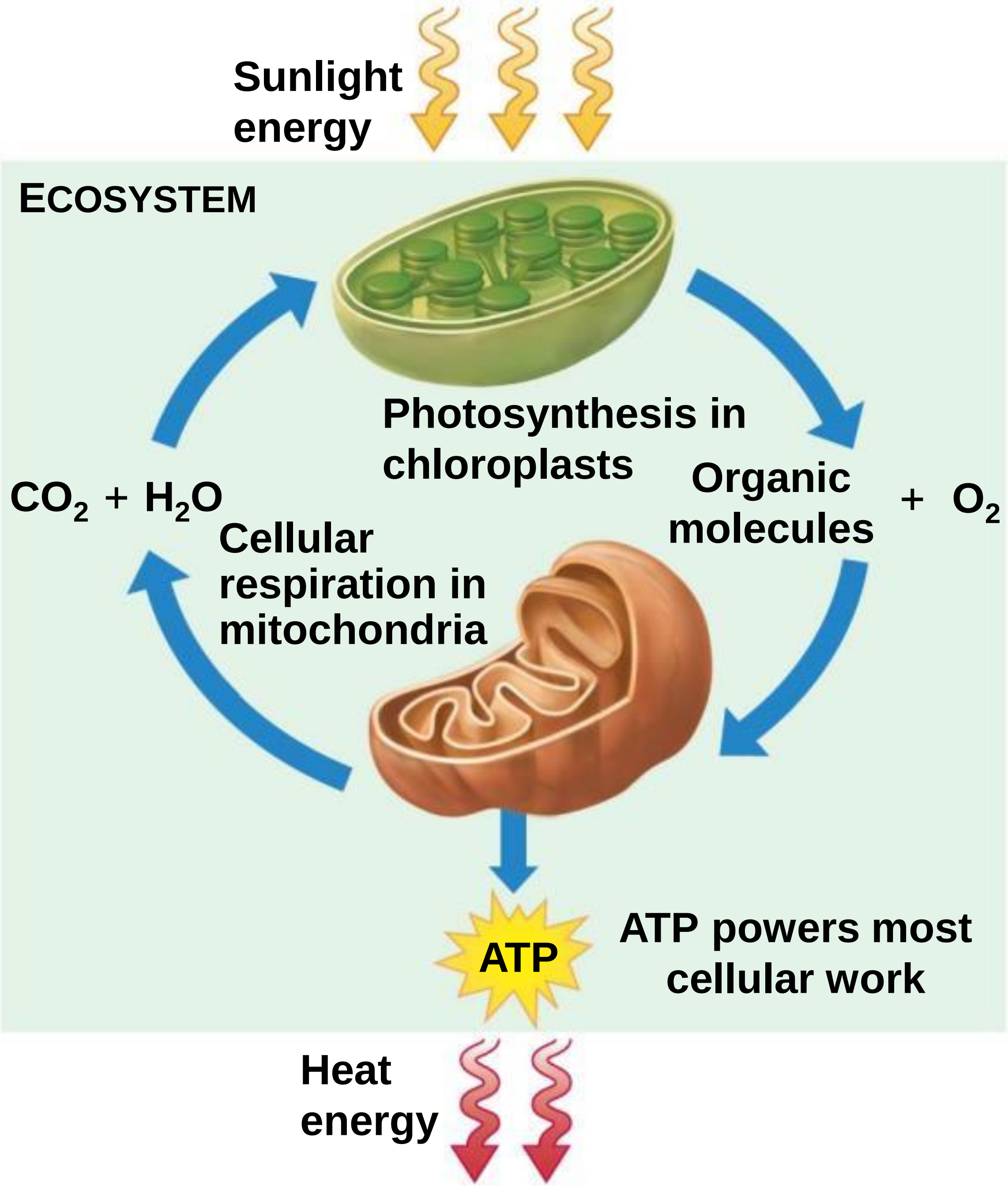
- Living cells require energy from outside sources
- Some animals obtain energy by eating plants, and some animals feed on other organisms that eat plants

Introduction

- Oxygen is a reactant in cellular respiration, the process that breaks down sugar and other food molecules and generates ATP, the energy currency in cells, and heat.
- Brown fat has a “short circuit” in its cellular respiration, which generates only heat, not ATP.
- Brown fat is important for heat production in small mammals, including humans.

Figure 6.0-1

Figure 6.1



Sunlight energy
ECOSYSTEM
Photosynthesis in chloroplasts
CO_2 + H_2O
Organic molecules
+ O_2
Cellular respiration in mitochondria
ATP
ATP powers most cellular work
Heat energy

6.1 Photosynthesis and cellular respiration provide energy for life

- In almost all ecosystems, energy ultimately comes from the sun.
- In photosynthesis,
  - some of the energy in sunlight is captured by chloroplasts,
  - atoms of carbon dioxide and water are rearranged, and
  - sugar and oxygen are produced.

Photosynthesis and cellular respiration provide energy for life

- In **cellular respiration**細胞呼吸,
  - sugar is broken down to carbon dioxide and water and
  - the cell captures some of the released energy to make ATP.
- Cellular respiration takes place in the mitochondria of eukaryotic cells.
- In these energy conversions, some energy is lost as heat.

Photosynthesis and cellular respiration provide energy for life

- Energy is necessary for life processes
  - These include growth, transport, manufacture, movement, reproduction, and others
  - Energy that supports life on Earth is captured from sun rays reaching Earth through plant, algae藻類, protist原生生物, and bacterial photosynthesis

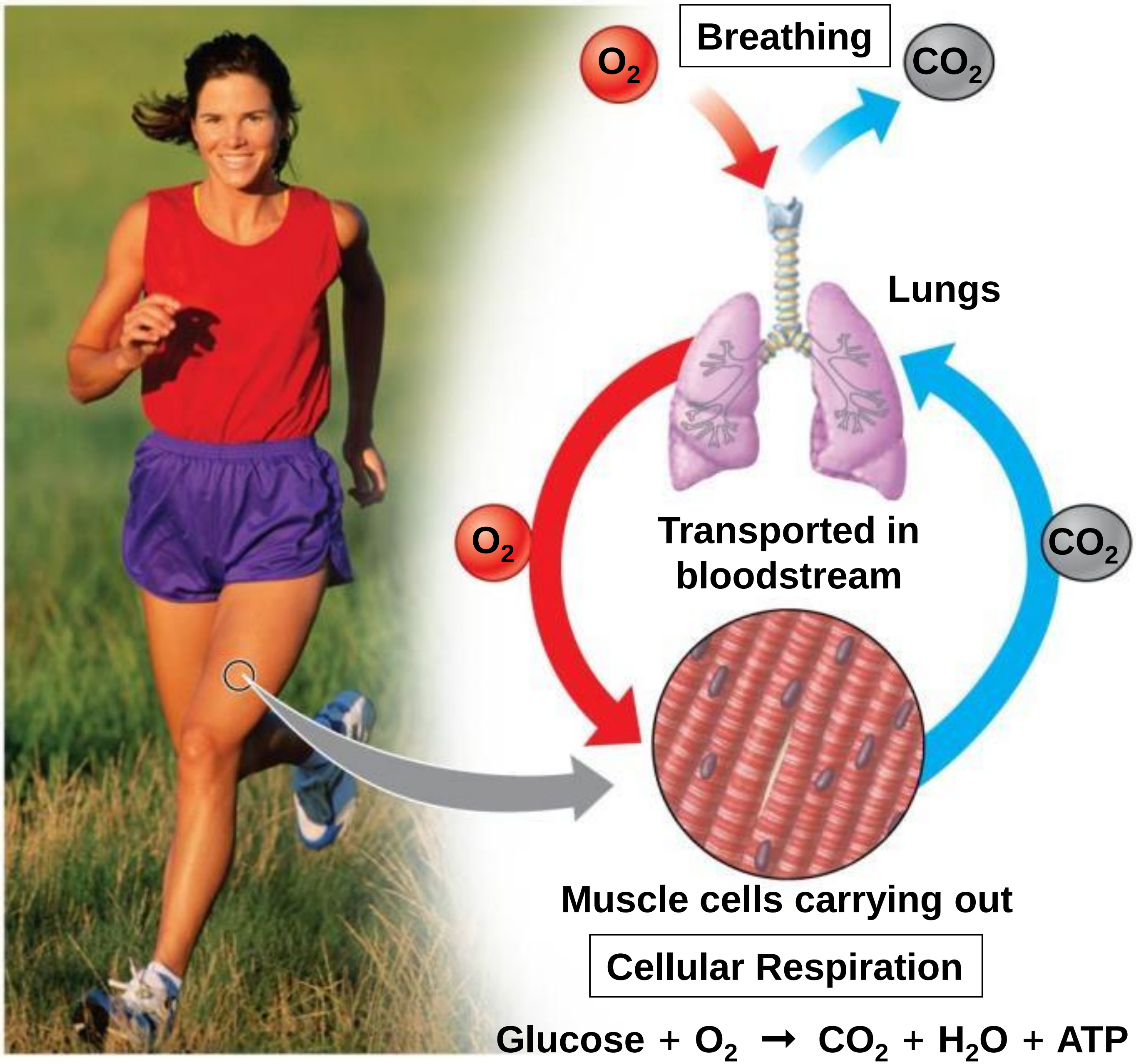
6.2 Breathing supplies oxygen for use in cellular respiration and removes carbon dioxide

- Breath: exchange of gases between an organism and its environment

- Cellular respiration: oxidation of organic molecules within cells, accompanied by the release of usable energy

- All organisms use the organic molecules in their food not only as energy resources but also as building materials for growth and repair

Figure 6.2-0

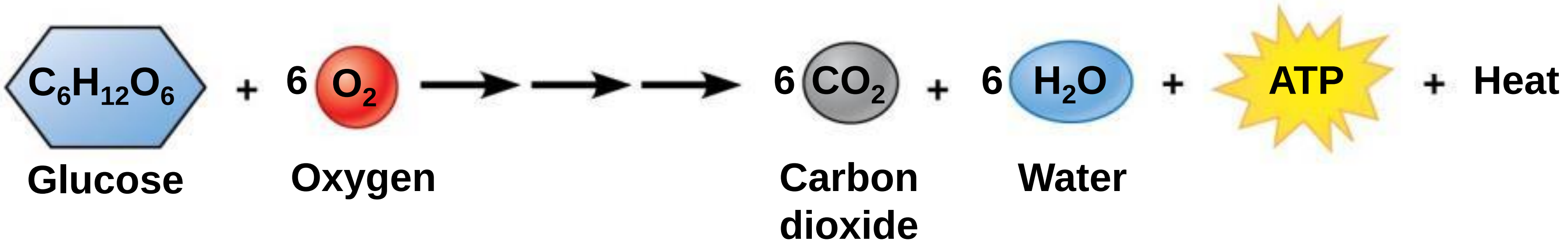


Breathing
O_2
CO_2
Lungs
O_2
Transported in bloodstream
CO_2
Muscle cells carrying out
Cellular Respiration
Glucose + O_2 → CO_2 + H_2O + ATP

6.3 Cellular respiration banks energy in ATP molecules

- Cellular respiration is an exergonic放熱反應 process that transfers energy from the bonds in glucose to ATP
  - Cellular respiration produces 32 ATP molecules from each glucose molecule
  - Other foods (organic molecules) can be used as a source of energy as well

Figure 6.3

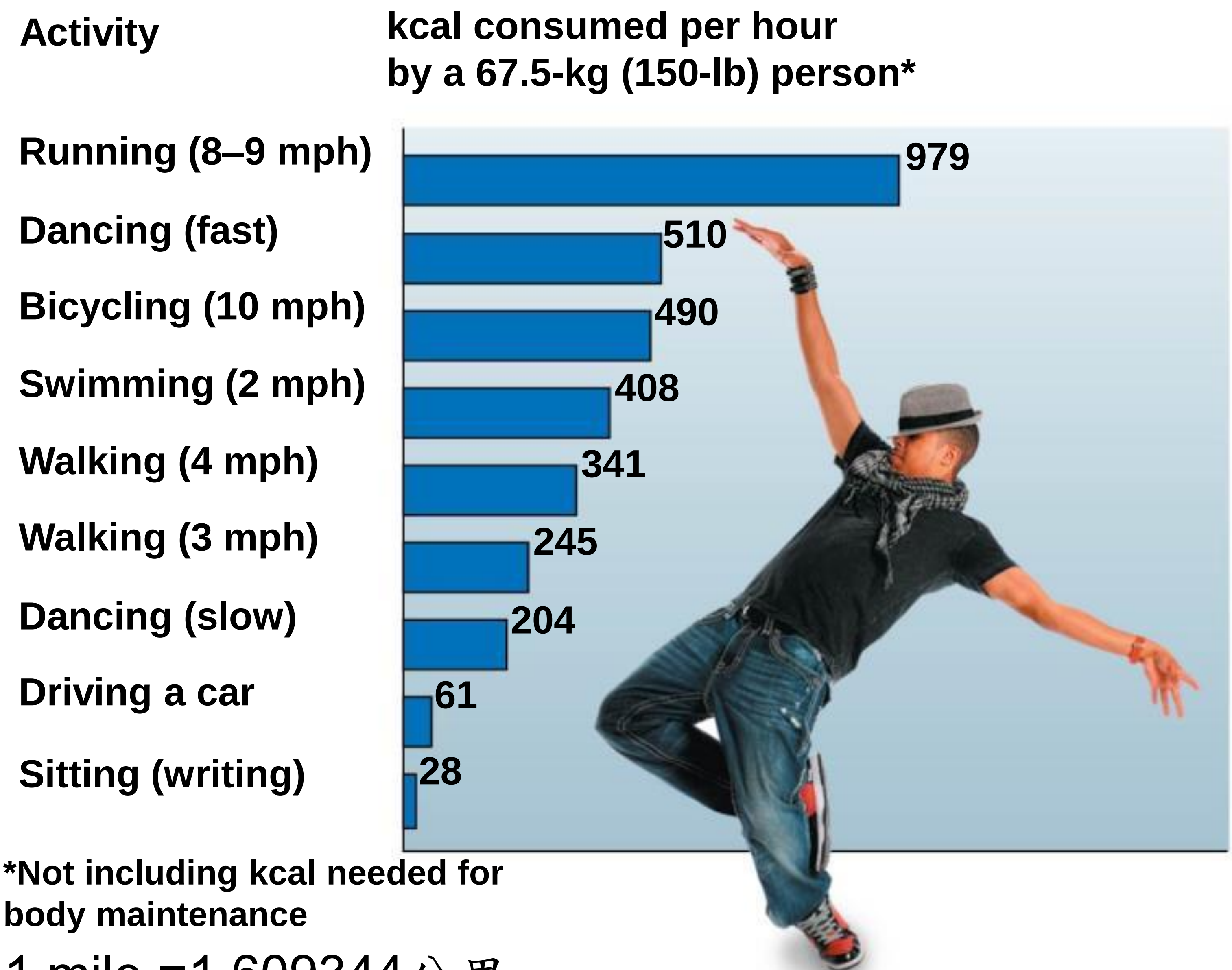


$C_6H_{12}O_6$
+
6
O_2
6
CO_2
+
6
H_2O
+
ATP
+
Heat
Glucose
Oxygen
Carbon dioxide
Water

6.4 The human body uses energy from ATP for all its activities

- The average adult human needs about 2,200 kcal of energy per day
  - A **kilocalorie** (**kcal**) is the quantity of heat required to raise the temperature of 1 kilogram (kg) of water by 1^{o}C
  - This energy is used for body maintenance and for voluntary activities
  - the same as a food Calorie, and
  - used to measure the nutritional values indicated on food labels.

Figure 6.4-0



1 mile =1.609344公里

6.5 Cells capture energy from electrons "falling" from organic fuels to oxygen

- The energy necessary for life is contained in the arrangement of electrons in chemical bonds in organic molecules
- An important question is how do cells extract this energy?

Cells capture energy from electrons "falling" from organic fuels to oxygen

- When the carbon-hydrogen bonds of glucose are broken, electrons are transferred to oxygen
  - Oxygen has a strong tendency to attract electrons

Cells capture energy from electrons “falling” from organic fuels to oxygen

- Energy can be released from glucose by simply burning it
- The energy is dissipated as heat and light and is not available to living organisms

Cells capture energy from electrons “falling” from organic fuels to oxygen

- On the other hand, cellular respiration is the controlled breakdown of organic molecules
  - Energy is released in small amounts that can be captured by a biological system and stored in ATP

- Unlike the explosive release of heat energy that would occur when H_2 and O_2 combine, cellular respiration uses an **electron transport chain** to break the fall of electrons to O_2 into several steps.

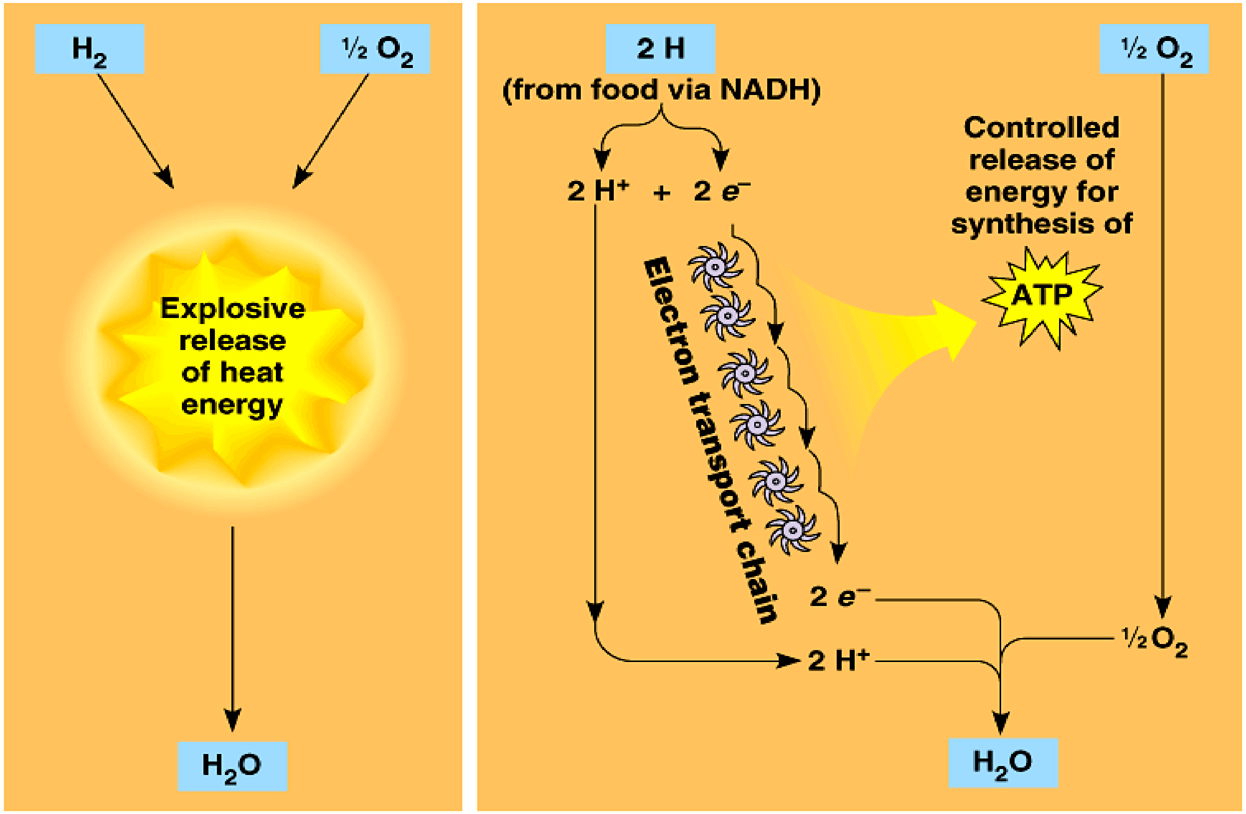


Fig. 9.5 (a) Uncontrolled reaction (b) Cellular respiration

Cells capture energy from electrons “falling” from organic fuels to oxygen

- A cellular respiration equation is helpful to show the changes in hydrogen atom distribution
  - Glucose loses its hydrogen atoms and is ultimately converted to CO_2
  - At the same time, O_2 gains hydrogen atoms and is converted to H_2O
    - Loss of electrons is called **oxidation**
    - Gain of electrons is called **reduction**

- Oxidation: a substance loses electrons
  reducing agent (electron donor)
- Reduction: a substance gains electrons
  oxidizing agent (electron acceptor)
- Redox reaction: oxidation-reduction reaction an oxidation reaction is always accompanied by a reduction, there are no free electrons in living cells, all electrons are in atoms
- At the same time as the oxidized molecule gives up electrons, it also gives up energy
- The reduced molecule receives energy when it gains electron

Figure 6.5a

Loss of hydrogen atoms
(becomes oxidized)

$$\underset{\text{(Glucose)}}{C_6H_{12}O_6} + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{ATP} + \text{Heat}$$

Gain of hydrogen atoms
(becomes reduced)

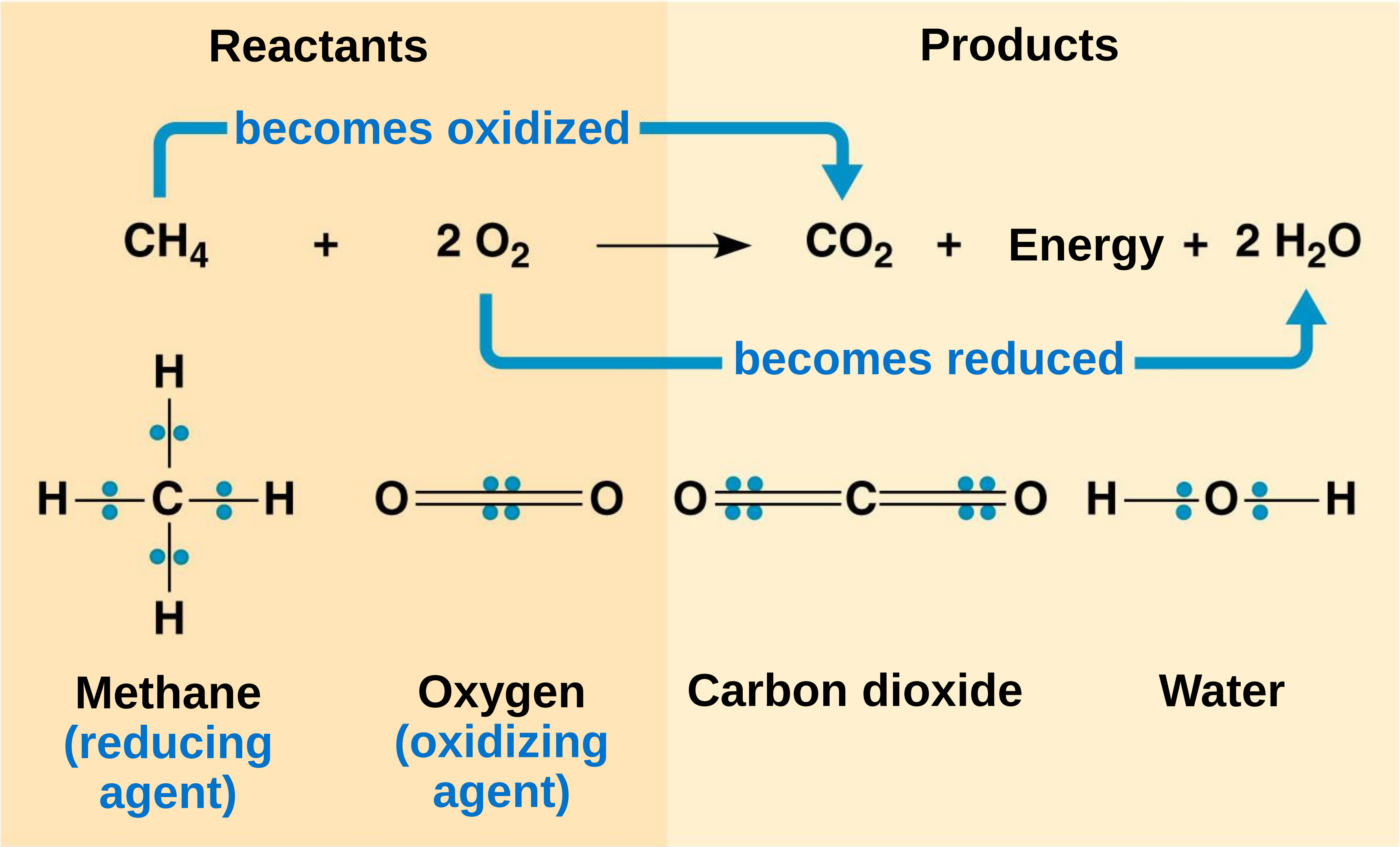
補充

- 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

補充

- Redox reactions also occur when the movement of electrons is not complete but involve a change in the degree of electron sharing in covalent bonds.
- In the combustion of methane to form water and carbon dioxide, the nonpolar covalent bonds of methane (C-H) and oxygen (O=O) are converted to polar covalent bonds (C=O and O-H).

補充



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- When these bonds shift from nonpolar to polar, the electrons move from positions equidistant between the two atoms for a closer position to oxygen, the more electronegative atom.
  - Oxygen is one of the most potent oxidizing agents.
- **An electron looses energy as it shifts from a less electronegative atom to a more electronegative one.**

- A redox reaction that relocates electrons closer to oxygen releases chemical energy that can do work.
- To reverse the process, energy must be added to pull an electron away from an atom.

6.5 Cells capture energy from electrons “falling” from organic fuels to oxygen

- An important player in the process of oxidizing glucose is a coenzyme called **NAD^+** (nicotinamide adenine dinucleotide).
  - accepts electrons and
  - becomes reduced to NADH.

- Dehydrogenase enzymes strip two hydrogen atoms from the fuel (e.g., glucose), pass two electrons and one proton to NAD^+ and release H^+.
  - $\text{H-C-OH} + NAD^+ \rightarrow \text{C=O} + NADH + H^+$

- This changes the oxidized form, NAD^+, to the reduced form NADH.
  - NAD^+ functions as the oxidizing agent in many of the redox steps during the catabolism of glucose.

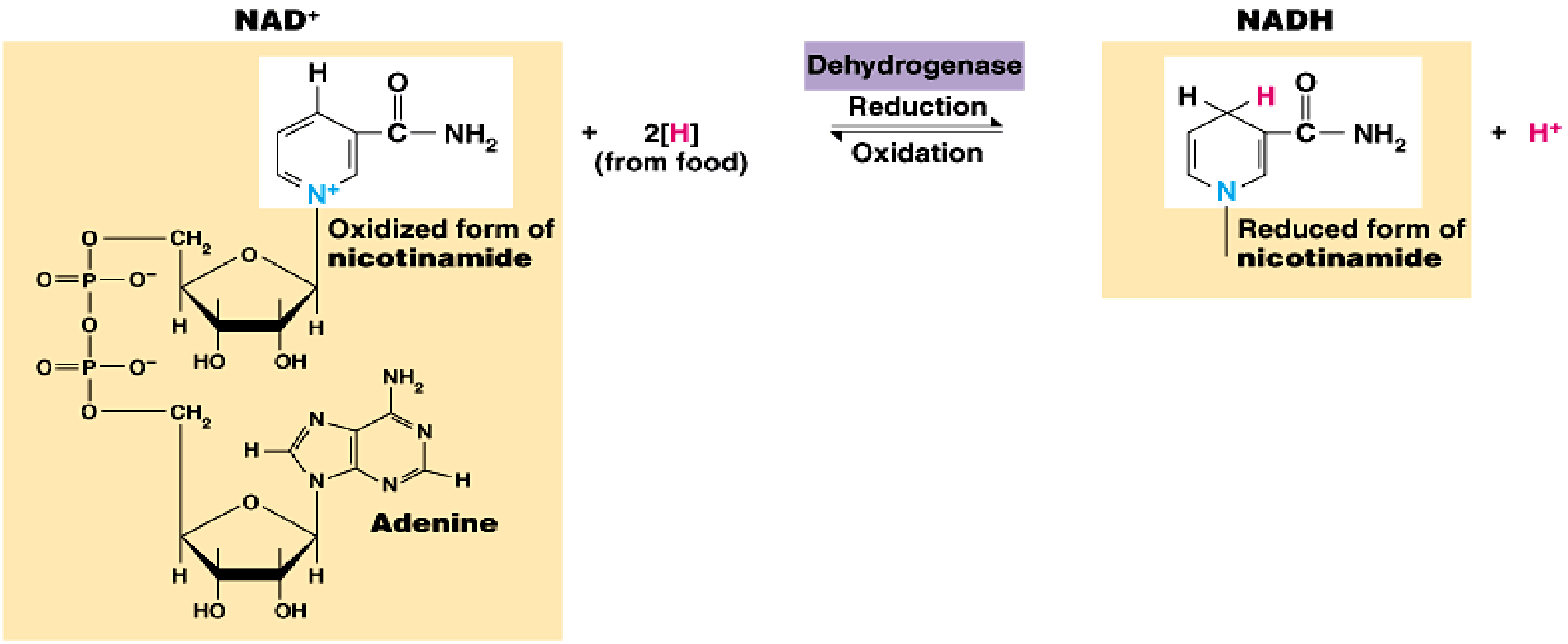
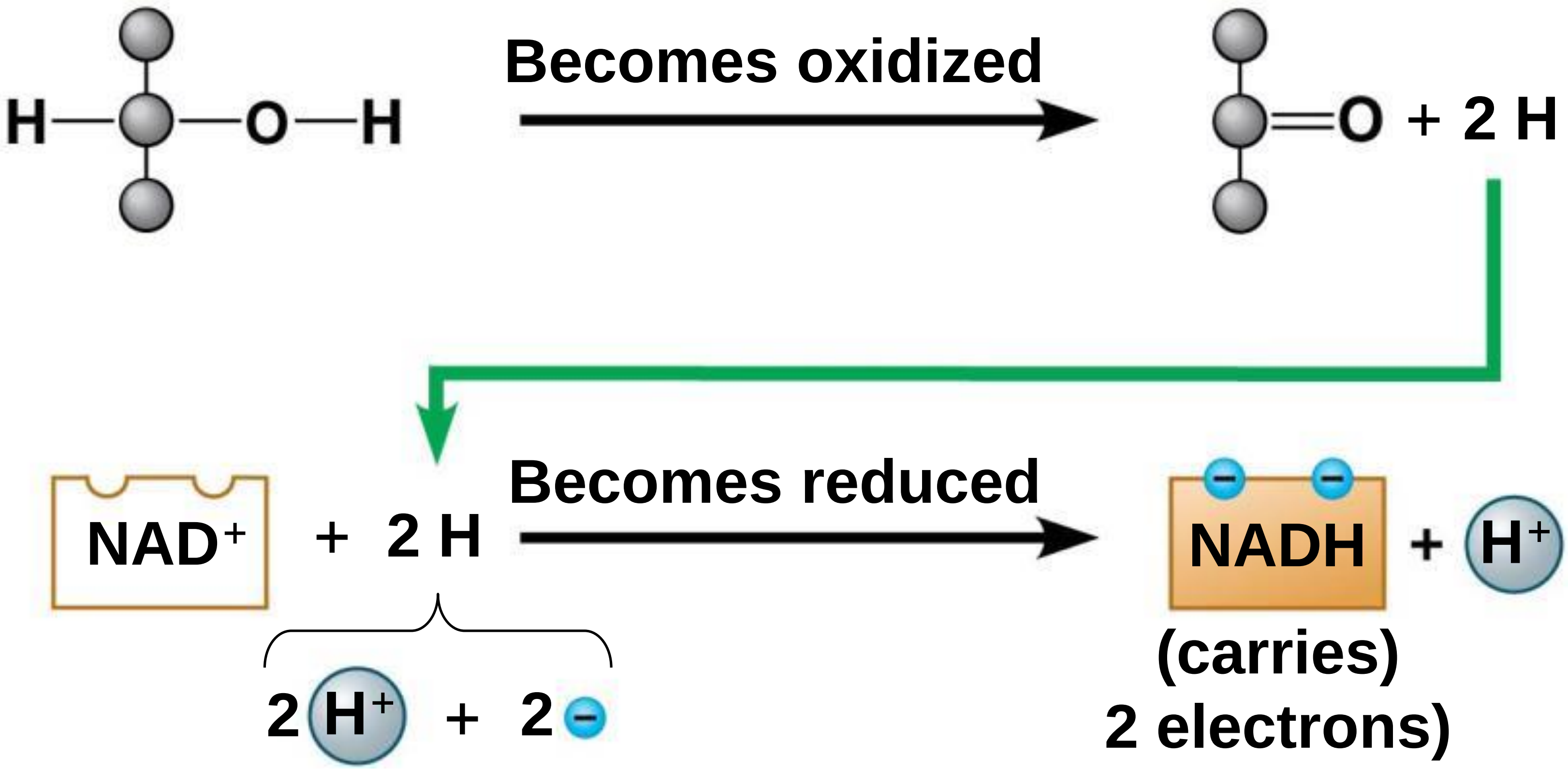


Fig. 9.4

Figure 6.5b



H—C—O—H
Becomes oxidized
O + 2 H
NAD+
+ 2 H
Becomes reduced
NADH
+ H+
2 H+
+ 2
(carries)
2 electrons)

The “fall” of electrons during respiration is stepwise, via NAD^+ and an electron transport chain

Cells capture energy from electrons "falling" from organic fuels to oxygen

- NADH delivers electrons to a string of electron carrier molecules, which moves electrons down a hill.
- These carrier molecules constitute an **electron transport chain**.

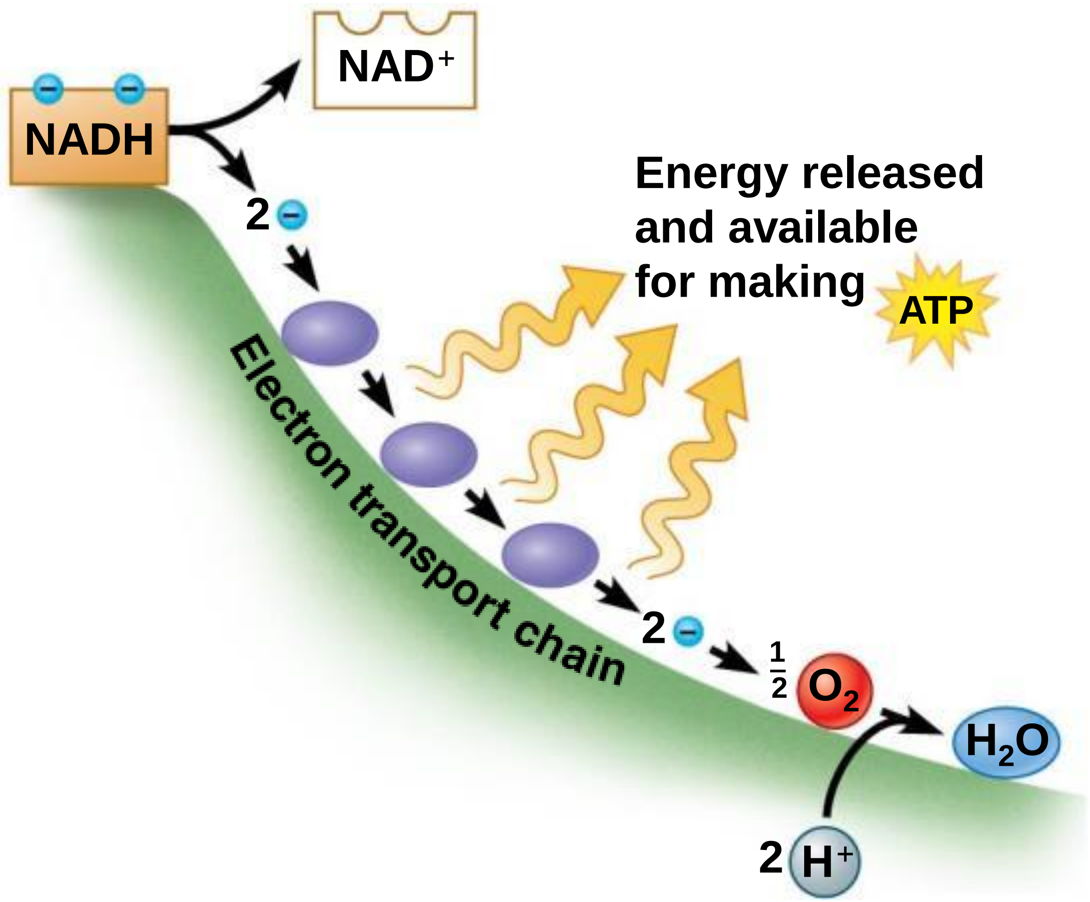
- The electrons carried by NADH loose very little of their potential energy in this process.
- This energy is tapped to synthesize ATP as electrons “fall” from NADH to oxygen.

- The electron transport chain, consisting of several molecules (primarily proteins), is built into the inner membrane of a mitochondrion.
- NADH shuttles electrons from food to the “top” of the chain.
- At the “bottom”, oxygen captures the electrons and H^+ to form water.

Cells capture energy from electrons "falling" from organic fuels to oxygen

- At the bottom of the hill is oxygen (1/2 O_2), which
  - accepts two electrons,
  - picks up two H^+, and
  - becomes reduced to water.

Figure 6.5c



NAD+
NADH
2
Energy released
and available
for making
ATP
Electron transport chain
2
1/2 O_2
H_2O
2 H^+

Electrons "fall" from organic molecules to oxygen during cellular respiration

- In cellular respiration, glucose and other fuel molecules are oxidized, releasing energy.
- Glucose is oxidized, oxygen is reduced, and electrons loose potential energy.
- **Molecules that have an abundance of hydrogen are excellent fuels** because their bonds are a source of "hilltop" electrons that "fall" closer to oxygen.

- The cell has a rich reservoir of electrons associated with hydrogen, especially in carbohydrates and fats.
- However, these fuels do not spontaneously combine with O_2 because they lack the activation energy.
- Enzymes lower the barrier of activation energy, allowing these fuels to be oxidized slowly.

Metabolism in cells

- **Metabolism新陳代謝**: the chemical processes that occur in a cell

- Anabolic reactions

(**anabolism同化作用**):

is a building-up process in which large, complex molecules are synthesized from simpler molecules

- e.g. Photosynthesis

$CO_2 + H_2O \longrightarrow$ glucose

Catabolic reactions (**catabolism異化作用**):

- energy is released from molecules
- is a breaking-down process in which complex molecules are split apart, or degraded, into simpler ones to release energy
- e.g. Cellular respiration

  glucose $\longrightarrow$ CO_2 + H_2O + energy

Catabolic Pathways and Production of ATP

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

- Metabolic pathways that release the energy stored in complex organic molecules are catabolic.
- One type of catabolic process, **fermentation**, leads to the partial degradation of sugars in the absence of oxygen.

- A more efficient and widespread catabolic process, **cellular respiration**, uses oxygen as a reactant to complete the breakdown of a variety of organic molecules.
  - Most of the processes in cellular respiration occur in mitochondria.

- The catabolism of glucose is exergonic(放能or放熱) with a delta G of - 686 kcal per mole of glucose.
  - Some of this energy is used to produce ATP that will perform cellular work.

Cells recycle the ATP they use for work

- ATP, adenosine triphosphate, is the pivotal molecule in cellular energetics.
- It is the chemical equivalent of a loaded spring.
  - The close packing of three negatively-charged phosphate groups is an unstable, energy-storing arrangement.
  - Loss of the end phosphate group “relaxes” the “spring”.

- **ATP (adenosine triphosphate)** is a type of nucleotide consisting of the nitrogenous base adenine, the sugar ribose, and a chain of three phosphate groups.

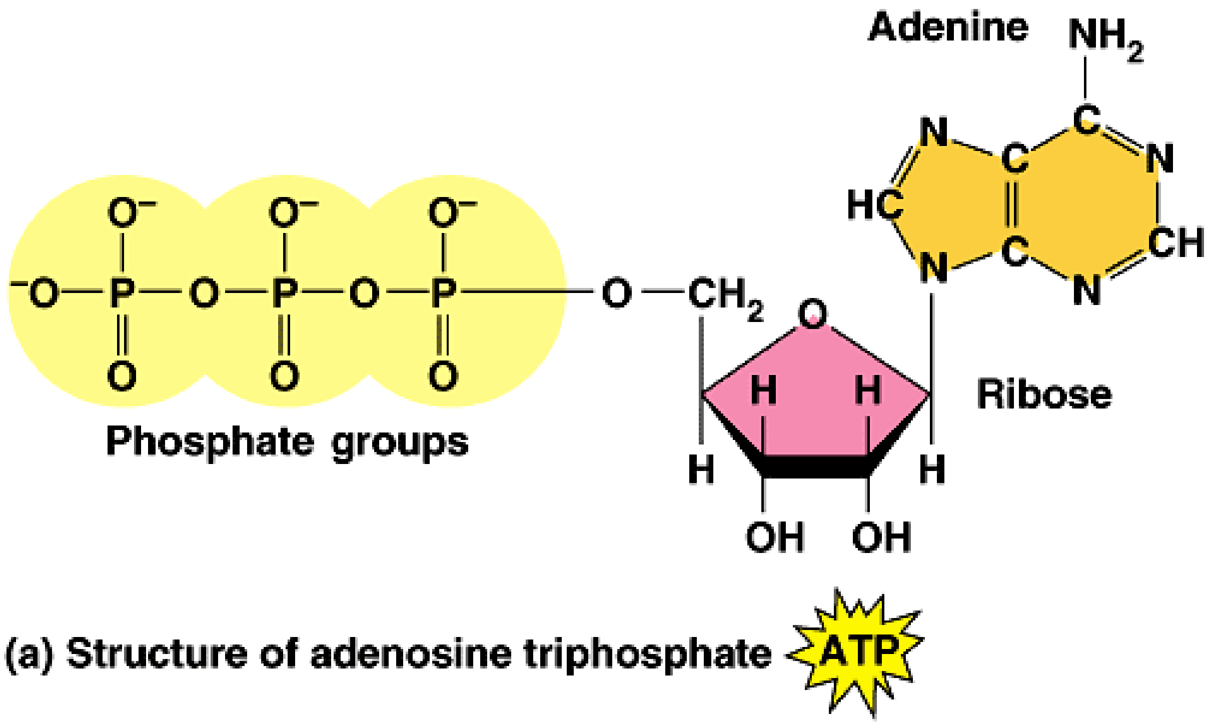
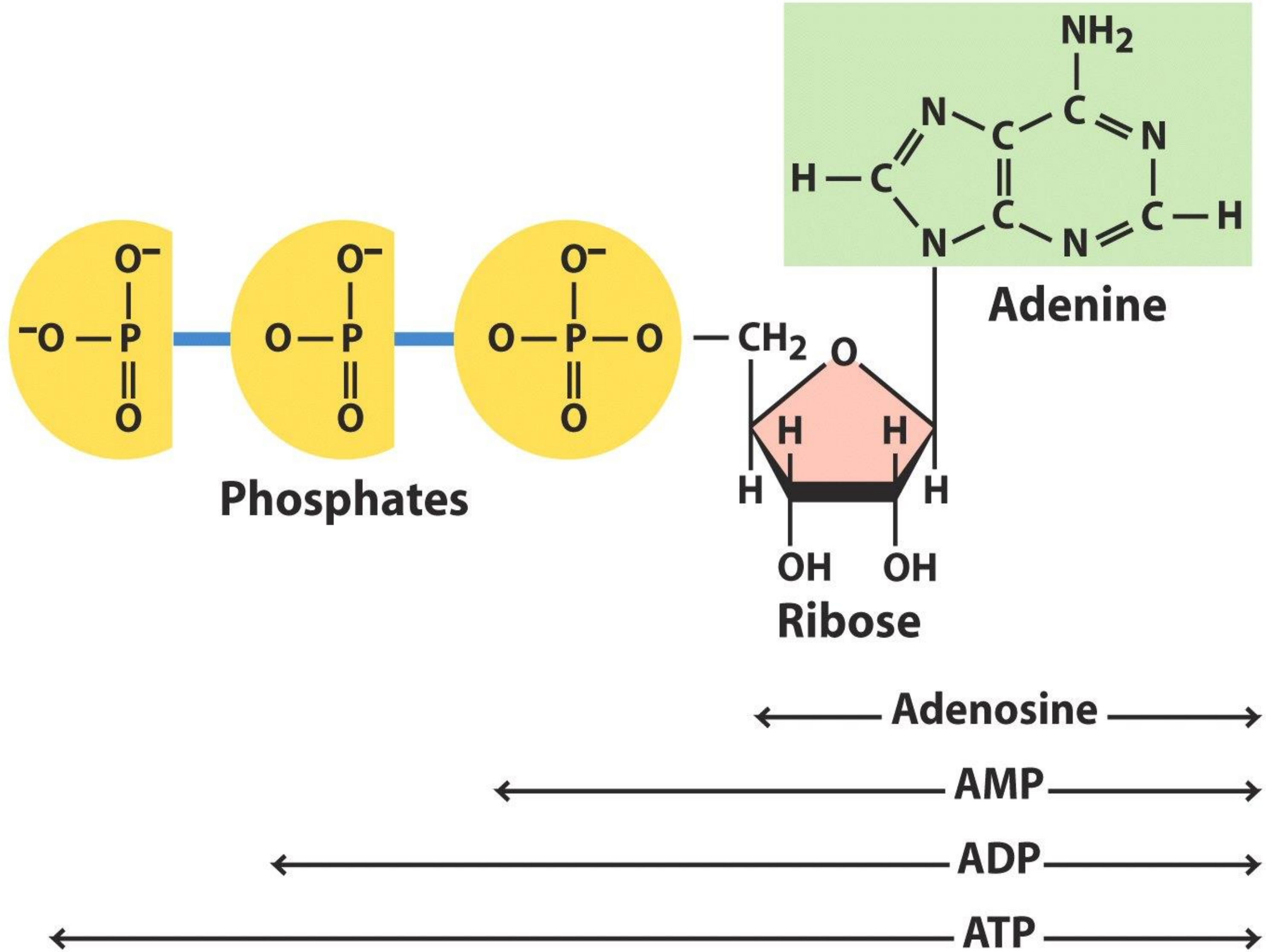


Fig. 6.8a



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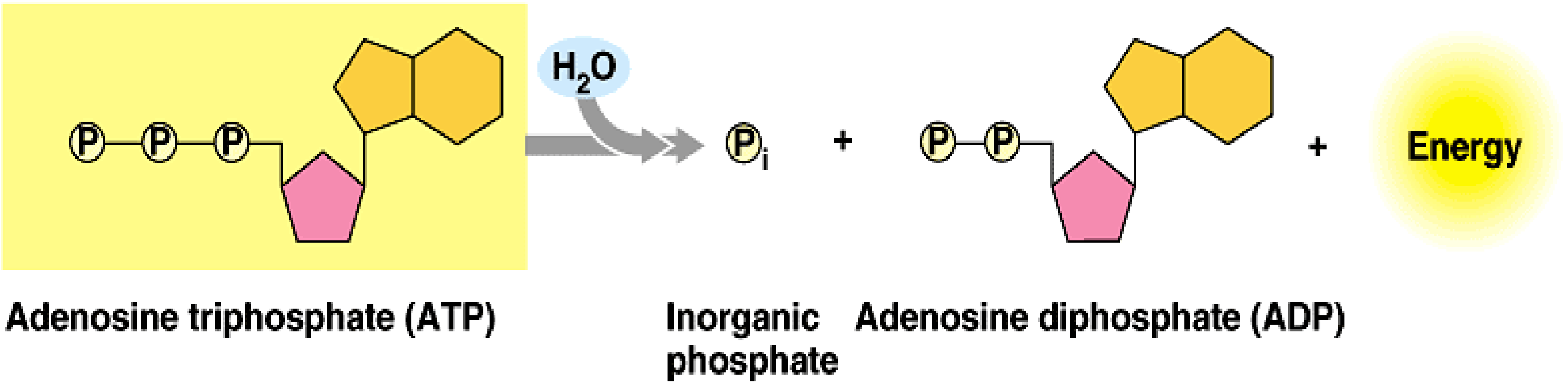
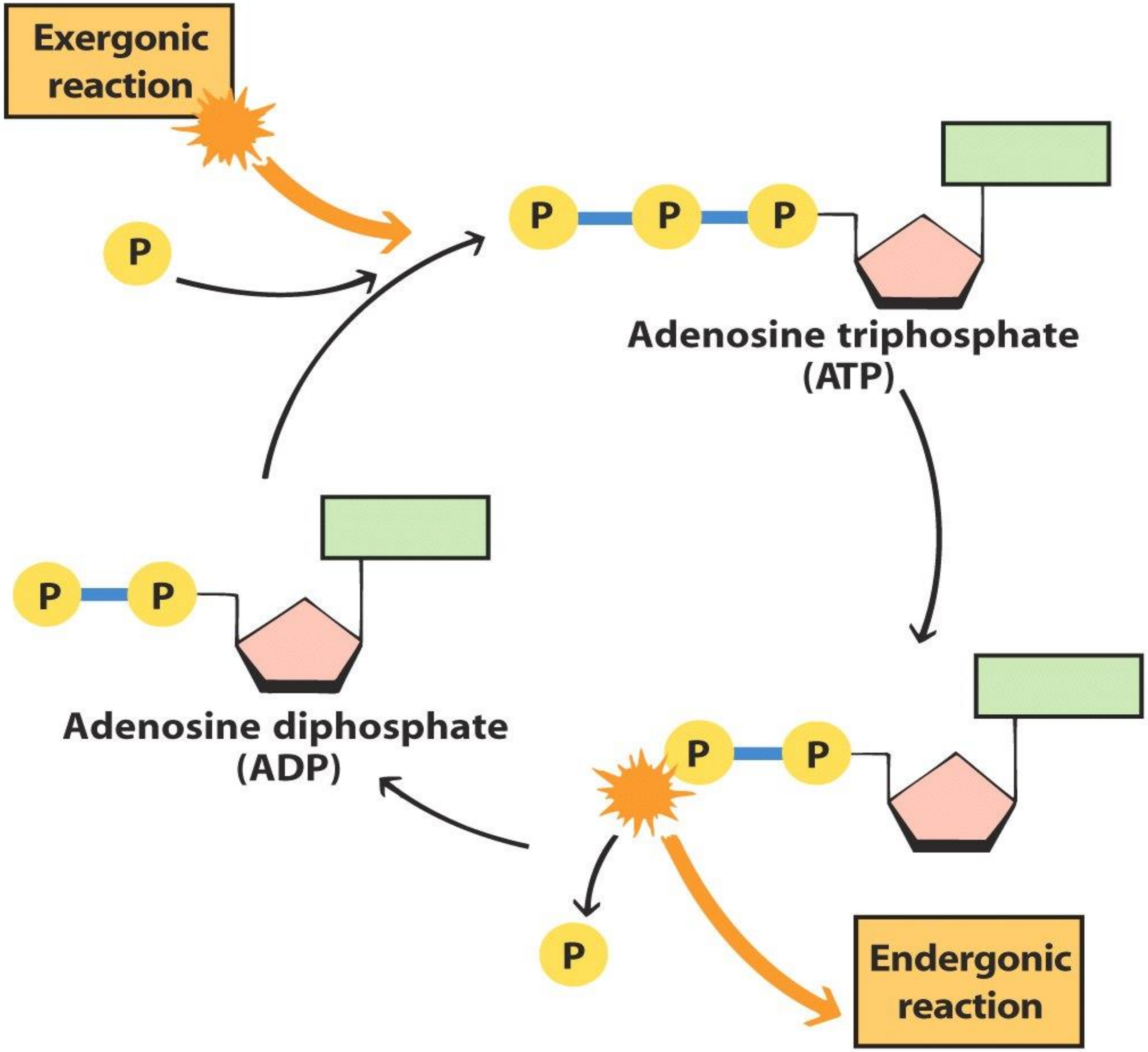
- The bonds between phosphate groups can be broken by hydrolysis.
  - Hydrolysis of the end phosphate group forms adenosine diphosphate [ATP -> ADP + P_i] and releases 7.3 kcal of energy per mole of ATP under standard conditions.



(b) Hydrolysis of ATP

Fig. 6.8b

- The price of most cellular work is the conversion of ATP to ADP and inorganic phosphate (P_i).
- An cell regenerates ATP from ADP and P_i by the catabolism of organic molecules.



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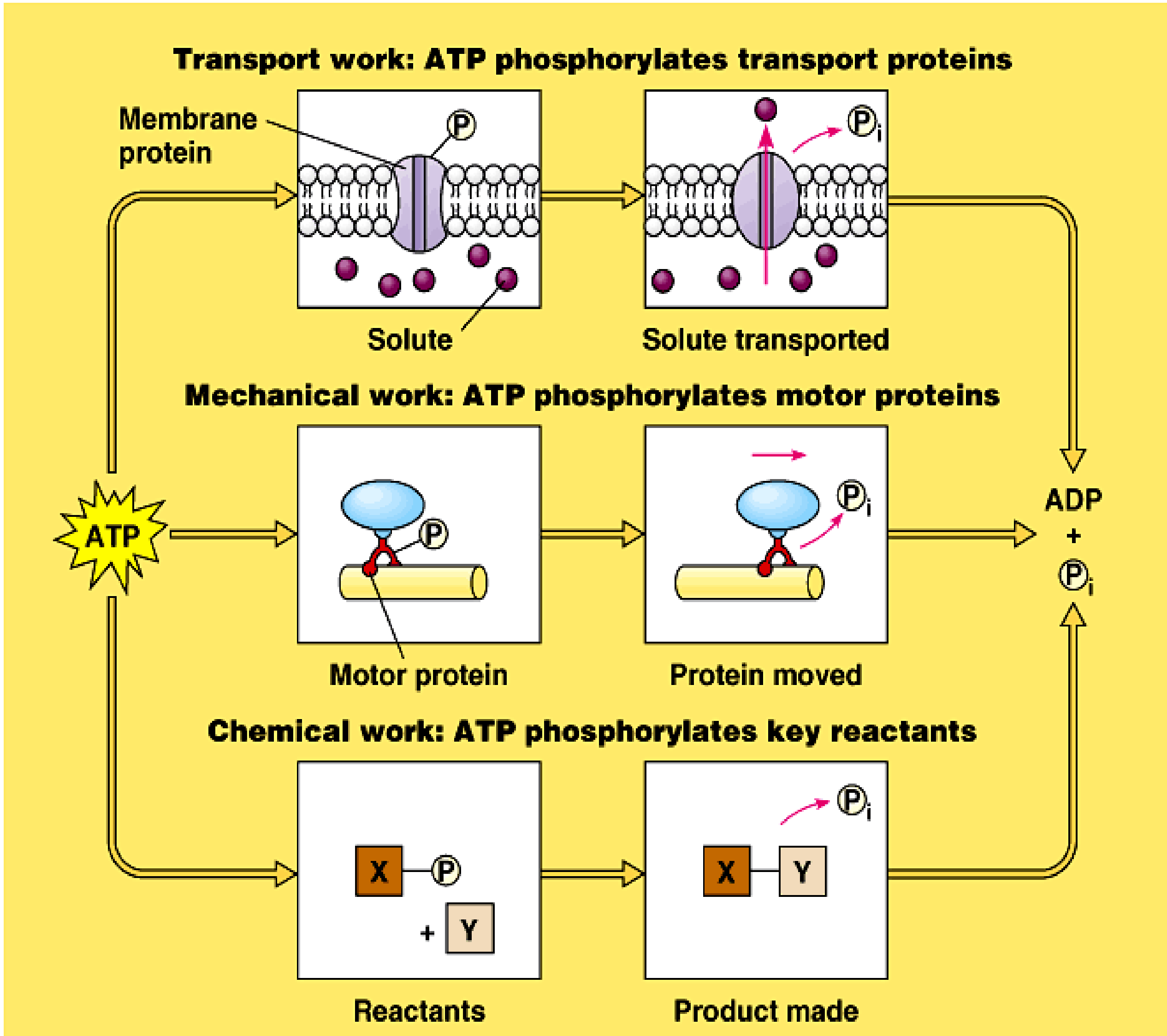
- While the phosphate bonds of ATP are sometimes referred to as high-energy phosphate bonds, these are actually fairly weak covalent bonds.
- They are unstable however and their hydrolysis yields energy as the products are more stable.
- The phosphate bonds are weak because each of the three phosphate groups has a negative charge
- Their repulsion contributes to the instability of this region of the ATP molecule.

- In the cell the energy from the hydrolysis of ATP is coupled directly to endergonic吸能反應 processes by transferring the phosphate group to another molecule.
  - This molecule is now **phosphorylated**磷酸化.
  - This molecule is now more reactive.

- The transfer of the terminal phosphate group from ATP to another molecule is phosphorylation.
  - This changes the shape of the receiving molecule, performing work (transport, mechanical, or chemical).
  - When the phosphate groups leaves the molecule, the molecule returns to its alternate shape.



Transport work: ATP phosphorylates transport proteins
Membrane protein
P
Pi
Solute
Solute transported
Mechanical work: ATP phosphorylates motor proteins
ATP
P
Pi
Motor protein
Protein moved
ADP
+
Pi
Chemical work: ATP phosphorylates key reactants
X
P
+ Y
Pi
X
Y
Reactants
Product made

- ATP is a renewable resource that is continually regenerated by adding a phosphate group to ADP.
  - The energy to support renewal comes from catabolic reactions in the cell.
  - In a working muscle cell the entire pool of ATP is recycled once each minute, over 10 million ATP consumed and regenerated per second per cell.

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.UN04

$$\mathrm{H{-}\overset{|}{\underset{|}{C}}{-}OH + NAD^{+}} \xrightarrow{\textbf{Dehydrogenase}} \mathrm{\overset{|}{\underset{|}{C}}{=}O + NADH + H^{+}}$$

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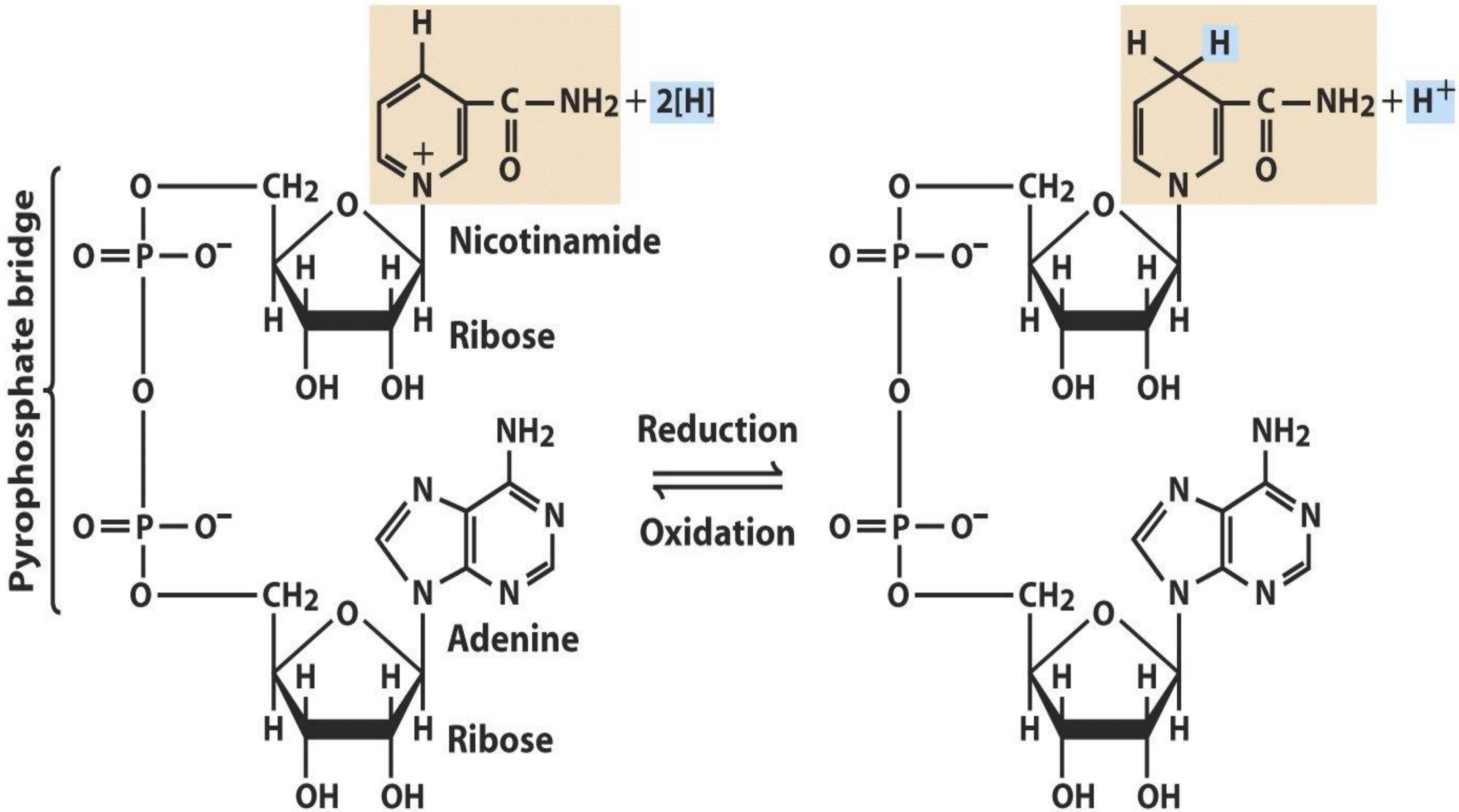

Nicotinamide adenine dinucleotide, oxidized (NAD^+)

Nicotinamide adenine dinucleotide, reduced (NADH)

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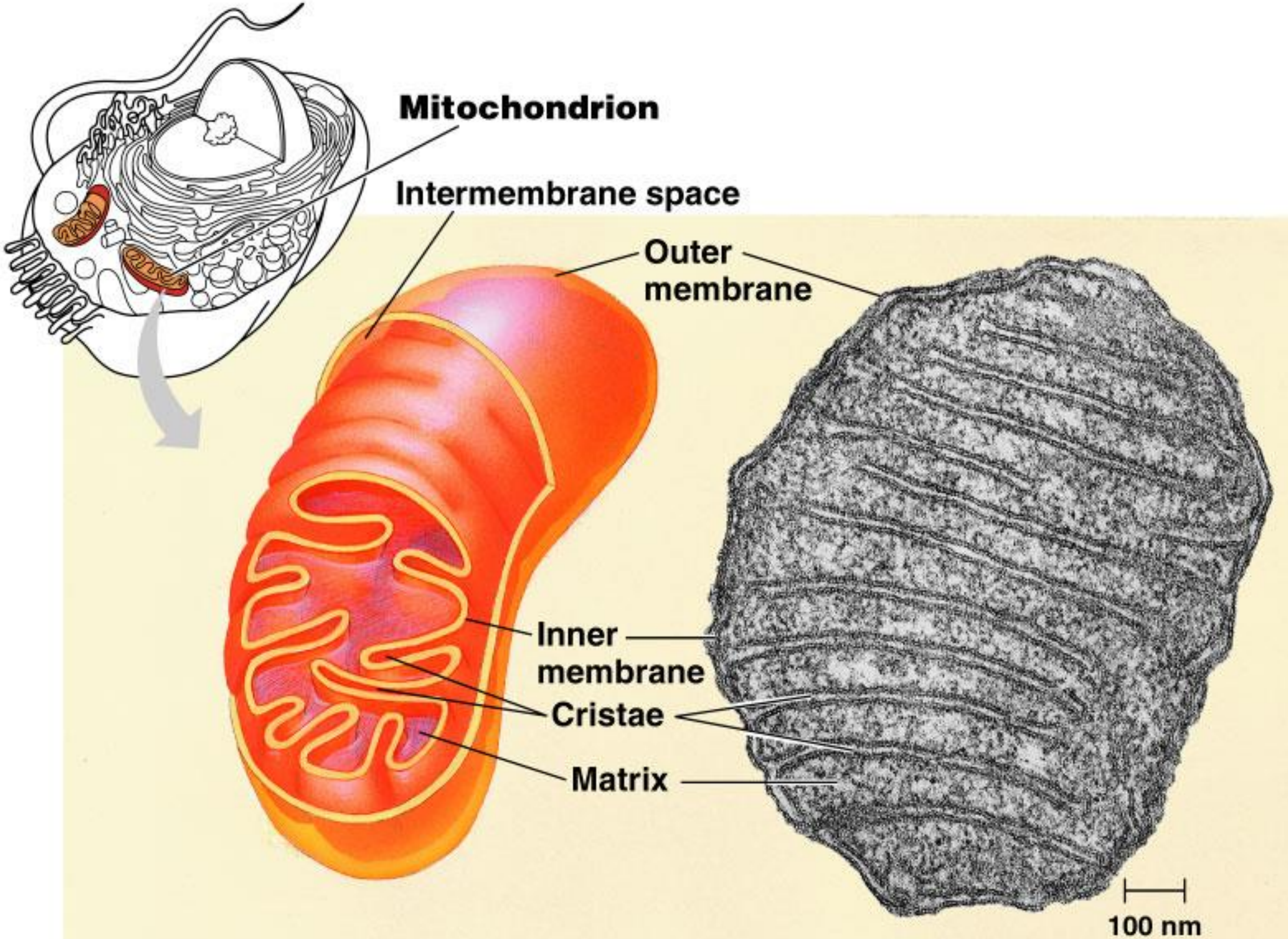

Mitochondrion
Intermembrane space
Outer membrane
Inner membrane
Cristae
Matrix
100 nm

Fig. 7.17

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)
  - The **electron transport chain** and **oxidative phosphorylation** (accounts for most of the ATP synthesis)

- **Glycolysis** occurs in the cytoplasm.
  - It begins catabolism by breaking glucose into two molecules of pyruvate.
- The **Krebs cycle** occurs in the mitochondrial matrix.
  - It degrades pyruvate to carbon dioxide.
- Several steps in glycolysis and the Krebs cycle transfer electrons from substrates to NAD^+, forming NADH.
- NADH passes these electrons to the electron transport chain.

- In the **electron transport chain**, the electrons move from molecule to molecule until they combine with oxygen and hydrogen ions to form water.
- As they are passed along the chain, the energy carried by these electrons is stored in the mitochondrion in a form that can be used to synthesize ATP via **oxidative phosphorylation**.
  - Oxidative phosphorylation produces almost 90% of the ATP generated by respiration.

- A smaller amount of ATP is formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation受質磷酸化**
- For each molecule of glucose degraded to CO_2 and water by respiration, the cell makes up to 32 molecules of ATP

- Some ATP is also generated in glycolysis and the Krebs cycle by **substrate-level phosphorylation**.
  - Here an enzyme transfers a phosphate group from an organic molecule (the substrate) to ADP, forming ATP.

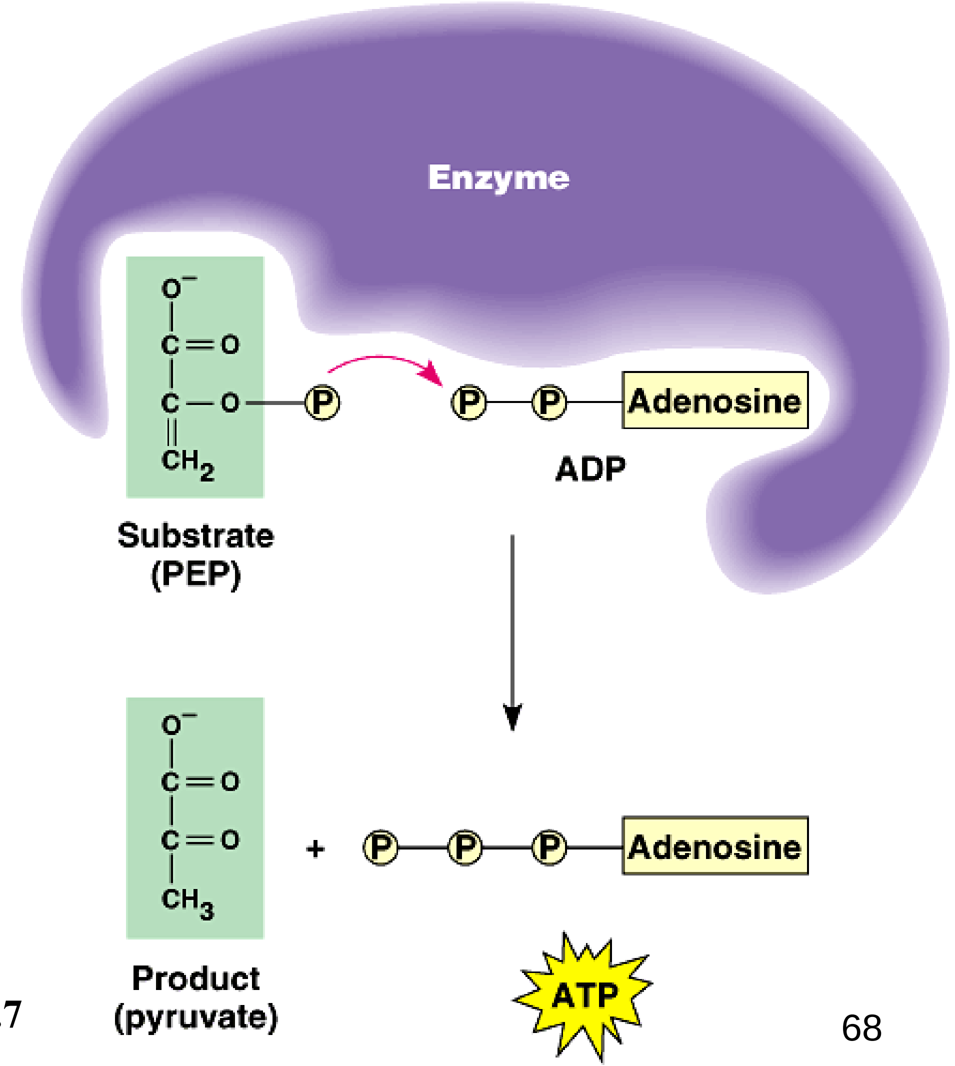
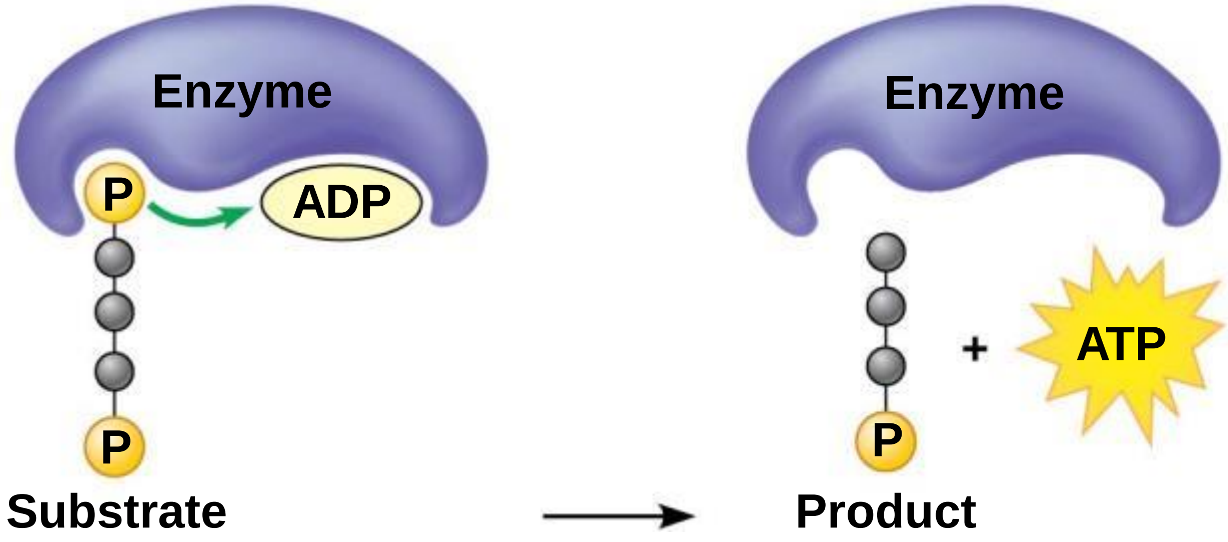


Fig. 9.7

Figure 6.7b



- Respiration uses the small steps in the respiratory pathway to break the large denomination of energy contained in glucose into the small change of ATP.
  - The quantity of energy in ATP is more appropriate for the level of work required in the cell.
- Ultimately 32 ATP are produced per mole of glucose that is degraded to carbon dioxide and water by respiration.

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)**

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Figure 9.6-1

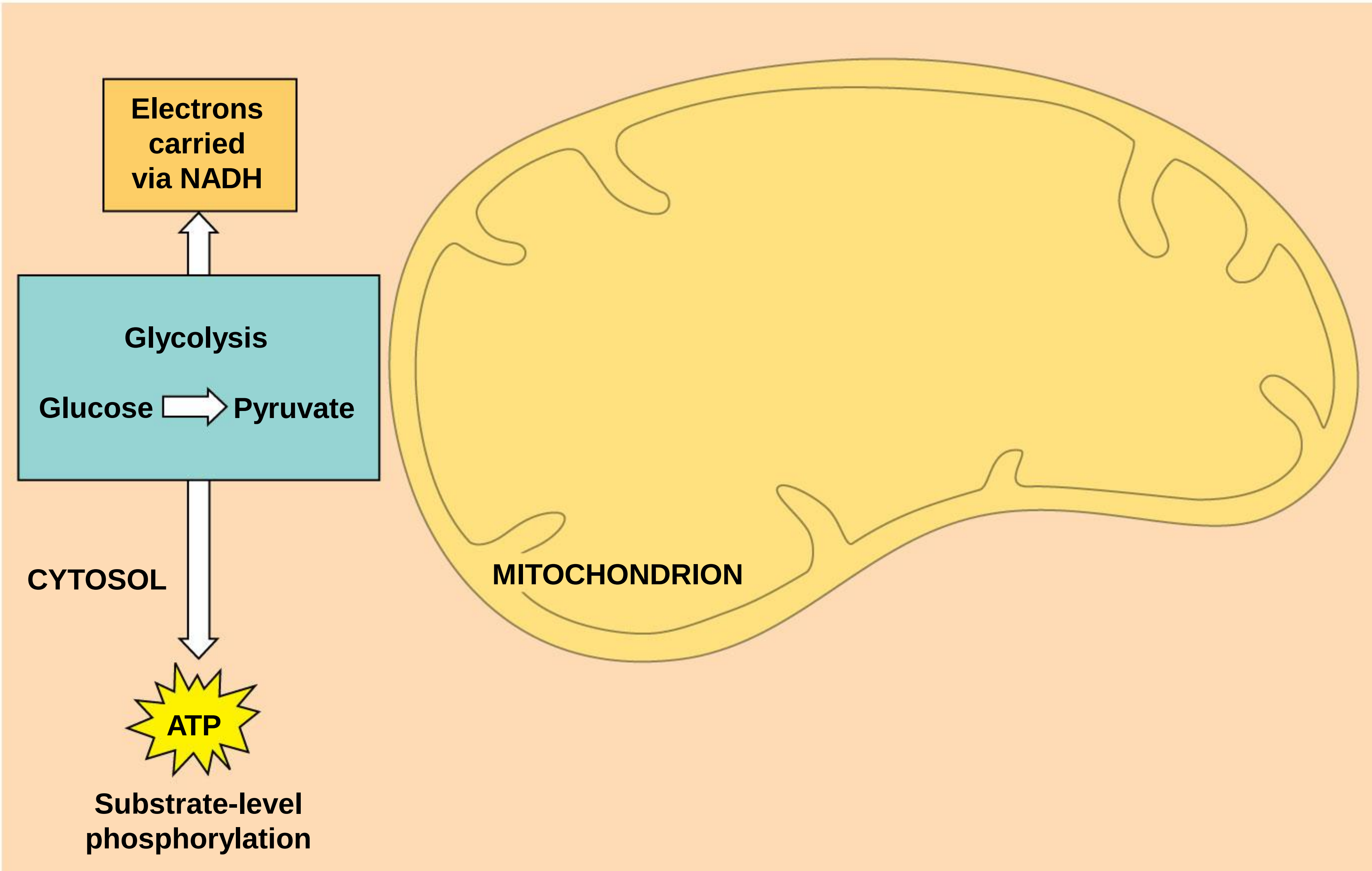

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Figure 9.6-2

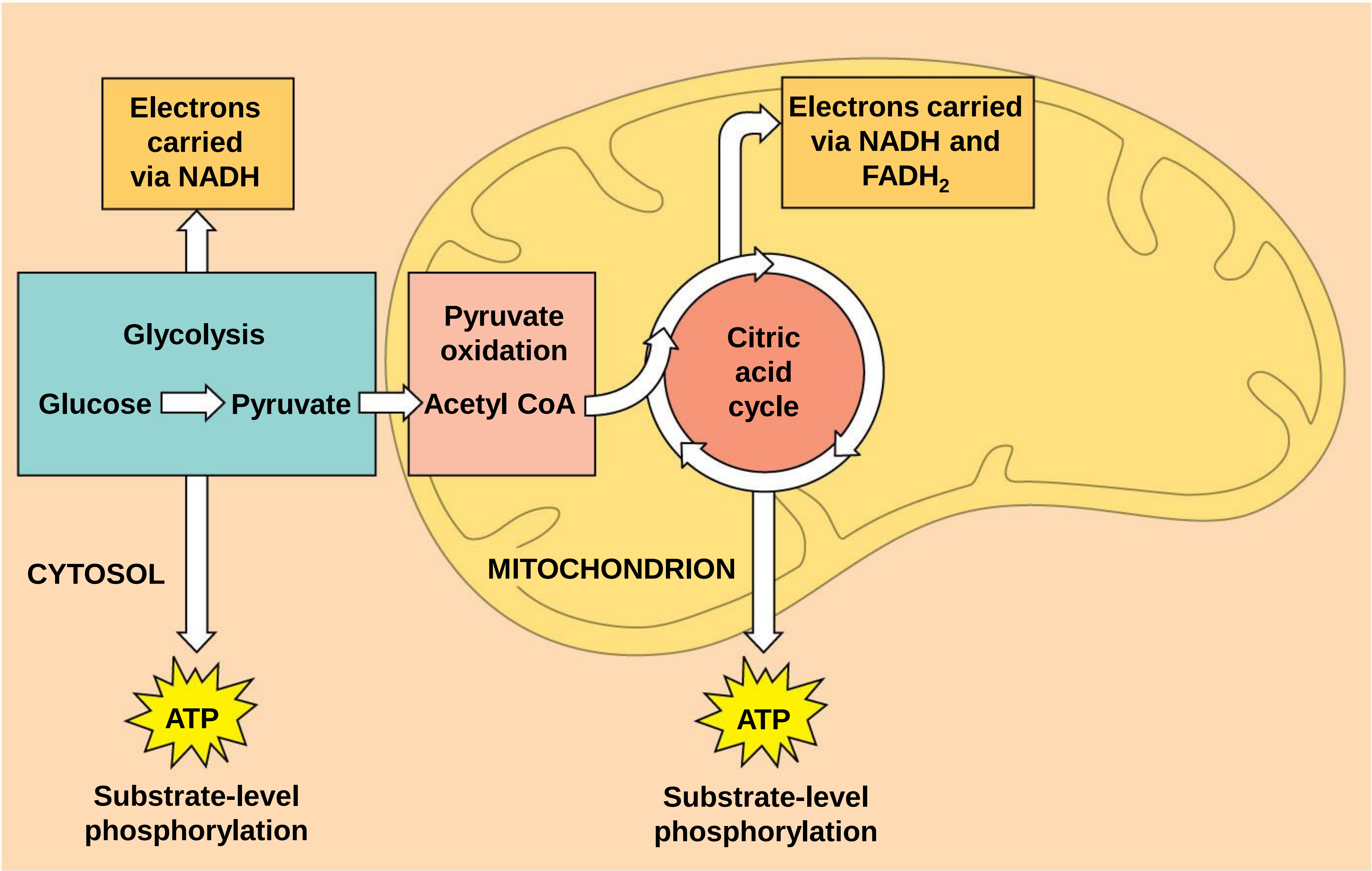

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Figure 9.6-3

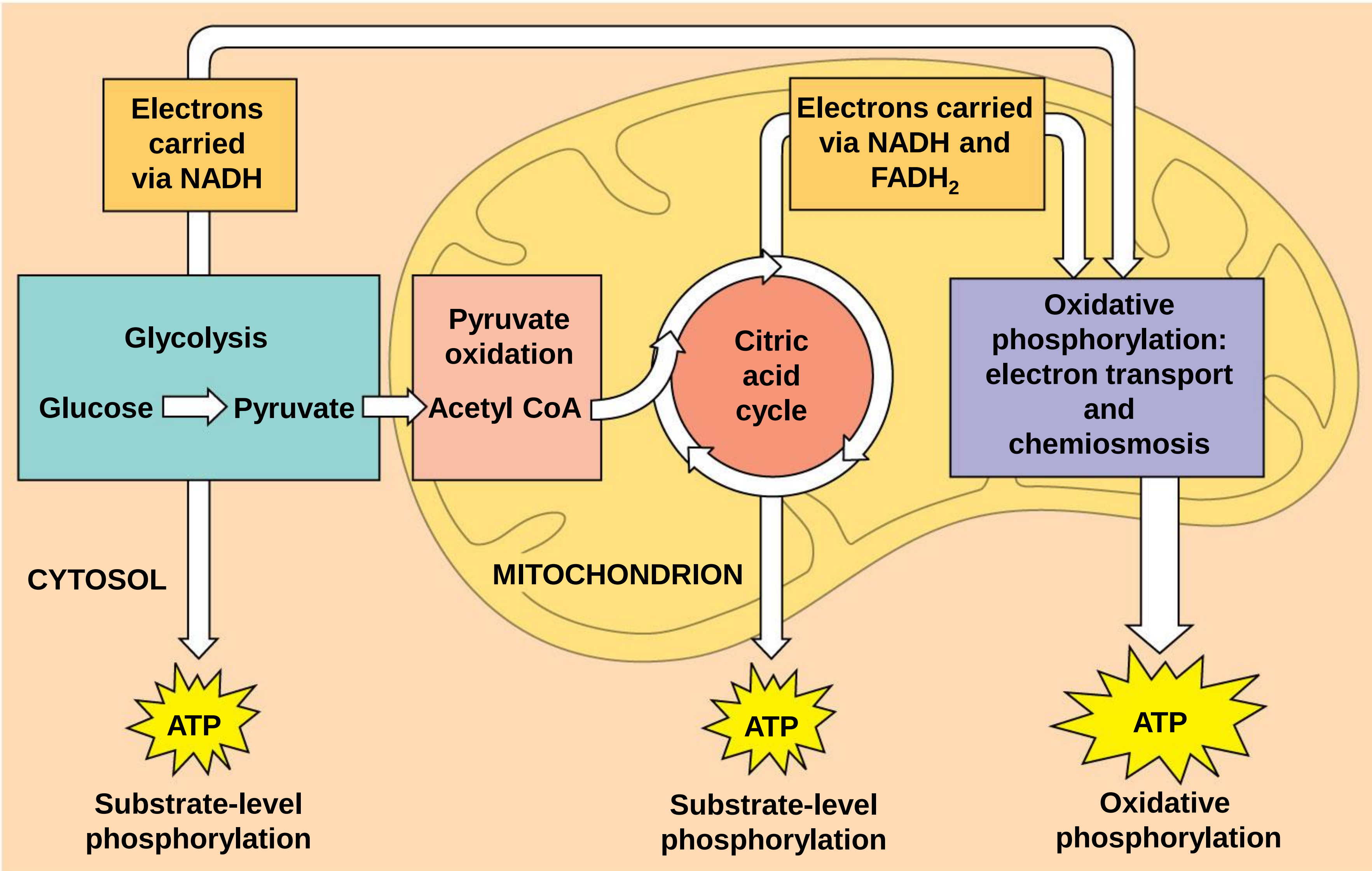

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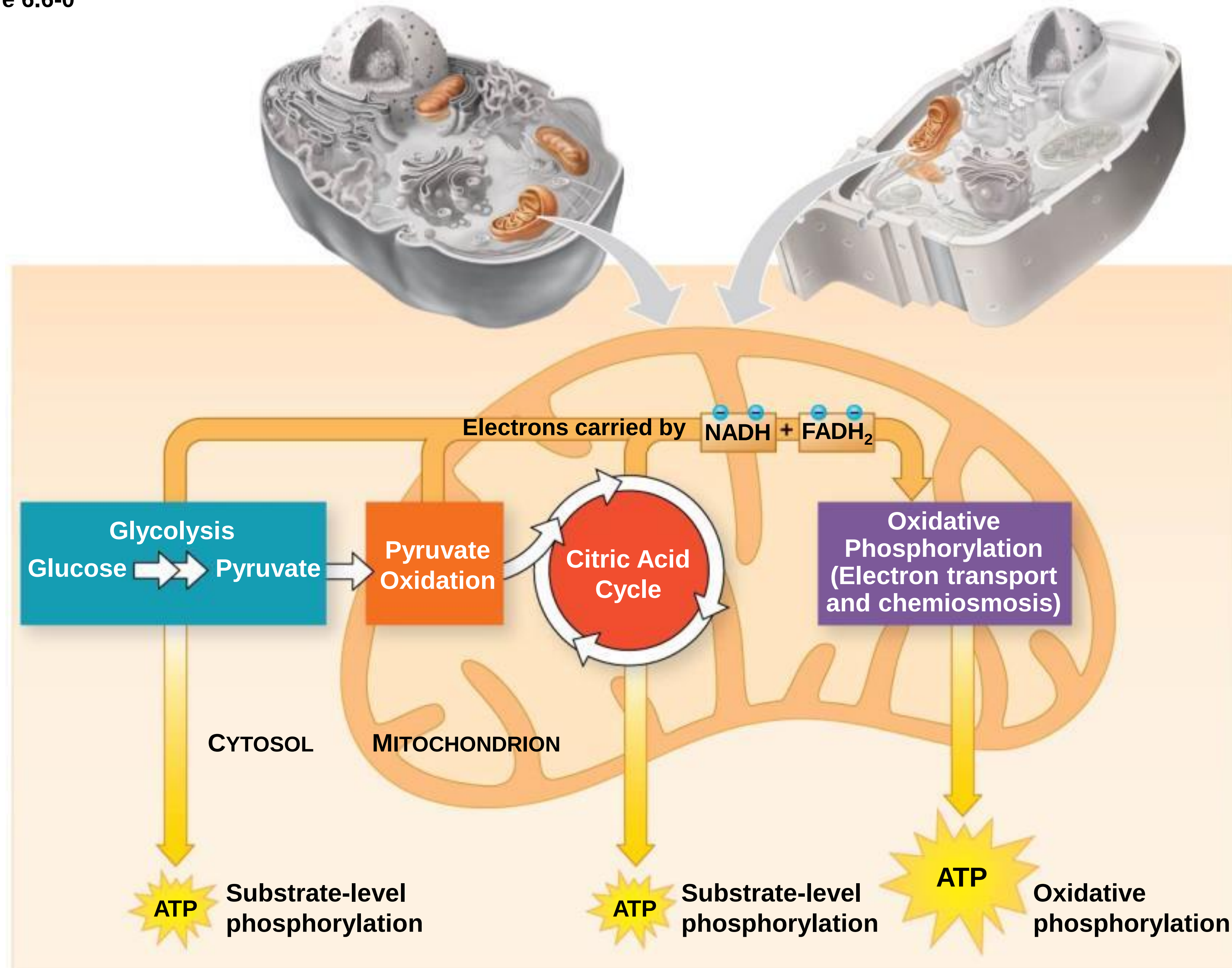
Figure 6.6-0



Electrons carried by
NADH
+
FADH2
Glycolysis
Glucose
Pyruvate
Pyruvate Oxidation
Citric Acid Cycle
Oxidative Phosphorylation (Electron transport and chemiosmosis)
CYTOSOL
MITOCHONDRION
ATP
Substrate-level phosphorylation
ATP
Substrate-level phosphorylation
ATP
Oxidative phosphorylation

Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- Glycolysis (“splitting of sugar”) breaks down glucose into two molecules of pyruvate
- Occur in cytosol
- No CO_2 is released
- Glycolysis occurs whether or not oxygen is present

- Glycolysis occurs in the cytoplasm and has two major phases
  - Energy investment phase
  - Energy payoff phase

- In the energy investment phase, ATP provides activation energy by phosphorylating glucose.
  - This requires 2 ATP per glucose.
- In the energy payoff phase, ATP is produced by substrate-level phosphorylation and NAD^+ is reduced to NADH.
- 2ATP (net) and 2 NADH are produced per glucose.

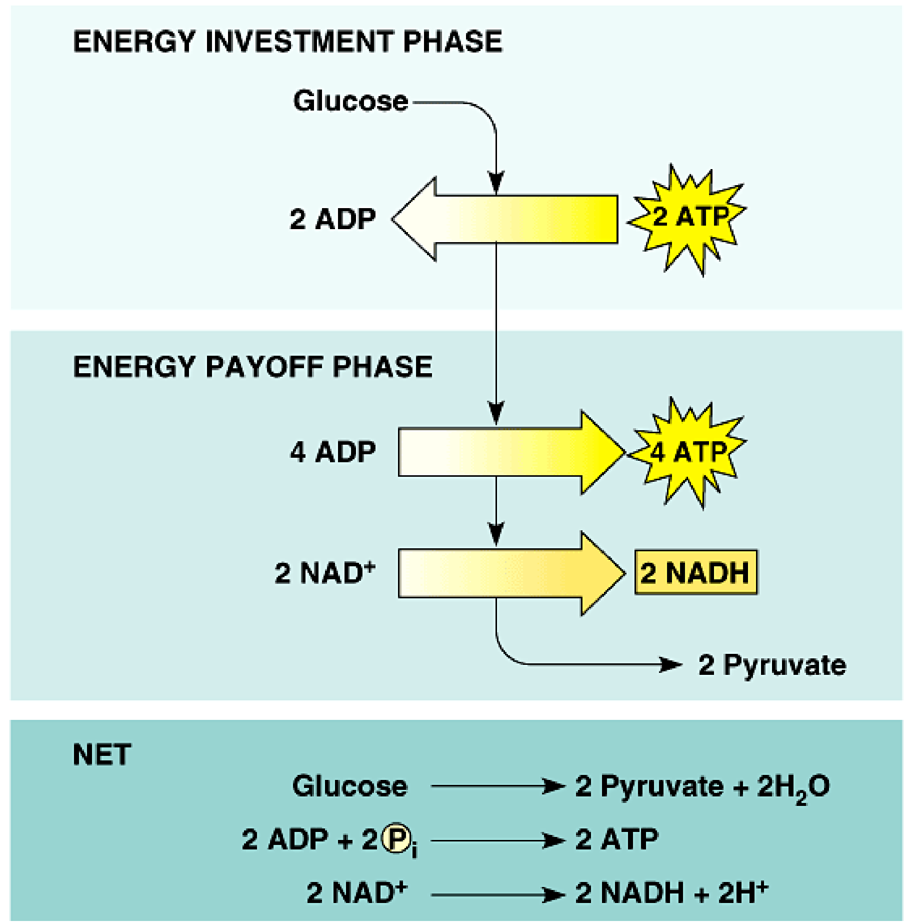


Fig. 9.8

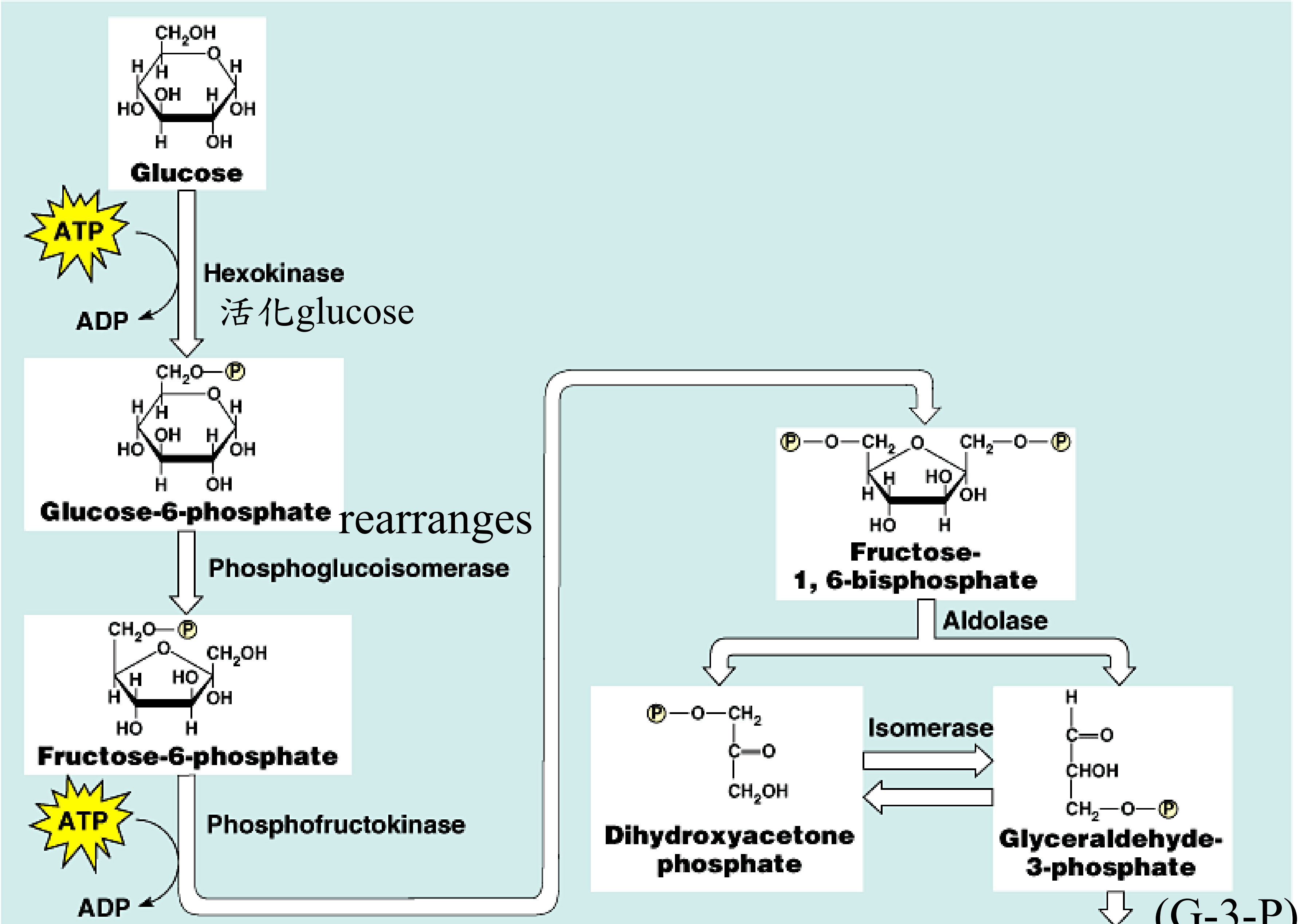

CH₂OH
Glucose
ATP
ADP
Hexokinase
活化glucose
Glucose-6-phosphate
rearranges
Phosphoglucoisomerase
Fructose-6-phosphate
ATP
ADP
Phosphofructokinase
Fructose-
1, 6-bisphosphate
Aldolase
Dihydroxyacetone
phosphate
Isomerase
Glyceraldehyde-
3-phosphate
(G-3-P)

Fig. 9.9a

2 G-3-P

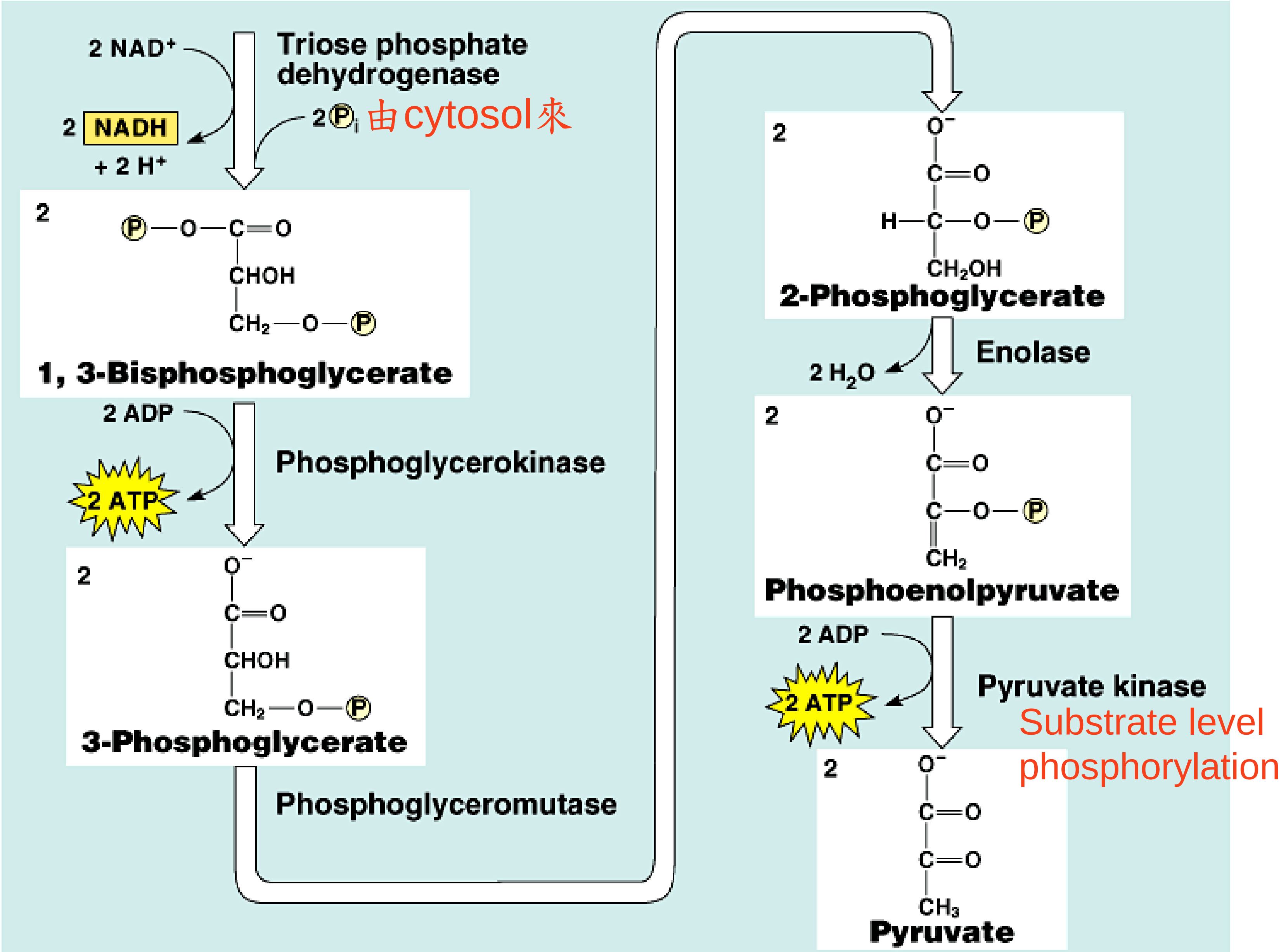

2 NAD+
2 NADH
+ 2 H+
Triose phosphate dehydrogenase
2 Pi 由cytosol來
2
1, 3-Bisphosphoglycerate
2 ADP
2 ATP
Phosphoglycerokinase
2
3-Phosphoglycerate
Phosphoglyceromutase
2
2-Phosphoglycerate
2 H2O
Enolase
2
Phosphoenolpyruvate
2 ADP
2 ATP
Pyruvate kinase
Substrate level phosphorylation
2
Pyruvate

Fig. 9.9b

- In the energy investment phase, ATP provides activation energy by phosphorylating glucose.
  - This requires 2 ATP per glucose.
- In the energy payoff phase, ATP is produced by substrate-level phosphorylation and NAD^+ is reduced to NADH.
- 2ATP (net) and 2 NADH are produced per glucose.

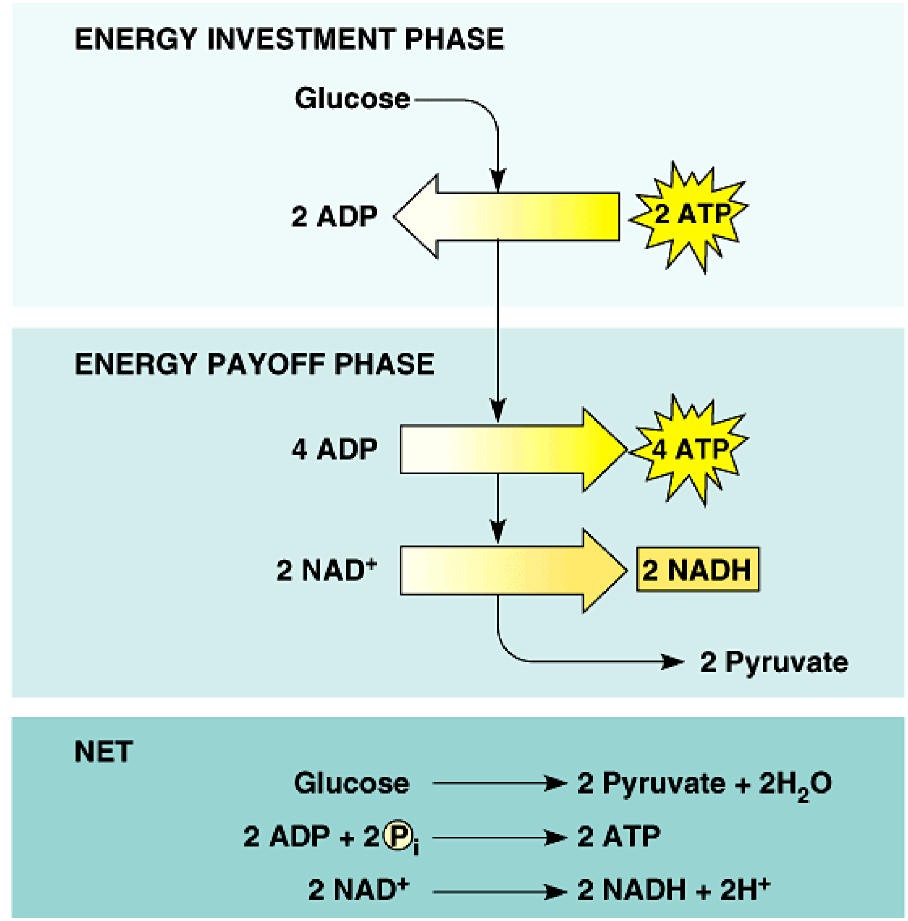


Fig. 9.8

- The net yield from glycolysis is 2 ATP and 2 NADH per glucose.
  - No CO_2 is produced during glycolysis.
- **Glycolysis occurs whether O_2 is present or not.**
  - If O_2 is present, pyruvate moves to the Krebs cycle and the energy stored in NADH can be converted to ATP by the electron transport system and oxidative phosphorylation.

The Krebs cycle completes the energy-yielding oxidation of organic molecules: *a closer look*

- More than three quarters of the original energy in glucose is still present in two molecules of pyruvate.
- If oxygen is present, pyruvate enters the mitochondrion where enzymes of the Krebs cycle complete the oxidation of the organic fuel to carbon dioxide.

- Coenzyme A: nucleotide linked to pantothenic acid (B-complex vitamins)

- **As pyruvate enters the mitochondrion, a multienzyme complex modifies pyruvate to acetyl CoA which enters the Krebs cycle in the matrix.**
  - A carboxyl group is removed as CO_2.
  - A pair of electrons is transferred from the remaining two-carbon fragment to NAD^+ to form NADH.
  - The oxidized fragment, acetat combines with coenzyme A to form acetyl CoA.

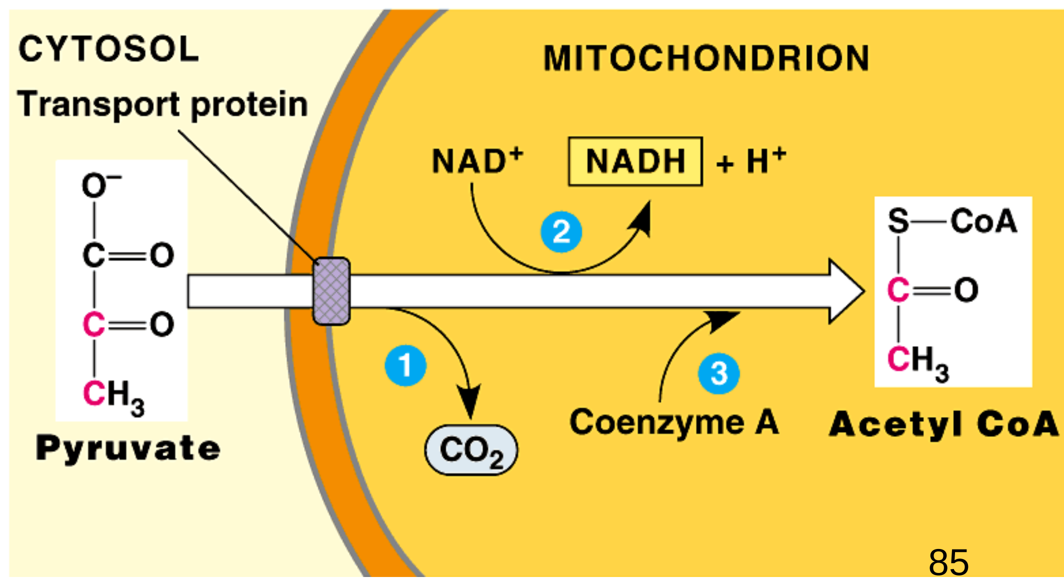
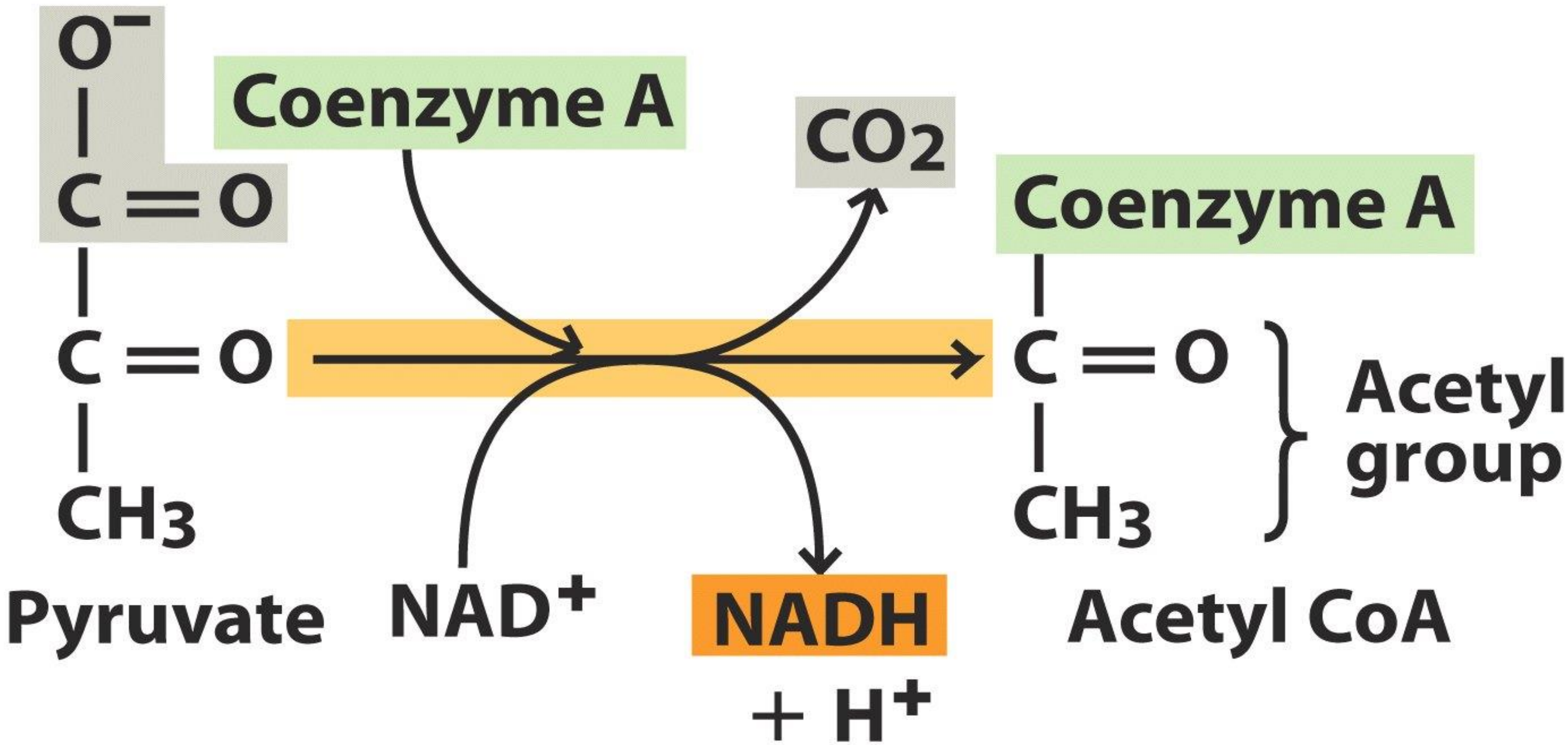


Fig. 9.10

Formation of acetyl Coenzyme A



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- The Krebs cycle is named after **Hans Krebs** who was largely responsible for elucidating its pathways in the 1930's.
  - This cycle begins when acetate from acetyl CoA combines with oxaloacetate to form citrate.
  - Ultimately, the oxaloacetate is recycled and the acetate is broken down to CO_2.
  - Each cycle produces one ATP by **substrate-level phosphorylation**, three NADH, and one $FADH_2$ (another electron carrier) per acetyl CoA.

- The Krebs cycle consists of eight steps.

FAD: flavin adenine dinucleotide
(derive from riboflavin, a Vit. B)

Citric acid cycle
Tricarboxylic acid cycle
TCA cycle

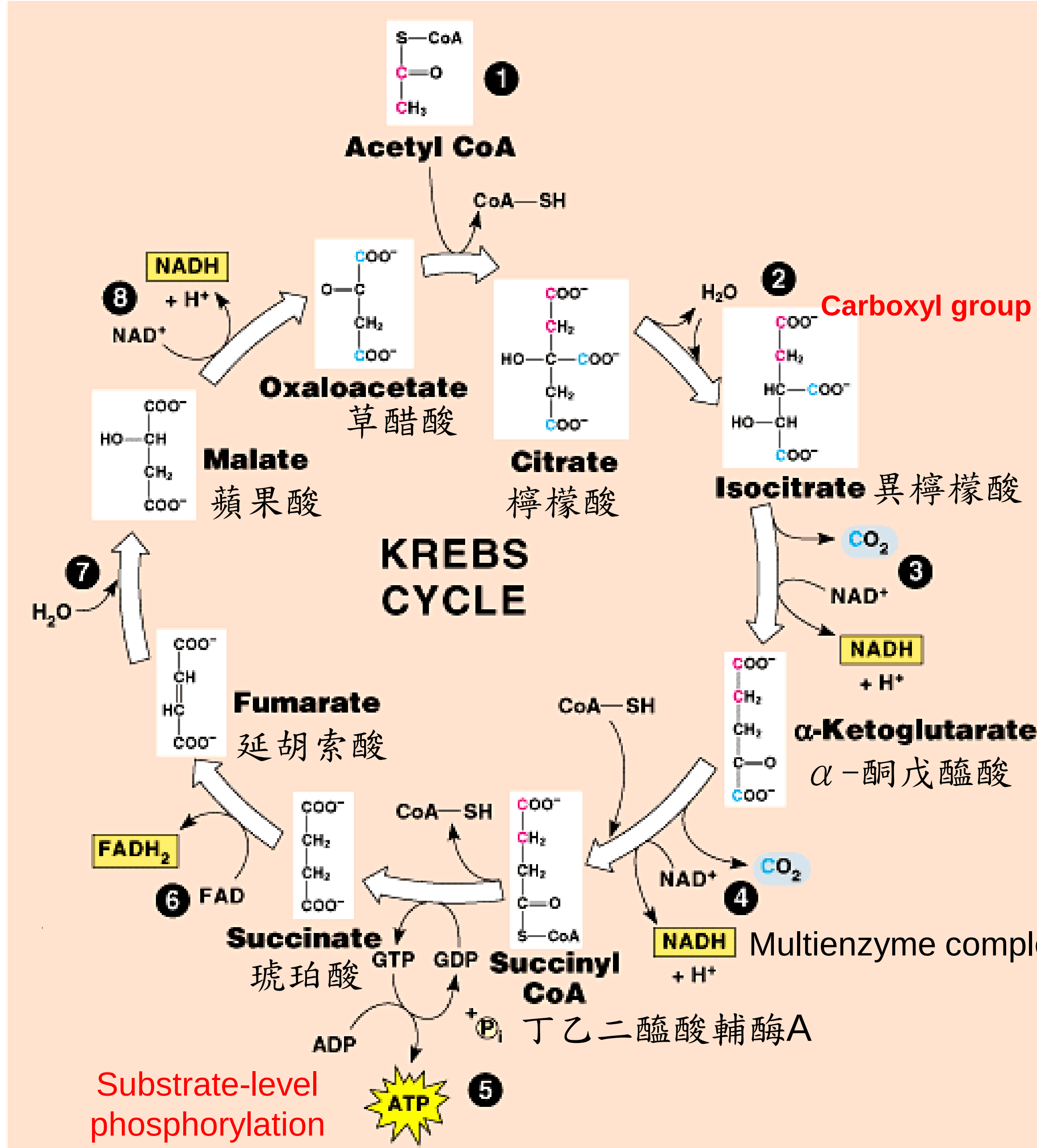


Fig. 9.11

- The conversion of pyruvate and the Krebs cycle produces large quantities of electron carriers.

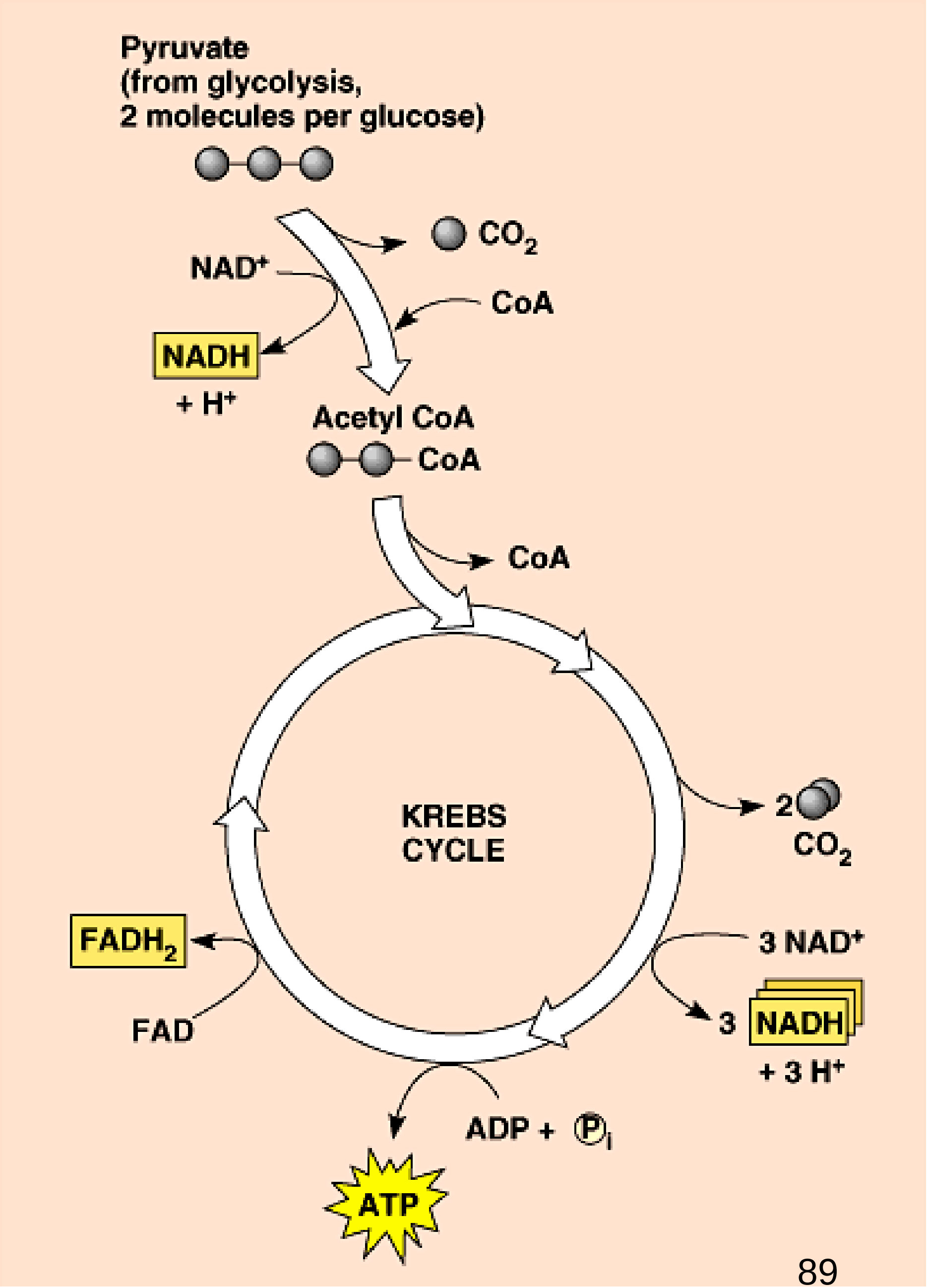


Fig. 9.12

The inner mitochondrial membrane couples electron transport to ATP synthesis: *a closer look*

- Only 4 of 32 ATP ultimately produced by respiration of glucose are derived from substrate-level phosphorylation.
- The vast majority of the ATP comes from the energy in the electrons carried by NADH (and $FADH_2$).
- The energy in these electrons is used in the electron transport system to power ATP synthesis.

- Thousands of copies of the electron transport chain are found in the extensive surface of the cristae, the inner membrane of the mitochondrion.
  - Most components of the chain are proteins that are bound with prosthetic groups that can alternate between reduced and oxidized states as they accept and donate electrons.
- Electrons drop in free energy as they pass down the electron transport chain.

- Electrons carried by NADH are transferred to the first molecule in the electron transport chain, flavoprotein(= FMN, flavin mononucleotide).
  - The electrons continue along the chain which includes several **cytochrome (cyt)** proteins and one lipid carrier. (heme group)
- The electrons carried by $FADH_2$ have lower free energy and are added to a later point in the chain.

Q: ubiquinone:lipid, coenzyme Q

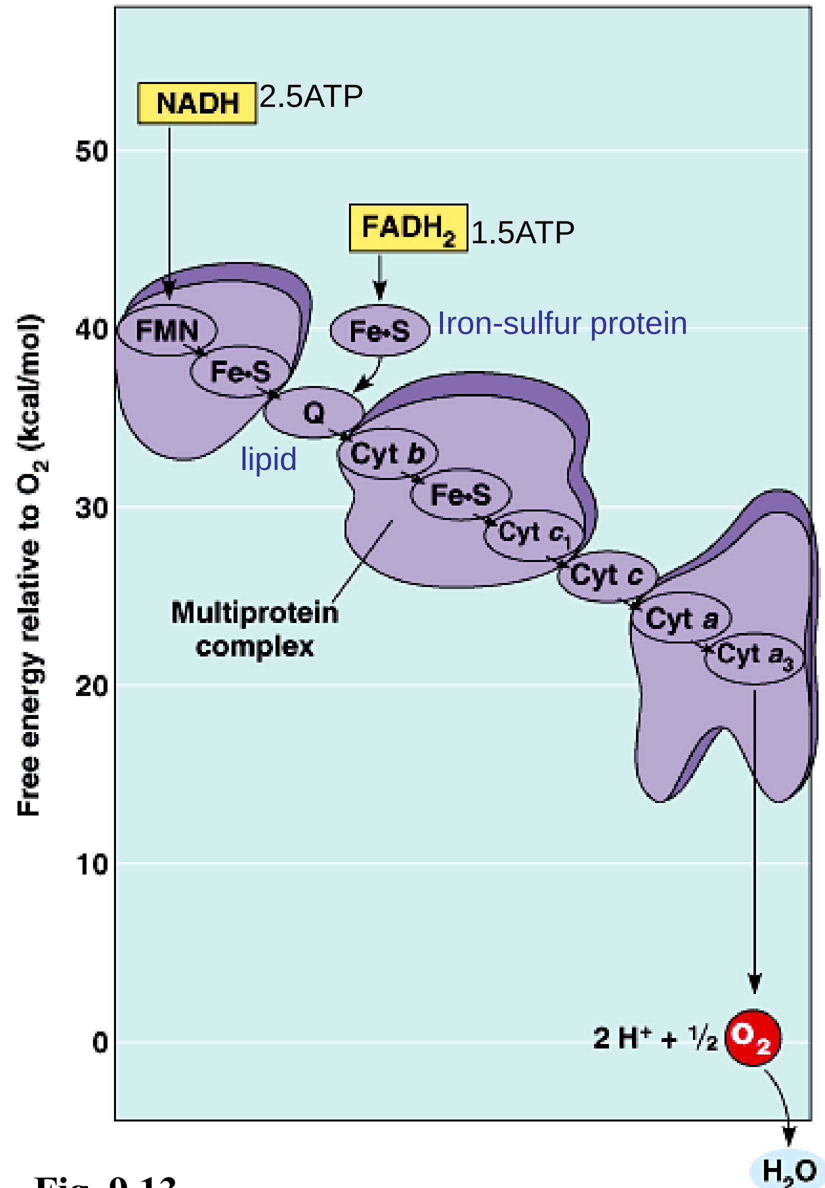
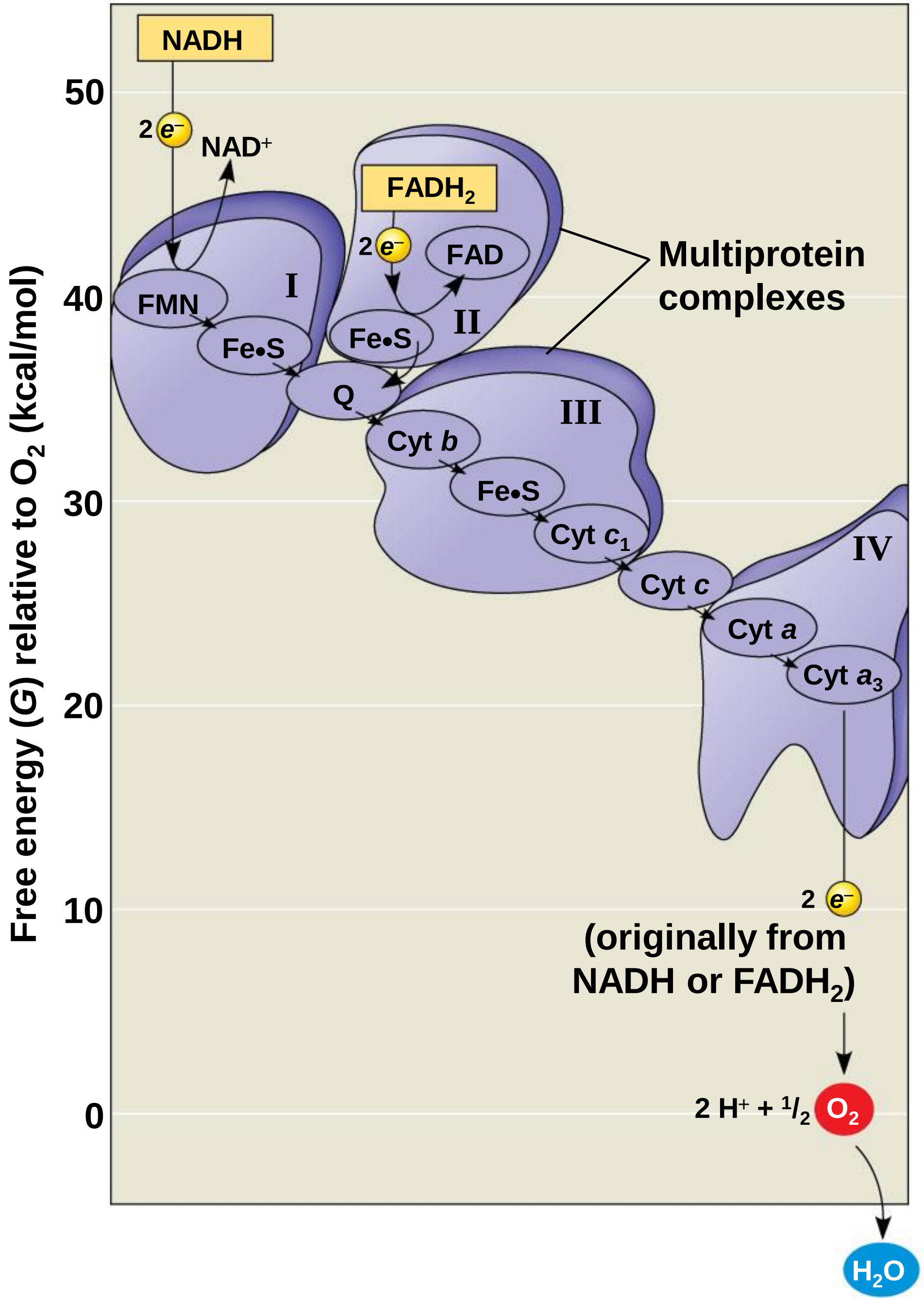


Fig. 9.13

Figure 9.13



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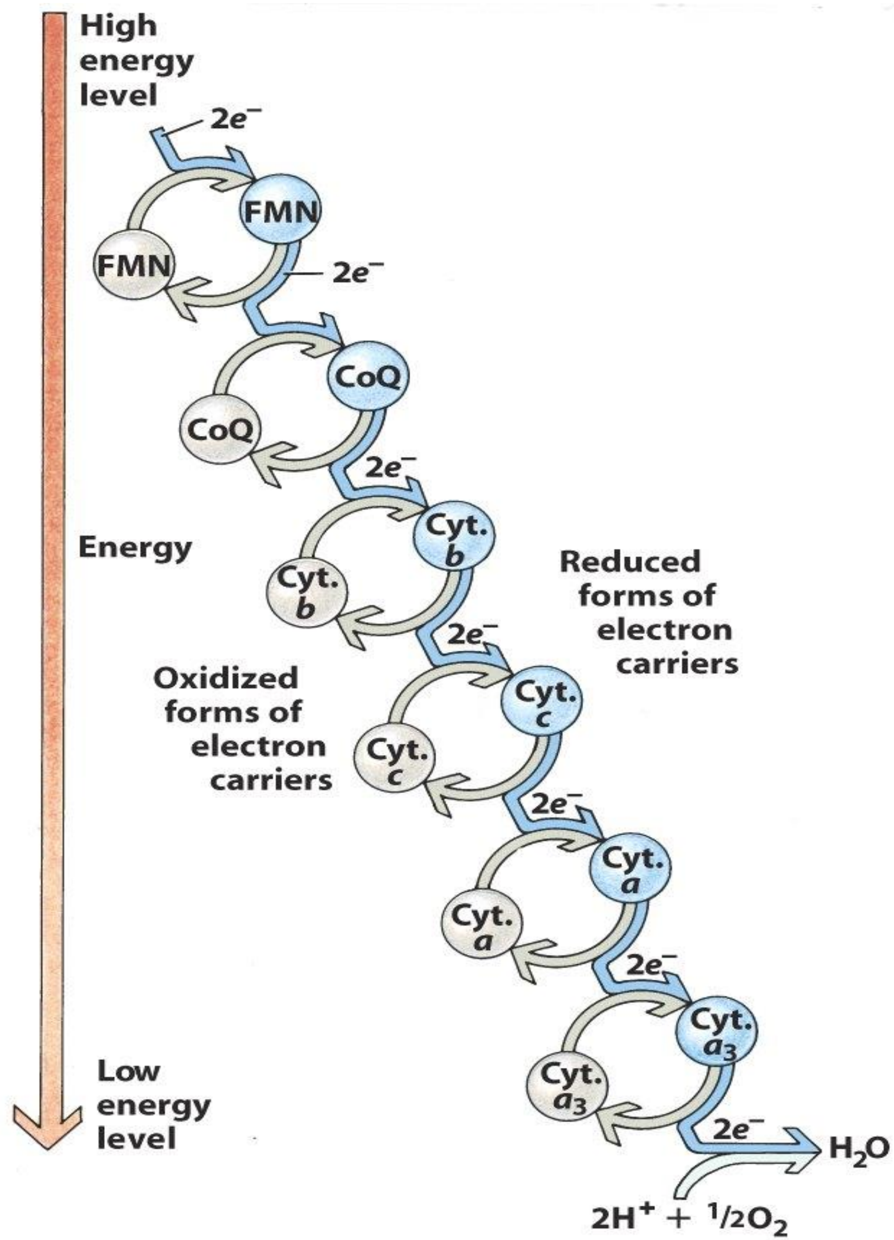

Figure 6-8
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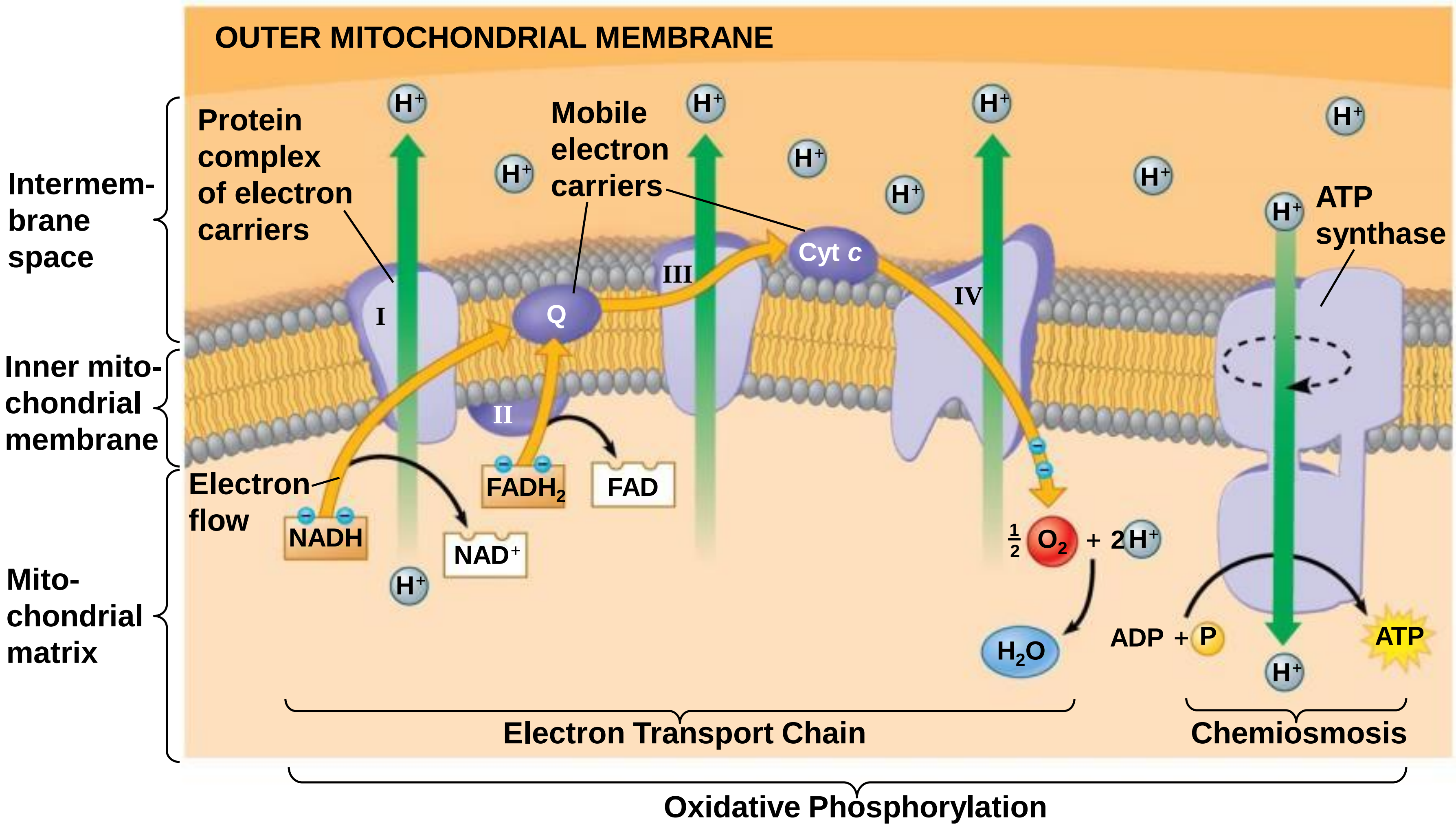
- Electrons from NADH or $FADH_2$ ultimately pass to oxygen.
- The electron transport chain generates no ATP directly.
- Its function is to break the large free energy drop from food to oxygen into a series of smaller steps that release energy in manageable amounts.
- The movement of electrons along the electron transport chain does contribute to chemiosmosis and ATP synthesis.

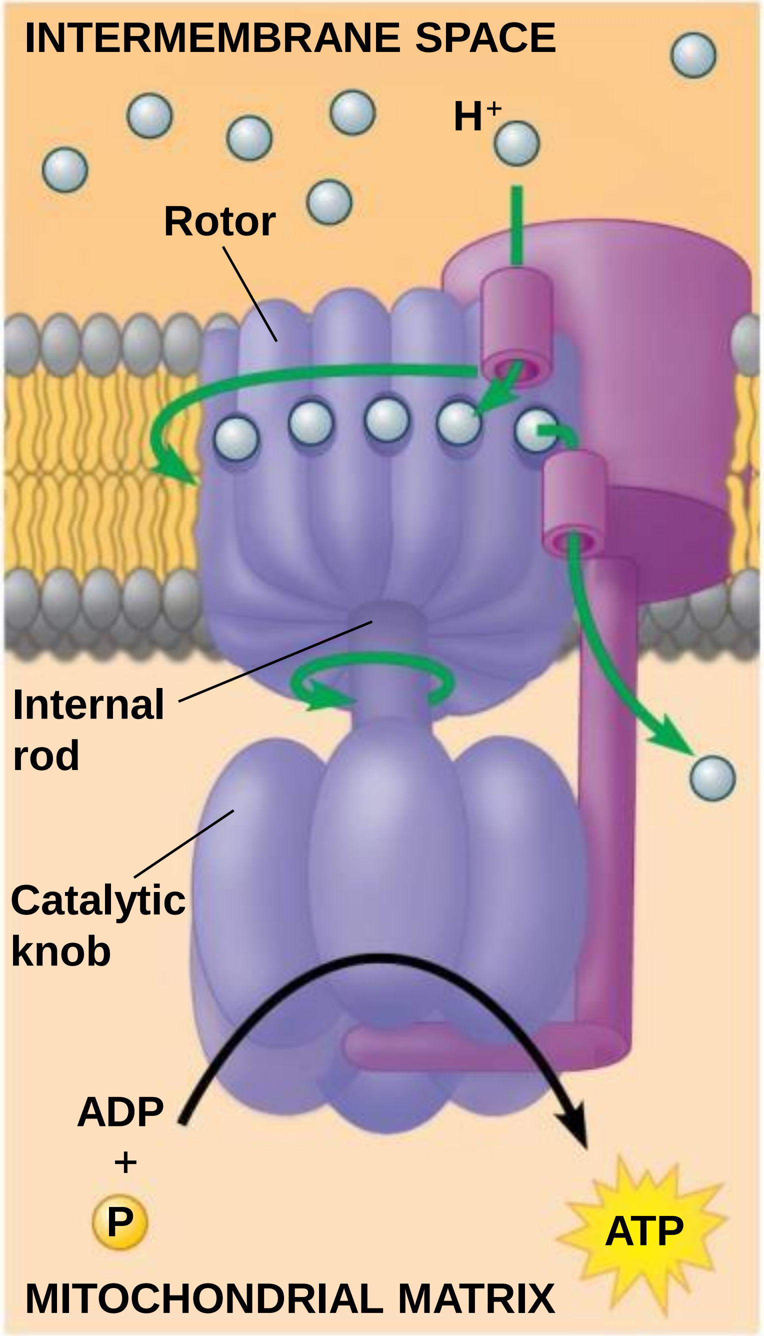
- A protein complex, **ATP synthase**, in the cristae actually makes ATP from ADP and P_i.
- ATP used the energy of an existing proton gradient to power ATP synthesis.
  - This proton gradient develops between the intermembrane space and the matrix.

Figure 6.10a



OUTER MITOCHONDRIAL MEMBRANE
Intermem-brane space
Inner mito-chondrial membrane
Mito-chondrial matrix
Protein complex of electron carriers
Mobile electron carriers
ATP synthase
H^+
I
II
III
IV
Q
Cyt c
Electron flow
NADH
NAD^+
$FADH_2$
FAD
$\frac{1}{2}$ O_2 + 2H^+
H_2O
ADP + P
ATP
Electron Transport Chain
Chemiosmosis
Oxidative Phosphorylation

Figure 6.10b



INTERMEMBRANE SPACE
H+
Rotor
Internal rod
Catalytic knob
ADP
+
P
ATP
MITOCHONDRIAL MATRIX

- The proton gradient is produced by the movement of electrons along the electron transport chain.
- **Several chain molecules can use the exergonic flow of electrons to pump H^+ from the matrix to the intermembrane space**.
  - This concentration of H^+ is the **proton-motive force**.

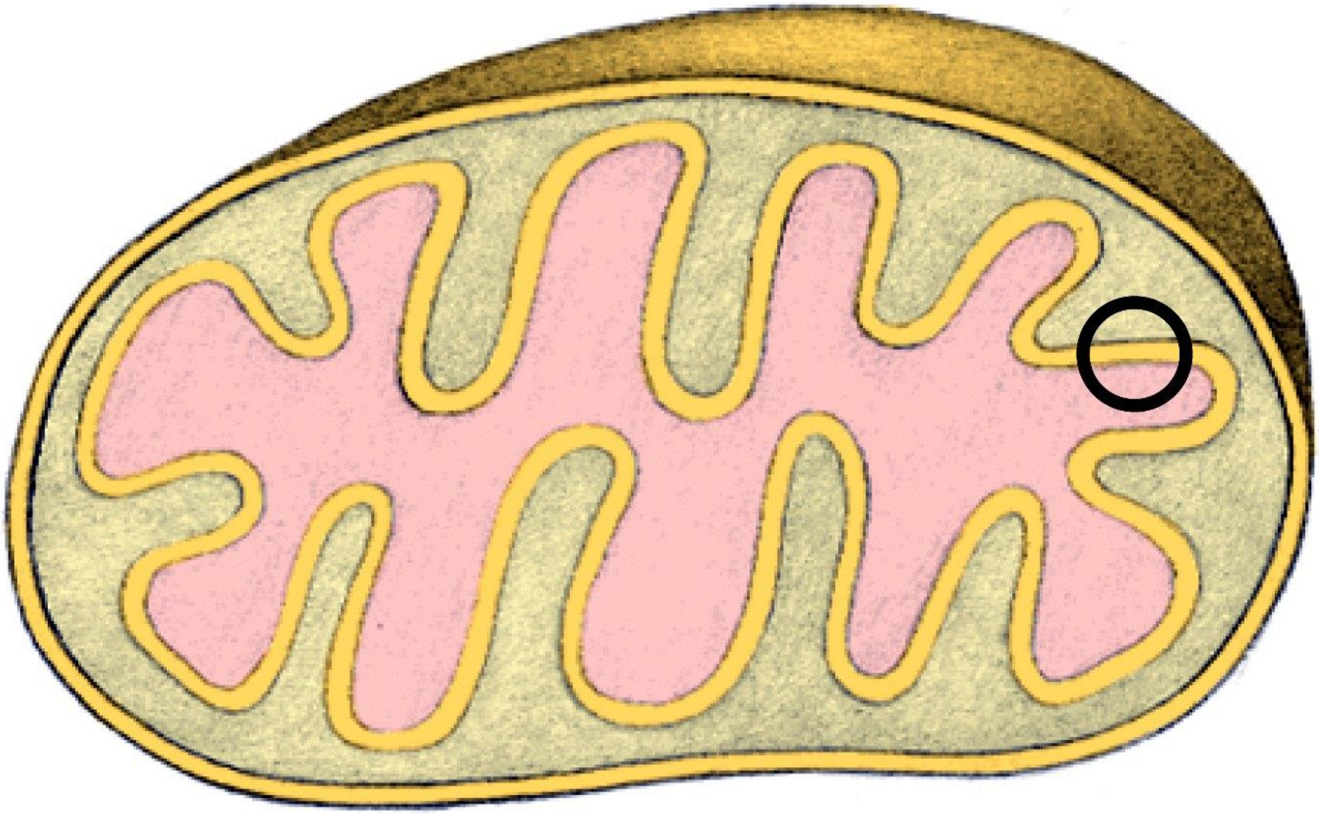


Figure 6-10 part 1
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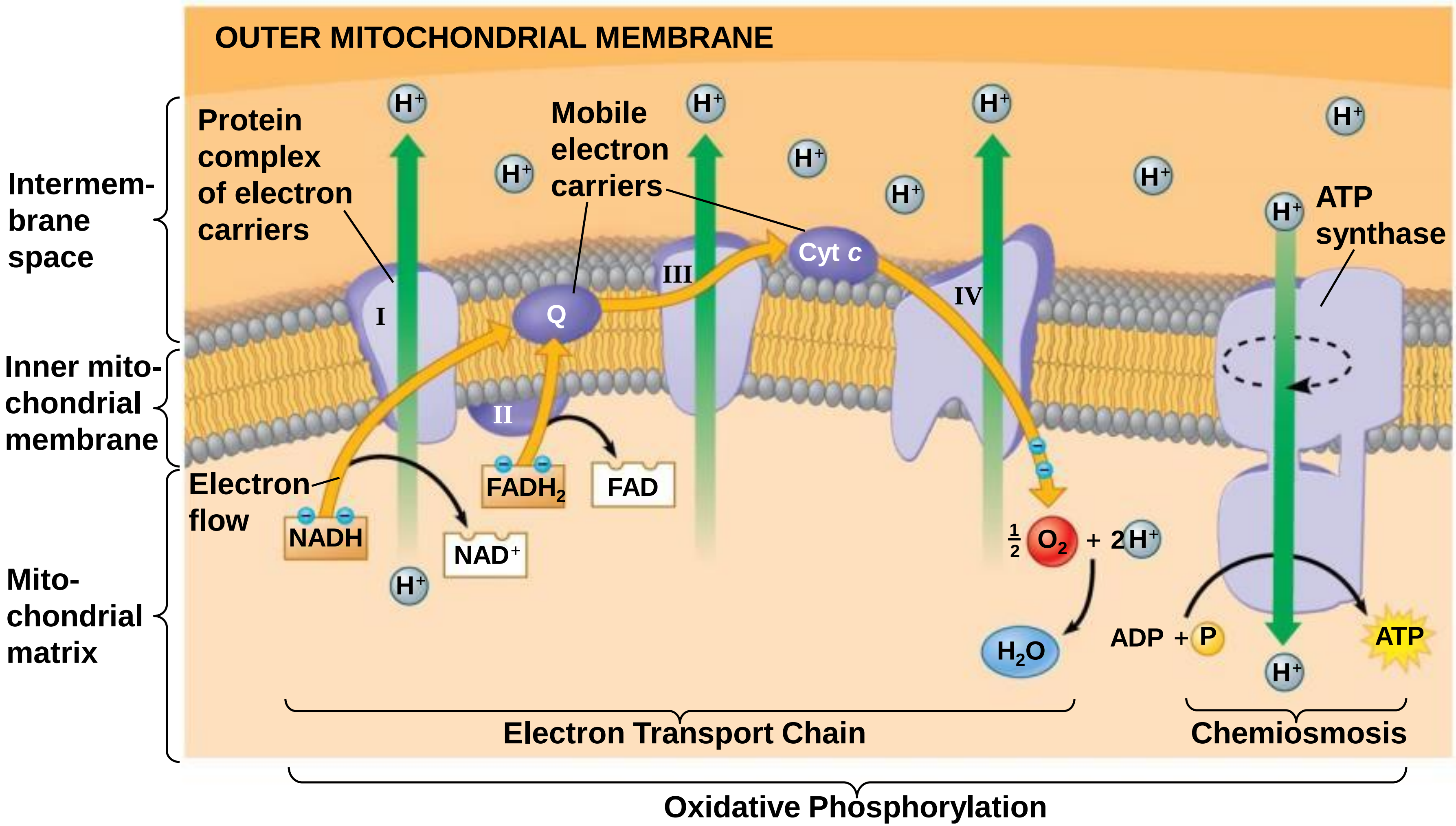
Figure 6.10a

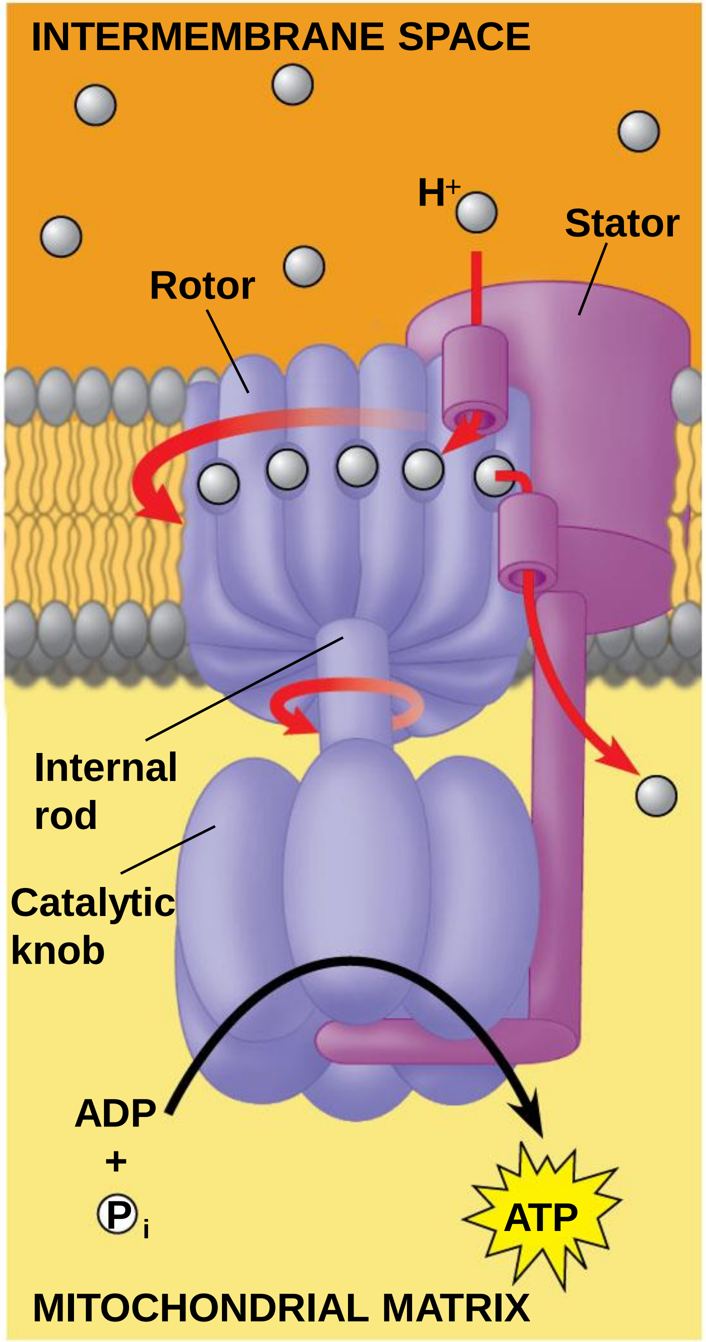


OUTER MITOCHONDRIAL MEMBRANE
Intermembrane space
Inner mitochondrial membrane
Mitochondrial matrix
Protein complex of electron carriers
Mobile electron carriers
ATP synthase
I
II
III
IV
Q
Cyt c
H^+
Electron flow
NADH
NAD^+
$FADH_2$
FAD
$\frac{1}{2}$ O_2 + 2 H^+
H_2O
ADP + P
ATP
Electron Transport Chain
Chemiosmosis
Oxidative Phosphorylation

- The ATP synthase molecules are the only place that will allow H^+ to diffuse back to the matrix.
- This exergonic flow of H^+ is used by the enzyme to generate ATP.
- This coupling of the redox reactions of the electron transport chain to ATP synthesis is called **chemiosmosis**.

- The mechanism of ATP generation by ATP synthase is still an area of active investigation.
  - As hydrogen ions flow down their gradient, they cause the cylinder portion and attached rod of ATP synthase to rotate.
  - The spinning rod causes a conformational change in the knob region, activating catalytic sites where ADP and inorganic phosphate combine to make ATP.

Figure 9.14



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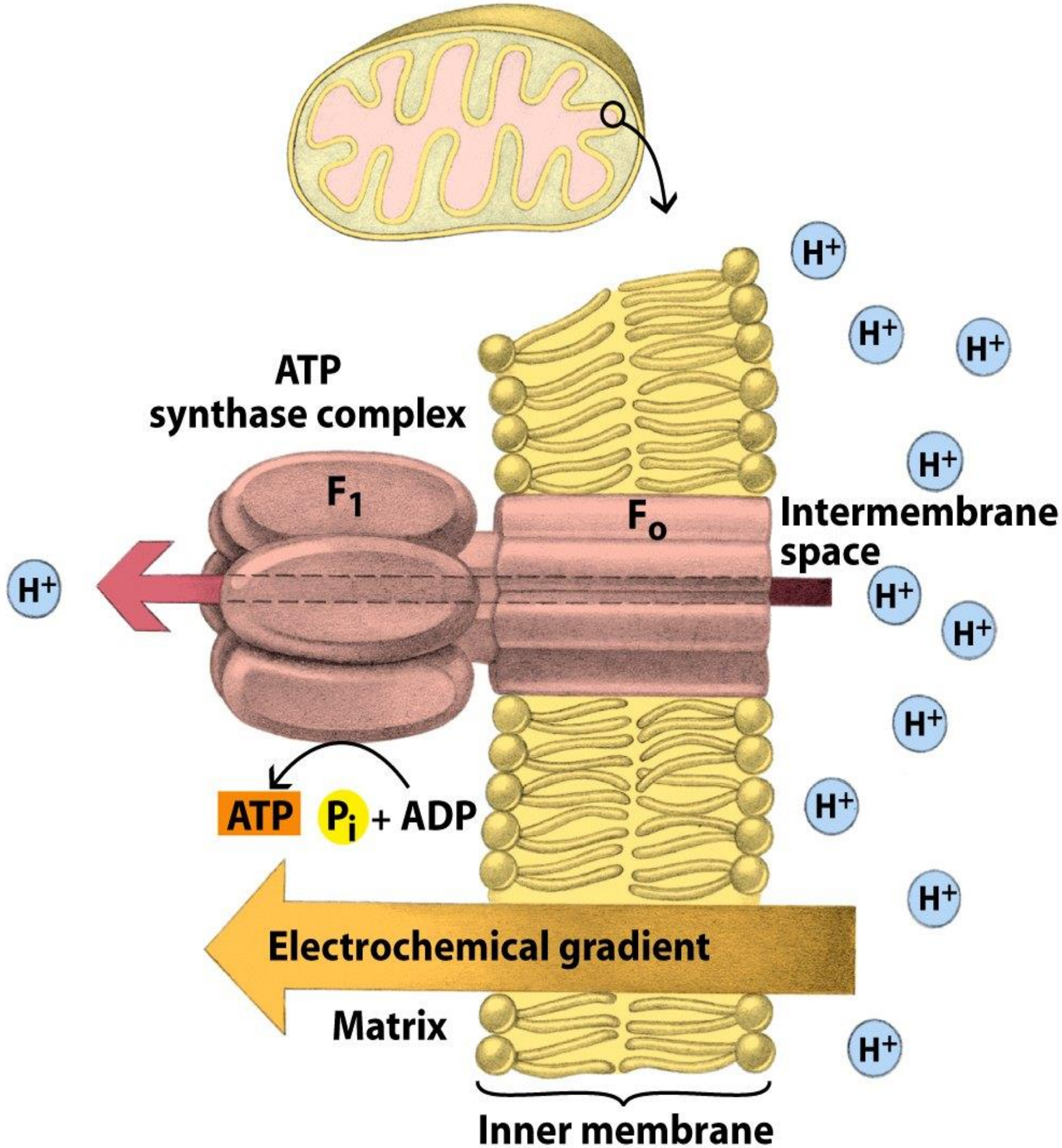

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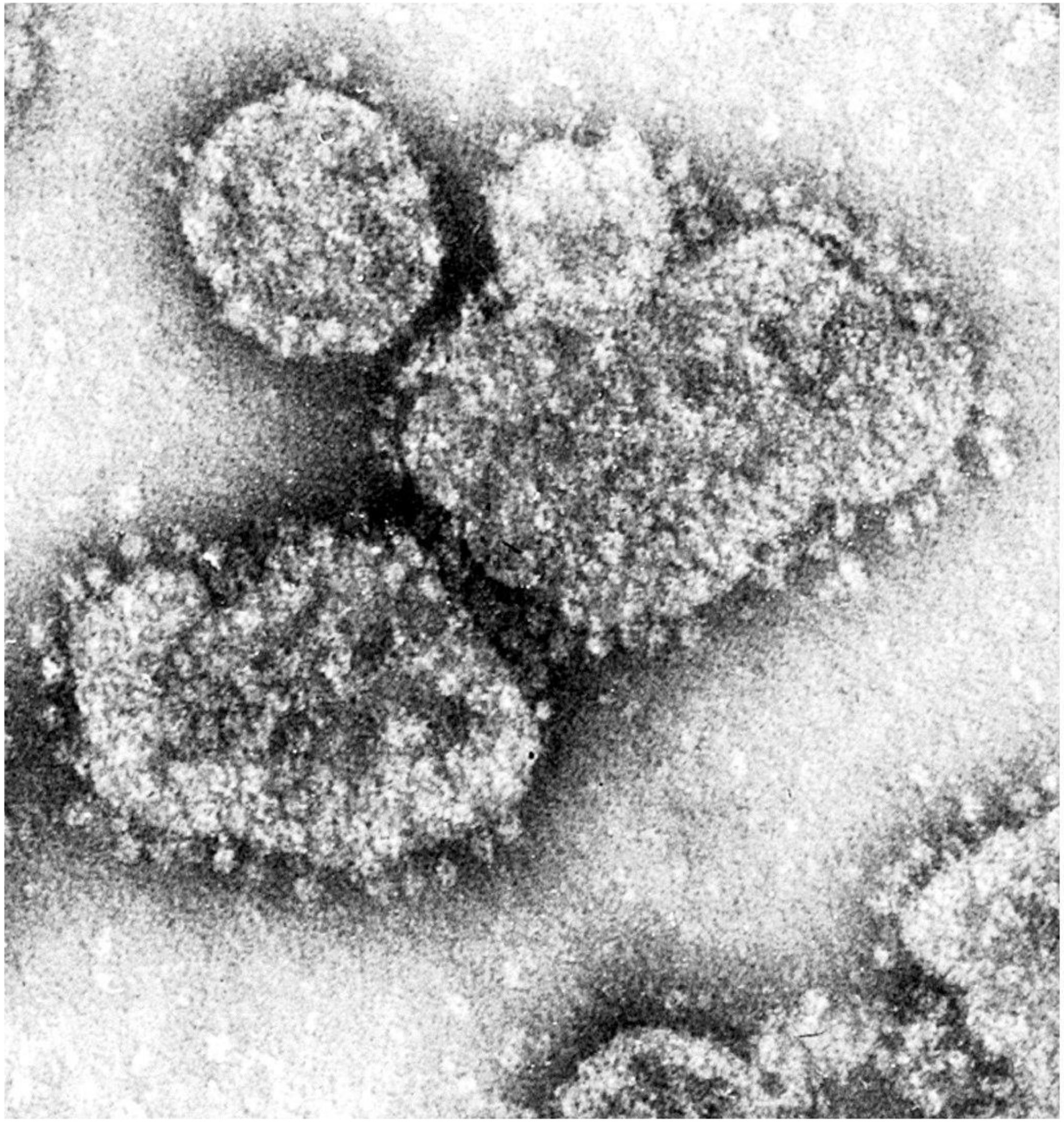

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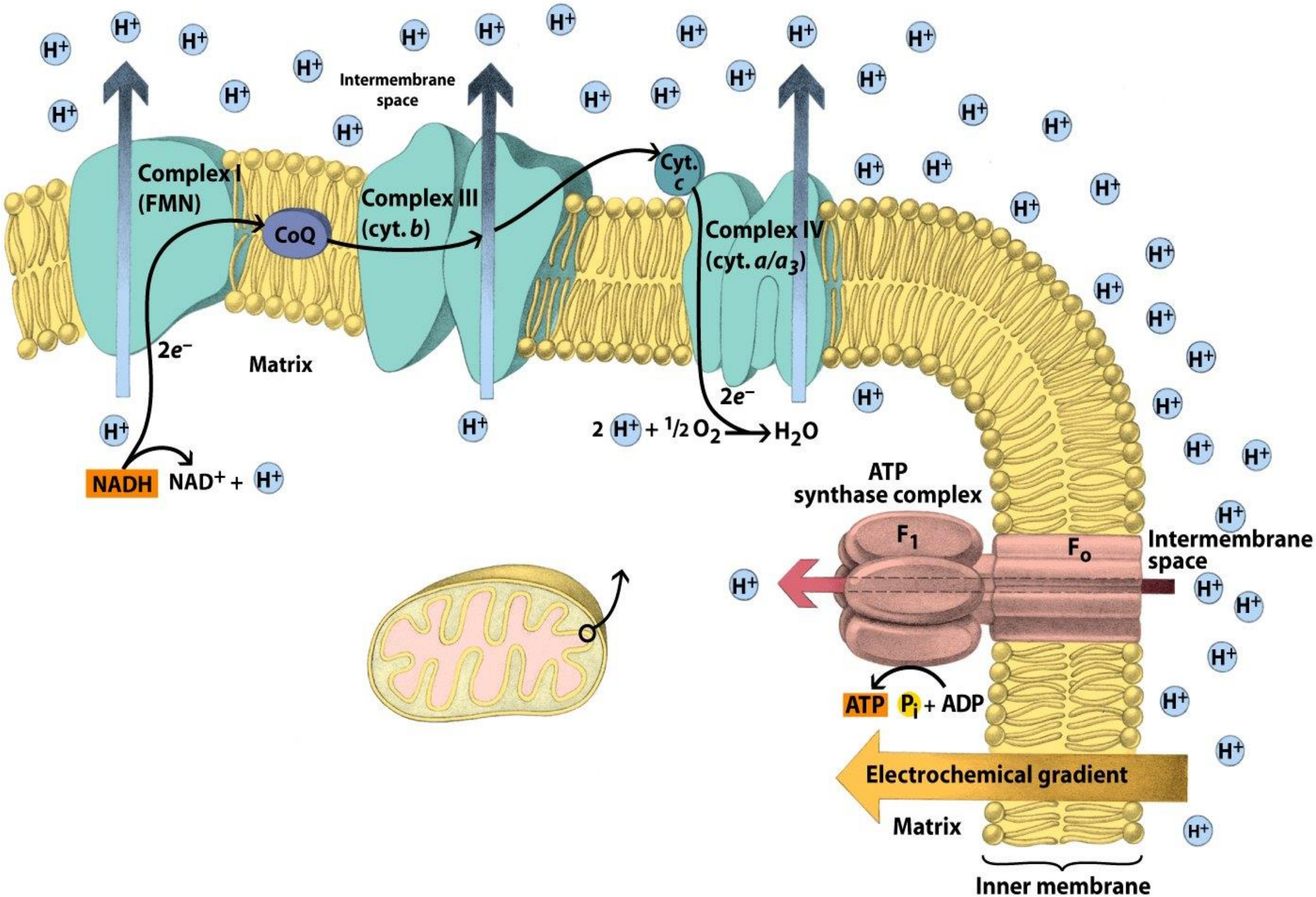

Figure 6-12
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- Chemiosmosis is an energy-coupling mechanism that uses energy stored in the form of an H^+ gradient across a membrane to drive cellular work.
  - In the mitochondrion, chemiosmosis generates ATP.
  - Chemiosmosis in chloroplasts also generates ATP, but light drives the electron flow down an electron transport chain and H^+ gradient formation.
  - Prokaryotes generate H^+ gradients across their plasma membrane.
    - They can use this proton-motive force not only to **generate ATP** but also to **pump nutrients and waste products across the membrane** and to **rotate their flagella**.

Cellular respiration generates many ATP molecules for each sugar molecule it oxidizes: *a review*

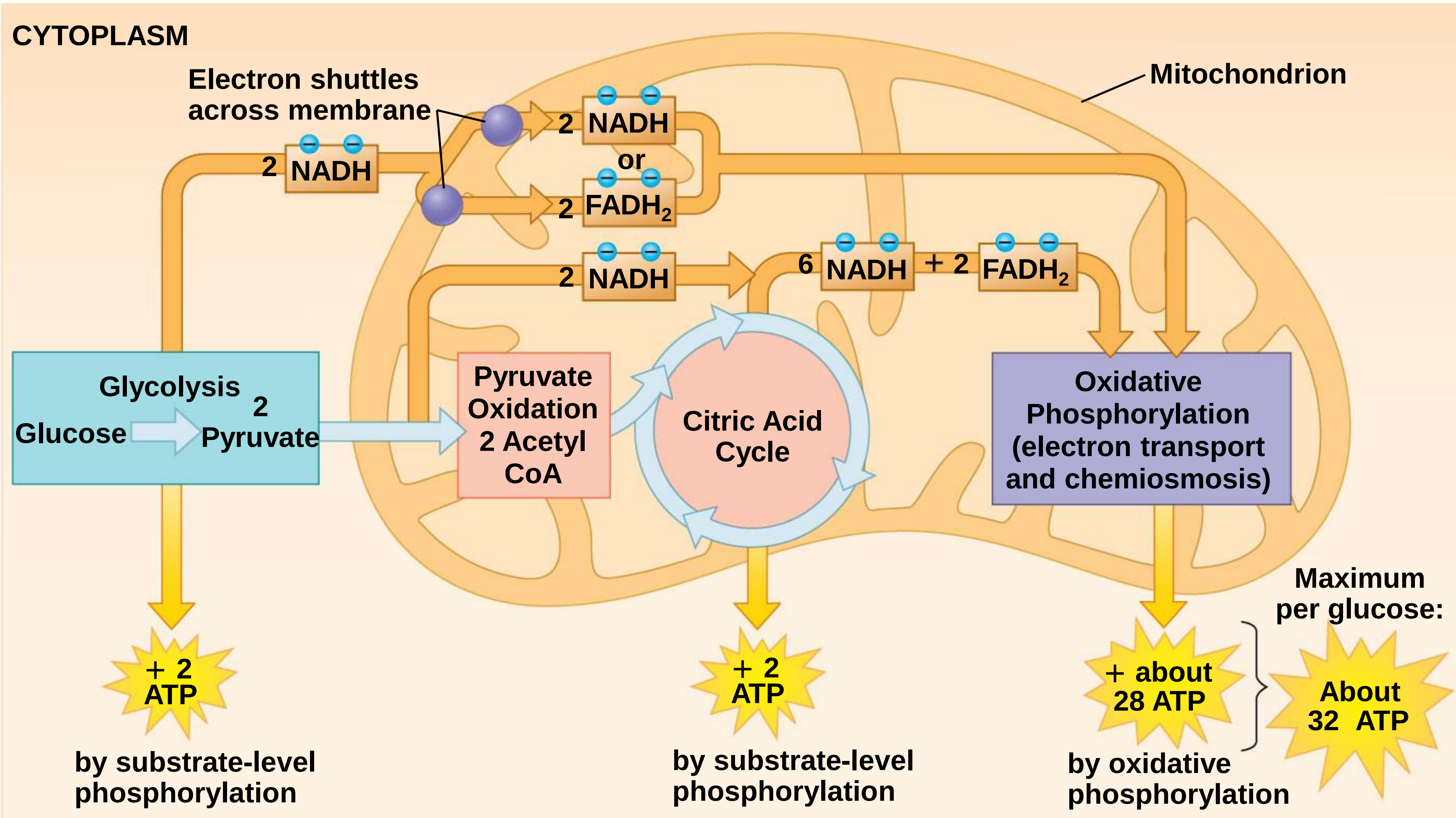
- During respiration, most energy flows from glucose -> NADH -> electron transport chain -> proton-motive force -> ATP.
- Considering the fate of carbon, one six-carbon glucose molecule is oxidized to six CO_2 molecules.
- Some ATP is produced by substrate-level phosphorylation during glycolysis and the Krebs cycle, but **most comes from oxidative phosphorylation**.

- **Each NADH** from the Krebs cycle and the conversion of pyruvate contributes enough energy to **generate a maximum of 2.5 ATP**.
  - The NADH from glycolysis may also yield 2.5 ATP.
- Each **$FADH_2$** from the Krebs cycle can be used to **generate about 1.5 ATP**.
- .

- In some eukaryotic cells, NADH produced in the cytosol by glycolysis may be worth only 2 ATP.
  - The electrons must be shuttled to the mitochondrion.
  - In some shuttle systems, the electrons are passed to NAD^+, in others the electrons are passed to FAD

- Assuming the most energy-efficient shuttle of NADH from glycolysis, a maximum yield of 28 ATP is produced by oxidative phosphorylation.
- This plus the 4 ATP from substrate-level phosphorylation gives a bottom line of 32 ATP.
  - This maximum figure does not consider other uses of the proton-motive force.

Figure 6.12



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- How efficient is respiration in generating ATP?
  - Complete oxidation of glucose releases 686 kcal per mole.
  - Formation of each ATP requires at least 7.3 kcal/mole.
  - Efficiency of respiration is 7.3 kcal/mole x 32 ATP/glucose/686 kcal/mole glucose = **34%**.
  - The other **approximately 66% is lost as heat**.
- Cellular respiration is remarkably efficient in energy conversion.

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

Figure 9.17

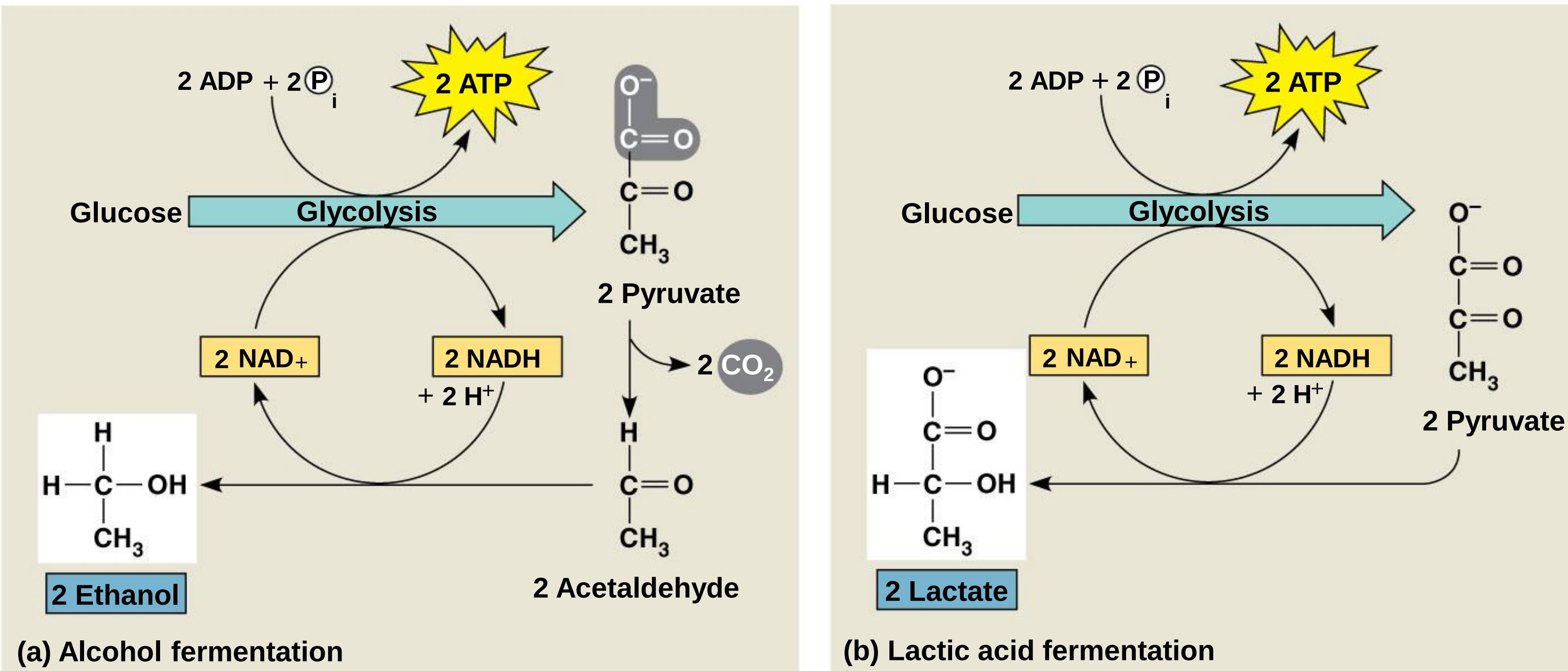

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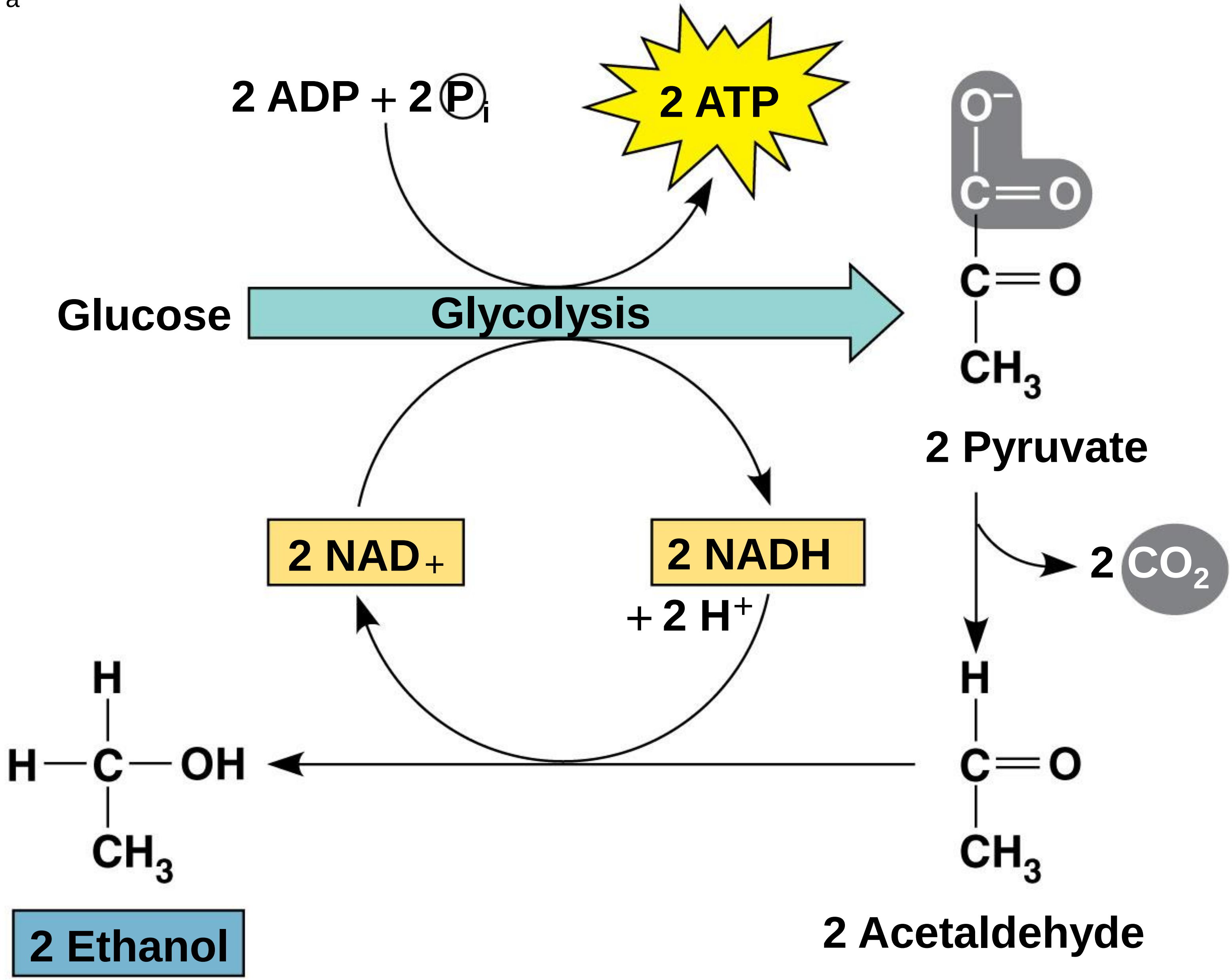
Figure 9.17a



(a) Alcohol fermentation

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Figure 6.13C_1

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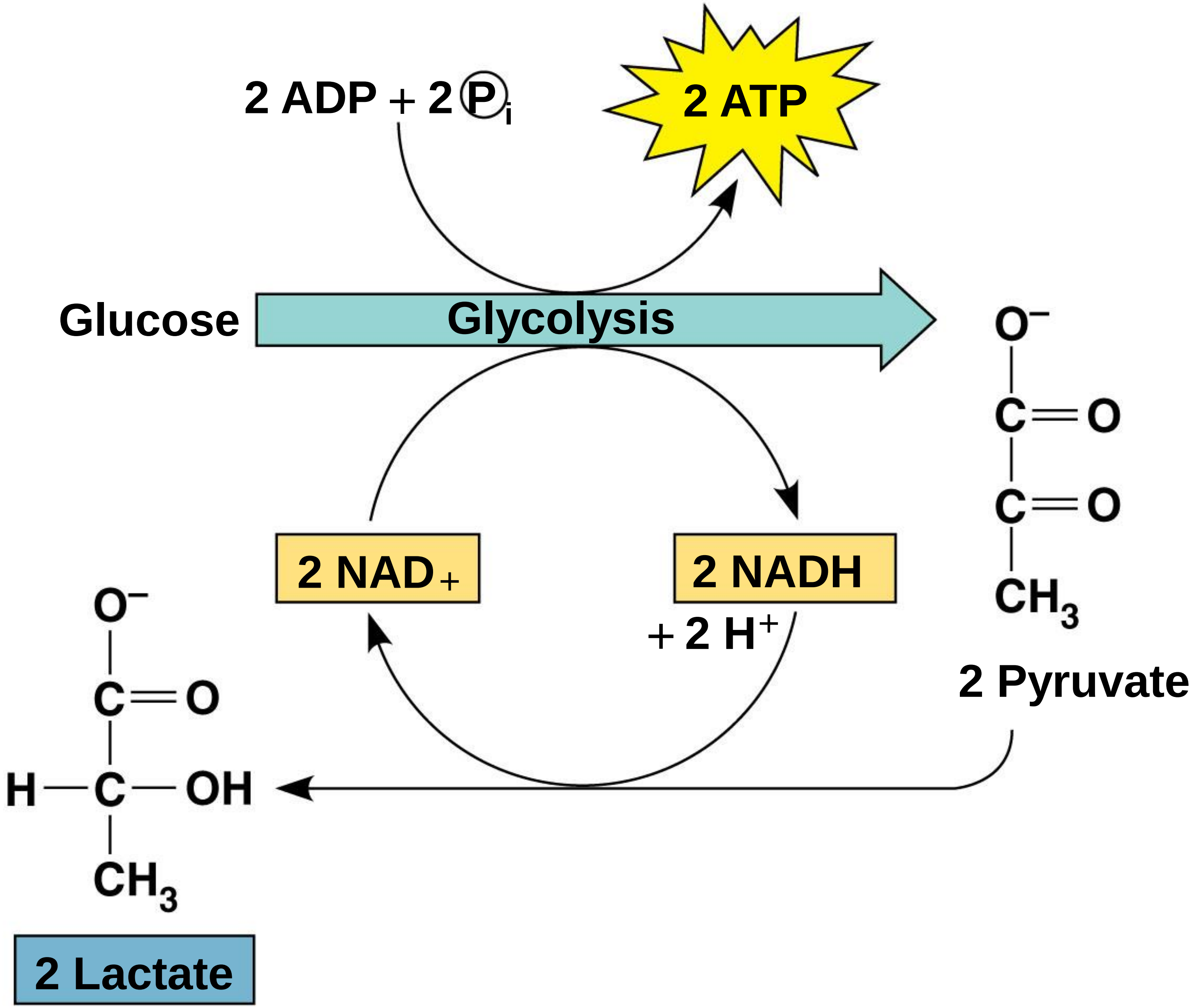
Figure 6.13c-2

Figure 9.17b



(b) Lactic acid fermentation

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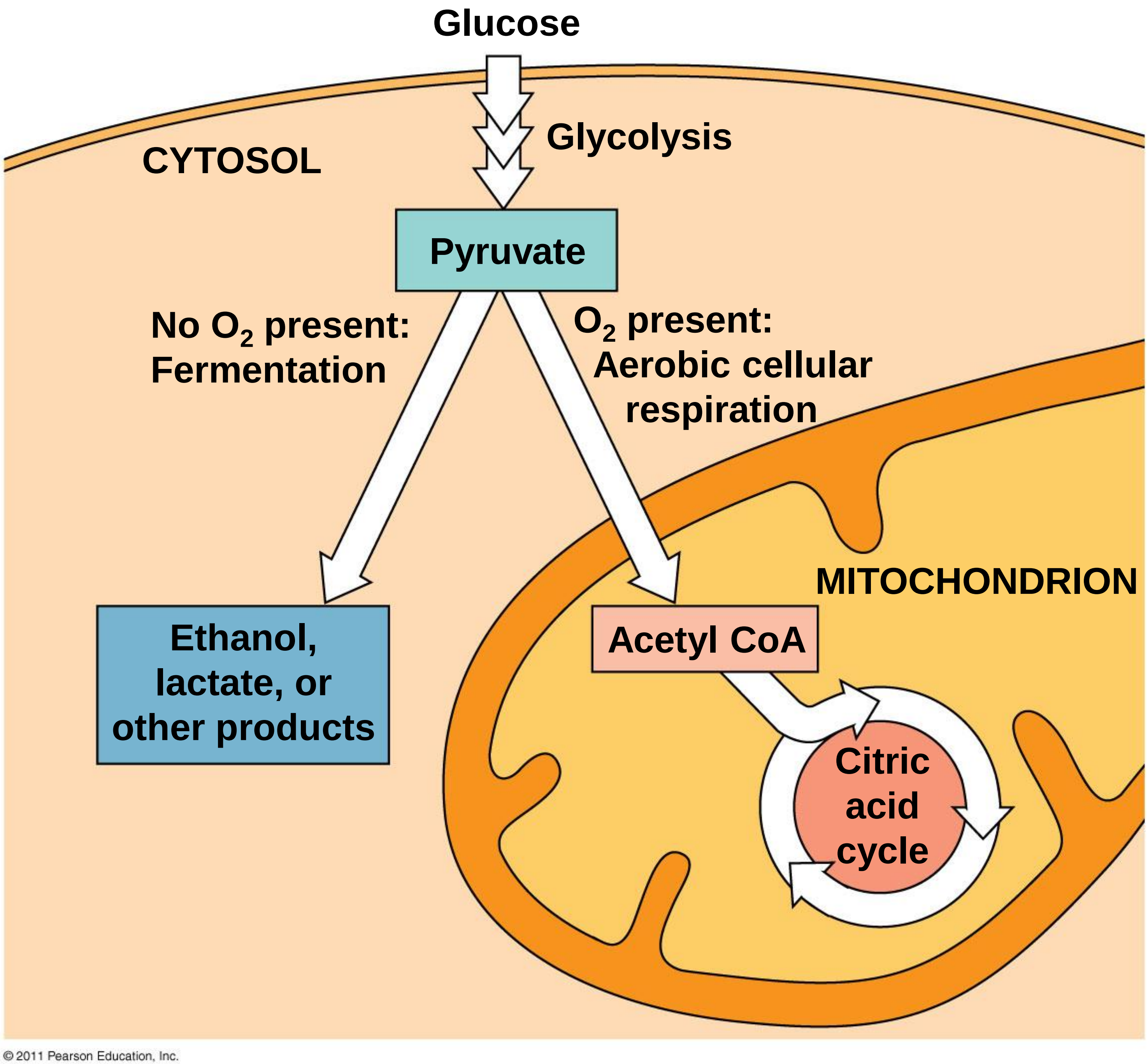
- In lactic acid fermentation, pyruvate is reduced to NADH, forming lactate as an end product, with no release of CO_2
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
- Human muscle cells use lactic acid fermentation to generate ATP when O_2 is scarce

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

Figure 9.18



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6.14 EVOLUTION CONNECTION: Glycolysis evolved early in the history of life on Earth

- Glycolysis is the universal energy-harvesting process of life.
- The role of glycolysis in fermentation and respiration dates back to life long before oxygen was present, when only prokaryotes inhabited the Earth, about 3.5 billion years ago.

6.14 EVOLUTION CONNECTION: Glycolysis evolved early in the history of life on Earth

- The ancient history of glycolysis is supported by its
  - occurrence in all the domains of life and
  - location within the cell, using pathways that do not involve any membrane-enclosed organelles of the eukaryotic cell.

- 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

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 6.15_1

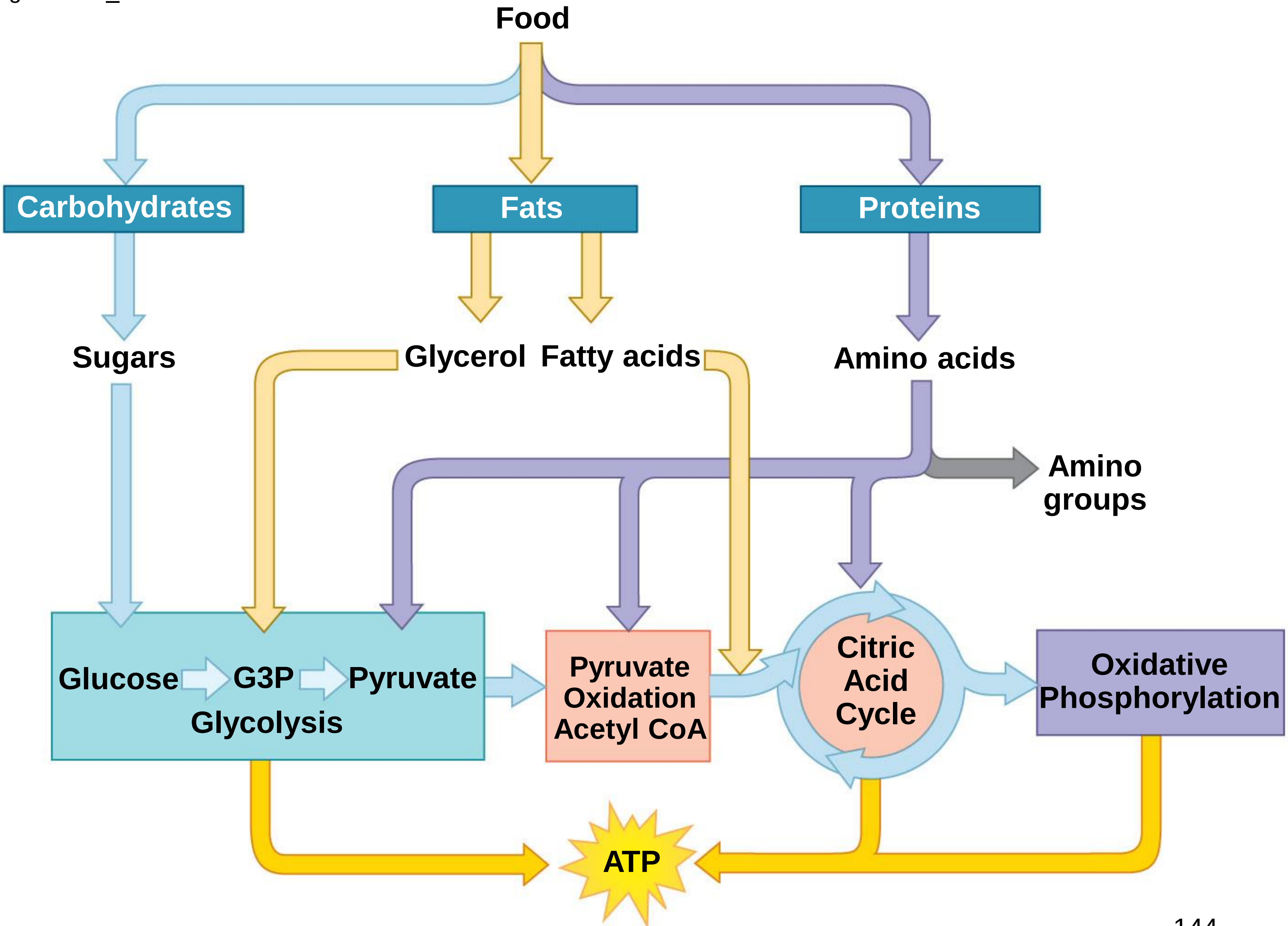

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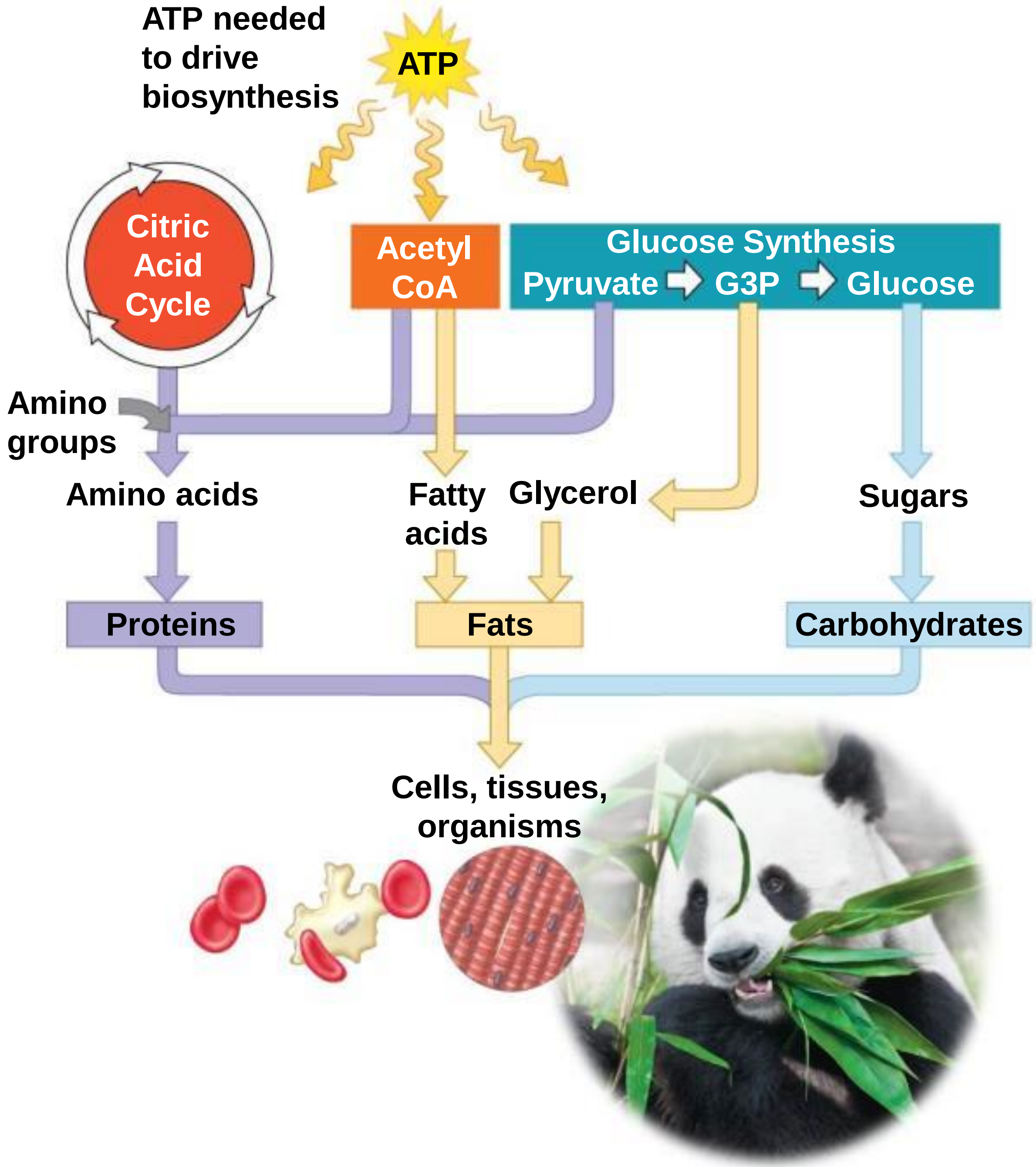
Figure 6.16-0


ATP needed
to drive
biosynthesis
ATP
Citric
Acid
Cycle
Acetyl
CoA
Glucose Synthesis
Pyruvate
G3P
Glucose
Amino
groups
Amino acids
Fatty
acids
Glycerol
Sugars
Proteins
Fats
Carbohydrates
Cells, tissues,
organisms

You should now be able to

1. Compare the processes and locations of cellular respiration and photosynthesis.
2. Explain how breathing and cellular respiration are related.
3. Provide the overall chemical equation for cellular respiration.
4. Explain how the human body uses its daily supply of ATP.

You should now be able to

5. Explain how the energy in a glucose molecule is released during cellular respiration.
6. Explain how redox reactions are used in cellular respiration.
7. Describe the general roles of dehydrogenase, NADH, and the electron transport chain in cellular respiration.
8. Compare the reactants, products, and energy yield of the three stages of cellular respiration.

You should now be able to

9. Describe the special function of brown fat.
10. Compare the reactants, products, and energy yield of alcohol and lactic acid fermentation.
11. Distinguish between strict anaerobes and facultative anaerobes.
12. Explain how carbohydrates, fats, and proteins are used as fuel for cellular respiration.

- Life requires energy.
- 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