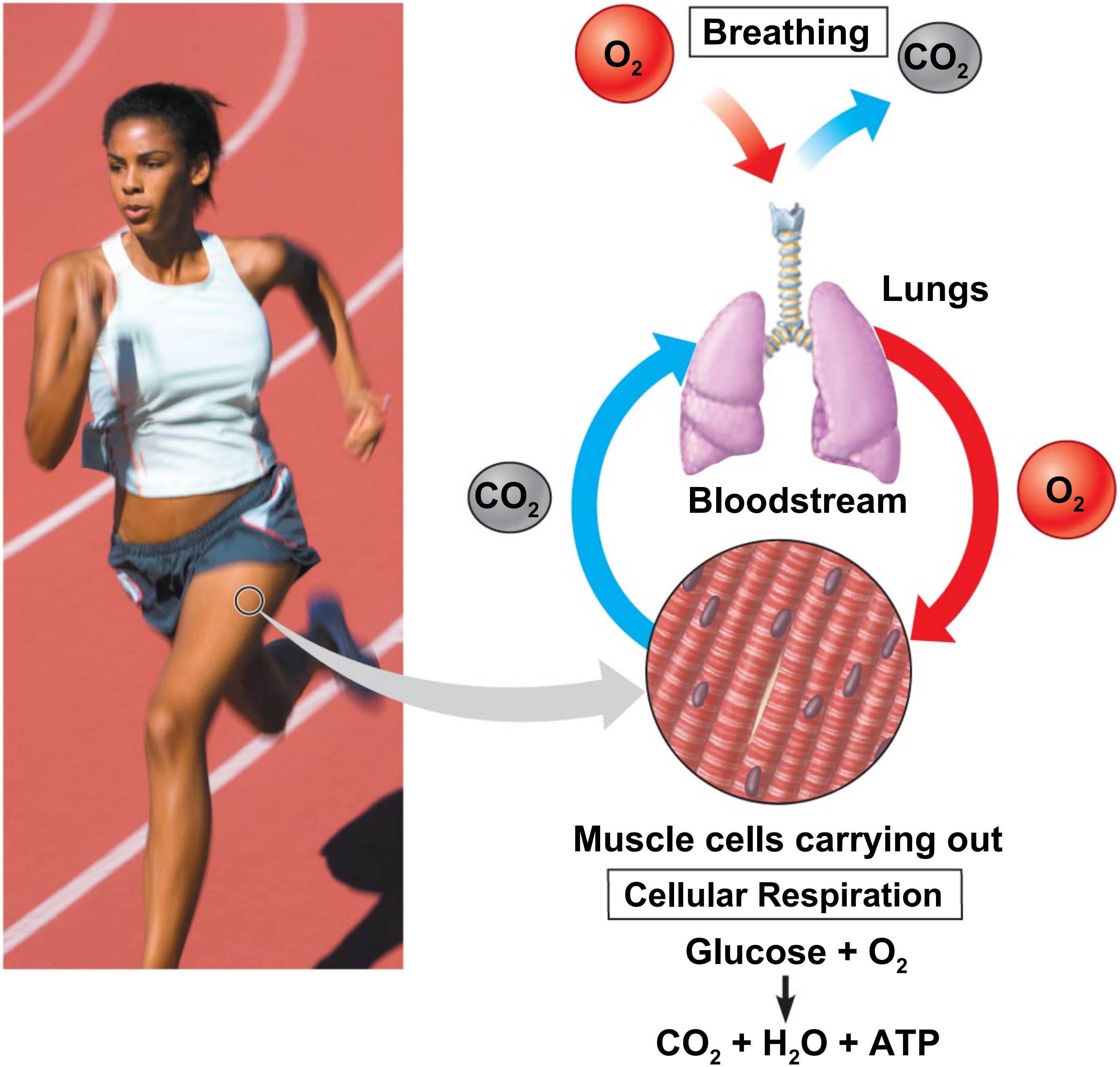
# INTRODUCTION TO CELLULAR RESPIRATION

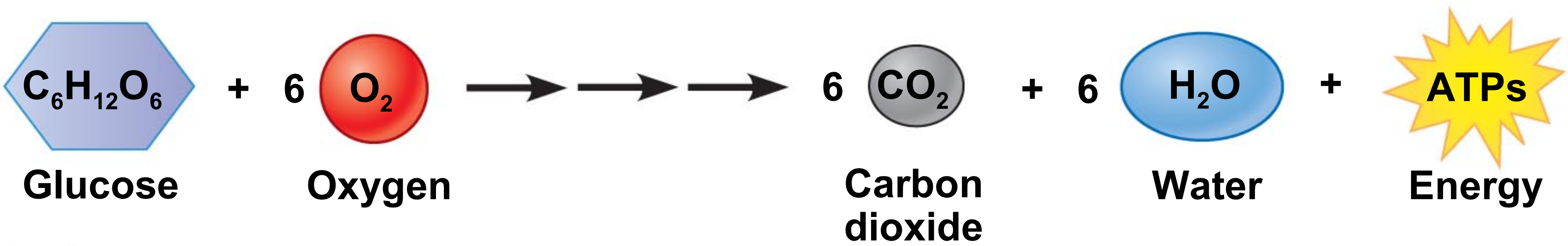
# 6.2 Breathing supplies oxygen to our cells for use in cellular respiration and removes carbon dioxide

- Breathing and cellular respiration are closely related
  - Breathing is necessary for exchange of $CO_2$ produced during cellular respiration for atmospheric $O_2$
  - Cellular respiration uses $O_2$ to help harvest energy from glucose and produces $CO_2$ in the process


Breathing
$O_2$
$CO_2$
Lungs
$CO_2$
Bloodstream
$O_2$
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 process that transfers energy from the bonds in glucose to ATP
  - Cellular respiration produces 38 ATP molecules from each glucose molecule
  - Other foods (organic molecules) can be used as a source of energy as well


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

# 6.5 Cells tap 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

# 6.5 Cells tap 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

# 6.5 Cells tap 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

# 6.5 Cells tap 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**

Loss of hydrogen atoms
(oxidation)

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

Glucose (ATP)

Gain of hydrogen atoms
(reduction)

# 6.5 Cells tap energy from electrons "falling" from organic fuels to oxygen

- The transfer of electrons to $NAD^+$ results in the formation of NADH, the reduced form of $NAD^+$
  - In this situation, $NAD^+$ is called an electron acceptor, but it eventually becomes oxidized (loses an electron) and is then called an electron donor

# 6.5 Cells tap energy from electrons "falling" from organic fuels to oxygen

- There are other electron "carrier" molecules that function like $NAD^+$
  - They form a staircase where the electrons pass from one to the next down the staircase
  - These electron carriers collectively are called the **electron transport chain**, and as electrons are transported down the chain, ATP is generated

# STAGES OF CELLULAR RESPIRATION AND FERMENTATION

# 6.6 Overview: Cellular respiration occurs in three main stages

- Stage 1: Glycolysis
  - Glycolysis begins respiration by breaking glucose, a six-carbon molecule, into two molecules of a three-carbon compound called pyruvate
  - This stage occurs in the cytoplasm

# 6.6 Overview: Cellular respiration occurs in three main stages

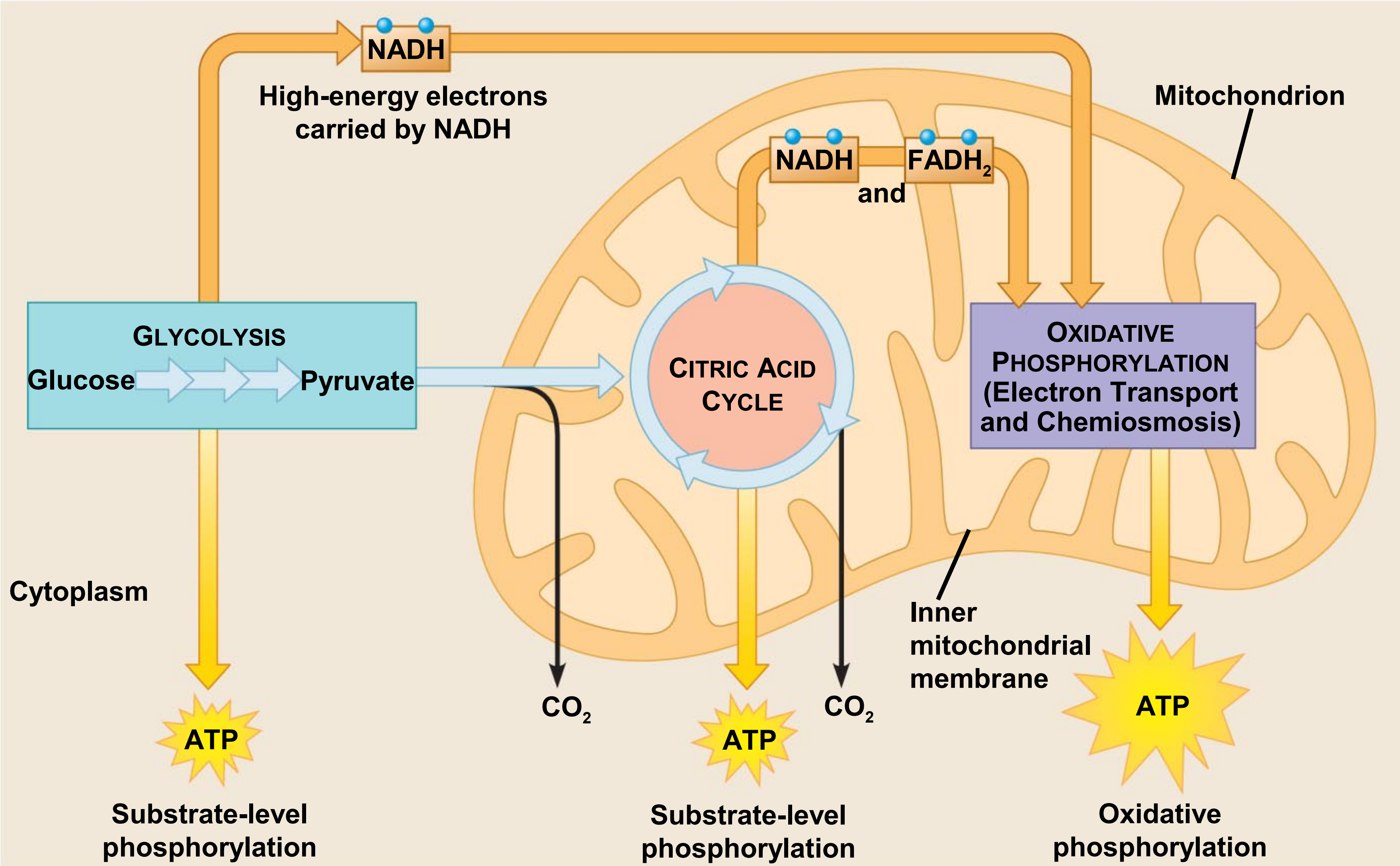
- Stage 2: The citric acid cycle
  - The citric acid cycle breaks down pyruvate into carbon dioxide and supplies the third stage with electrons
  - This stage occurs in the mitochondria

# 6.6 Overview: Cellular respiration occurs in three main stages

- Stage 3: Oxidative phosphorylation
  - During this stage, electrons are shuttled through the electron transport chain
  - As a result, ATP is generated through oxidative phosphorylation associated with chemiosmosis
  - This stage occurs in the inner mitochondrion membrane

# 6.6 Overview: Cellular respiration occurs in three main stages

- During the transport of electrons, a concentration gradient of $H^+$ ions is formed across the inner membrane into the intermembrane space
  - The potential energy of this concentration gradient is used to make ATP by a process called **chemiosmosis**
  - The concentration gradient drives $H^+$ through **ATP synthases** and enzymes found in the membrane, and ATP is produced



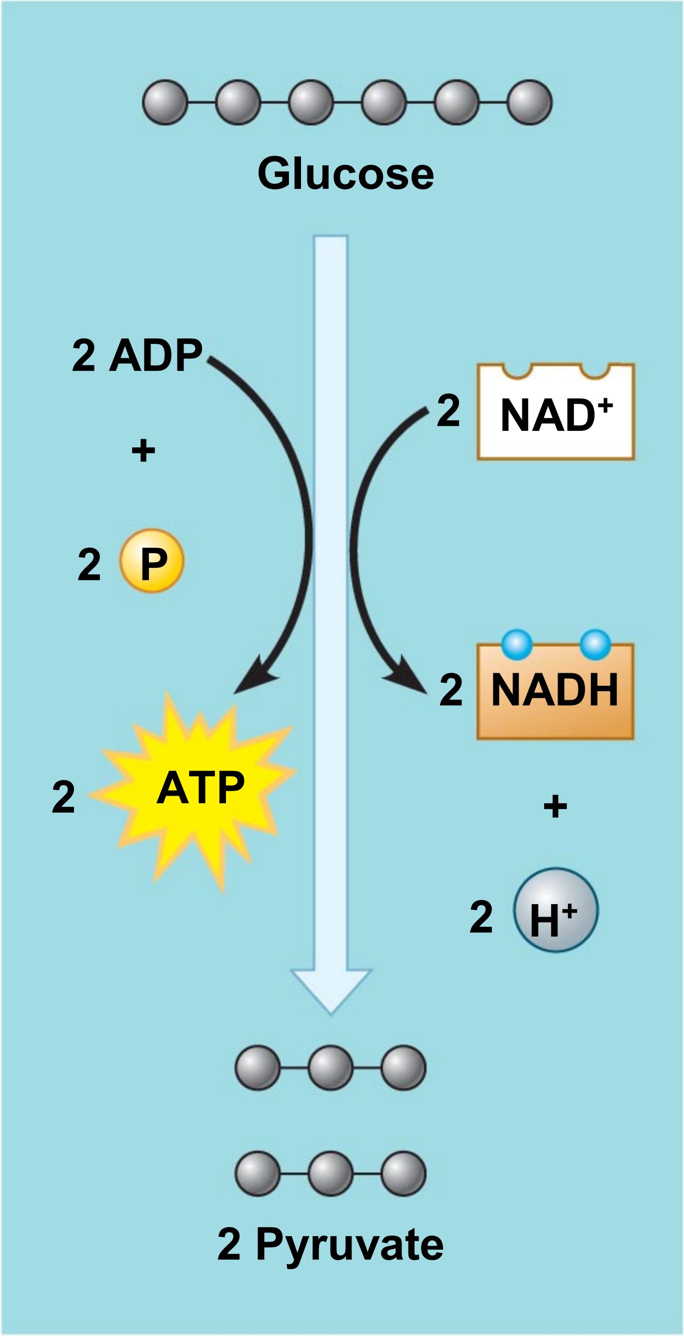
NADH
High-energy electrons carried by NADH
Mitochondrion
NADH
and
FADH$_2$
GLYCOLYSIS
Glucose
Pyruvate
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION (Electron Transport and Chemiosmosis)
Cytoplasm
Inner mitochondrial membrane
$CO_2$
$CO_2$
ATP
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation

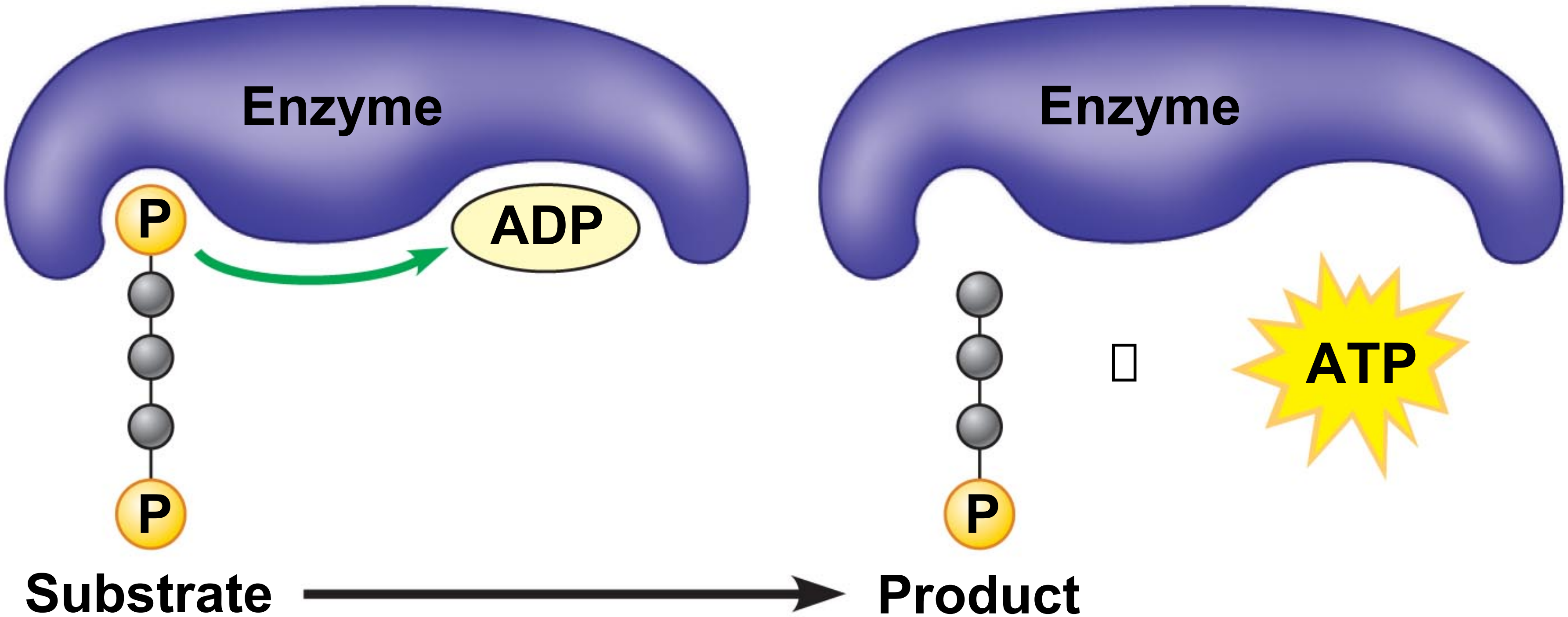
# 6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- In glycolysis, a single molecule of glucose is enzymatically cut in half through a series of steps to produce two molecules of pyruvate
  - In the process, two molecules of $NAD^+$ are reduced to two molecules of NADH
  - At the same time, two molecules of ATP are produced by substrate-level phosphorylation

# 6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

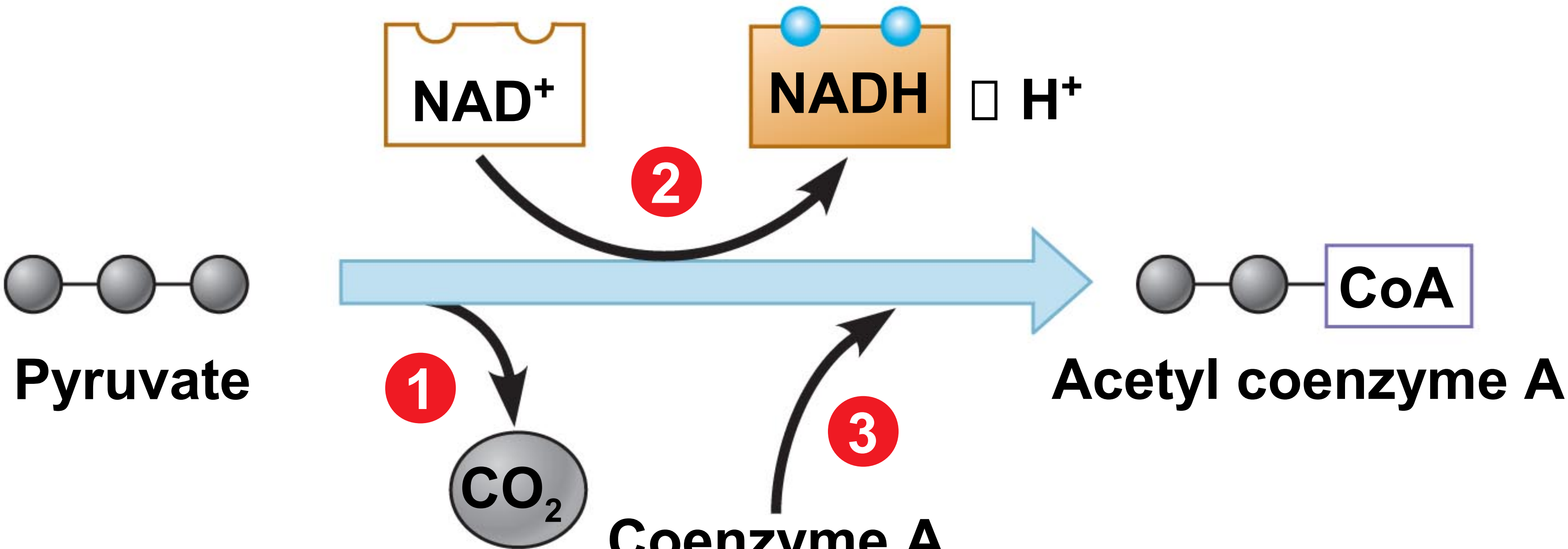
- In **substrate-level phosphorylation**, an enzyme transfers a phosphate group from a substrate molecule to ADP, forming ATP
  - This ATP can be used immediately, but NADH must be transported through the electron transport chain to generate additional ATP


Glucose
2 ADP
+
2 P
2 ATP
2 NAD+
2 NADH
+
2 H+
2 Pyruvate


Enzyme
P
ADP
P
Enzyme
ATP
P
Substrate
Product

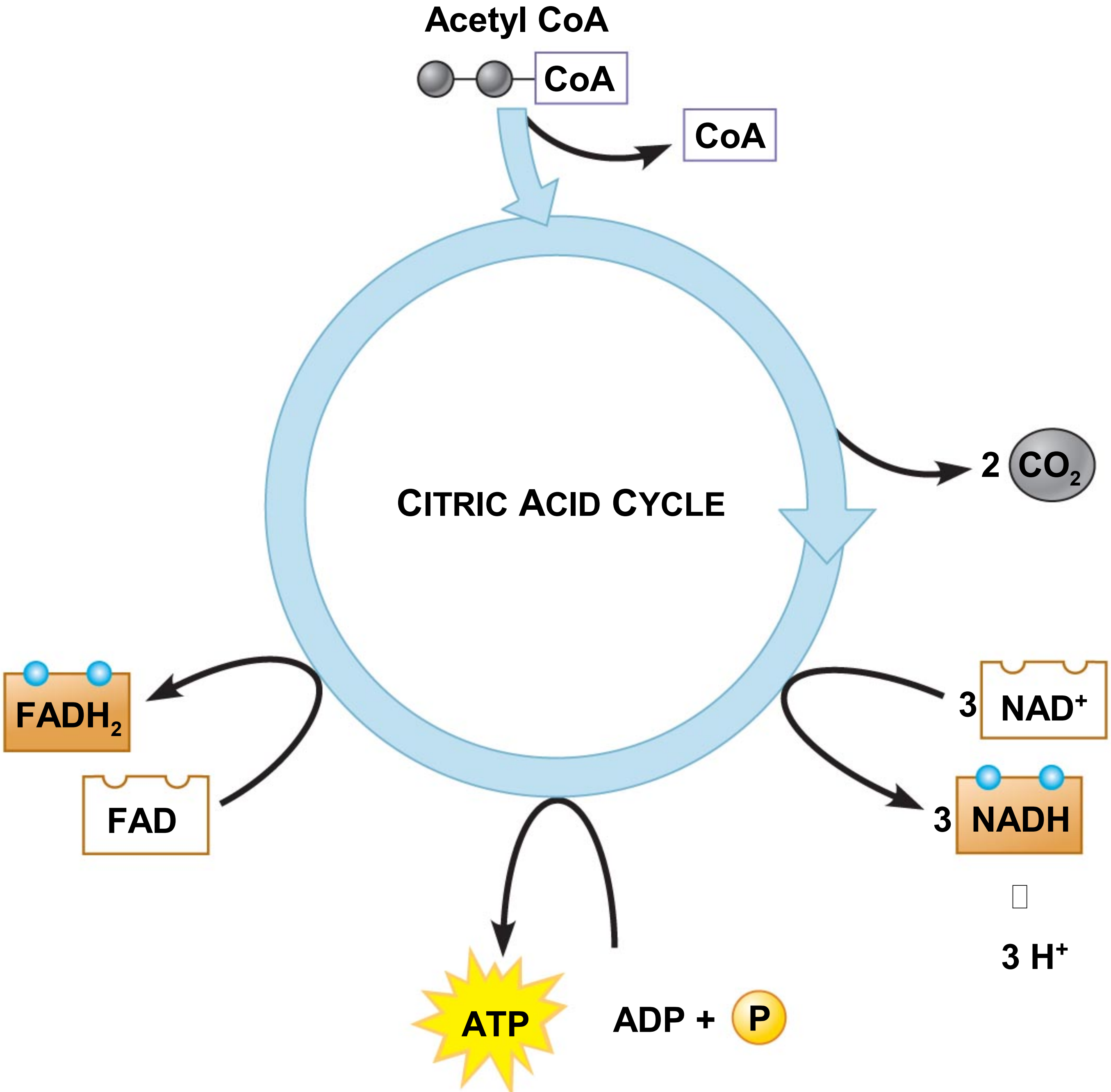
# 6.8 Pyruvate is chemically groomed for the citric acid cycle

- The pyruvate formed in glycolysis is transported to the mitochondria, where it is prepared for entry into the citric acid cycle
  - The first step is removal of a carboxyl group that forms $CO_2$
  - The second is oxidization of the two-carbon compound remaining
  - Finally, coenzyme A binds to the two-carbon fragment forming acetyl coenzyme A


NAD+
NADH
H+
2
CoA
Pyruvate
1
3
Acetyl coenzyme A
CO2
Coenzyme A

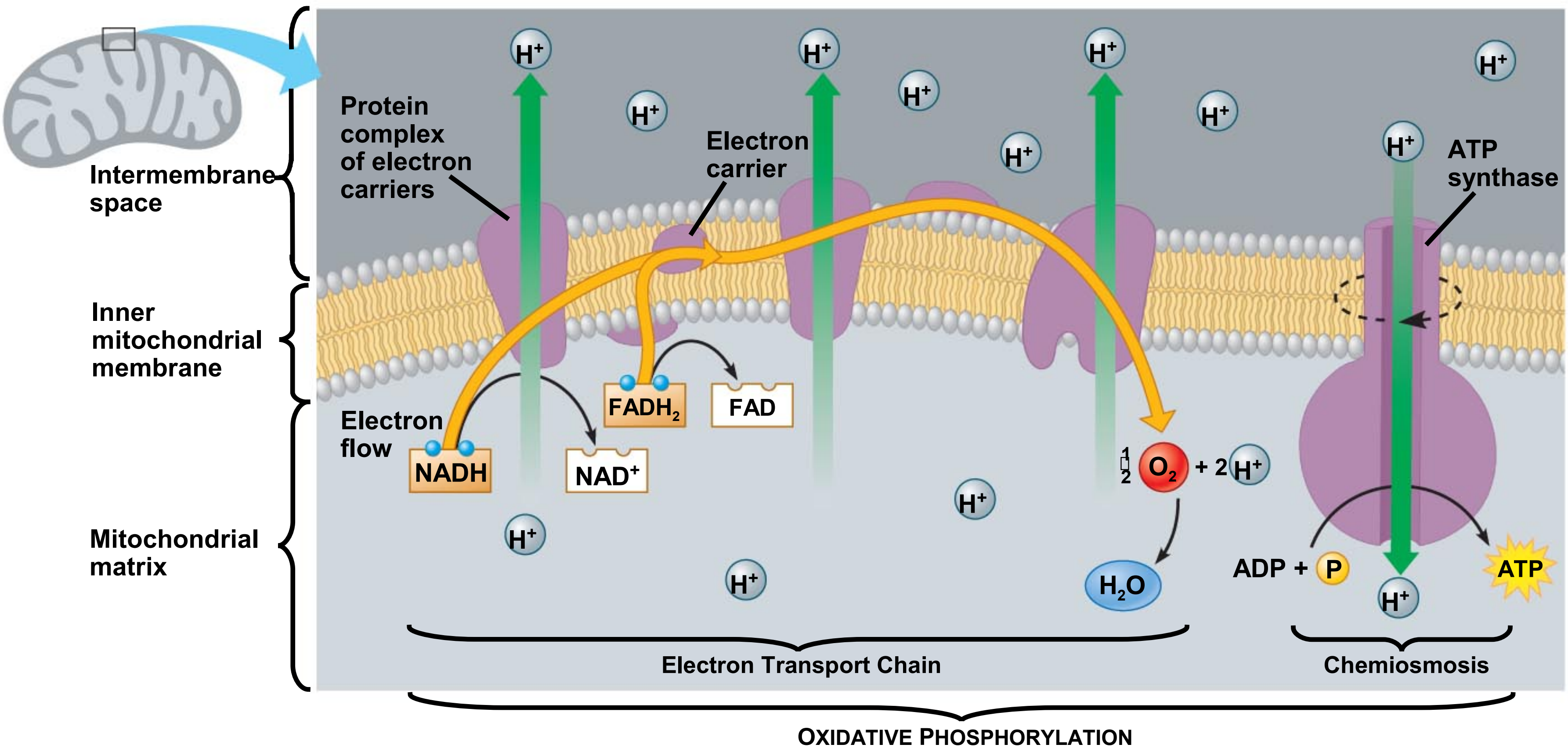
# 6.9 The citric acid cycle completes the oxidation of organic molecules, generating many NADH and $FADH_2$ molecules

- With the help of CoA, the acetyl (two-carbon) compound enters the citric acid cycle
  - At this point, the acetyl group associates with a four-carbon molecule forming a six-carbon molecule
  - The six-carbon molecule then passes through a series of redox reactions that regenerate the four-carbon molecule (thus the "cycle" designation)


Acetyl CoA
CoA
CoA
CITRIC ACID CYCLE
2 $CO_2$
3 $NAD^+$
3 NADH
3 $H^+$
$FADH_2$
FAD
ATP
ADP + P

# 6.10 Most ATP production occurs by oxidative phosphorylation

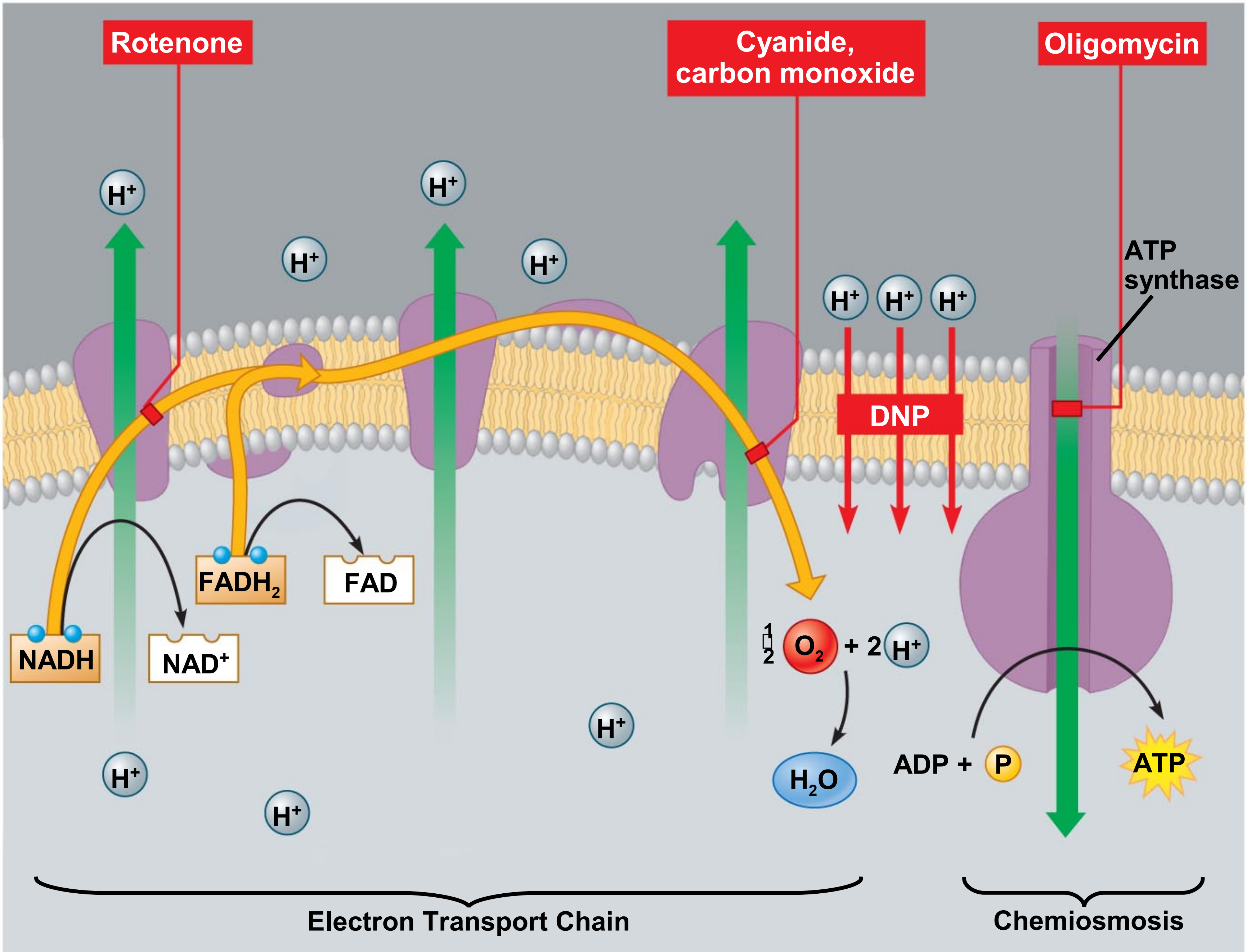
- Oxidative phosphorylation involves electron transport and chemiosmosis and requires an adequate supply of oxygen
  - NADH and $FADH_2$ and the inner membrane of the mitochondria are also involved
  - A $H^+$ ion gradient formed from all of the redox reactions of glycolysis and the citric acid cycle provide energy for the synthesis of ATP



Protein complex of electron carriers
Electron carrier
ATP synthase
Intermembrane space
Inner mitochondrial membrane
Mitochondrial matrix
Electron flow
NADH
NAD+
FADH2
FAD
H+
1/2 O2 + 2 H+
H2O
ADP + P
ATP
Electron Transport Chain
Chemiosmosis
OXIDATIVE PHOSPHORYLATION

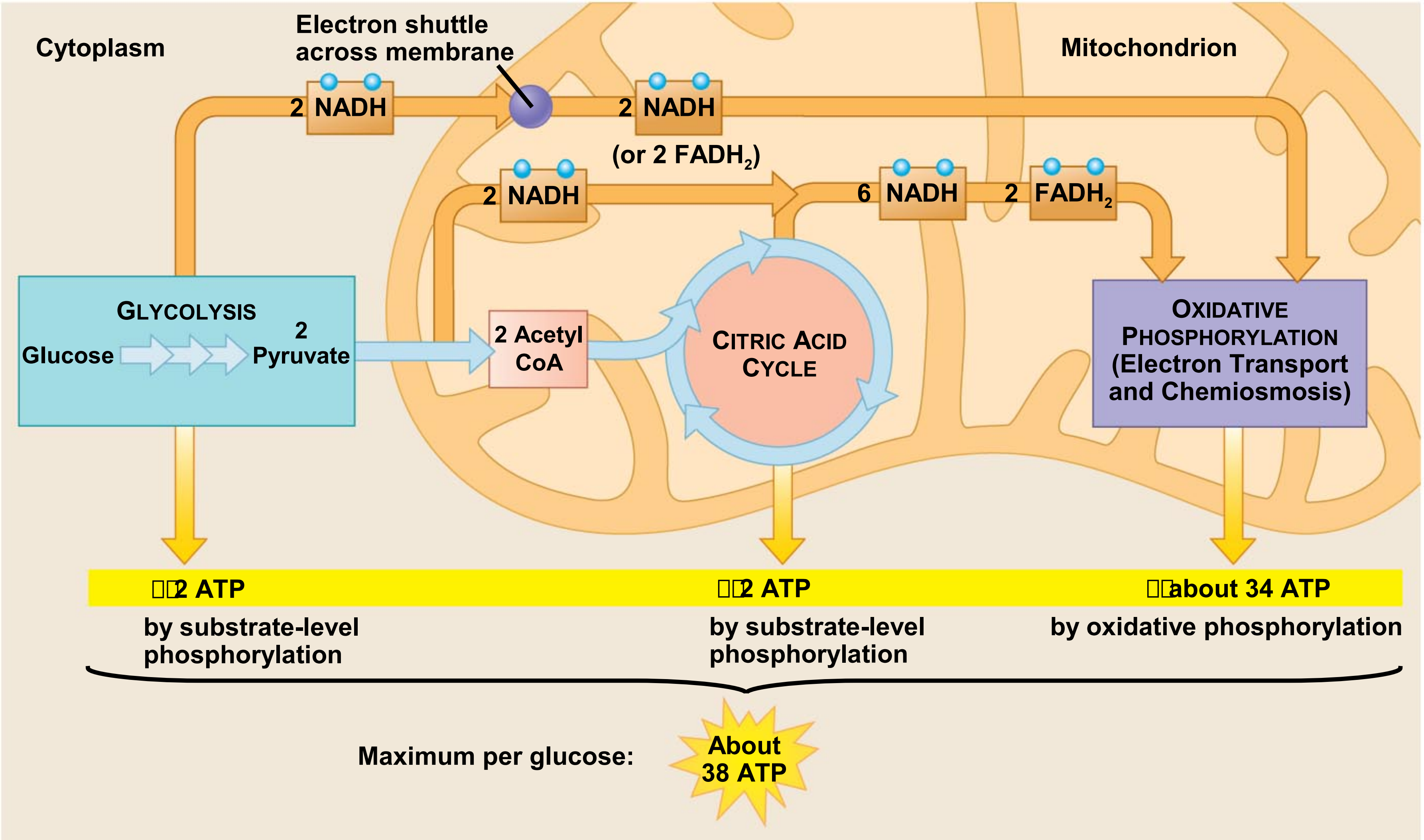
# 6.11 CONNECTION: Certain poisons interrupt critical events in cellular respiration

- There are three different categories of cellular poisons that affect cellular respiration
  - The first category blocks the electron transport chain (for example, rotenone, cyanide, and carbon monoxide)
  - The second inhibits ATP synthase (for example, oligomycin)
  - Finally, the third makes the membrane leaky to hydrogen ions (for example, dinitrophenol)


Rotenone
Cyanide, carbon monoxide
Oligomycin
H+
ATP synthase
DNP
NADH
NAD+
FADH2
FAD
1/2 O2 + 2 H+
H2O
ADP + P
ATP
Electron Transport Chain
Chemiosmosis

# 6.12 Review: Each molecule of glucose yields many molecules of ATP

- Recall that the energy payoff of cellular respiration involves (1) glycolysis, (2) alteration of pyruvate, (3) the citric acid cycle, and (4) oxidative phosphorylation
  - The total yield of ATP molecules per glucose molecule has a theoretical maximum of about 38
  - This is about 40% of a glucose molecule potential energy
  - Additionally, water and $CO_2$ are produced



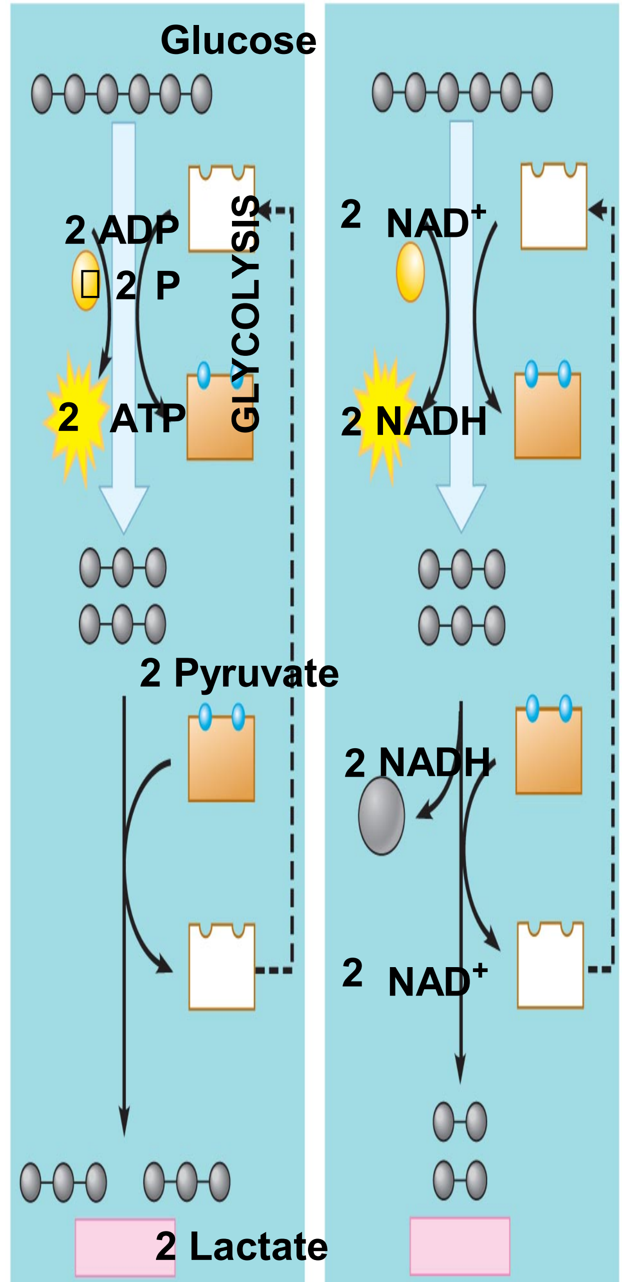
Cytoplasm
Electron shuttle across membrane
Mitochondrion
2 NADH
2 NADH
(or 2 $FADH_2$)
2 NADH
6 NADH
2 $FADH_2$
GLYCOLYSIS
Glucose
2 Pyruvate
2 Acetyl CoA
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION (Electron Transport and Chemiosmosis)
2 ATP
by substrate-level phosphorylation
2 ATP
by substrate-level phosphorylation
about 34 ATP
by oxidative phosphorylation
Maximum per glucose:
About 38 ATP

# 6.13 Fermentation enables cells to produce ATP without oxygen

- Fermentation is an anaerobic (without oxygen) energy-generating process
  - It takes advantage of glycolysis, producing two ATP molecules and reducing $NAD^+$ to NADH
  - The trick is to oxidize the NADH without passing its electrons through the electron transport chain to oxygen

# 6.13 Fermentation enables cells to produce ATP without oxygen

- Your muscle cells and certain bacteria can oxidize NADH through **lactic acid fermentation**
  - NADH is oxidized to $NAD^+$ when pyruvate is reduced to lactate
  - In a sense, pyruvate is serving as an "electron sink," a place to dispose of the electrons generated by oxidation reactions in glycolysis




**Lactic acid fermentation**