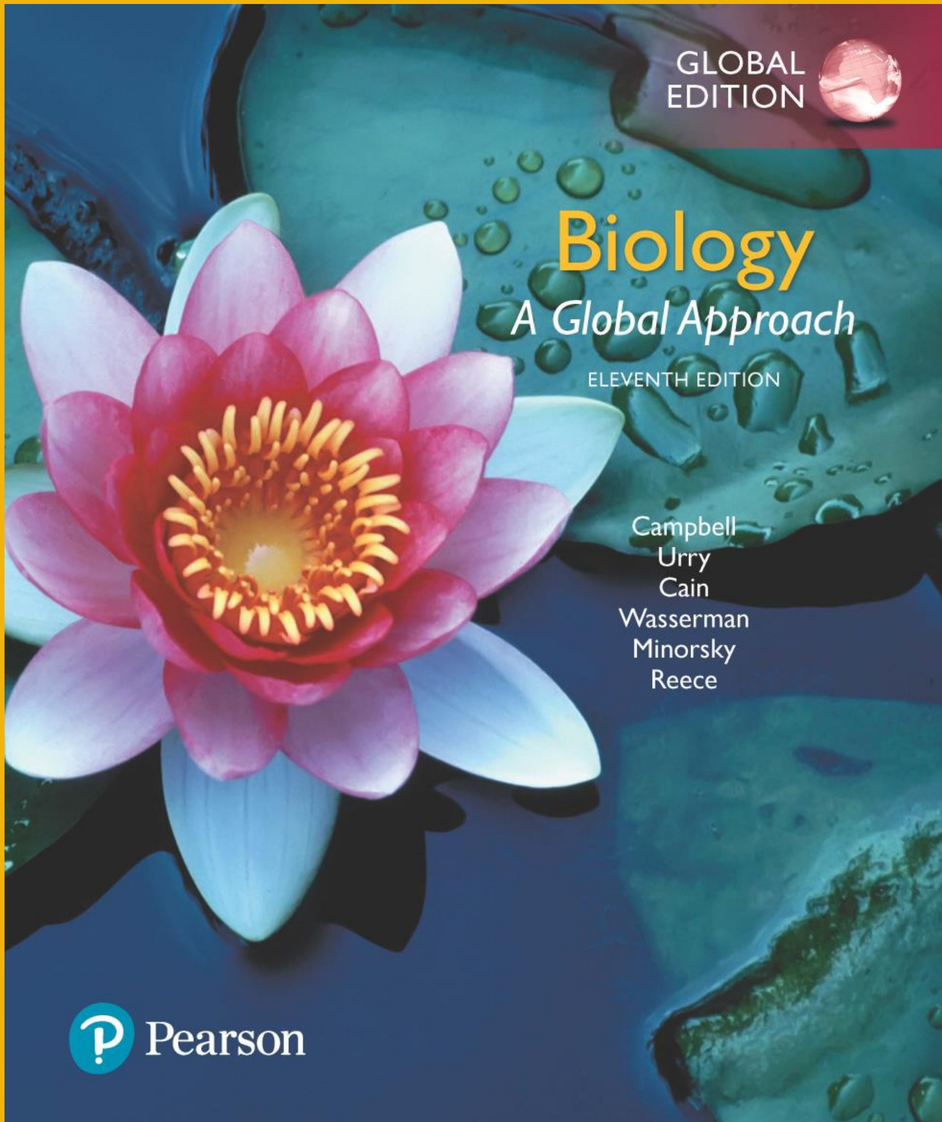


Chapter 10

Cell Respiration

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Life Is Work

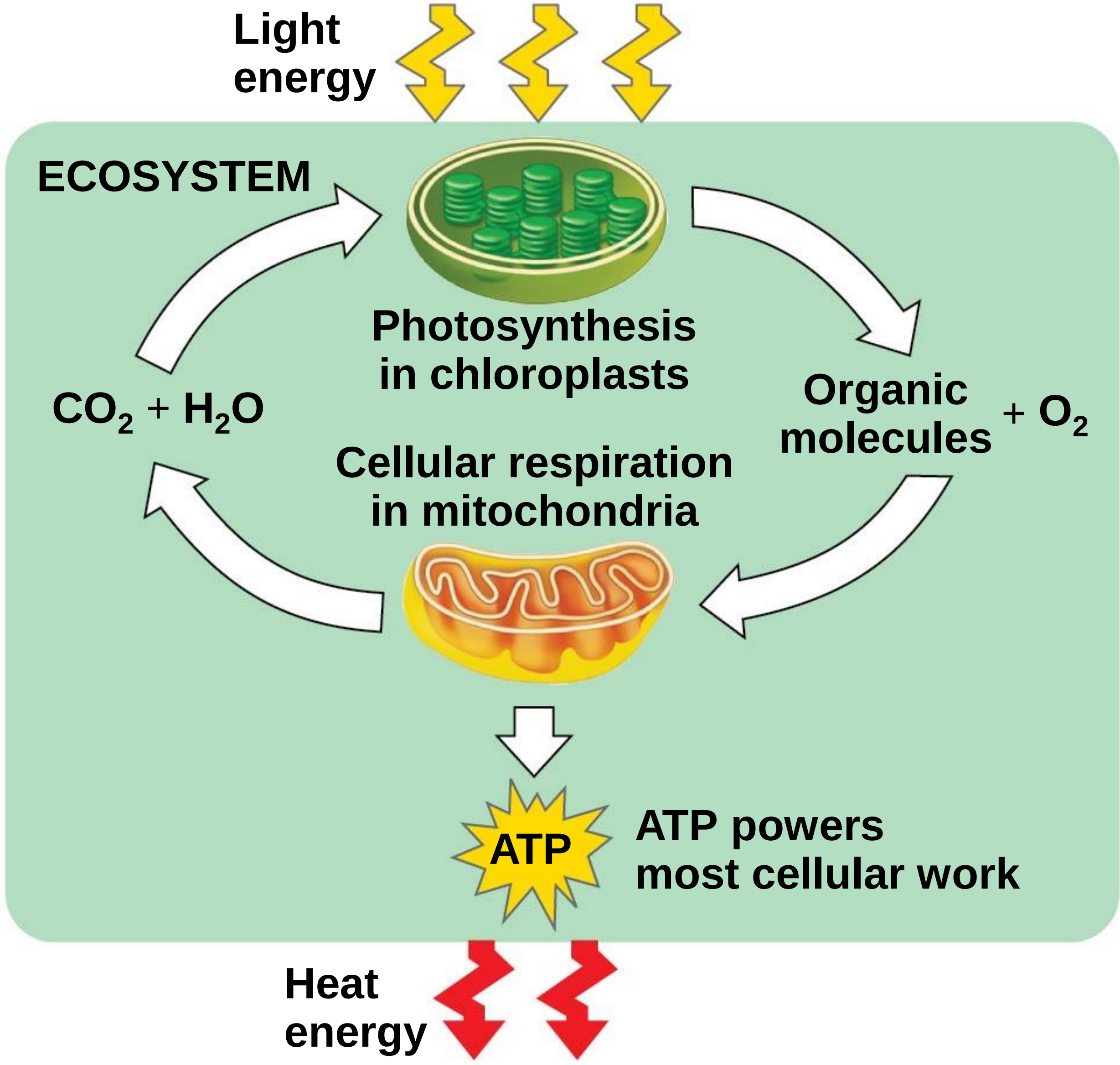
- Living cells require energy from outside sources to do work
- The work of the cell includes assembling polymers, membrane transport, moving, and reproducing
- Animals can obtain energy to do this work by feeding on other animals or photosynthetic organisms

Figure 10.1

Figure 10.1a

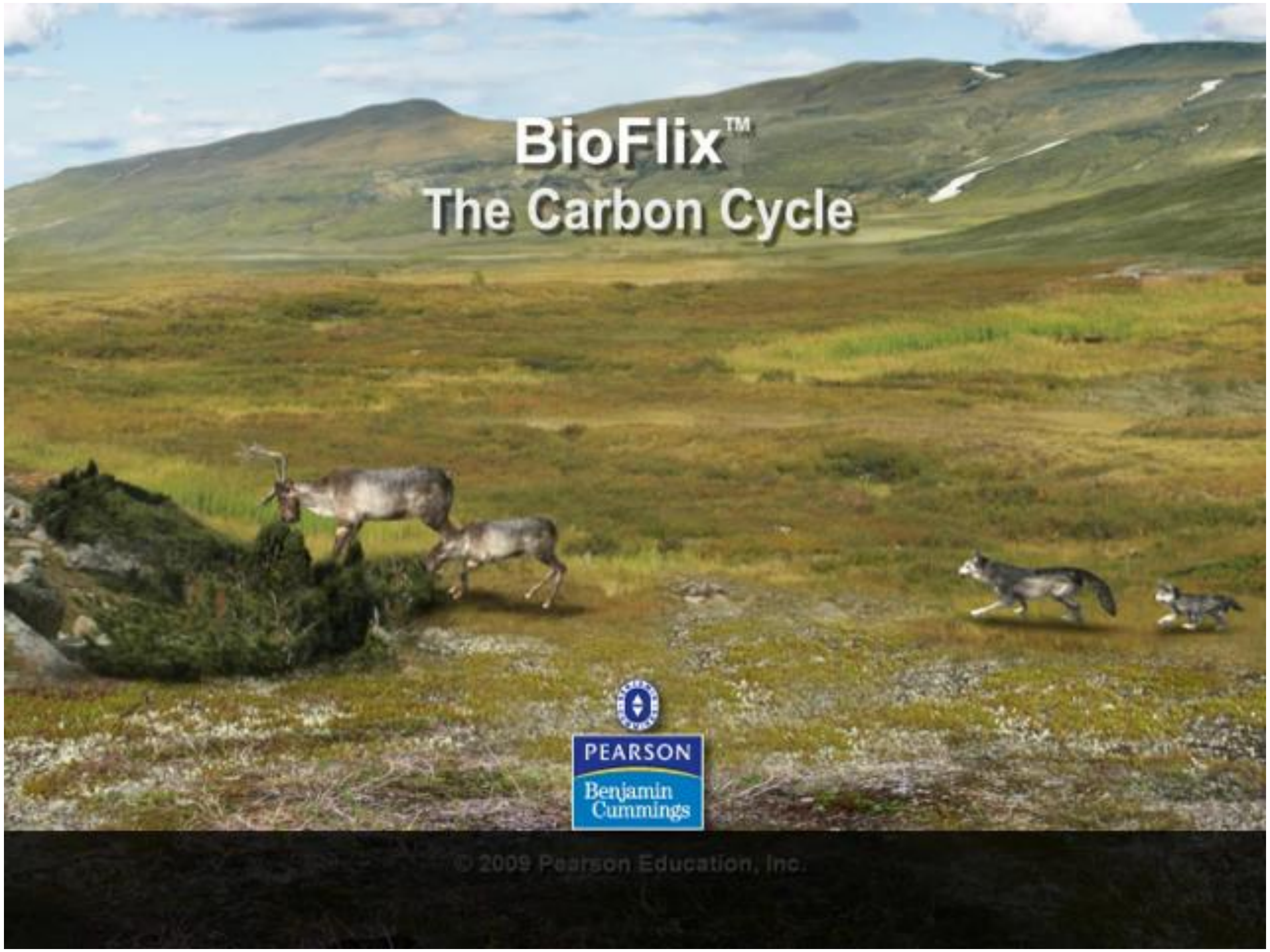
- Energy flows into an ecosystem as sunlight and leaves as heat
- The chemical elements essential to life are recycled
- Photosynthesis generates O_2 and organic molecules, which are used in cellular respiration
- Cells use chemical energy stored in organic molecules to generate ATP, which powers work

Figure 10.2



Light
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

BioFlix: The Carbon Cycle



Concept 10.1: Catabolic pathways yield energy by oxidizing organic fuels

- Catabolic pathways release stored energy by breaking down complex molecules
- Electron transfer plays a major role in these pathways
- These processes are central to cellular respiration

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 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)

Figure 10.UN01

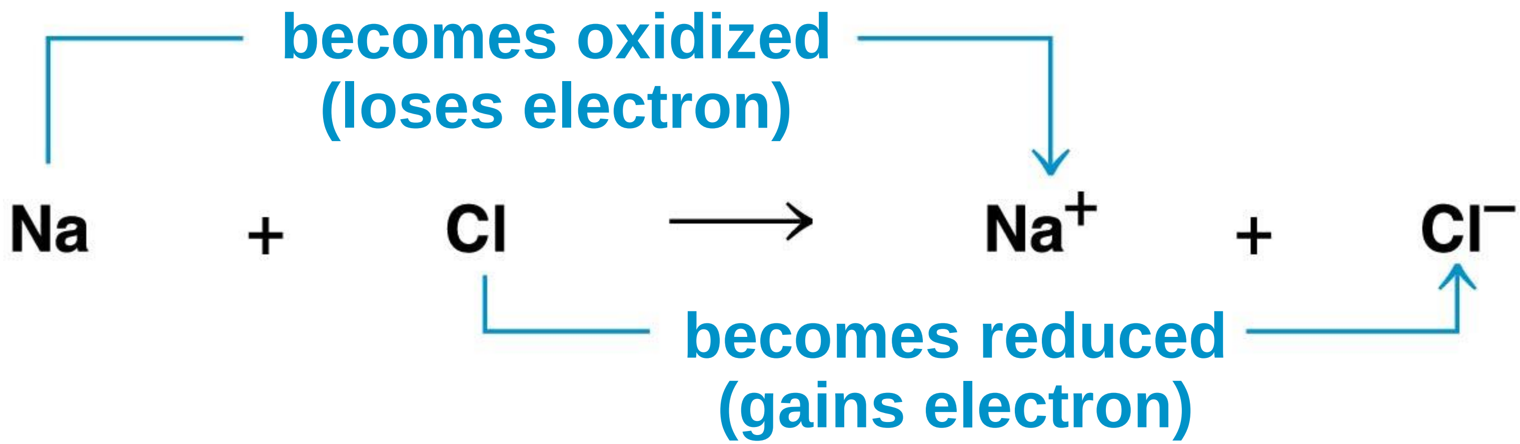
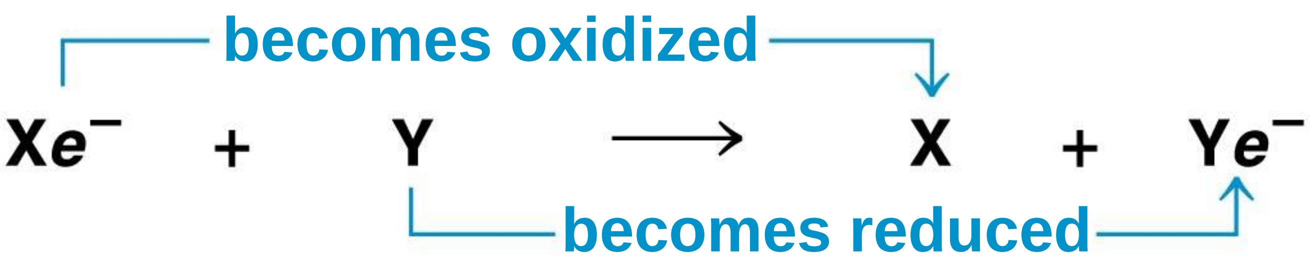
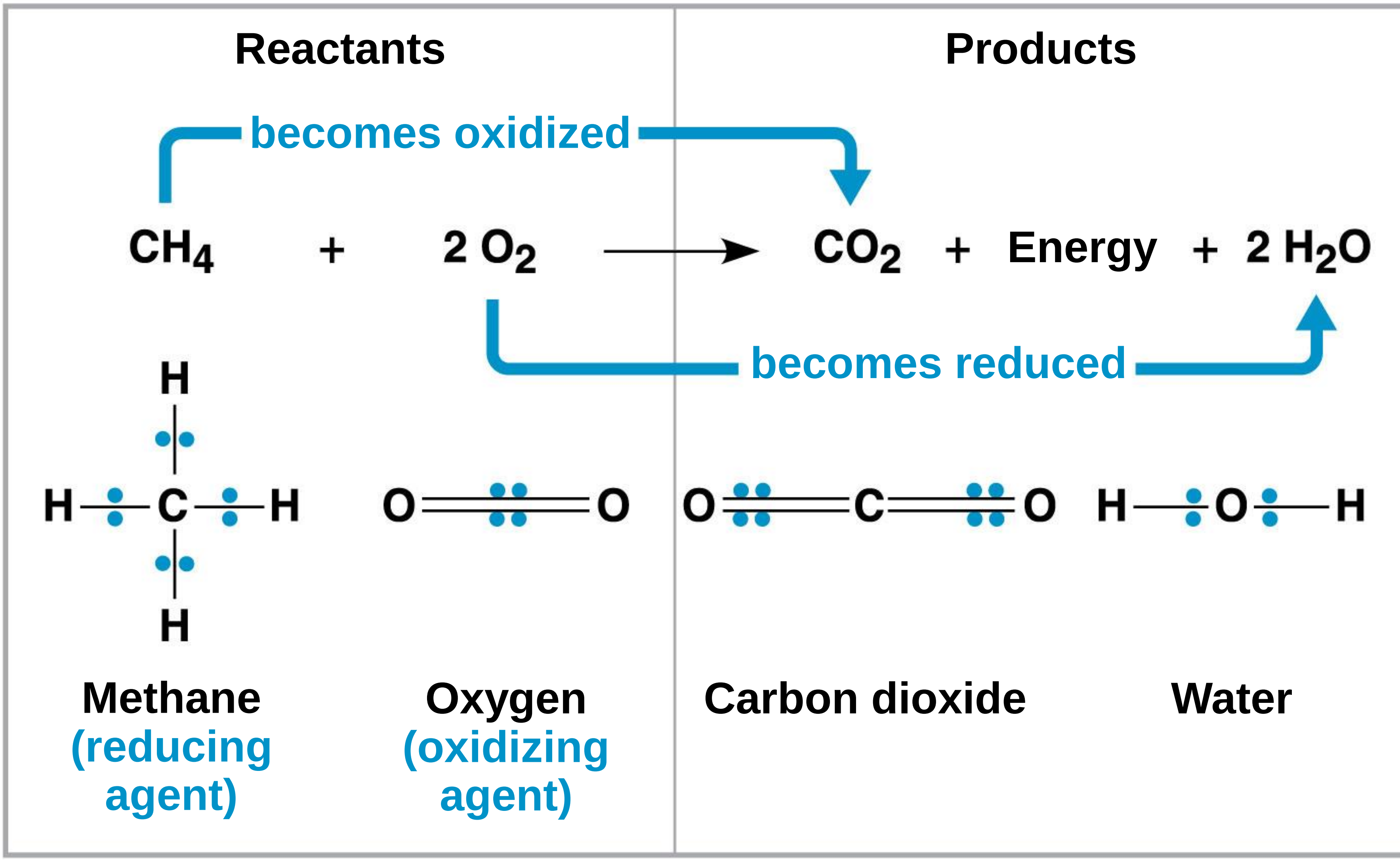


Figure 10.UN02



- 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 10.3



Reactants
Products
becomes oxidized
CH4 + 2 O2 → CO2 + Energy + 2 H2O
becomes reduced
H
H C H
H
O O
O C O
H O H
Methane
(reducing agent)
Oxygen
(oxidizing agent)
Carbon dioxide
Water

Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, the fuel (such as glucose) is oxidized, and O_2 is reduced
- Organic molecules with an abundance of hydrogen are excellent sources of high-energy electrons
- Energy is released as the electrons associated with hydrogen ions are transferred to oxygen, a lower energy state

Figure 10.UN03

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
- 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 10.4

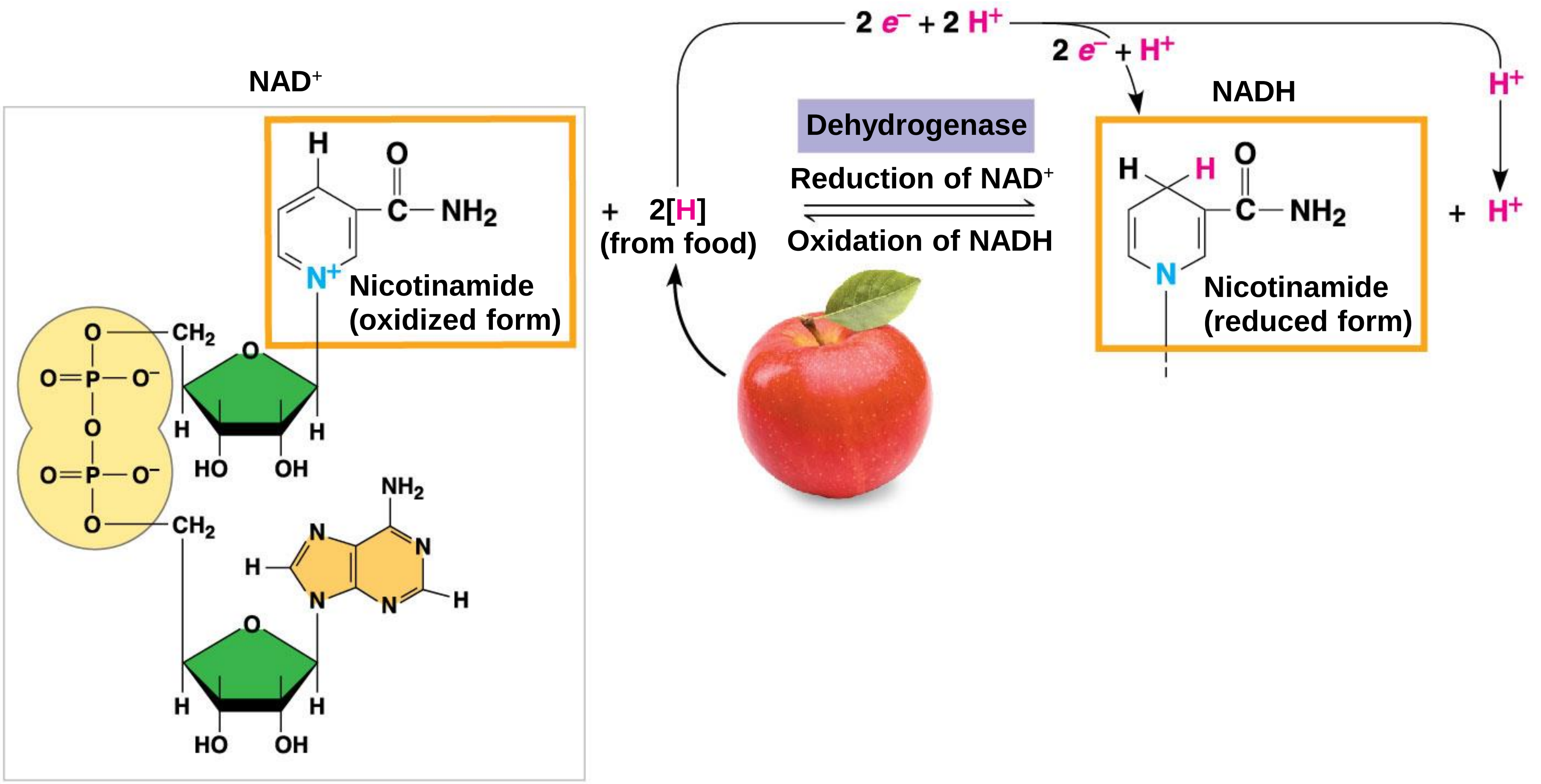
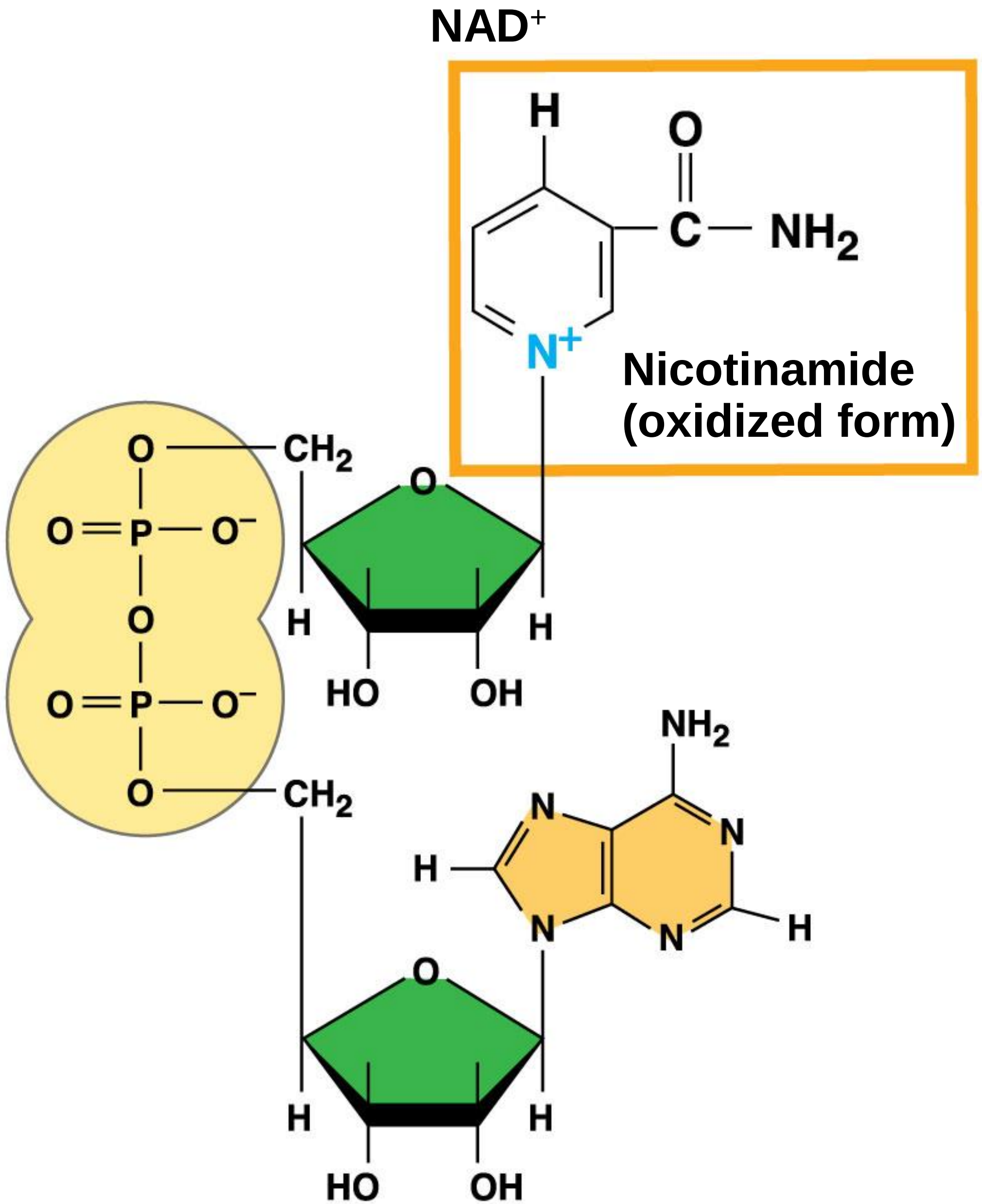
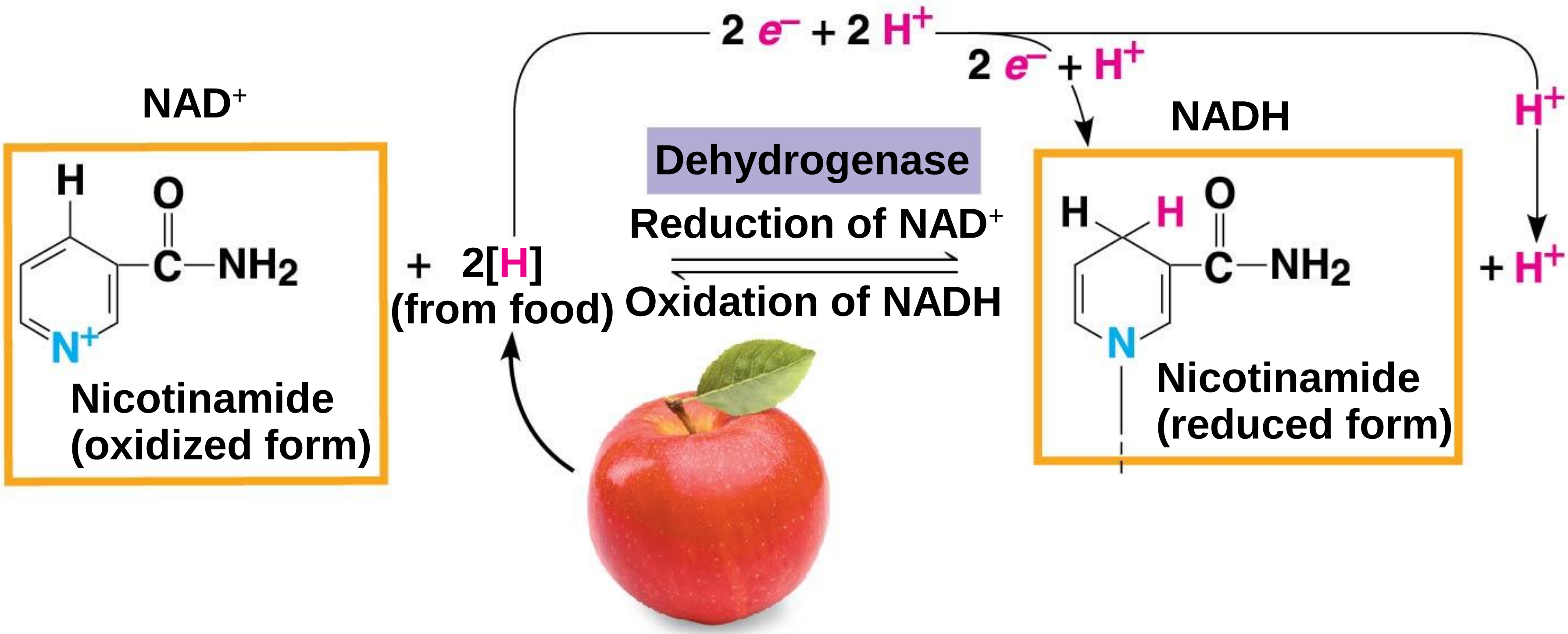

2 e^- + 2 H^+
2 e^- + H^+
H^+
NAD+
NADH
Dehydrogenase
Reduction of NAD+
Oxidation of NADH
+ 2[H]
(from food)
+ H^+
Nicotinamide
(oxidized form)
Nicotinamide
(reduced form)
N^+
NH_2
CH_2
HO
OH

Figure 10.4a



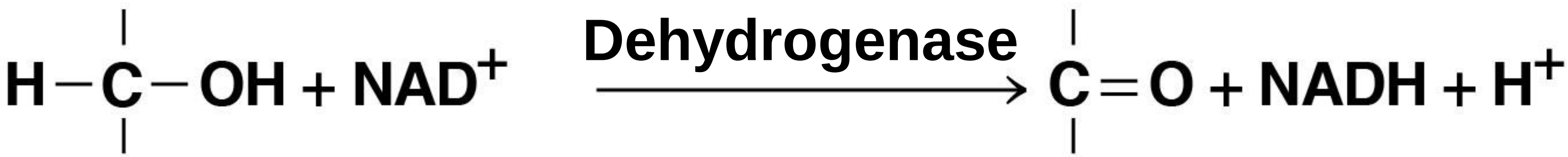
NAD+
H
O
C
NH2
N+
Nicotinamide
(oxidized form)
O
CH2
O=P—O−
O
O=P—O−
O
CH2
O
H
H
HO
OH
NH2
N
N
H
N
N
H
O
H
H
HO
OH

Figure 10.4b



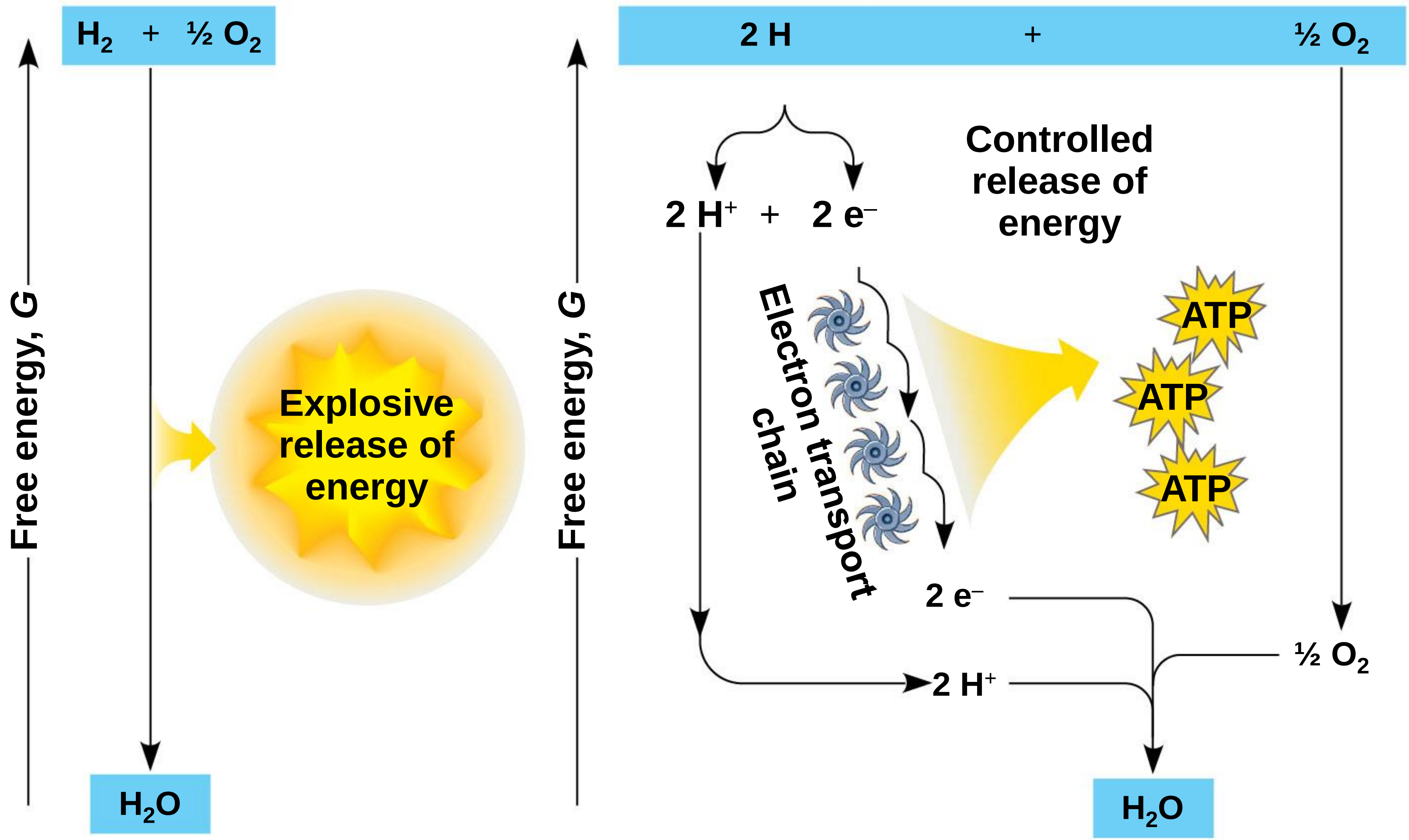
NAD+
H
O
C
NH2
N+
Nicotinamide
(oxidized form)
+ 2[H]
(from food)
2 e− + 2 H+
2 e− + H+
Dehydrogenase
Reduction of NAD+
Oxidation of NADH
NADH
H
H
O
C
NH2
N
Nicotinamide
(reduced form)
H+
+ H+

Figure 10.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 10.5



(a) Uncontrolled reaction (b) Cellular respiration

The Stages of Cellular Respiration: *A Preview*

- Harvesting of energy from glucose has three stages
  1. **Glycolysis** (breaks down glucose into two molecules of pyruvate)
  2. The **citric acid cycle** (completes the breakdown of glucose)
  3. **Oxidative phosphorylation** (accounts for most of the ATP synthesis)

Figure 10.UN05

1. GLYCOLYSIS (color-coded blue throughout the chapter)
2. PYRUVATE OXIDATION and the CITRIC ACID CYCLE (color-coded light orange and dark orange)
3. OXIDATIVE PHOSPHORYLATION: Electron transport and chemiosmosis (color-coded purple)

Figure 10.6_1

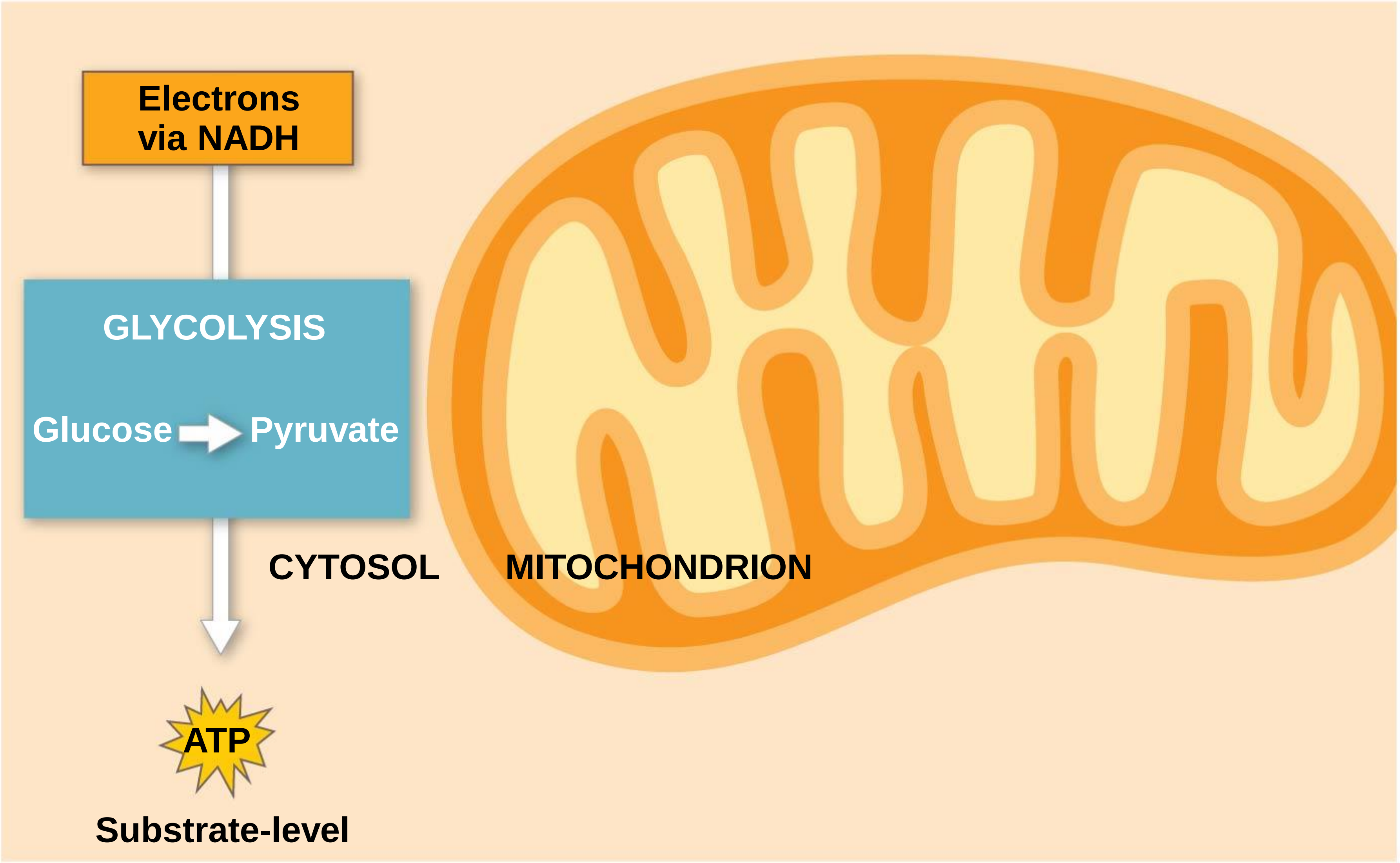
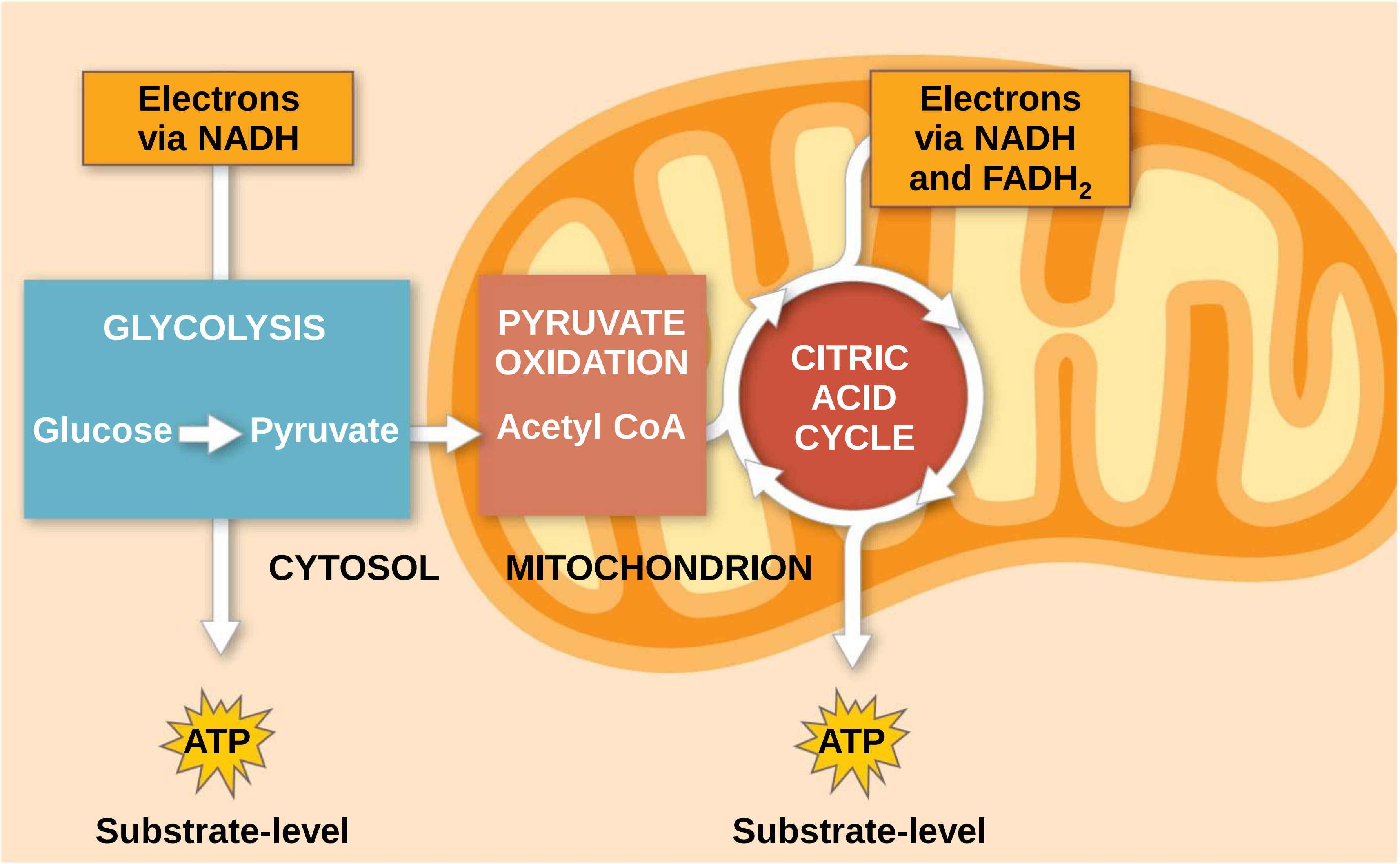
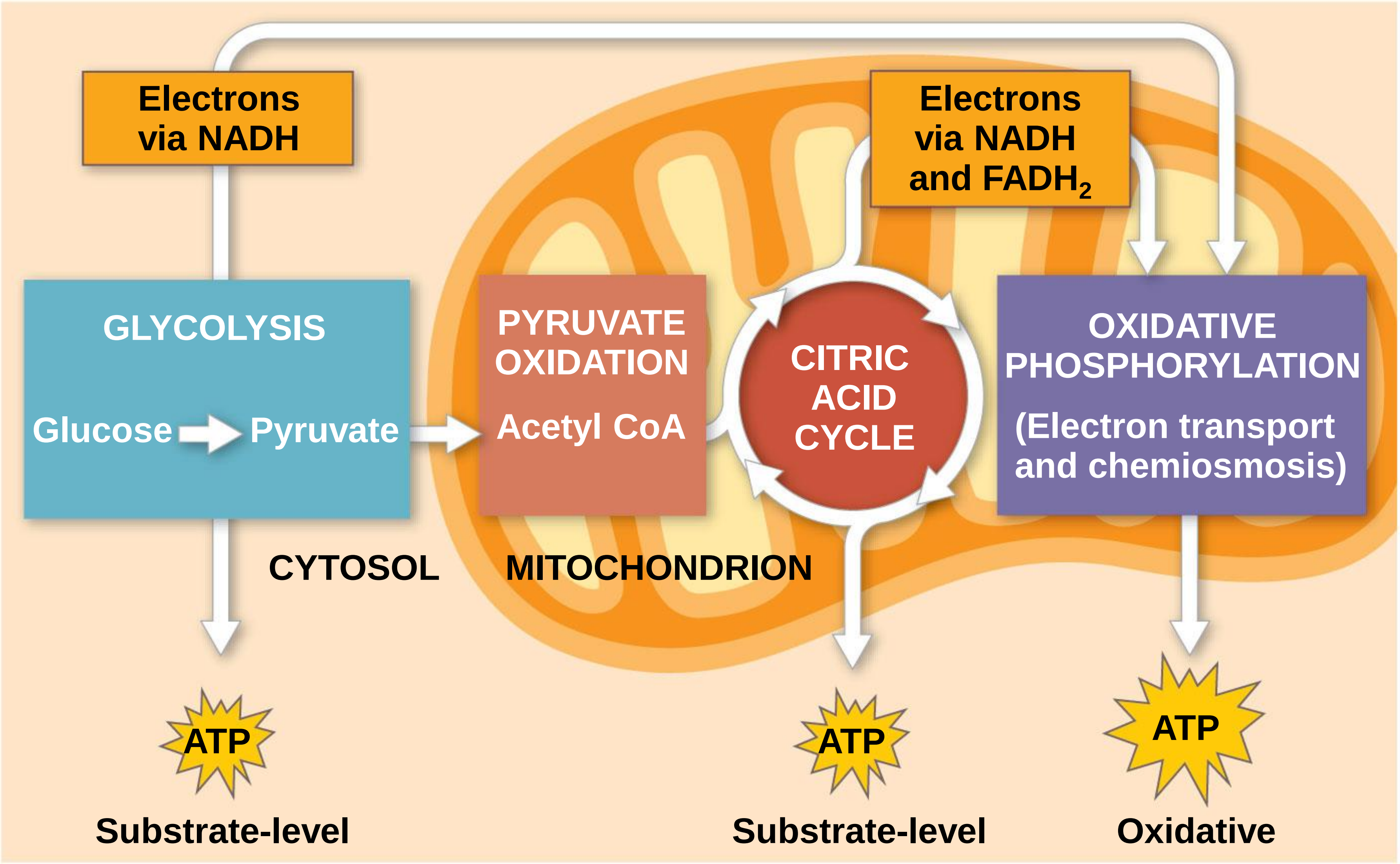

Electrons via NADH
GLYCOLYSIS
Glucose
Pyruvate
CYTOSOL
MITOCHONDRION
ATP
Substrate-level

Figure 10.6_2



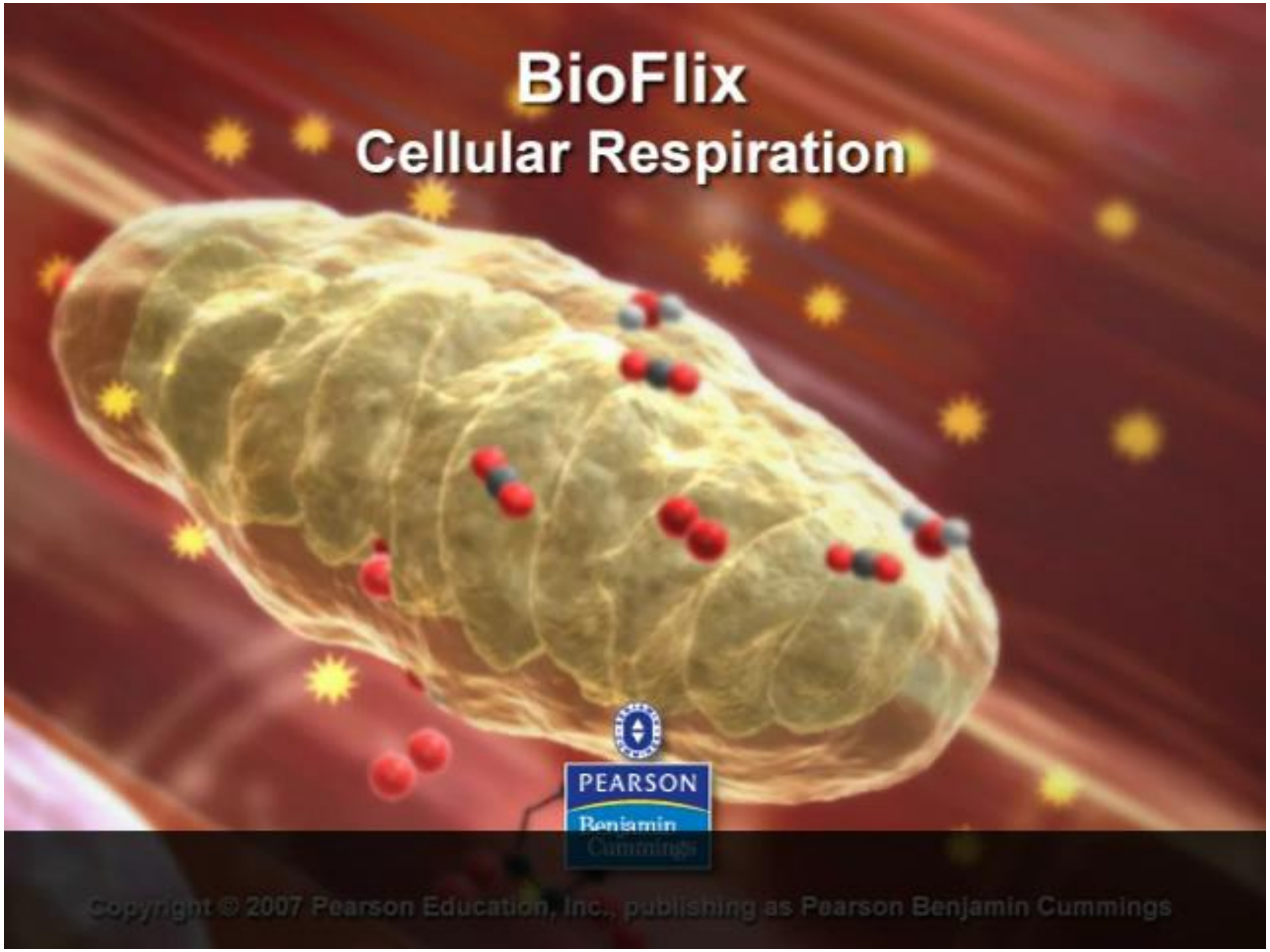
Electrons via NADH
Electrons via NADH and $FADH_2$
GLYCOLYSIS
Glucose
Pyruvate
PYRUVATE OXIDATION
Acetyl CoA
CITRIC ACID CYCLE
CYTOSOL
MITOCHONDRION
ATP
Substrate-level
ATP
Substrate-level

Figure 10.6_3



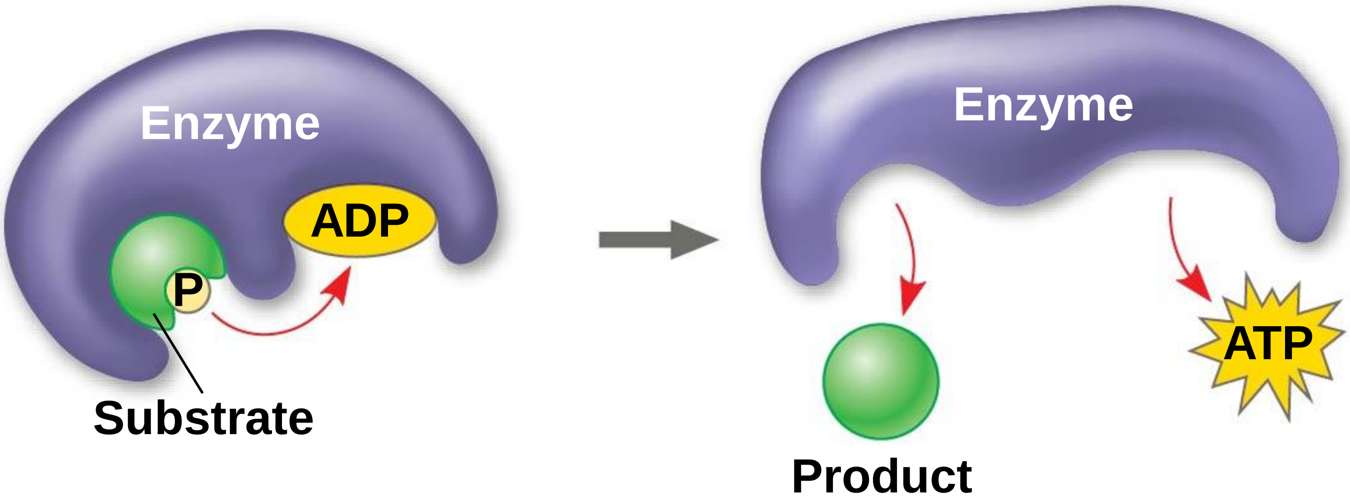
Electrons via NADH
Electrons via NADH and FADH$_2$
GLYCOLYSIS
Glucose
Pyruvate
PYRUVATE OXIDATION
Acetyl CoA
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION
(Electron transport and chemiosmosis)
CYTOSOL
MITOCHONDRION
ATP
ATP
ATP
Substrate-level
Substrate-level
Oxidative

BioFlix: Cellular Respiration



- The process that generates almost 90% of the ATP is called **oxidative phosphorylation** because it is powered by redox reactions
- A smaller amount of ATP is formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation**

Figure 10.7



- For each molecule of glucose degraded to CO_2 and water by respiration, the cell makes up to 32 molecules of ATP

- We can use money as an analogy for cellular respiration:
  - Glucose is like a larger-denomination bill—it is worth a lot, but it is hard to spend
  - ATP is like a number of smaller-denomination bills of equivalent value—they can be spent more easily
  - Cellular respiration cashes in a large denomination of energy (glucose) for the small change of many molecules of ATP

Concept 10.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- Glycolysis ("sugar splitting") 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 10.UN06

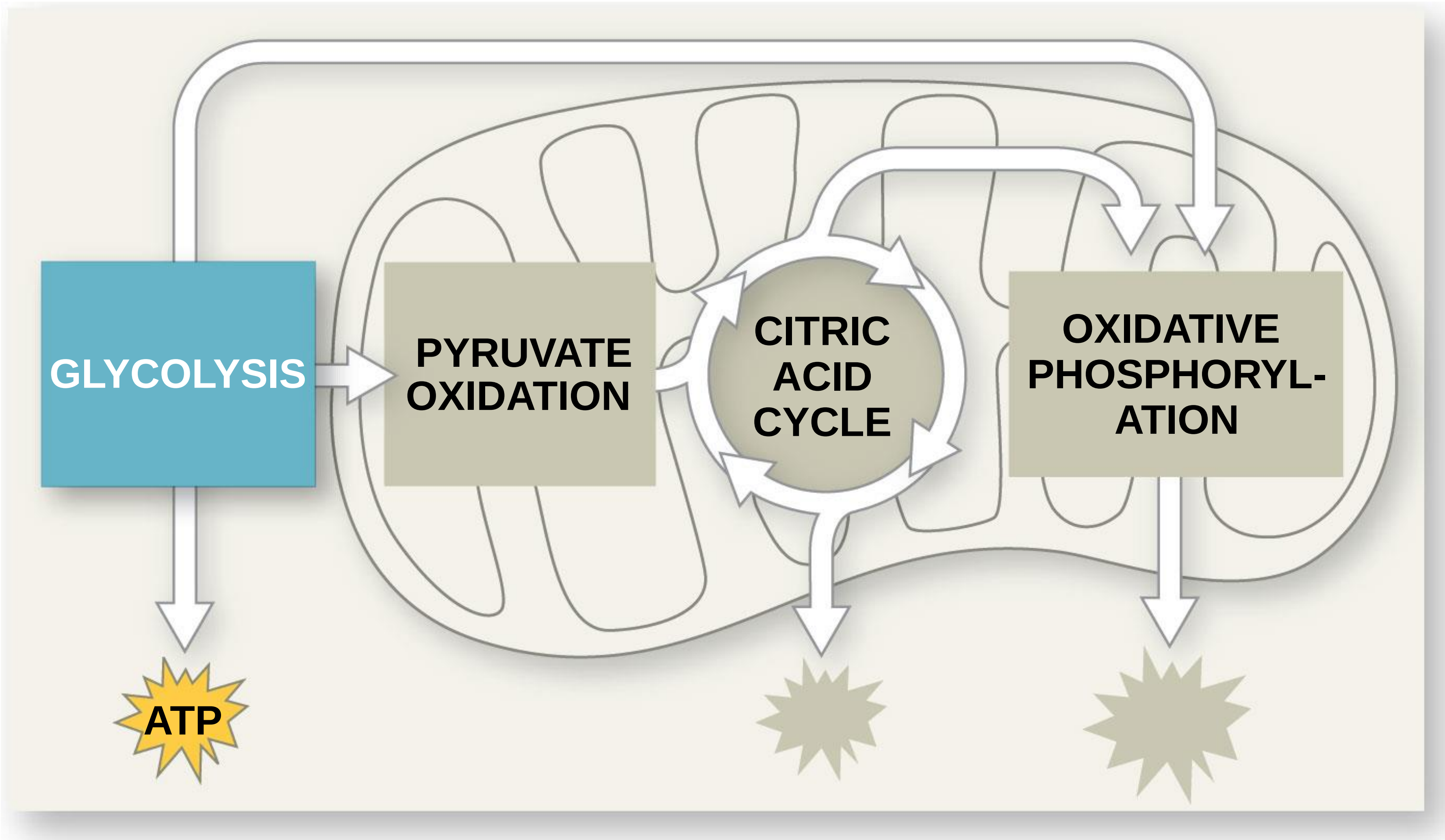


Figure 10.8

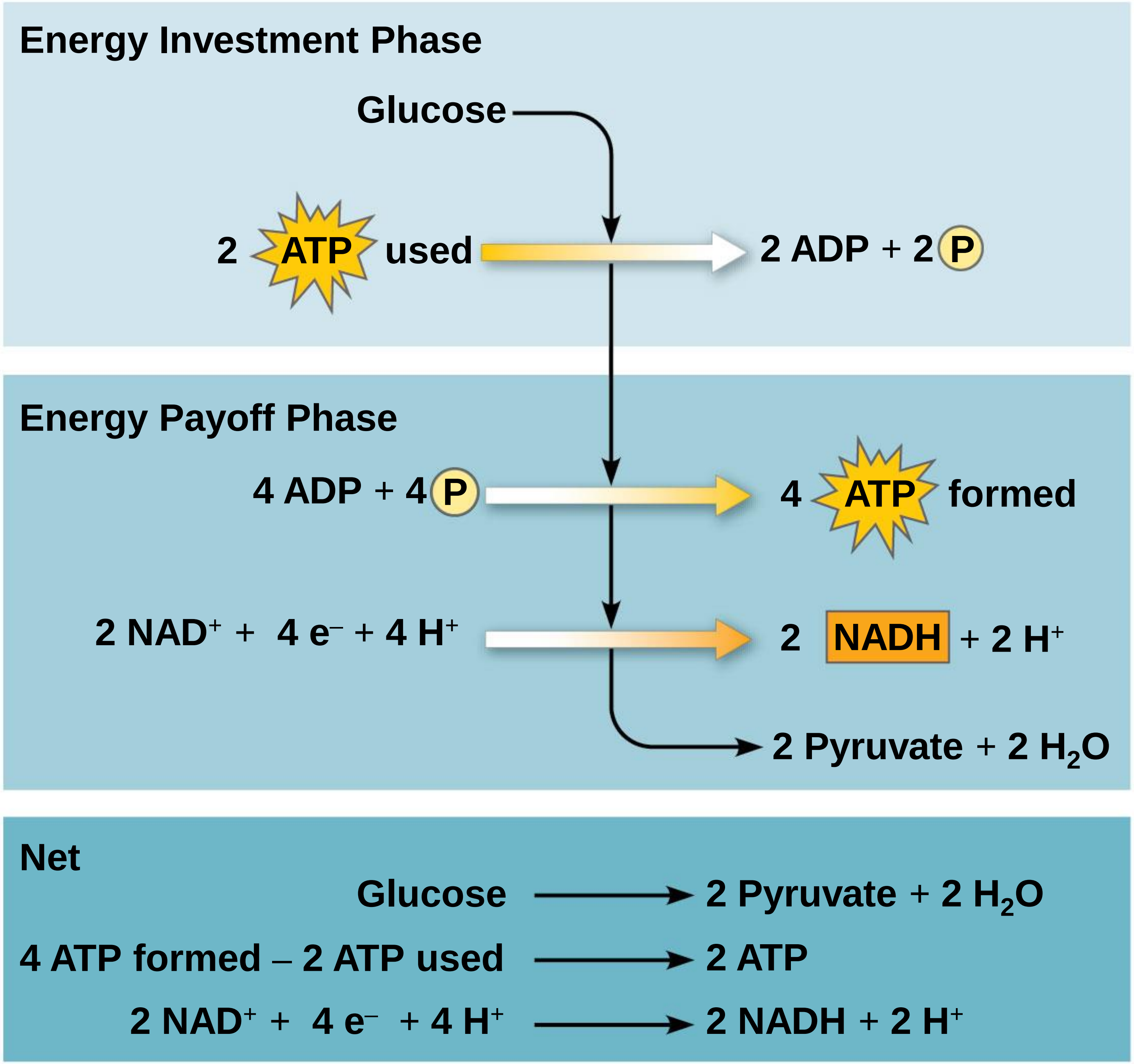
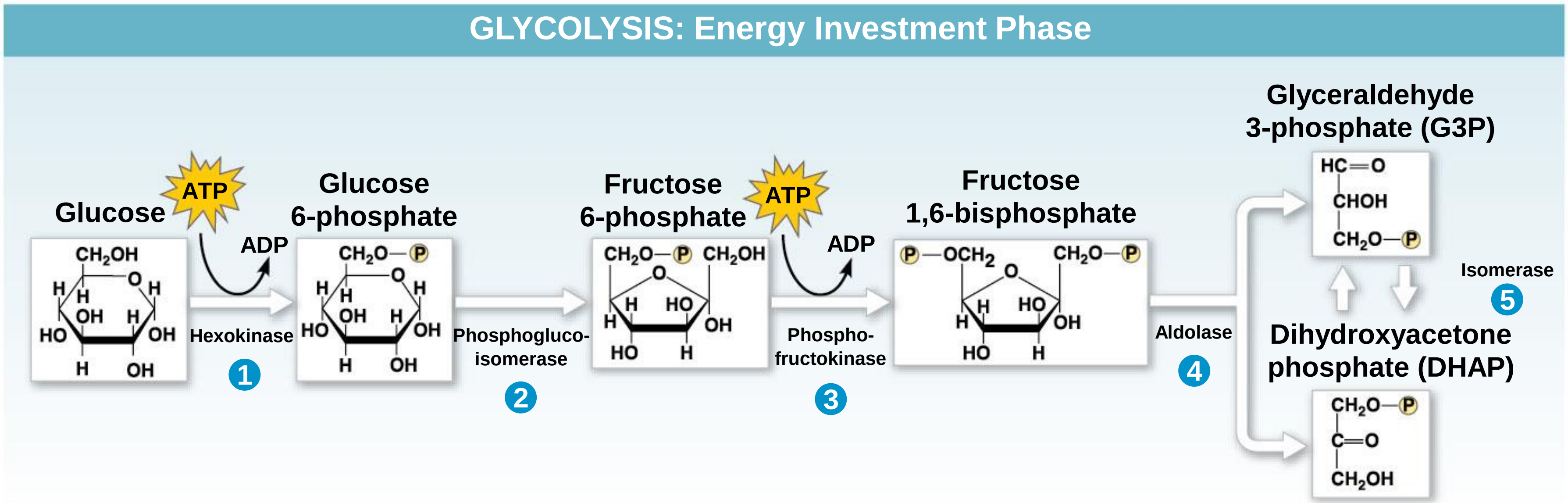

Energy Investment Phase
Glucose
2 ATP used
2 ADP + 2 P
Energy Payoff Phase
4 ADP + 4 P
4 ATP formed
2 NAD$^+$ + 4 e$^-$ + 4 H$^+$
2 NADH + 2 H$^+$
2 Pyruvate + 2 H_2O
Net
Glucose → 2 Pyruvate + 2 H_2O
4 ATP formed – 2 ATP used → 2 ATP
2 NAD$^+$ + 4 e$^-$ + 4 H$^+$ → 2 NADH + 2 H$^+$

Figure 10.9a



GLYCOLYSIS: Energy Investment Phase
Glucose
ATP
ADP
Hexokinase
1
Glucose 6-phosphate
Phosphogluco-isomerase
2
Fructose 6-phosphate
ATP
ADP
Phospho-fructokinase
3
Fructose 1,6-bisphosphate
Aldolase
4
Glyceraldehyde 3-phosphate (G3P)
Isomerase
5
Dihydroxyacetone phosphate (DHAP)

Figure 10.9aa_1

GLYCOLYSIS: Energy Investment Phase

Glucose

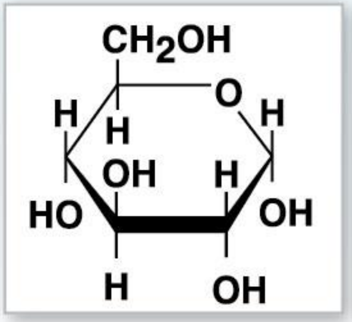


Figure 10.9aa_2

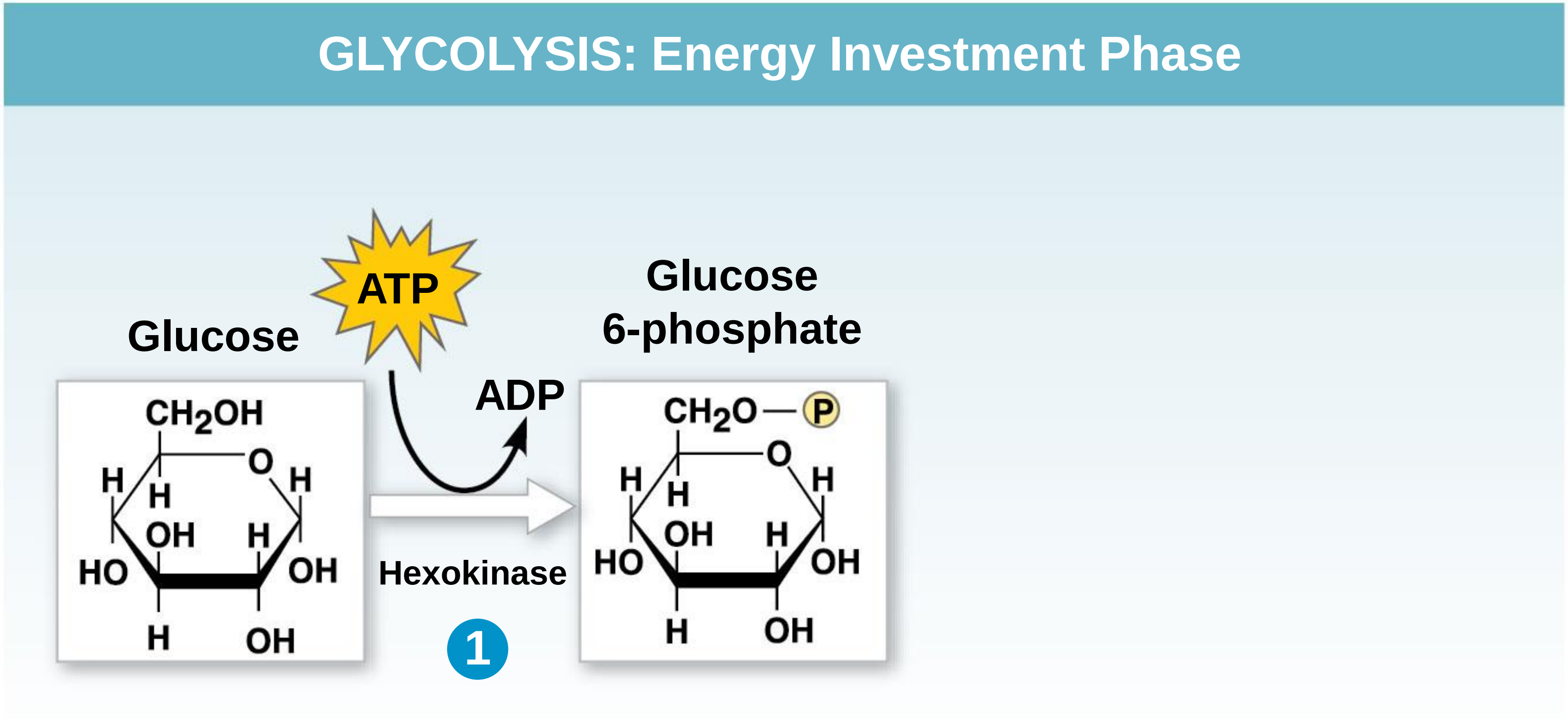


Figure 10.9aa_3

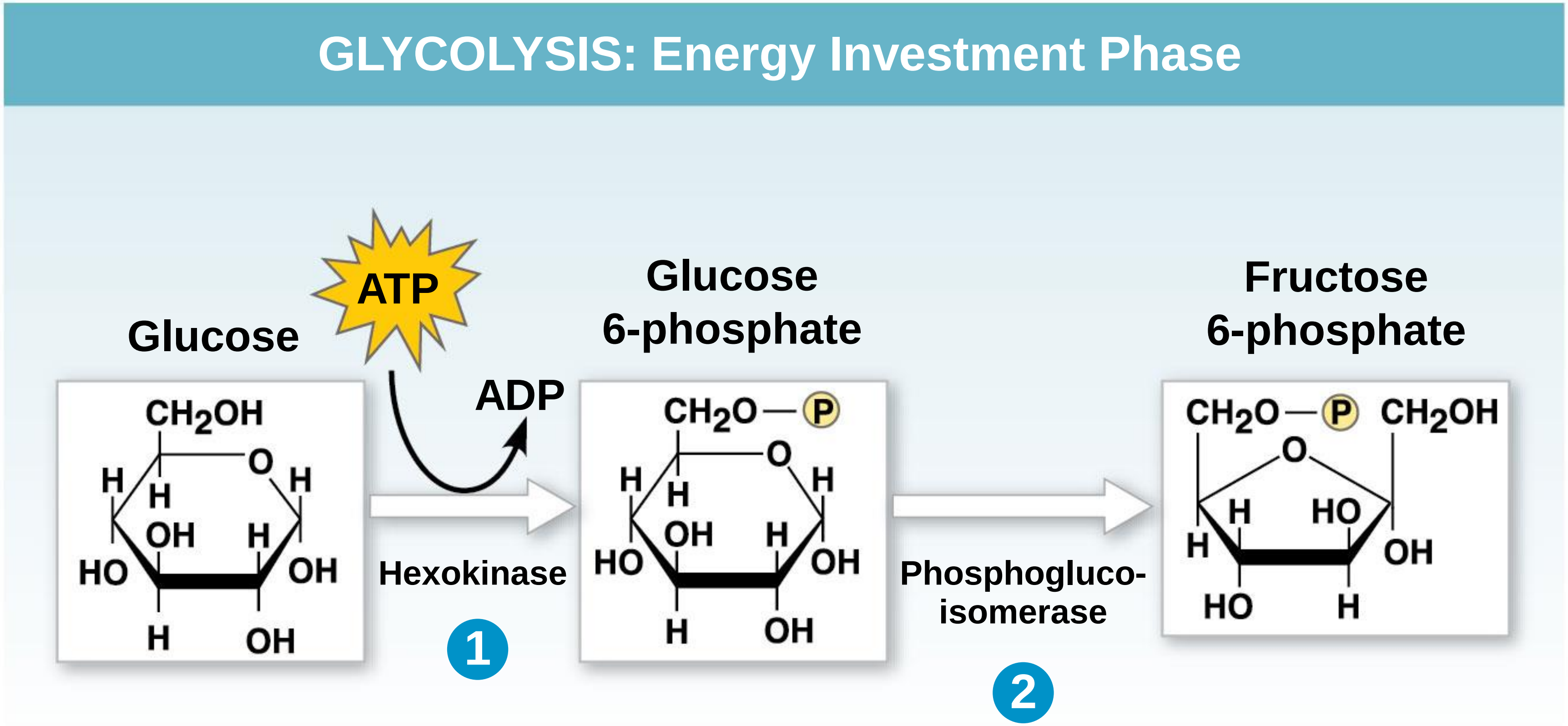


Figure 10.9ab_1

GLYCOLYSIS: Energy Investment Phase

Fructose 6-phosphate

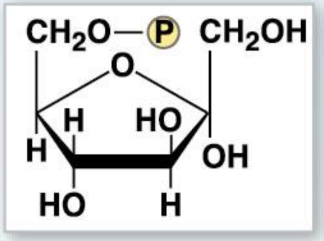


Figure 10.9ab_2

GLYCOLYSIS: Energy Investment Phase

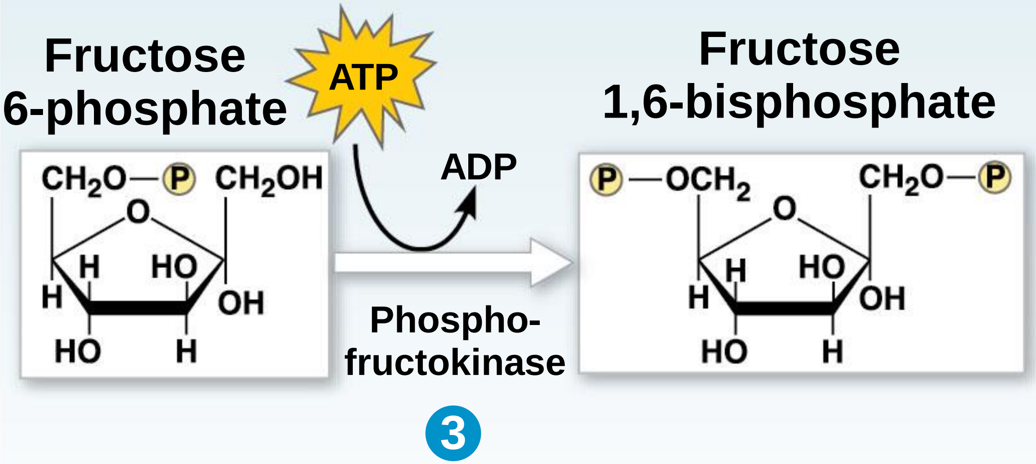


Figure 10.9ab_3

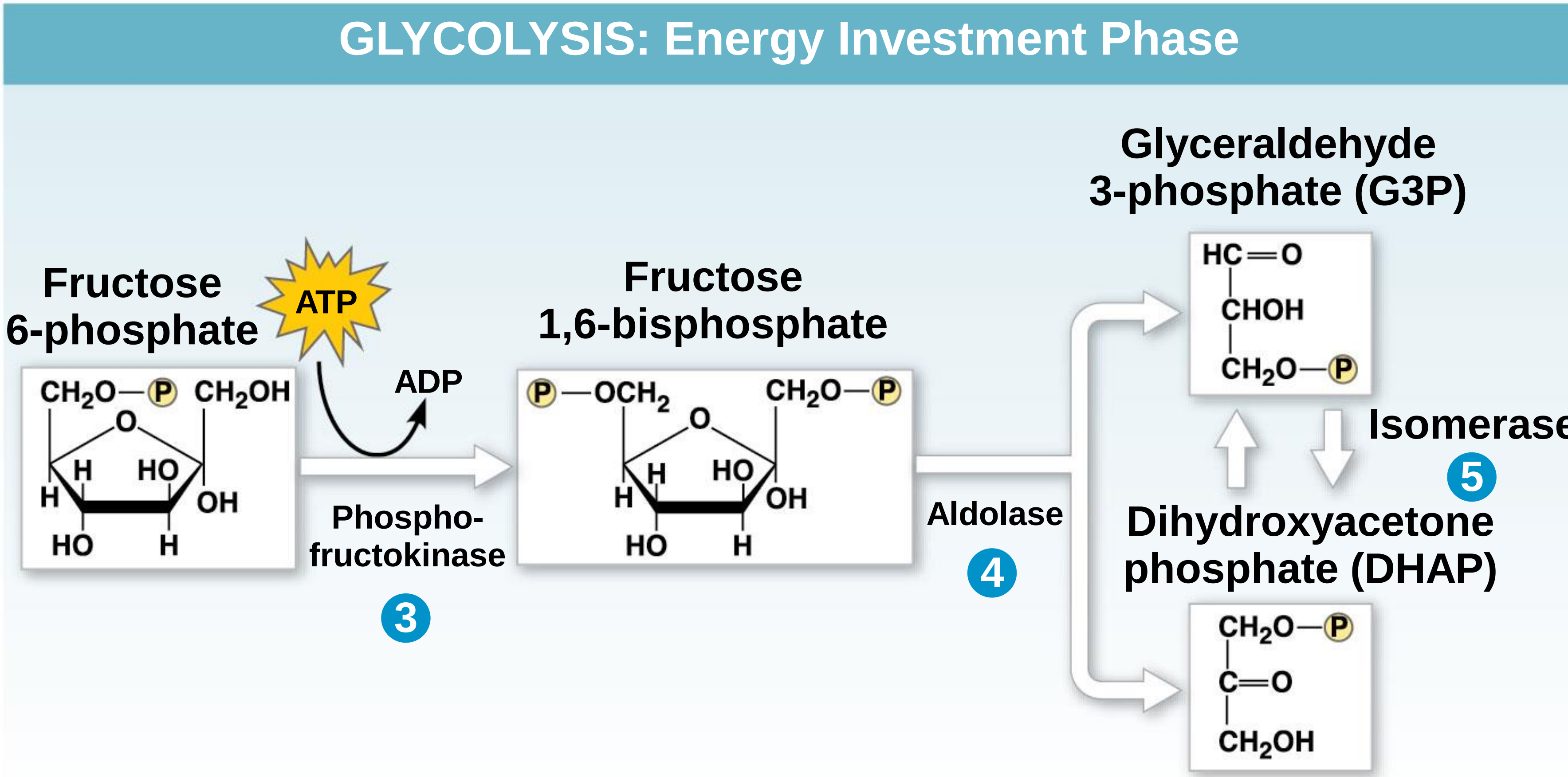
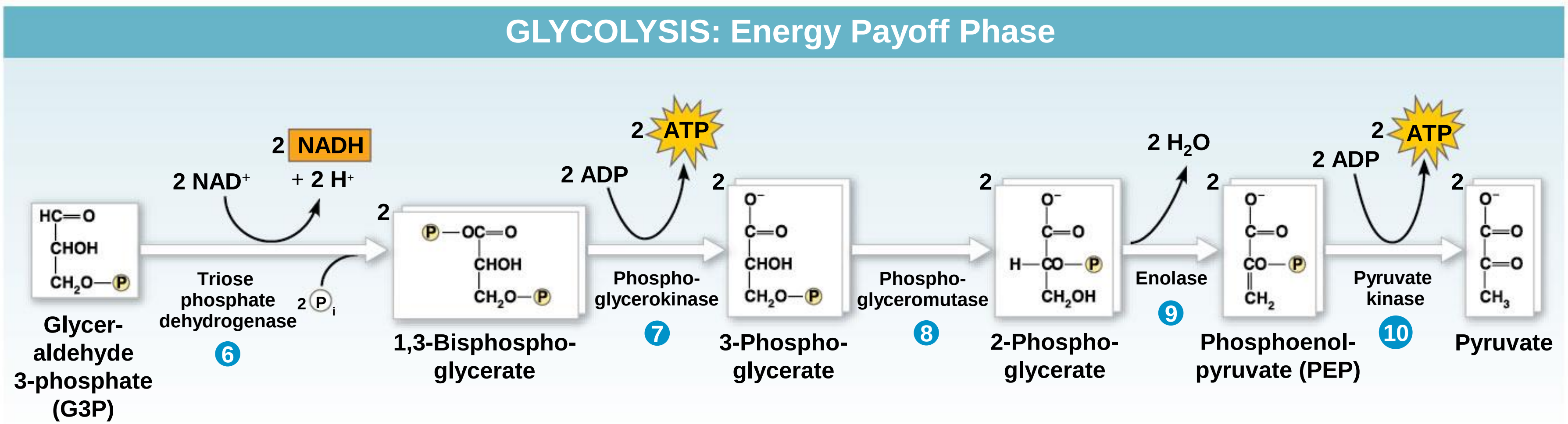


Figure 10.9b



GLYCOLYSIS: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
2 ATP
2 ADP
2 ATP
2 ADP
2 H2O
2
2
2
2
2
2 Pi
Triose phosphate dehydrogenase
6
Phospho-glycerokinase
7
Phospho-glyceromutase
8
Enolase
9
Pyruvate kinase
10
Glycer-aldehyde 3-phosphate (G3P)
1,3-Bisphospho-glycerate
3-Phospho-glycerate
2-Phospho-glycerate
Phosphoenol-pyruvate (PEP)
Pyruvate

Figure 10.9ba_1

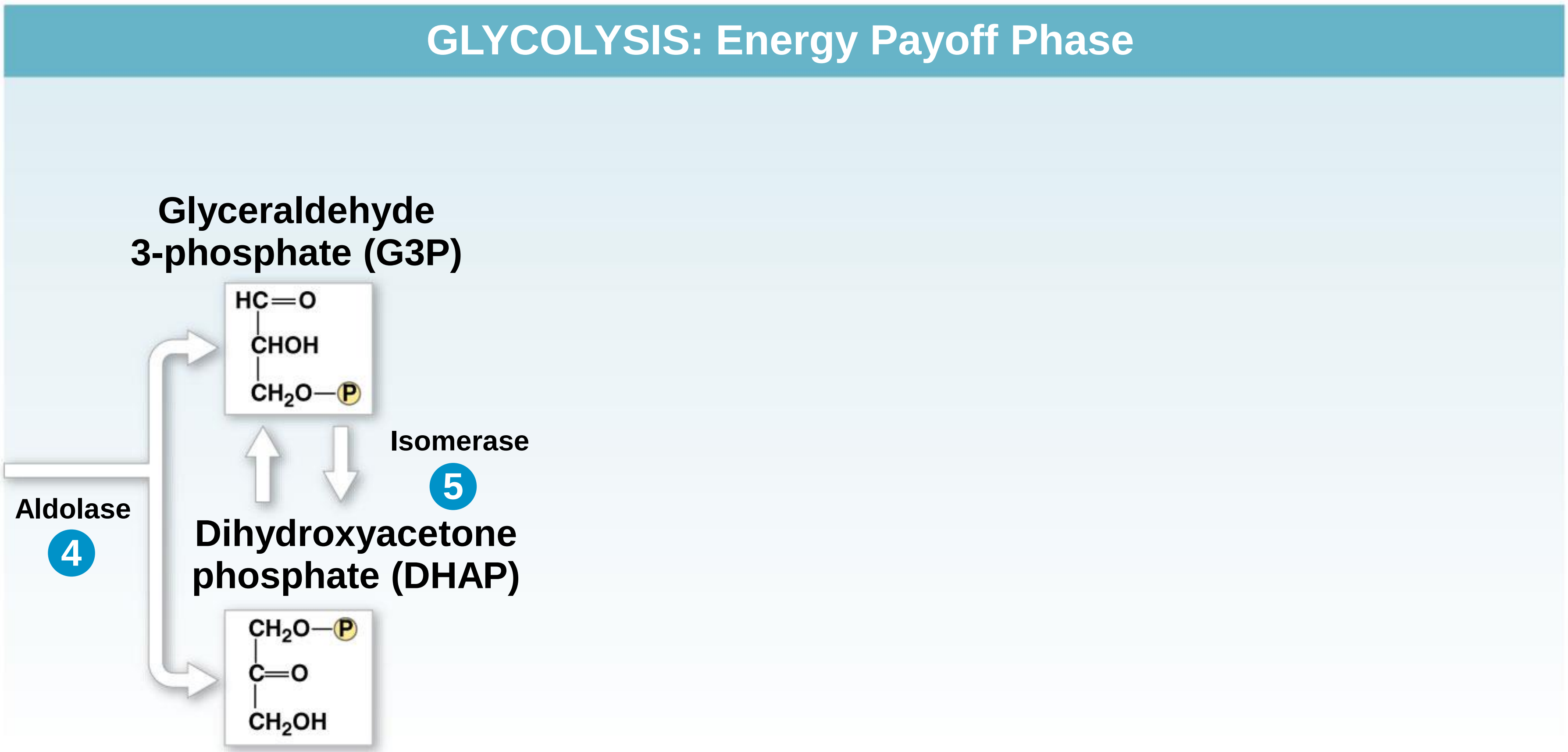


Figure 10.9ba_2

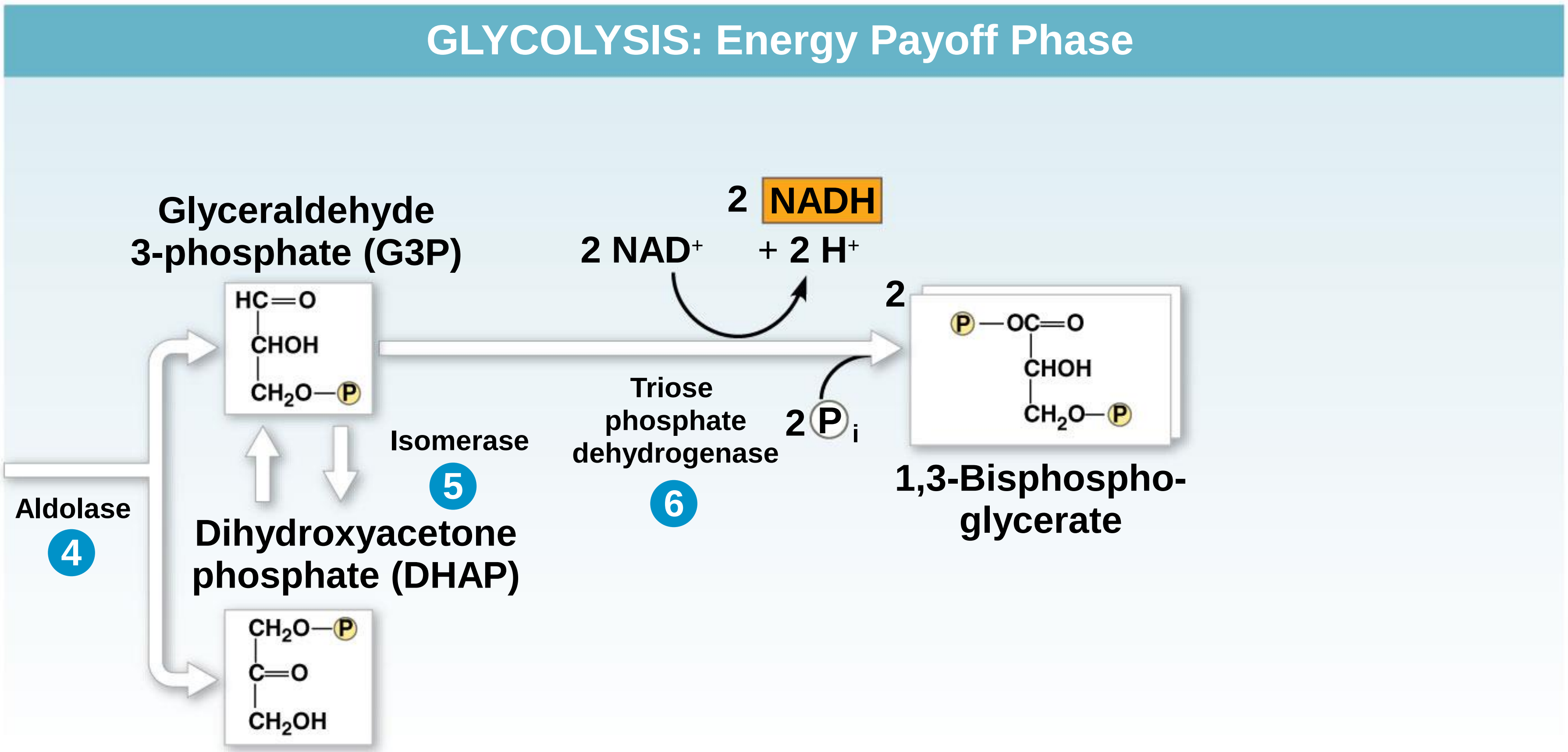


Figure 10.9ba_3

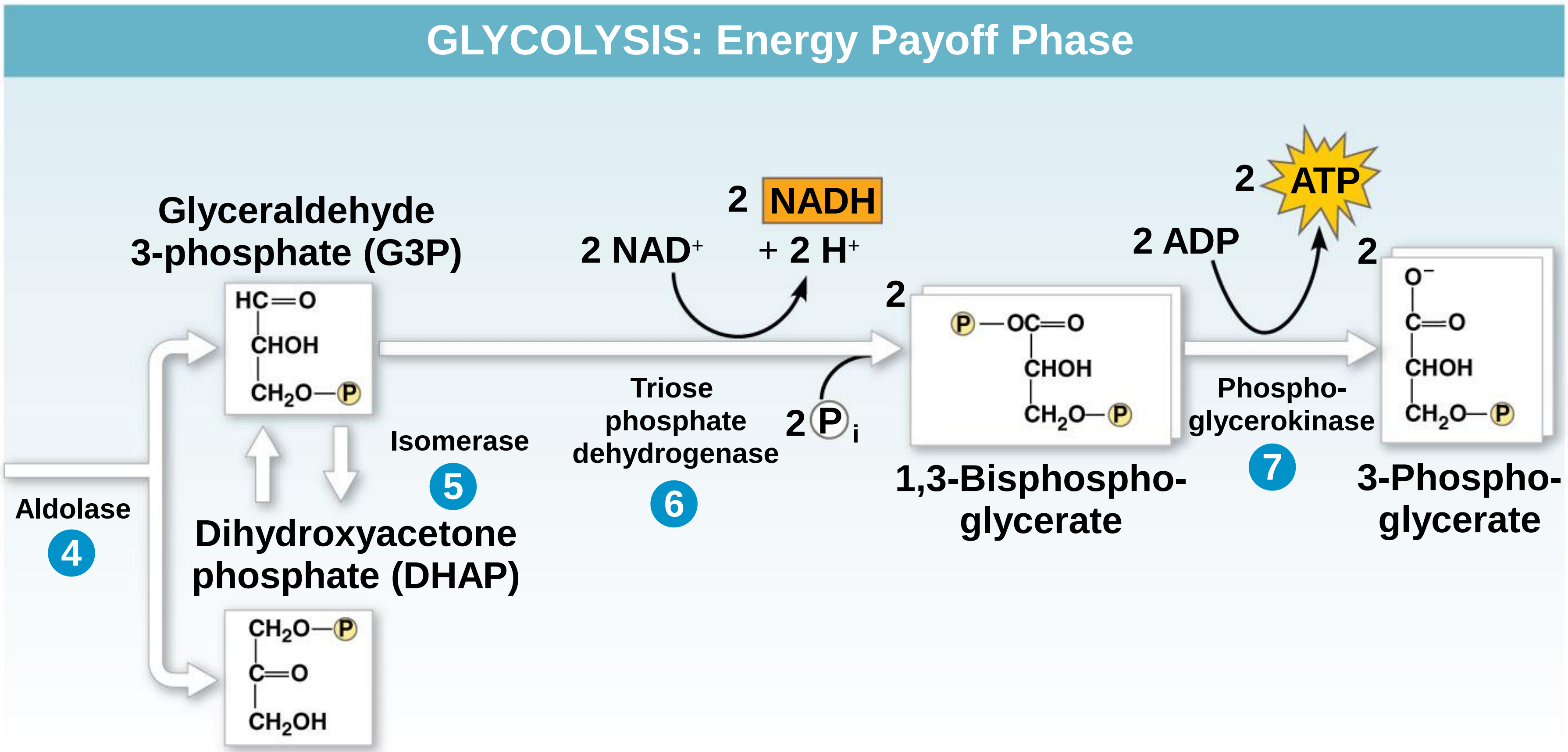
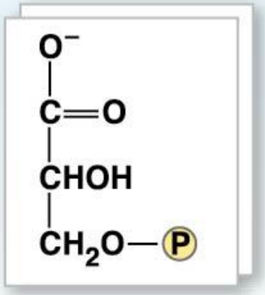


Figure 10.9bb_1

GLYCOLYSIS: Energy Payoff Phase

2



3-Phospho-
glycerate

Figure 10.9bb_2

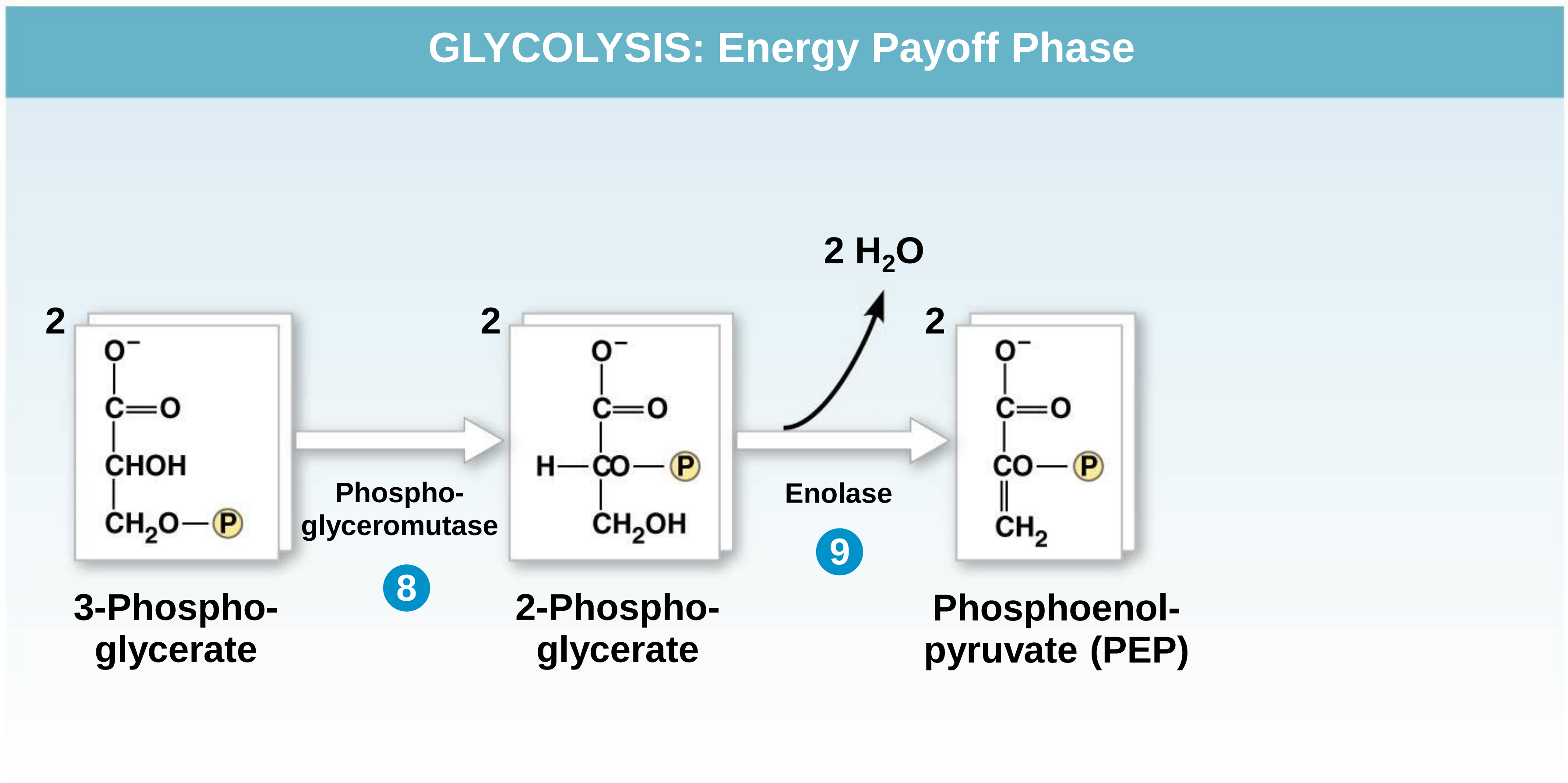
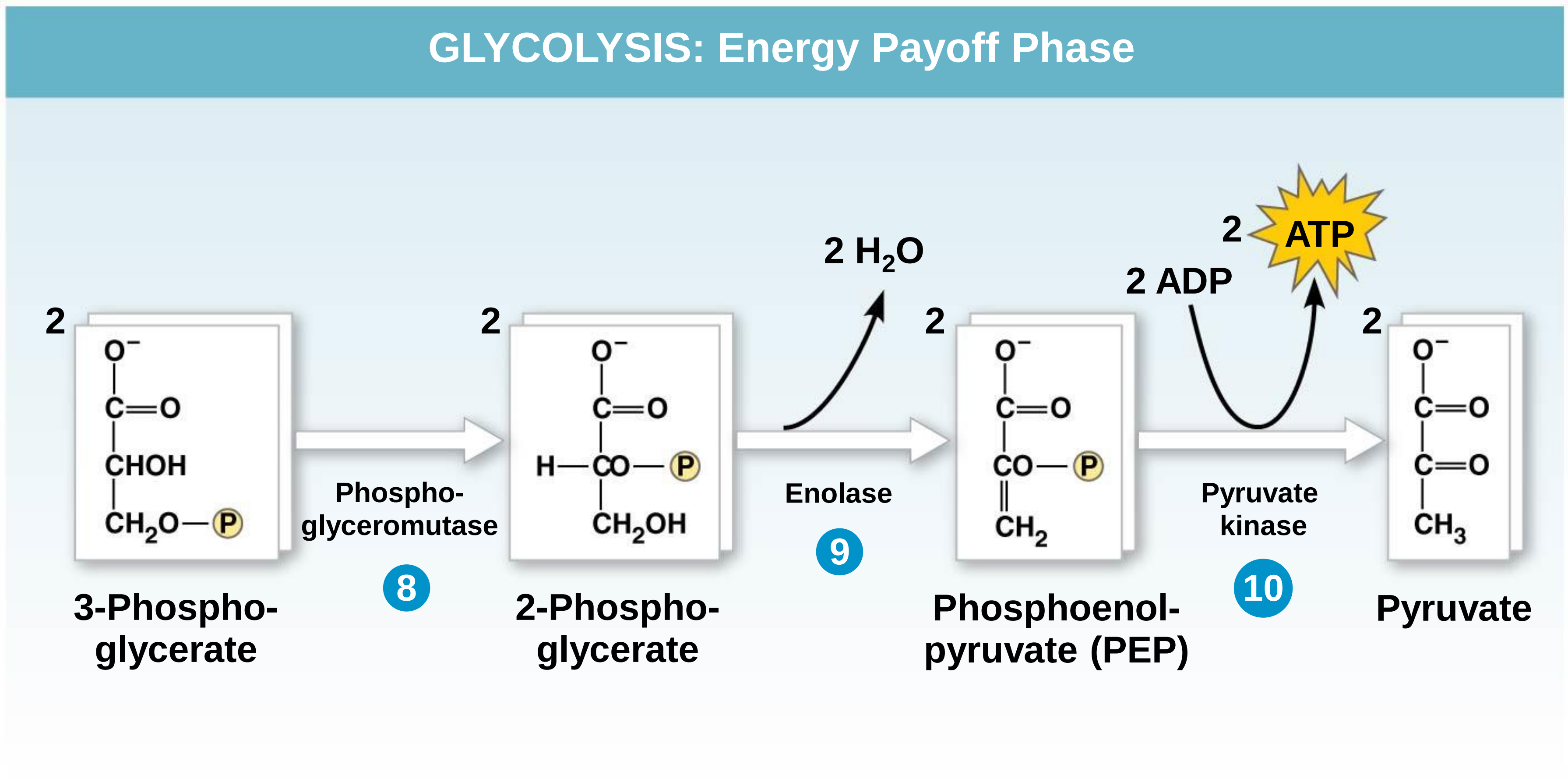


Figure 10.9bb_3



Concept 10.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

- In the presence of O_2, pyruvate enters a 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 catalyzes three reactions
  1. Oxidation of pyruvate and release of CO_2
  2. Reduction of NAD^+ to NADH
  3. Combination of the remaining two-carbon fragment and coenzyme A to form acetyl CoA

Figure 10.UN07

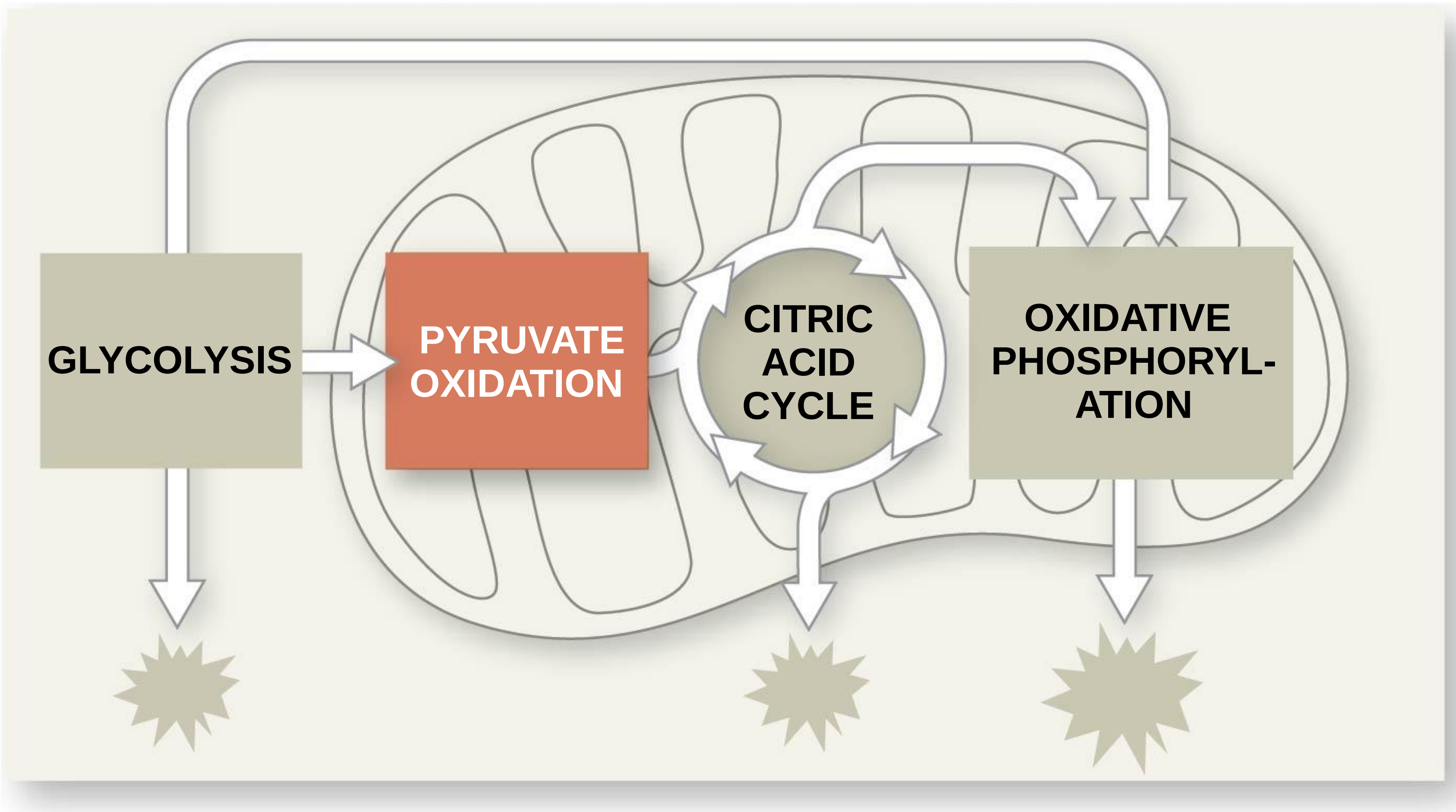
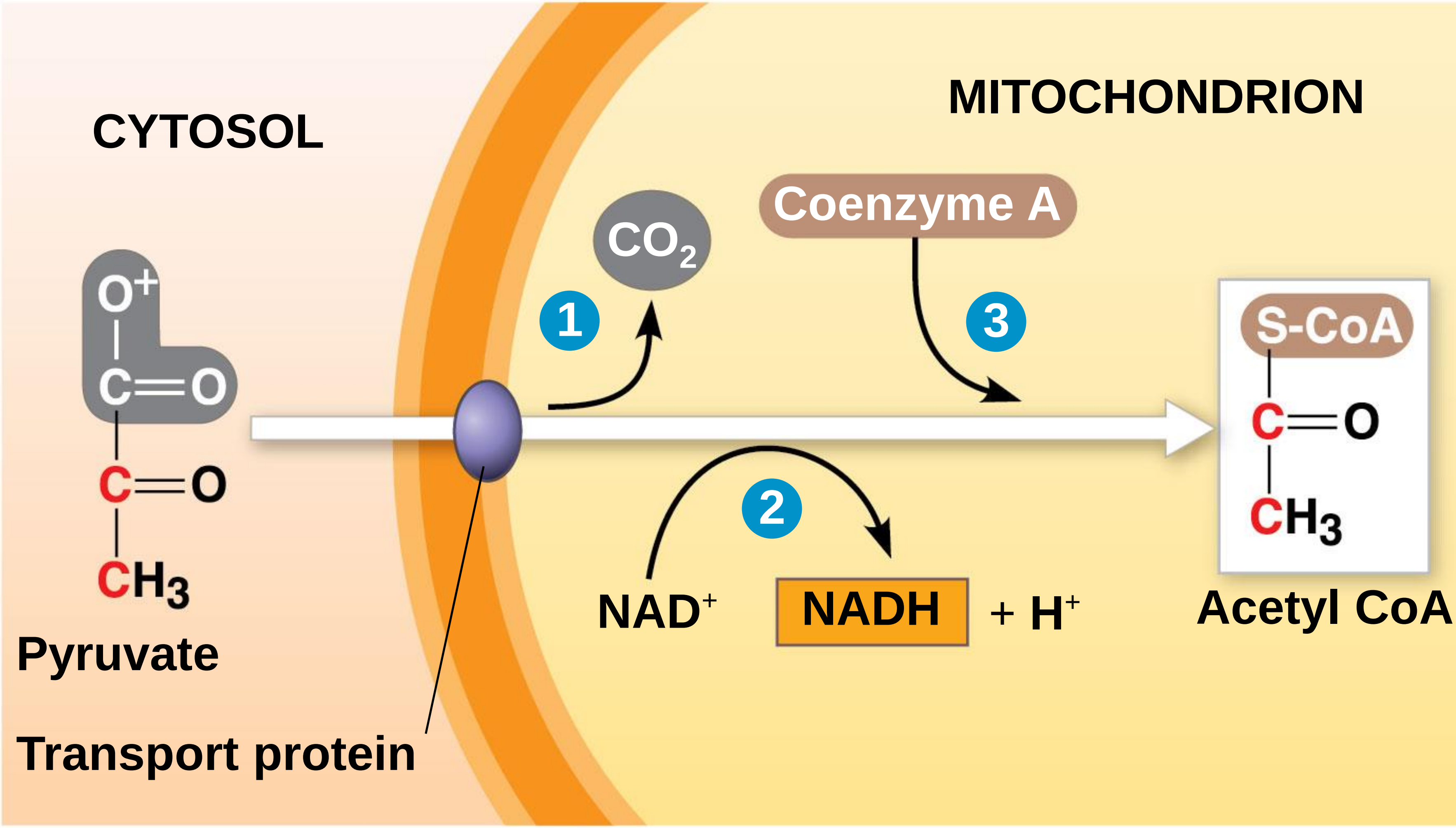


Figure 10.10



CYTOSOL
MITOCHONDRION
O⁻
C=O
C=O
CH3
Pyruvate
Transport protein
CO2
1
Coenzyme A
3
2
NAD+
NADH
+ H+
S-CoA
C=O
CH3
Acetyl CoA

The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, completes the breakdown of pyruvate to CO_2
- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn

- 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 $FADH_2$ produced by the cycle relay electrons extracted from food to the electron transport chain

Figure 10.UN08

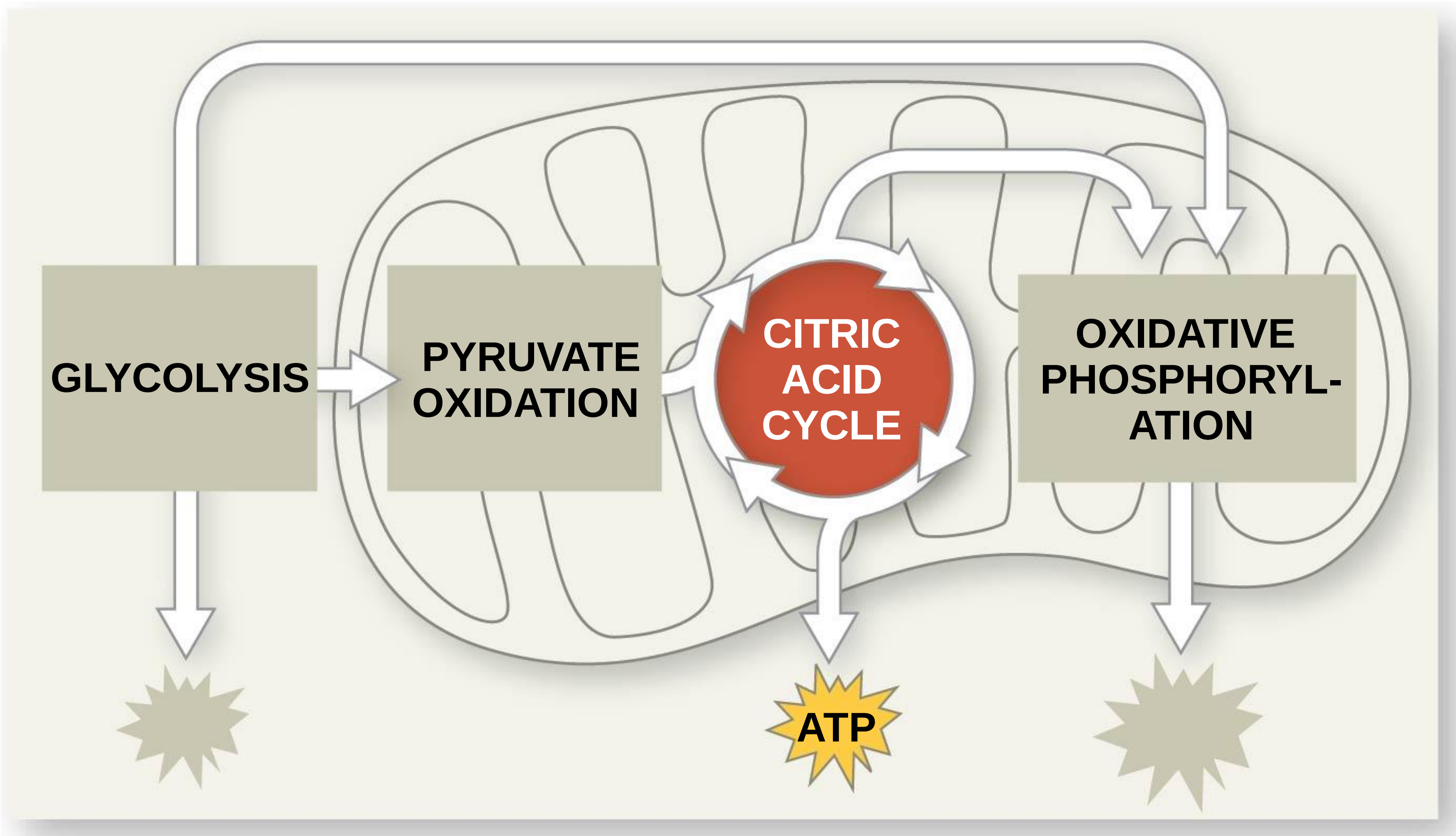
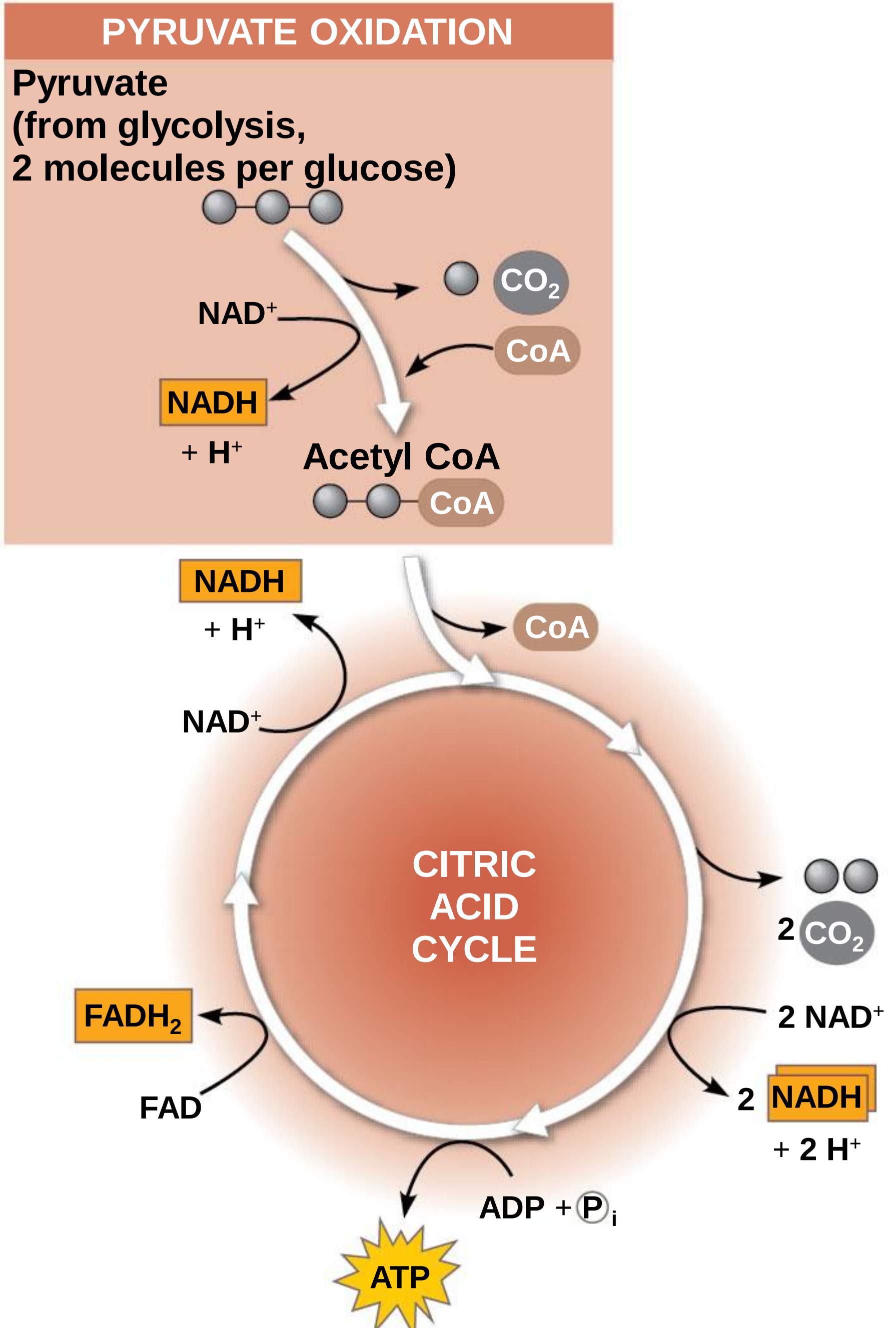


Figure 10.11



PYRUVATE OXIDATION
Pyruvate
(from glycolysis,
2 molecules per glucose)
CO2
NAD+
CoA
NADH
+ H+
Acetyl CoA
CoA
NADH
+ H+
CoA
NAD+
CITRIC
ACID
CYCLE
2 CO2
2 NAD+
2 NADH
+ 2 H+
FADH2
FAD
ADP + P i
ATP

Figure 10.11a

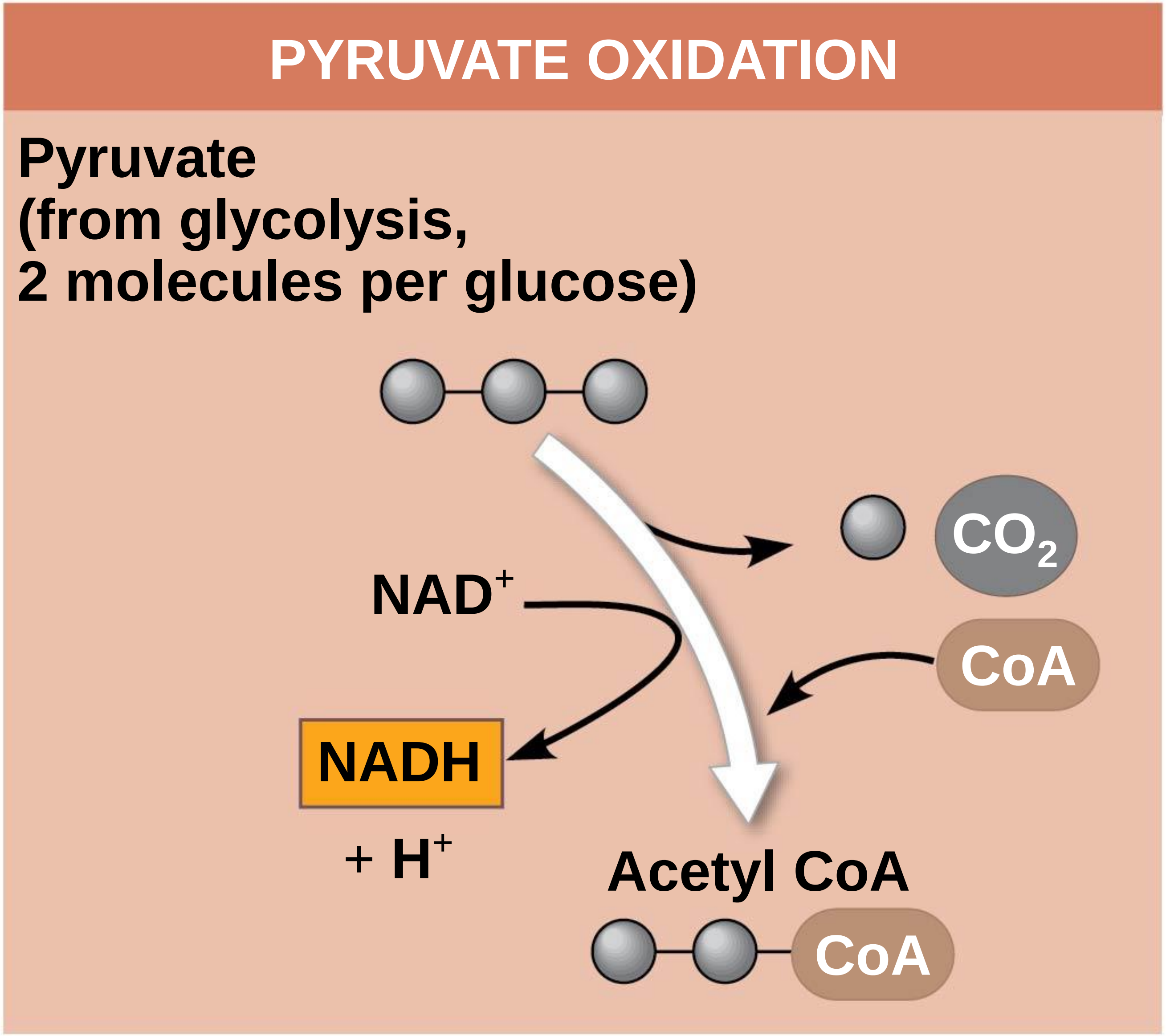


Figure 10.11b

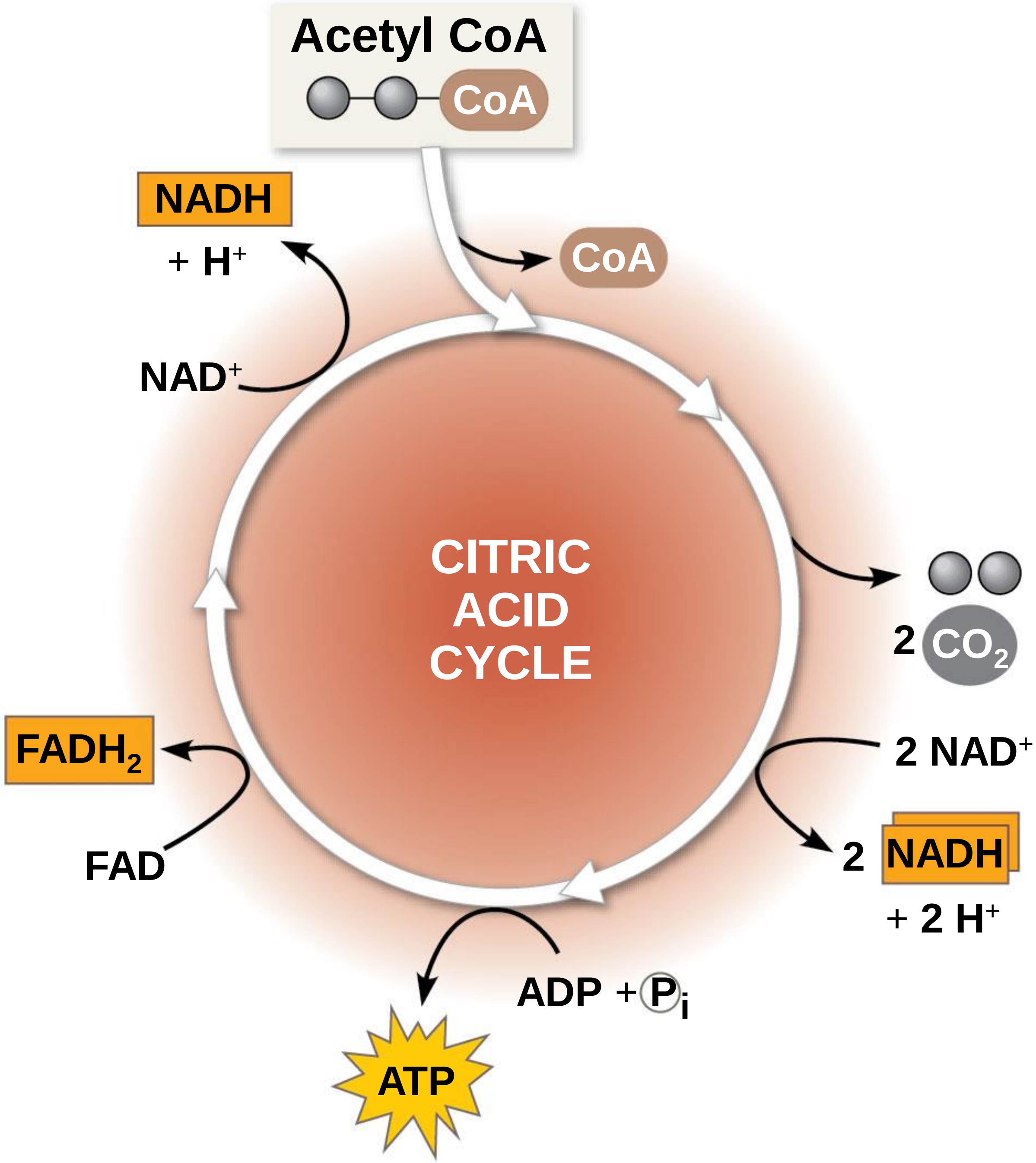


Figure 10.12_1

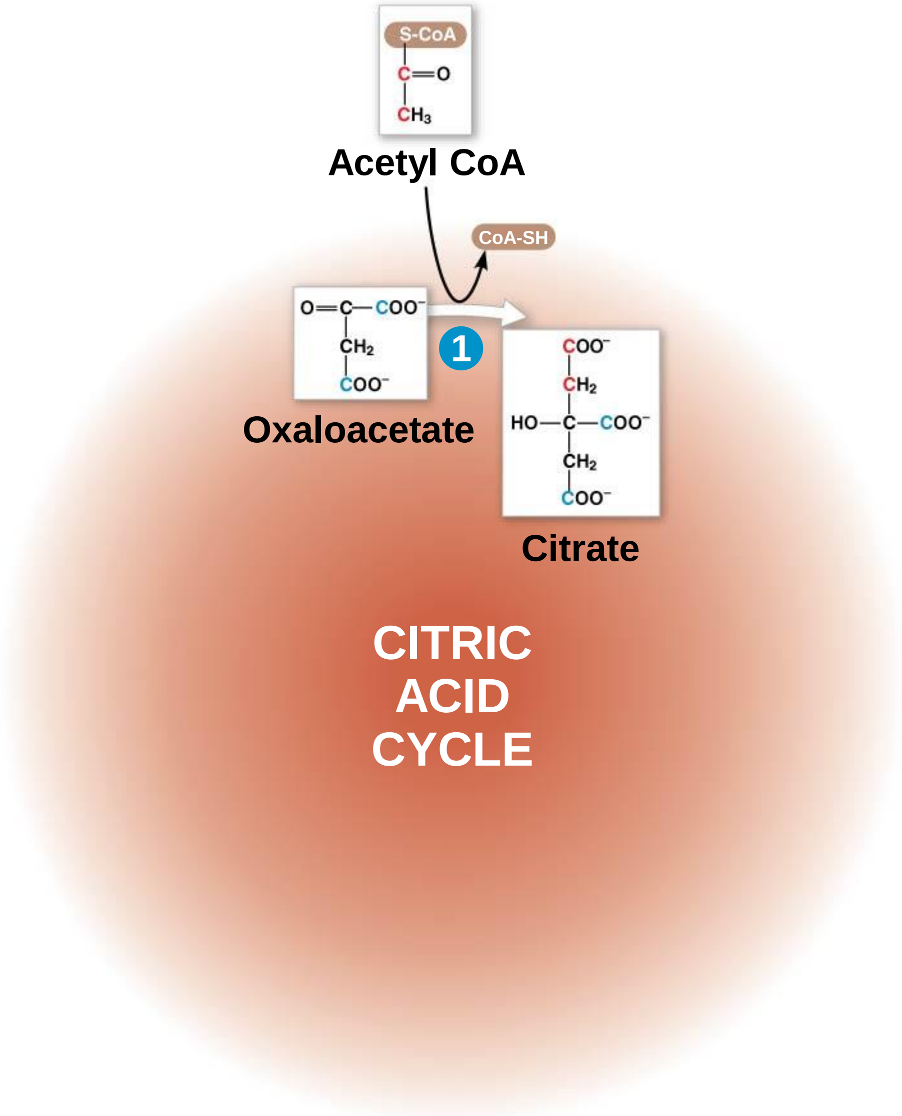


Figure 10.12_2

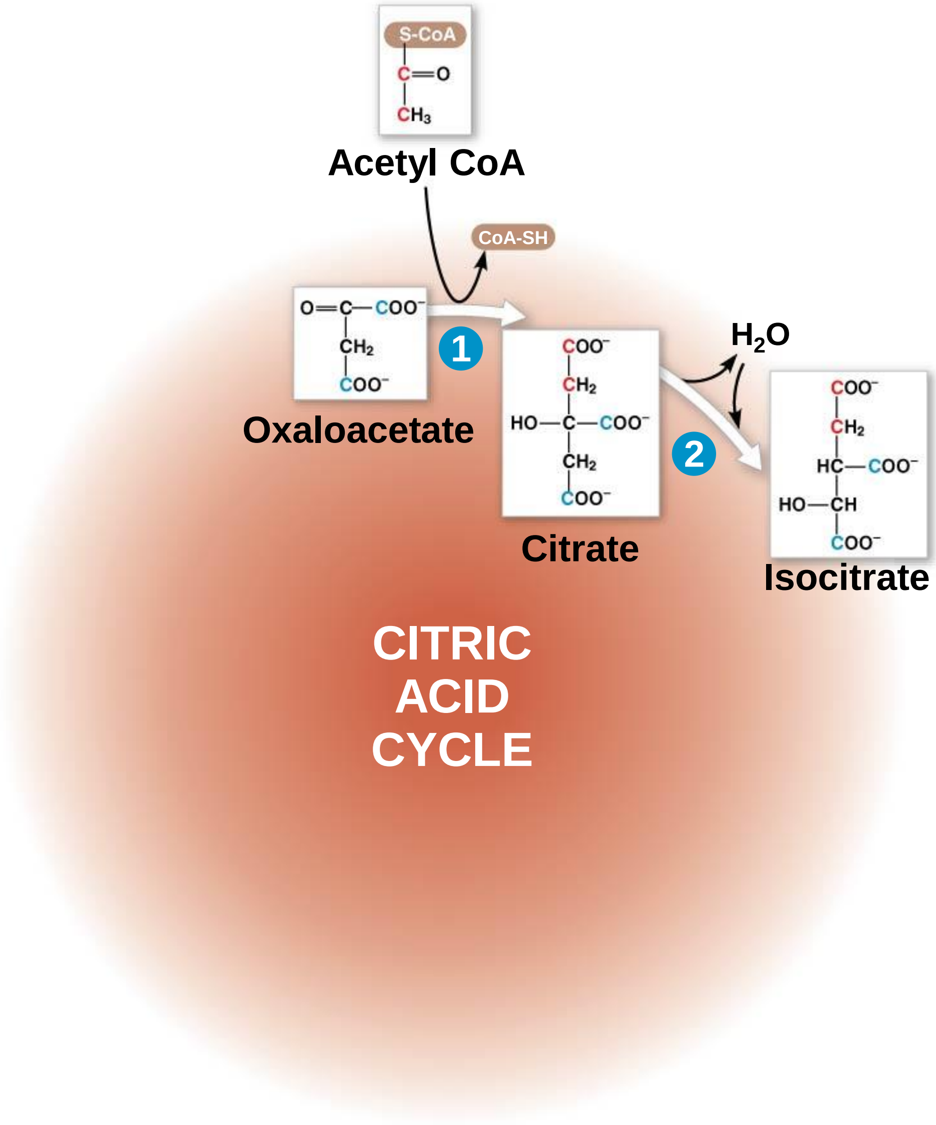


Figure 10.12_3

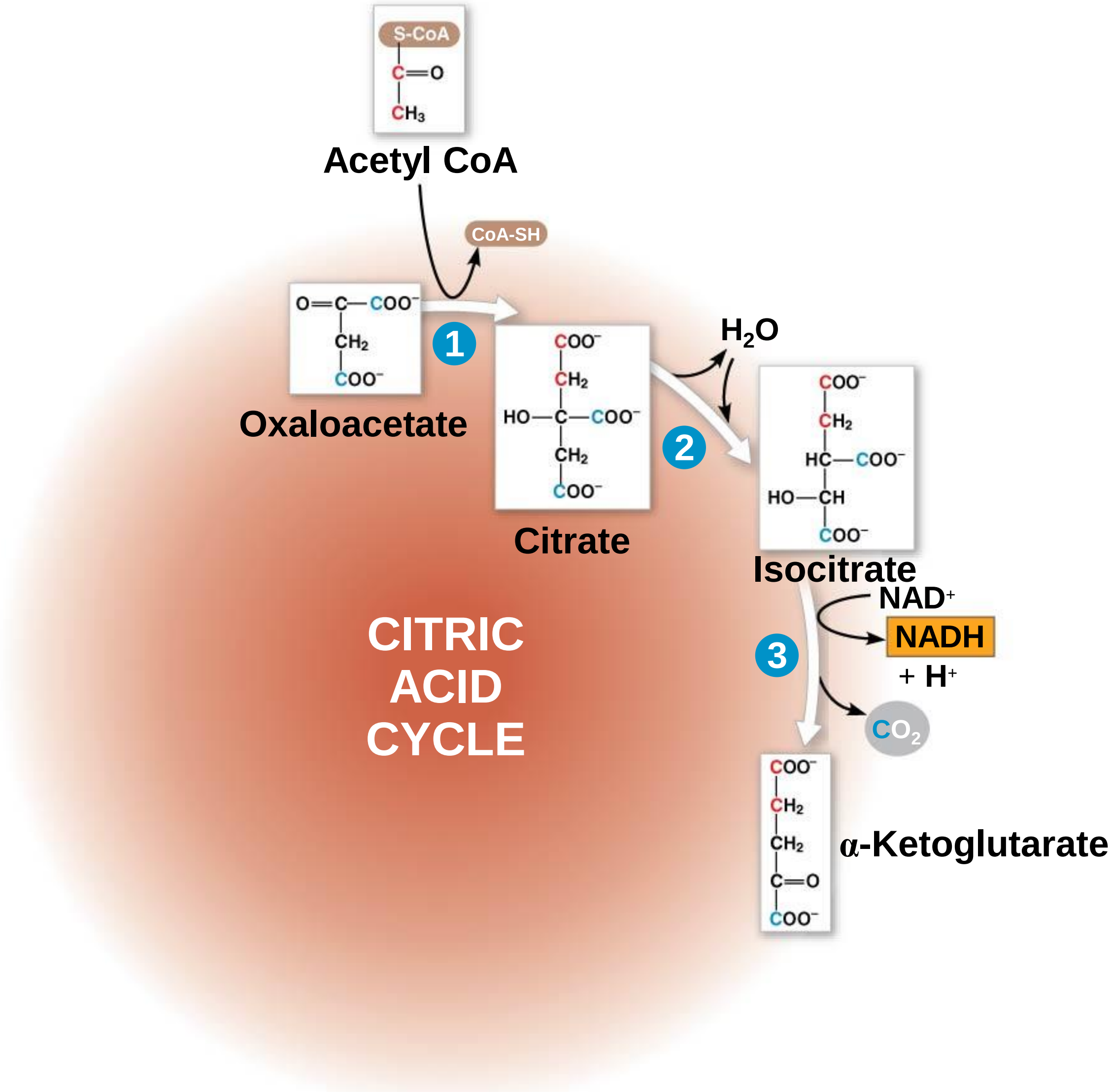


Figure 10.12_4

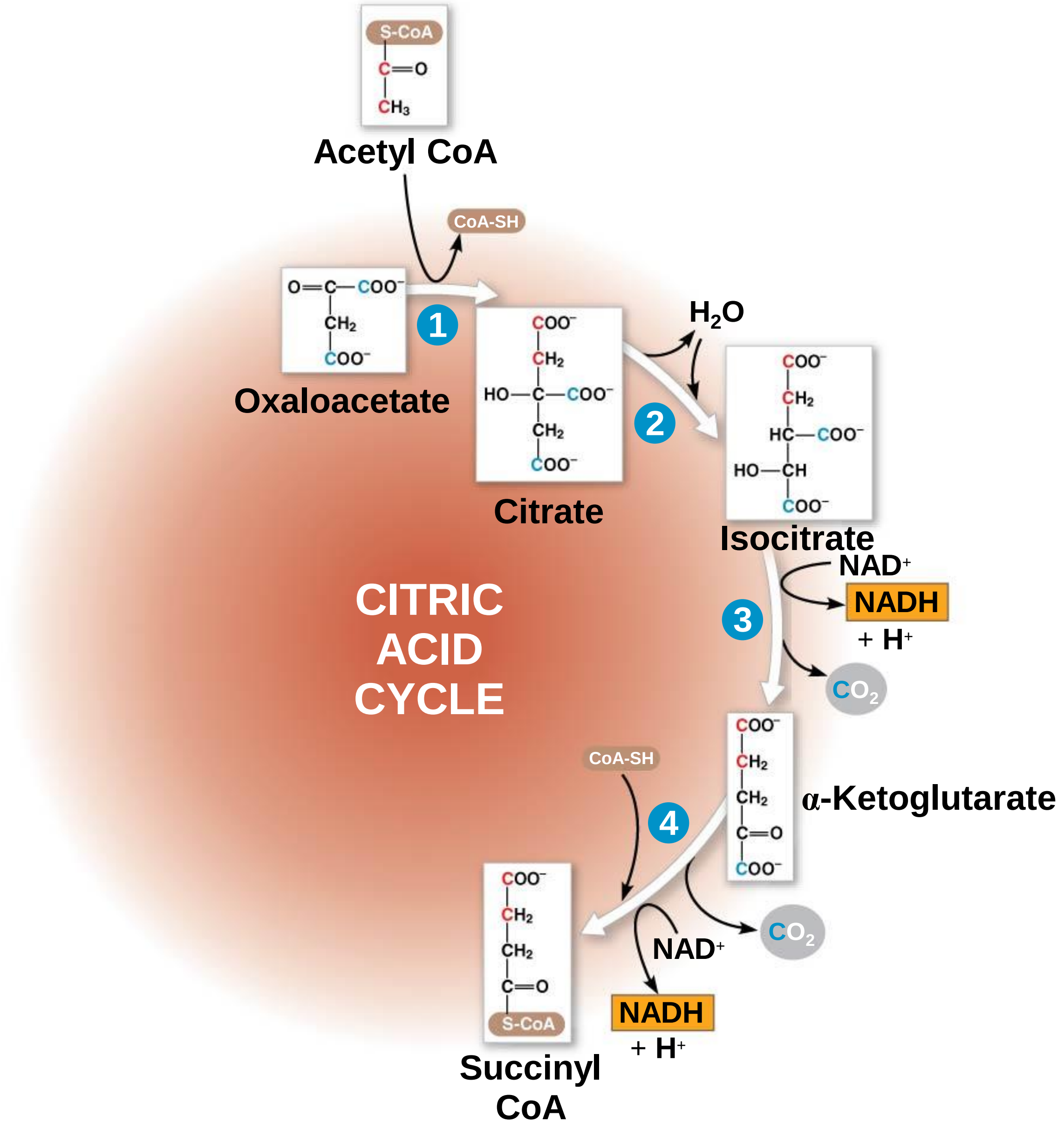


Figure 10.12_5

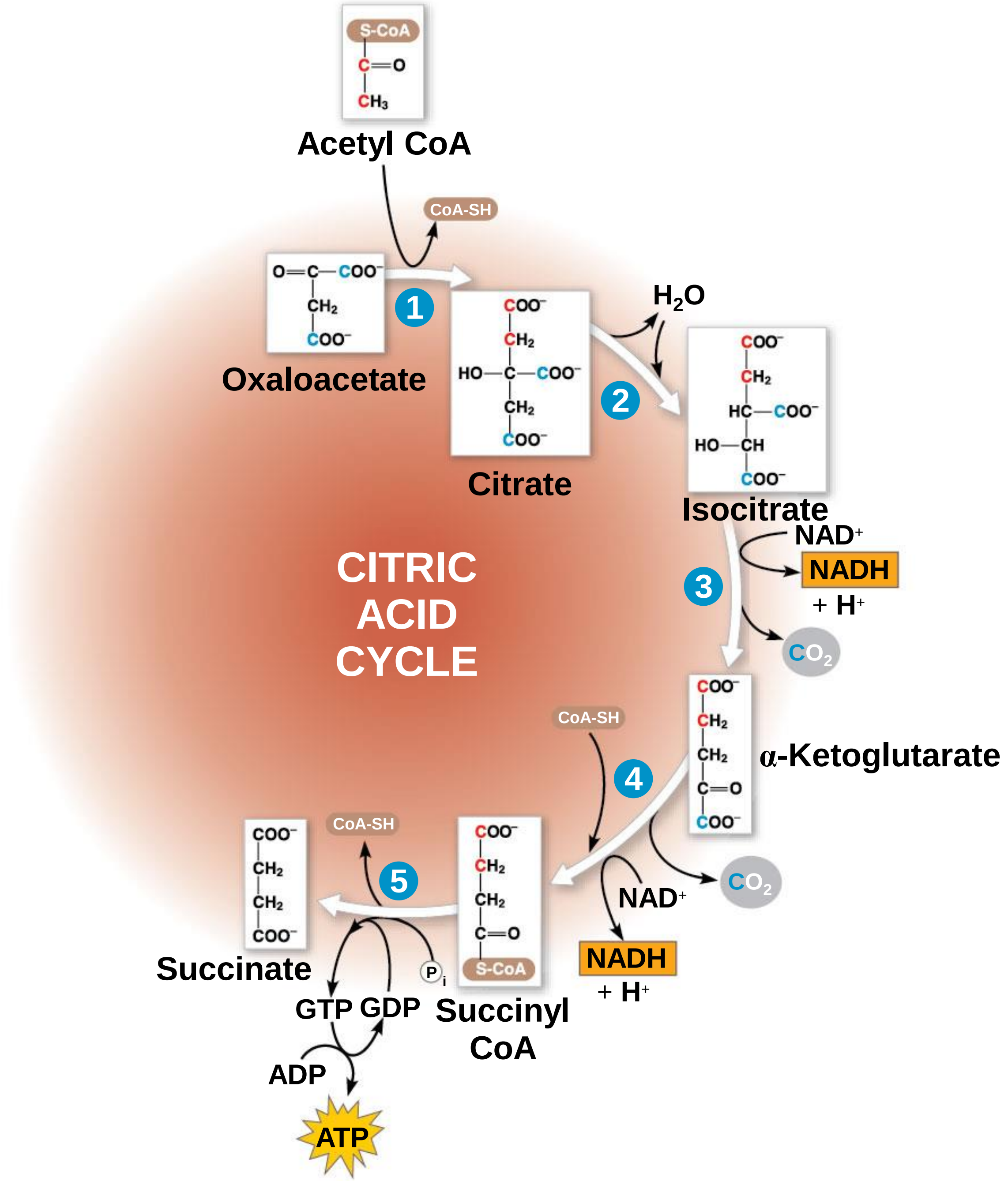


Figure 10.12_6

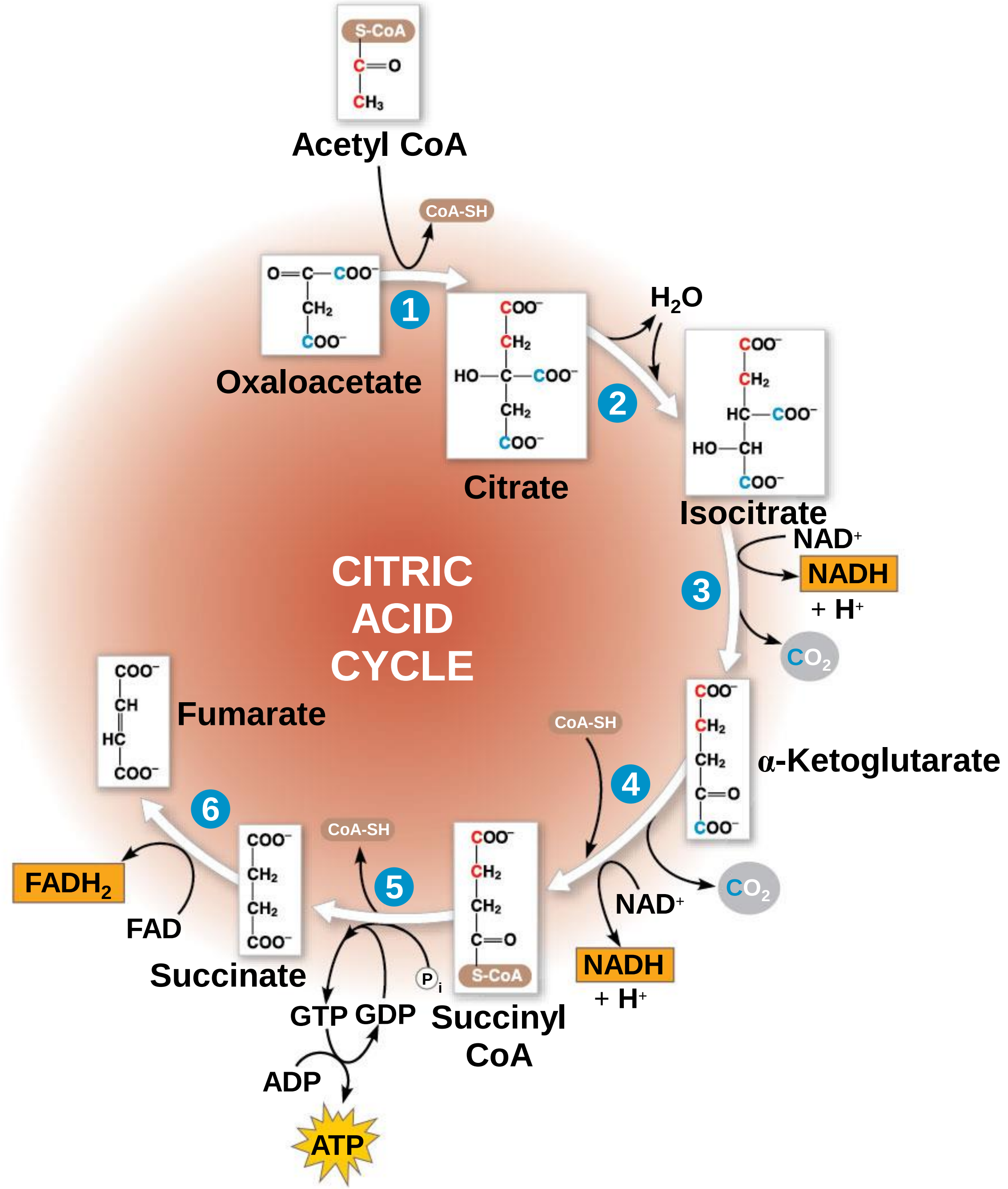


Figure 10.12_7

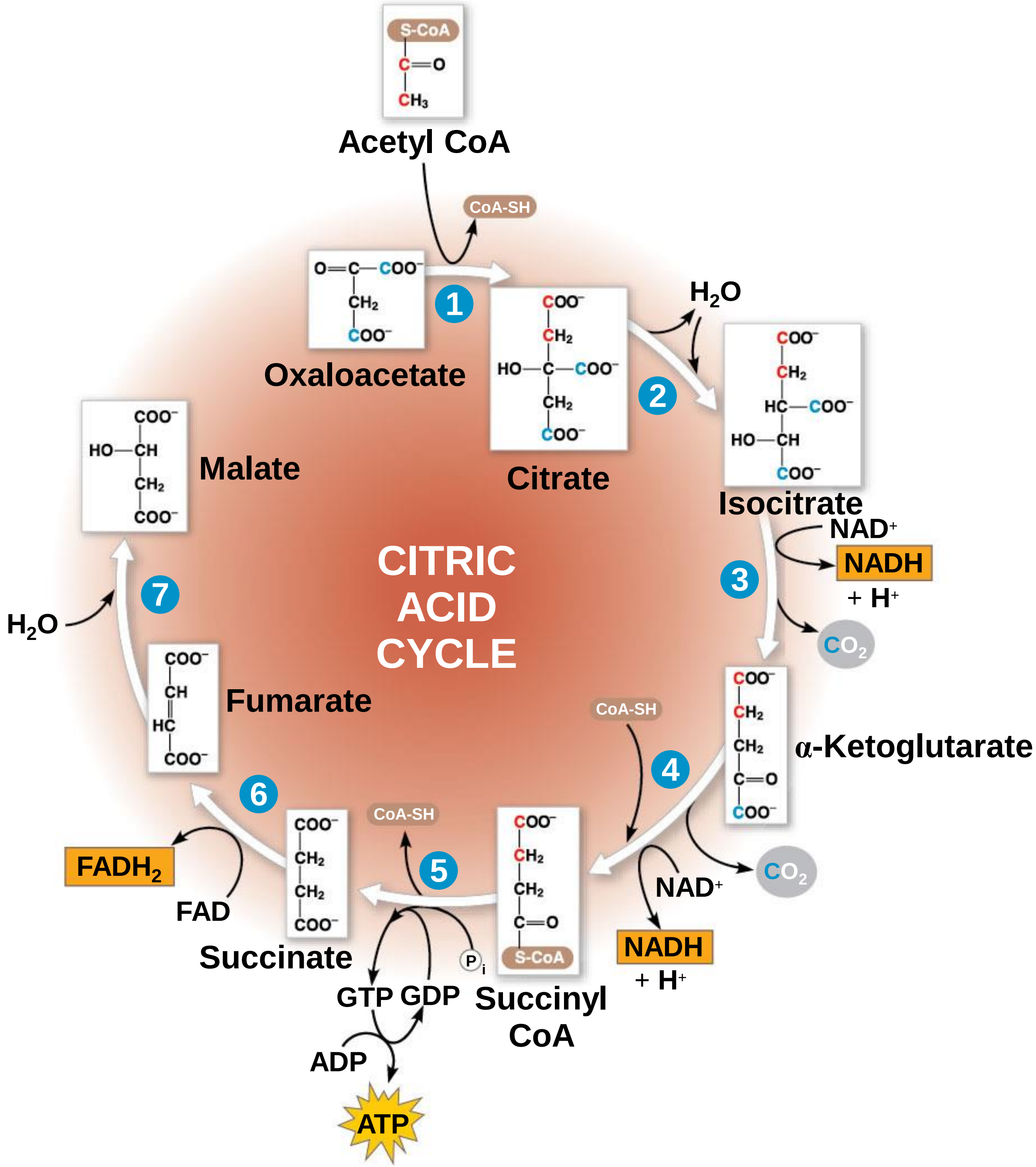


Figure 10.12_8

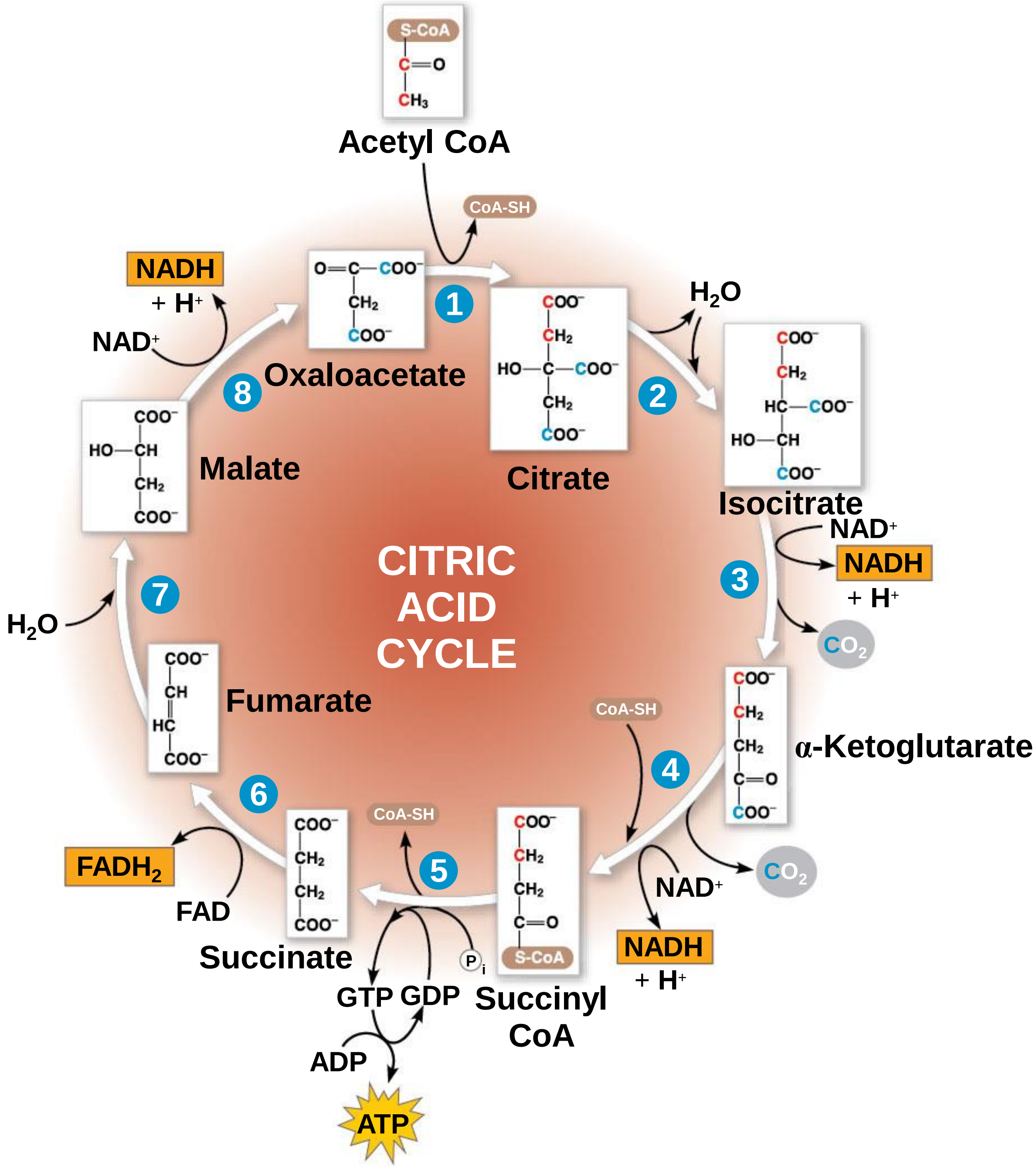


Figure 10.12a

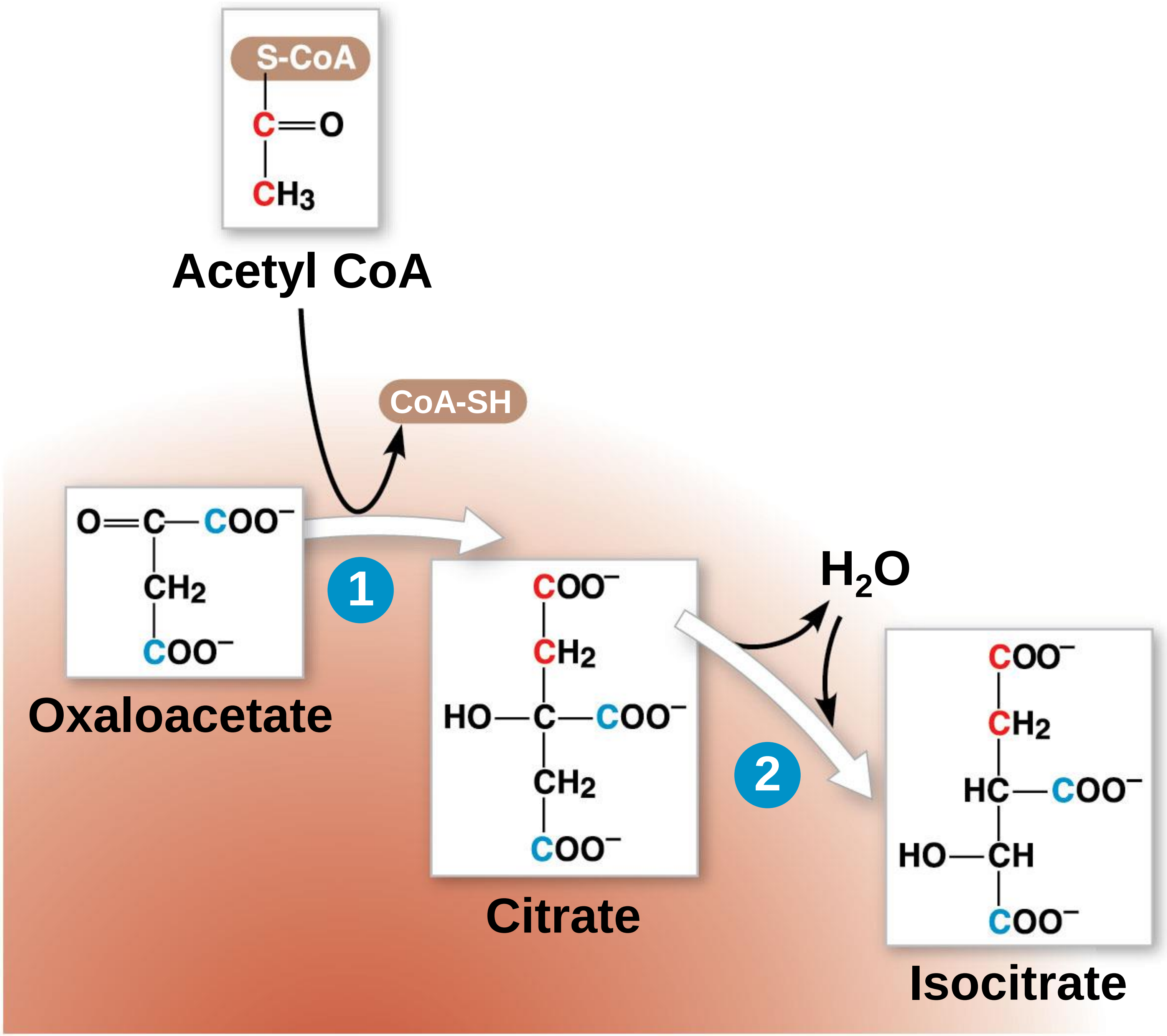


Figure 10.12b

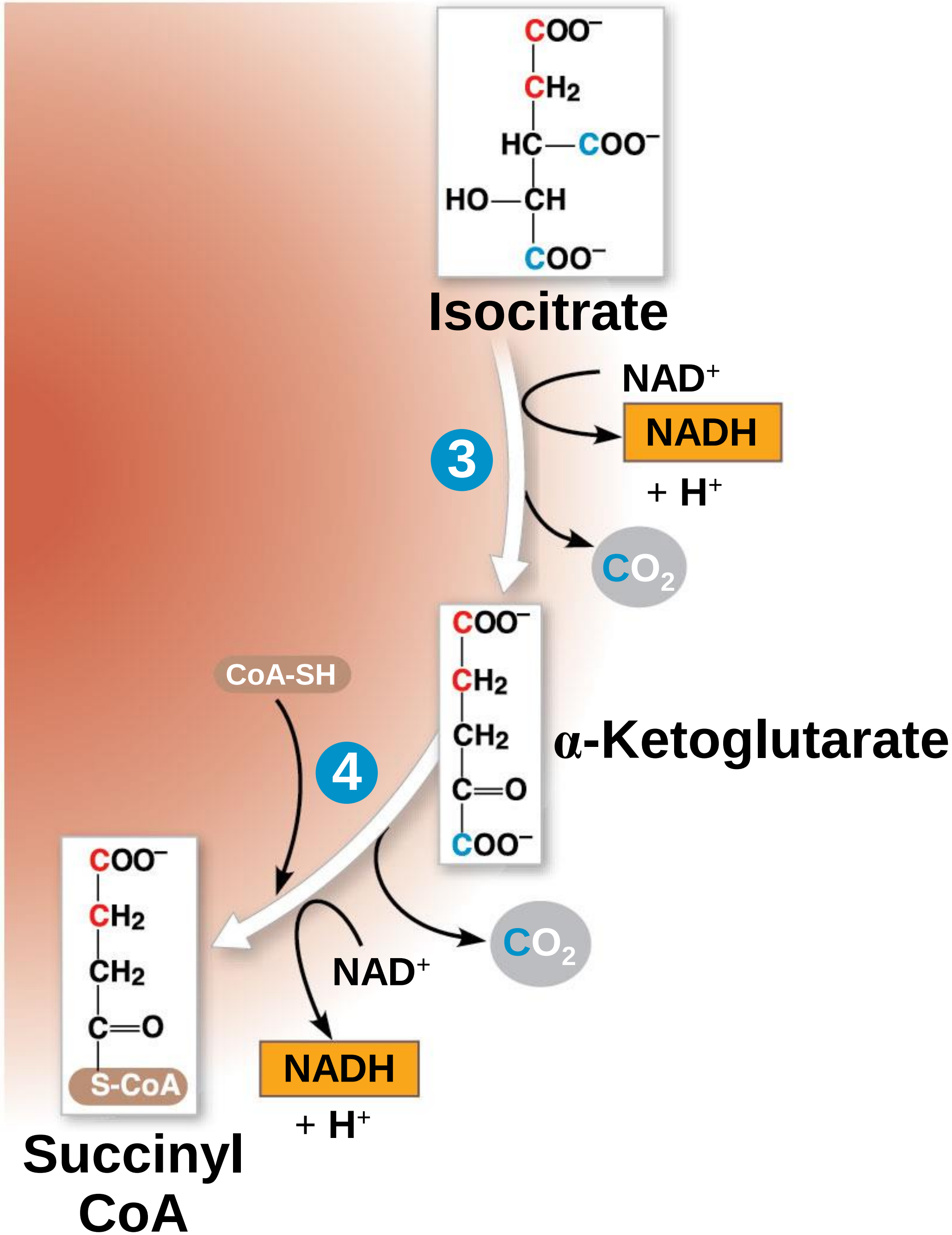


Figure 10.12c

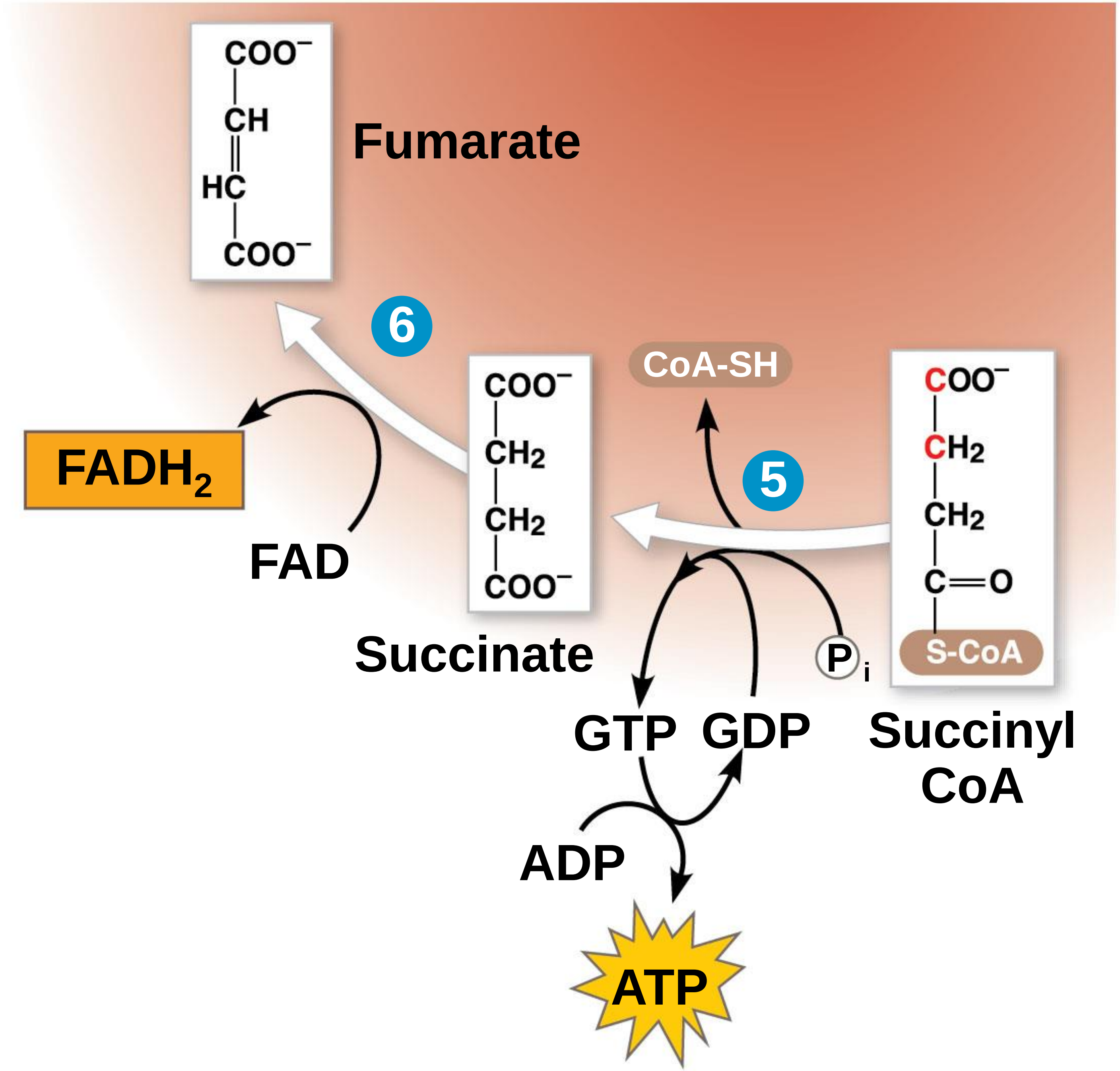
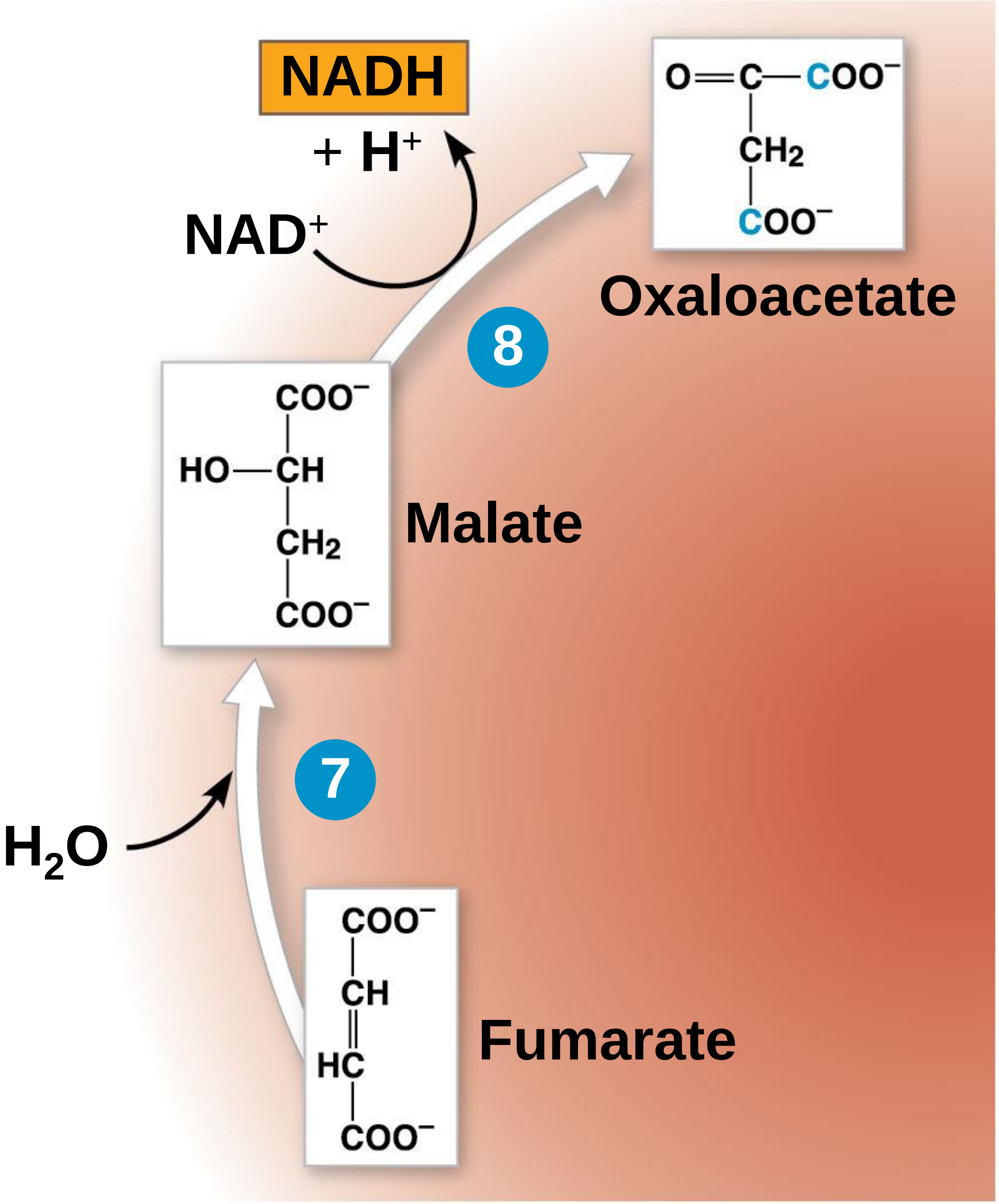


Figure 10.12d



Concept 10.4: 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 inner membrane (cristae) of the mitochondrion
- Most of the chain's components are proteins, which exist in multiprotein complexes
- Electrons drop in free energy as they go down the chain and are finally passed to O_2, forming H_2O
- Electron carriers alternate between reduced and oxidized states as they accept and donate electrons

- Electrons are transferred from NADH or $FADH_2$ to the electron transport chain
- Electrons are passed through a number of proteins including **cytochromes** (each with an iron atom) to O_2
- The electron transport chain generates no ATP directly
- It breaks the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts

Figure 10.UN09

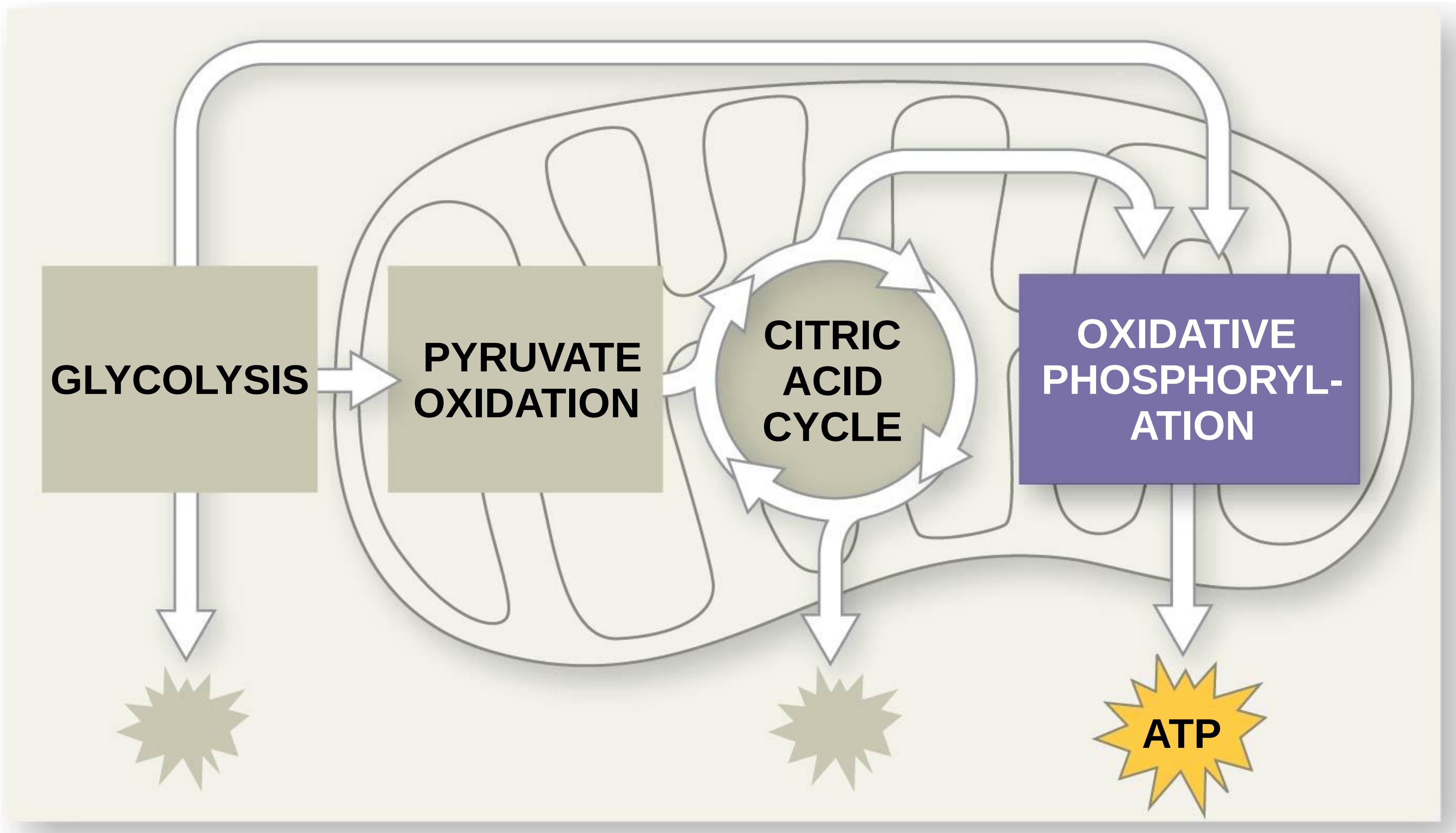
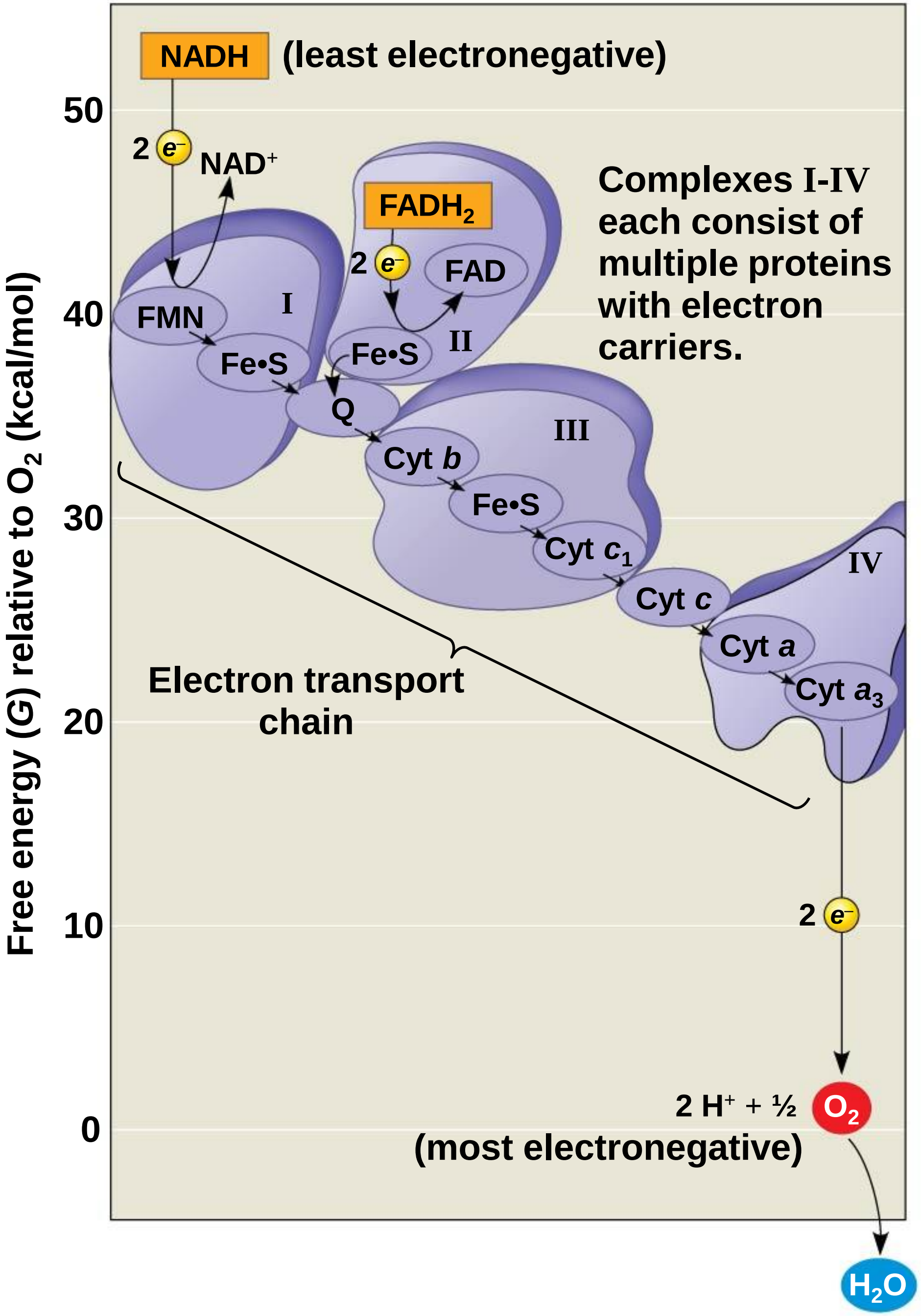


Figure 10.13



NADH
(least electronegative)
50
40
30
20
10
0
Free energy (G) relative to O_2 (kcal/mol)
2 e^-
NAD^+
$FADH_2$
2 e^-
FAD
FMN
I
Fe•S
Fe•S
II
Q
III
Cyt *b*
Fe•S
Cyt c_1
Cyt *c*
IV
Cyt *a*
Cyt a_3
Complexes I-IV each consist of multiple proteins with electron carriers.
Electron transport chain
2 e^-
2 H^+ + ½ O_2
(most electronegative)
H_2O

Figure 10.13a

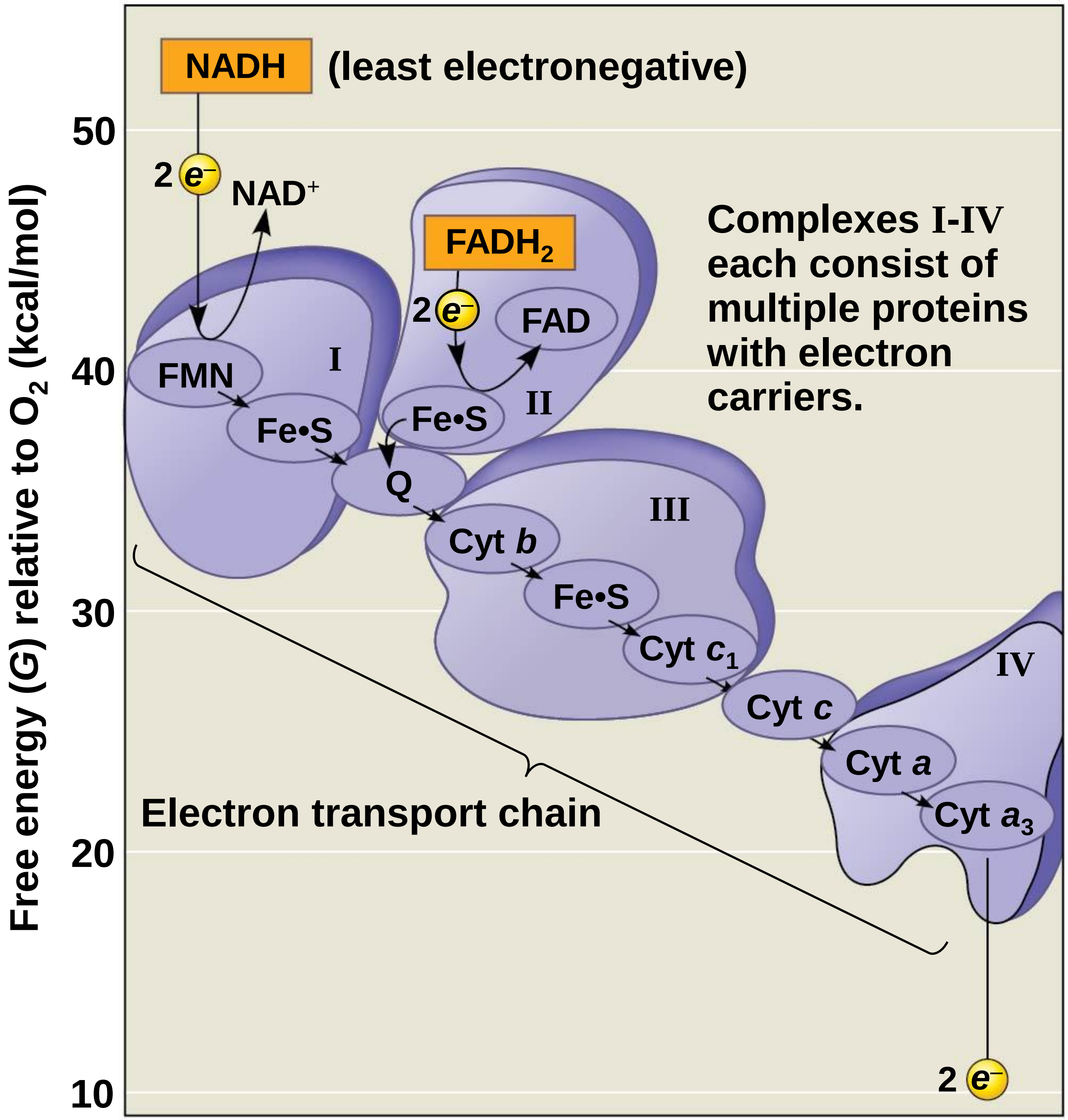
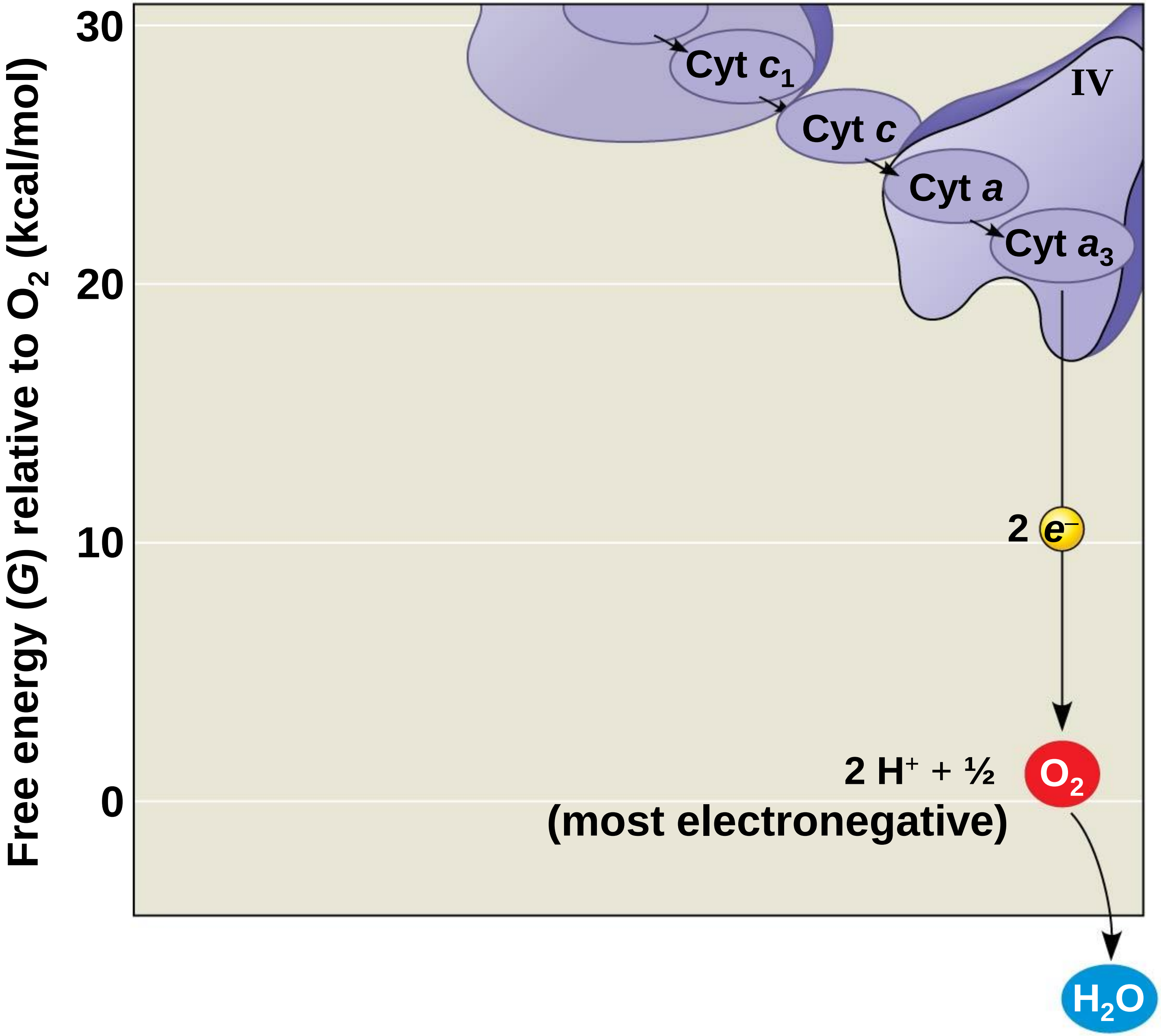


Figure 10.13b

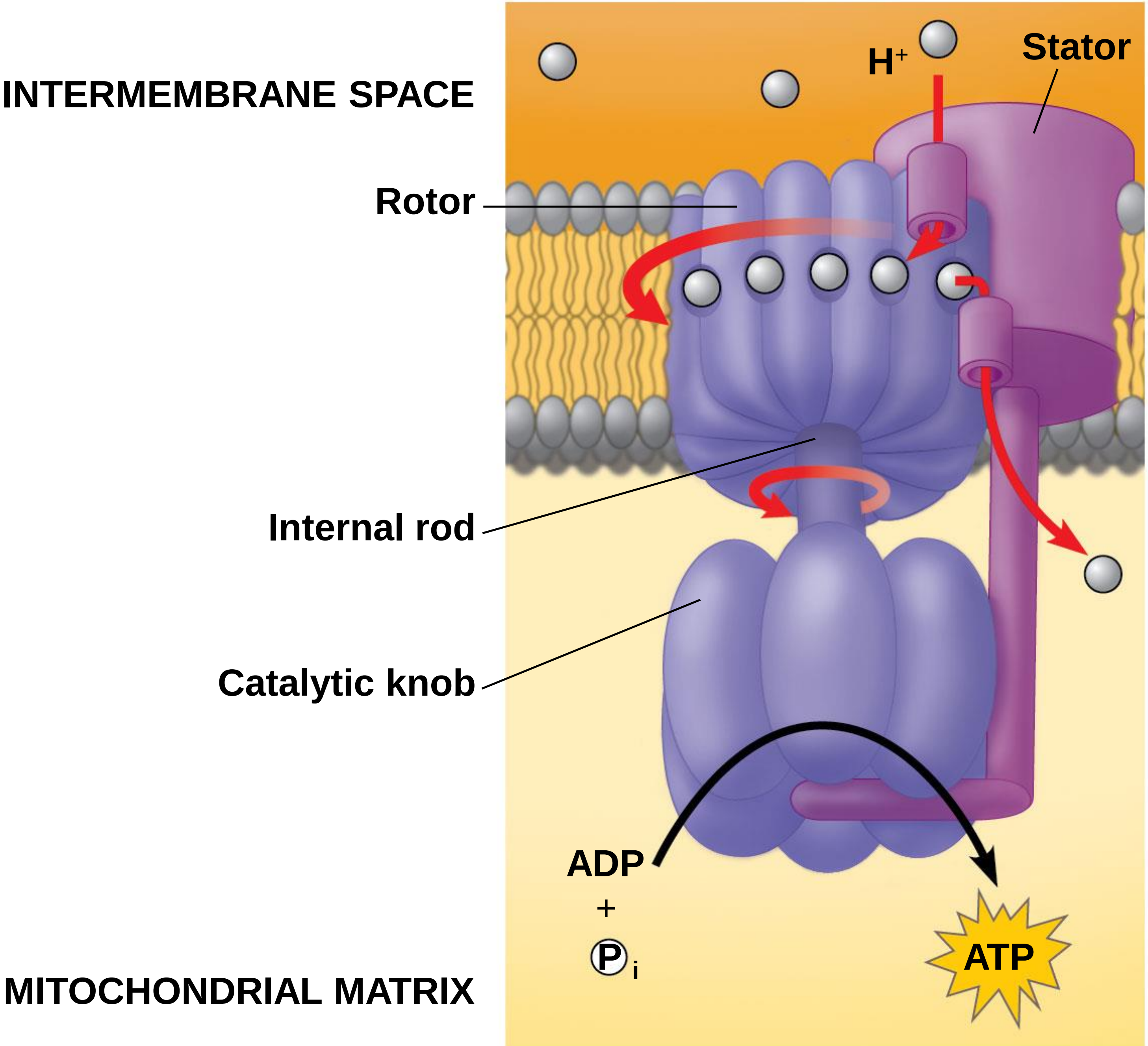


Chemiosmosis: The Energy-Coupling Mechanism

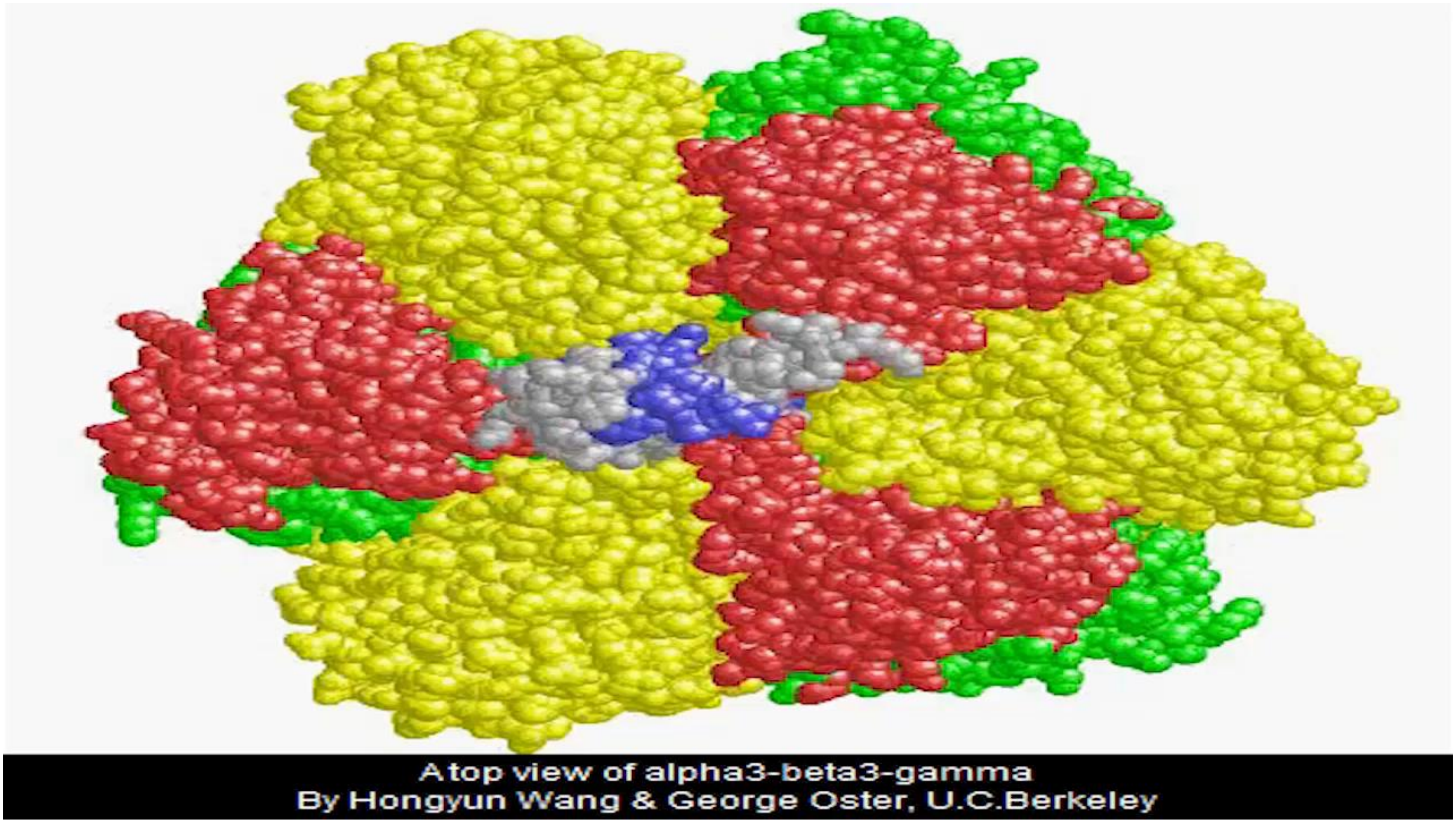
- The energy released as electrons are passed down the electron transport chain is used to pump H^+ from the mitochondrial matrix to the intermembrane space
- H^+ then moves down its concentration gradient back across the membrane, passing through the protein complex **ATP synthase**

- H^+ moves into binding sites on the rotor of ATP synthase, causing it to spin in a way that catalyzes phosphorylation of ADP to ATP
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive cellular work

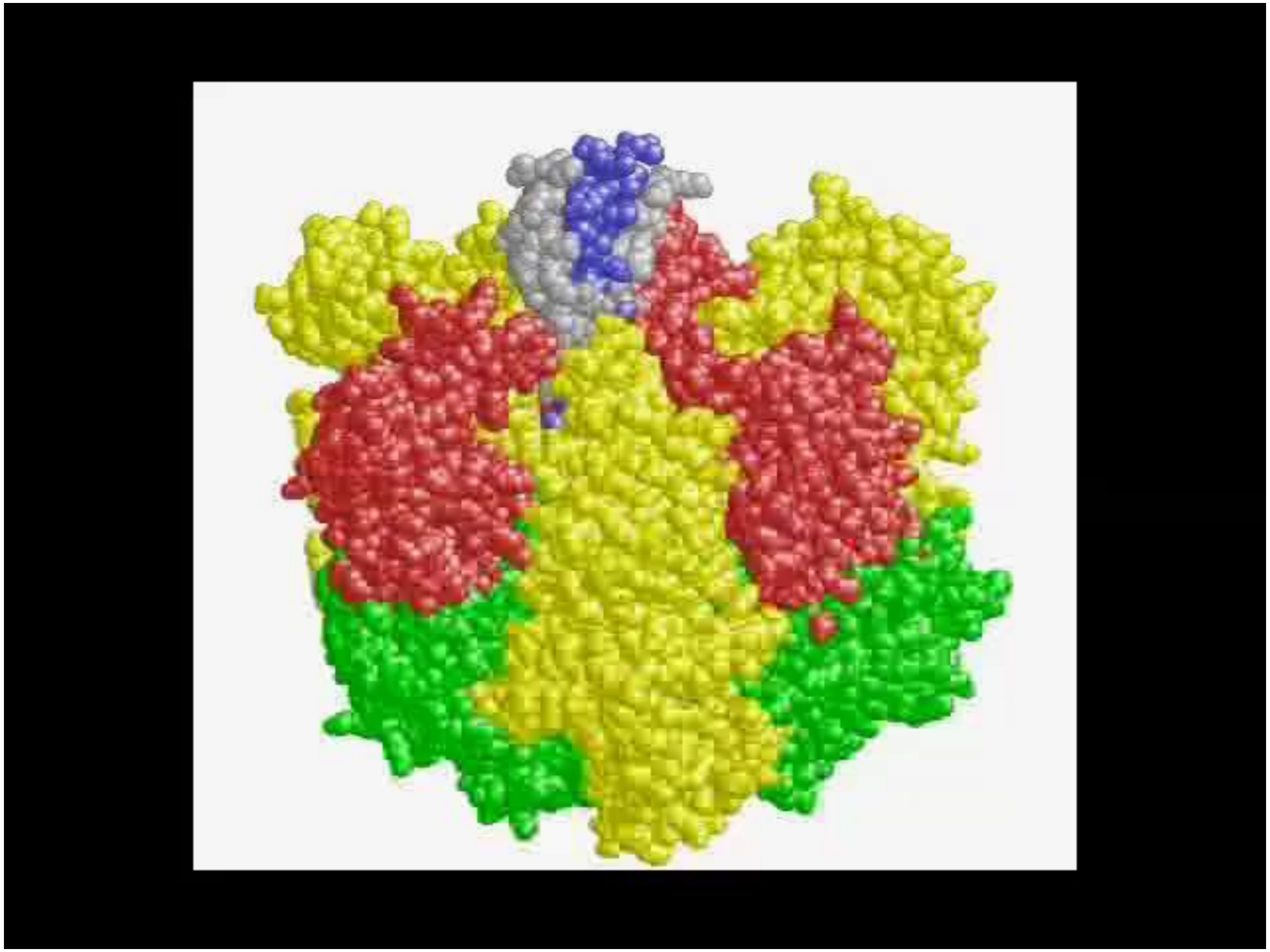
Figure 10.14


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

Video: ATP Synthase 3-D Structure, Top View

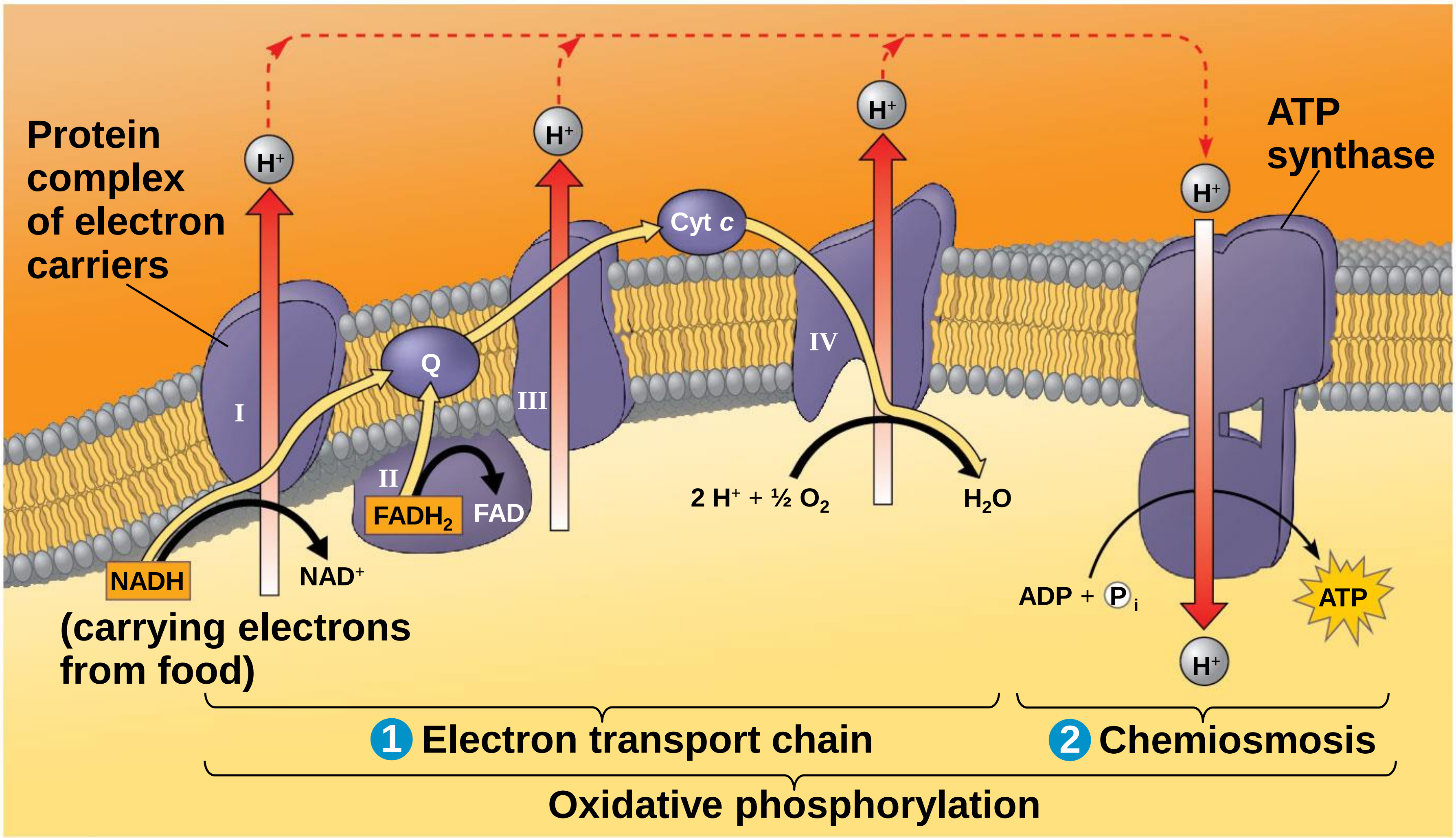


Video: ATP Synthase 3-D Structure, Side View



- Certain electron carriers in the electron transport chain accept and release H^+ along with the electrons
- In this way, 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

Figure 10.15



Protein complex of electron carriers
H+
H+
H+
H+
ATP synthase
Cyt c
Q
I
II
III
IV
FADH2
FAD
NADH
NAD+
(carrying electrons from food)
2 H+ + ½ O2
H2O
ADP + P i
ATP
H+
1 Electron transport chain
2 Chemiosmosis
Oxidative phosphorylation

Figure 10.15a

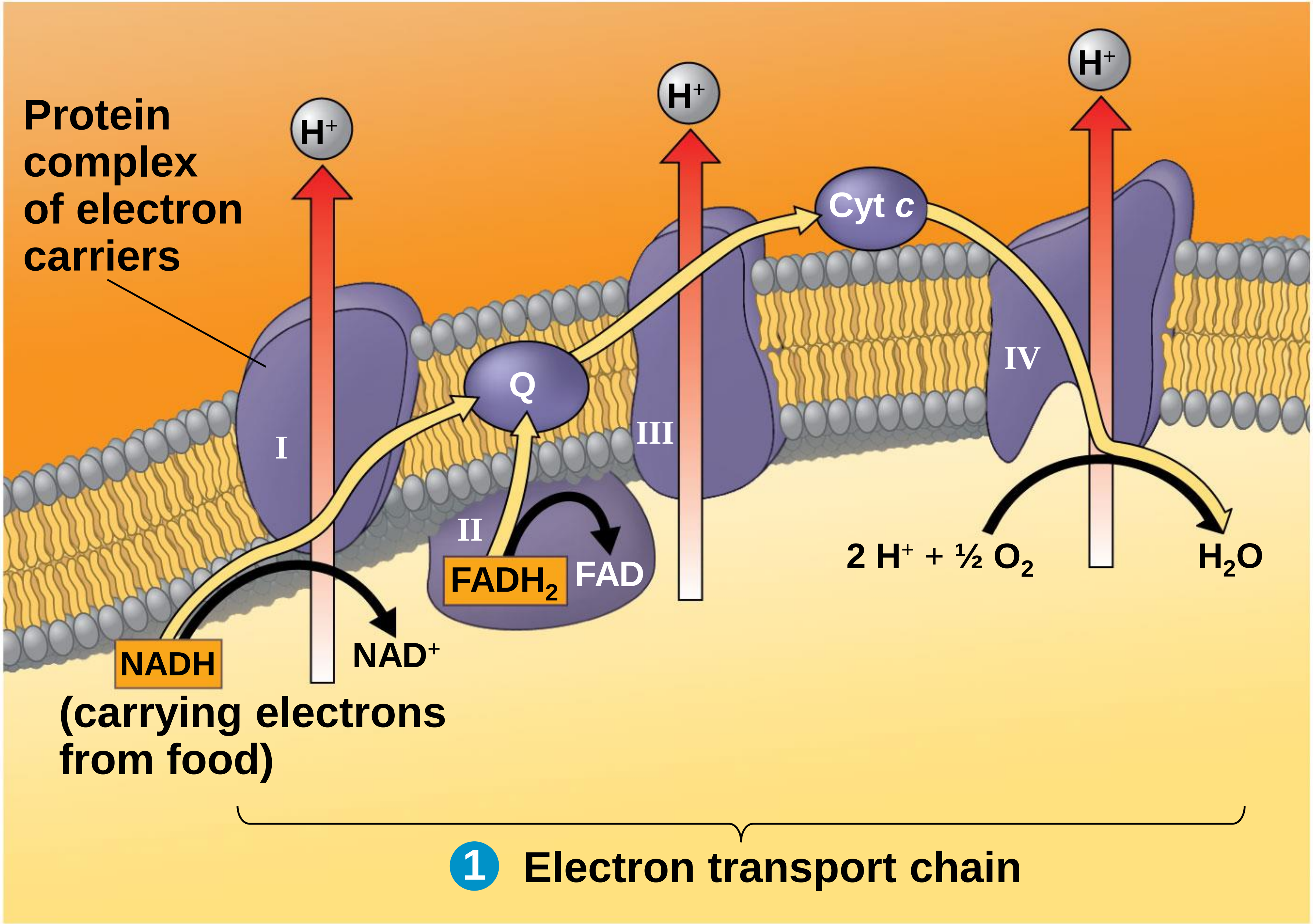
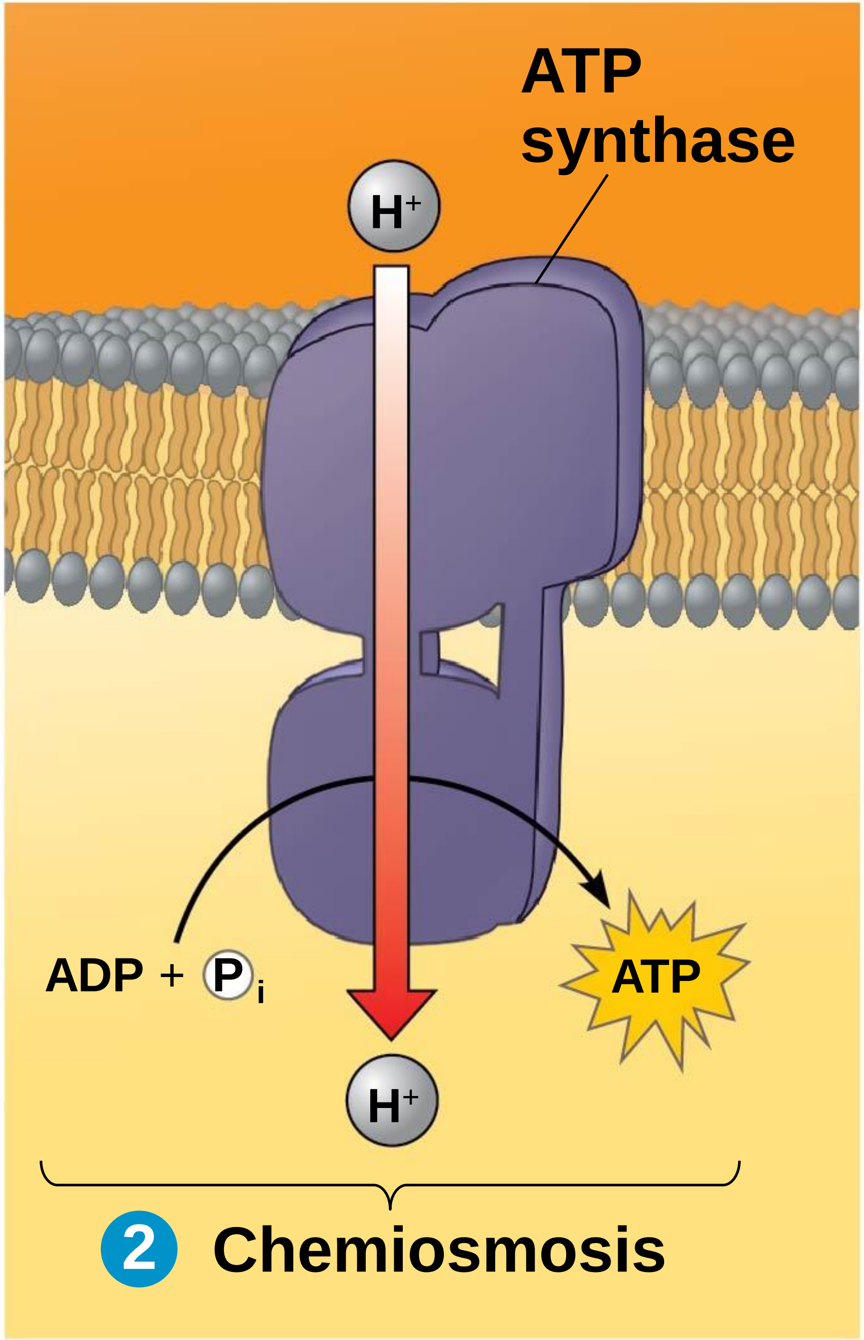


Figure 10.15b



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
- The rest of the energy is lost as heat

Figure 10.16

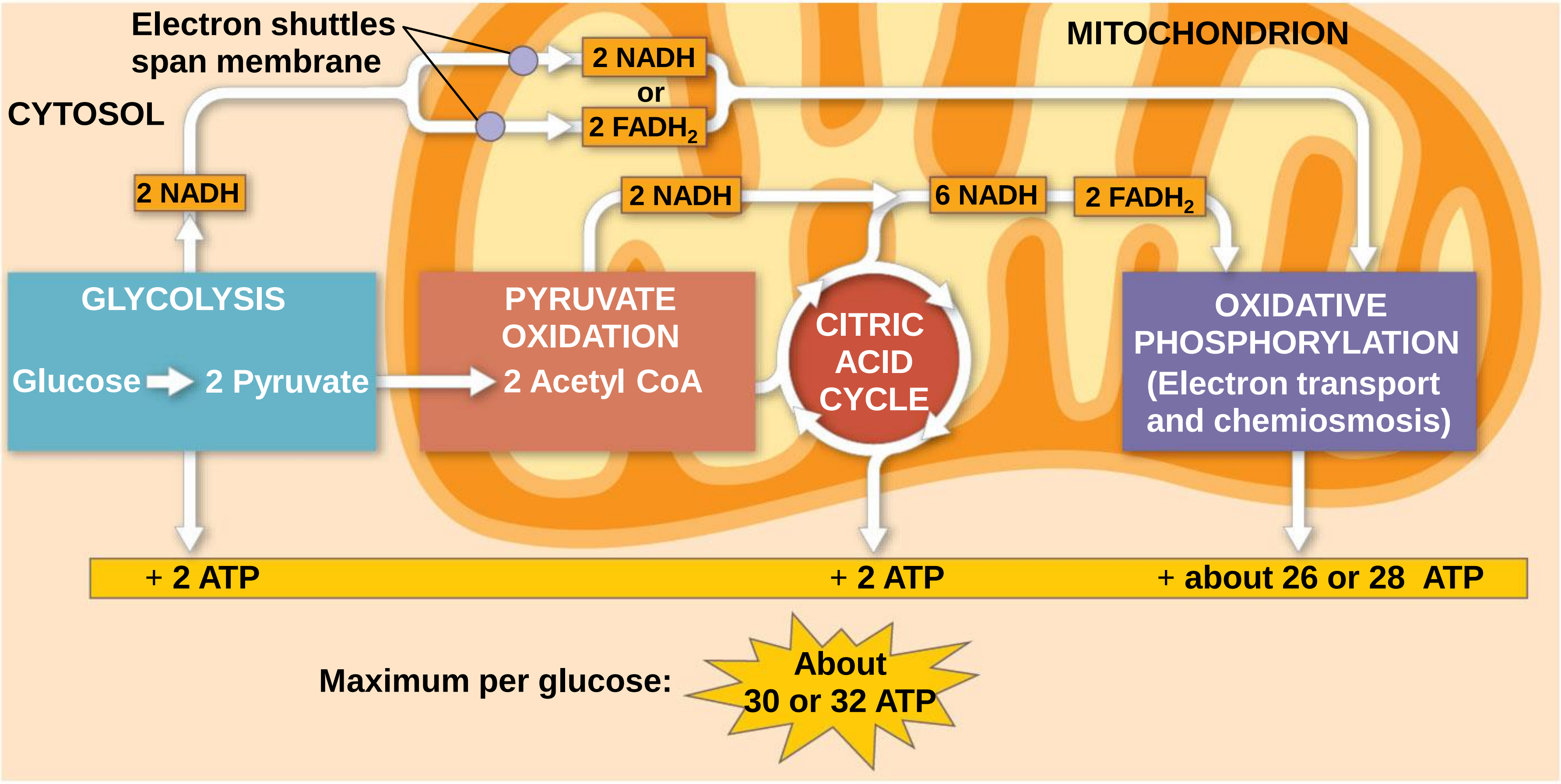

Electron shuttles
span membrane
MITOCHONDRION
CYTOSOL
2 NADH
or
2 FADH2
2 NADH
2 NADH
6 NADH
2 FADH2
GLYCOLYSIS
Glucose
2 Pyruvate
PYRUVATE
OXIDATION
2 Acetyl CoA
CITRIC
ACID
CYCLE
OXIDATIVE
PHOSPHORYLATION
(Electron transport
and chemiosmosis)
+ 2 ATP
+ 2 ATP
+ about 26 or 28 ATP
Maximum per glucose:
About
30 or 32 ATP

Figure 10.16a

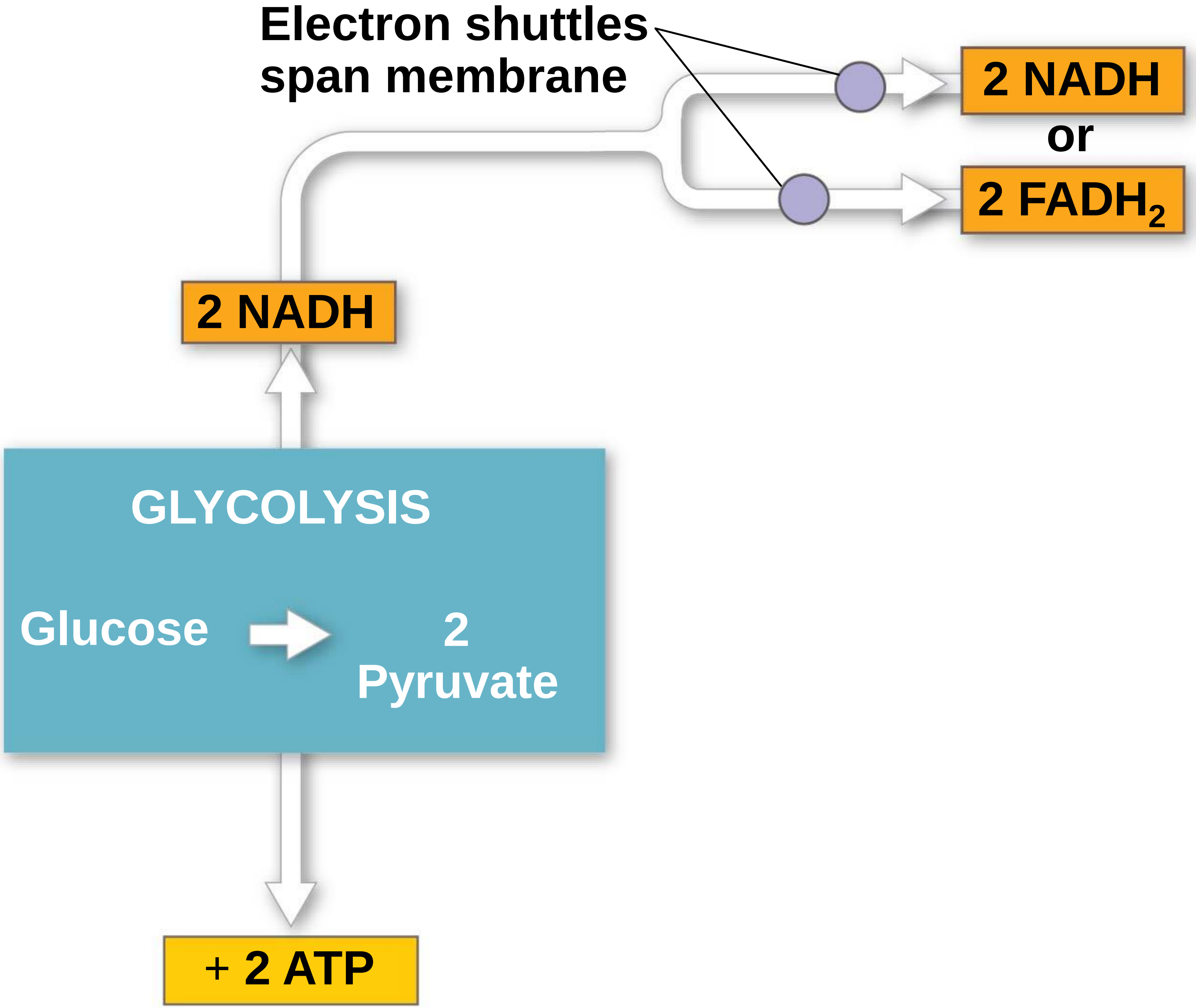


Figure 10.16b

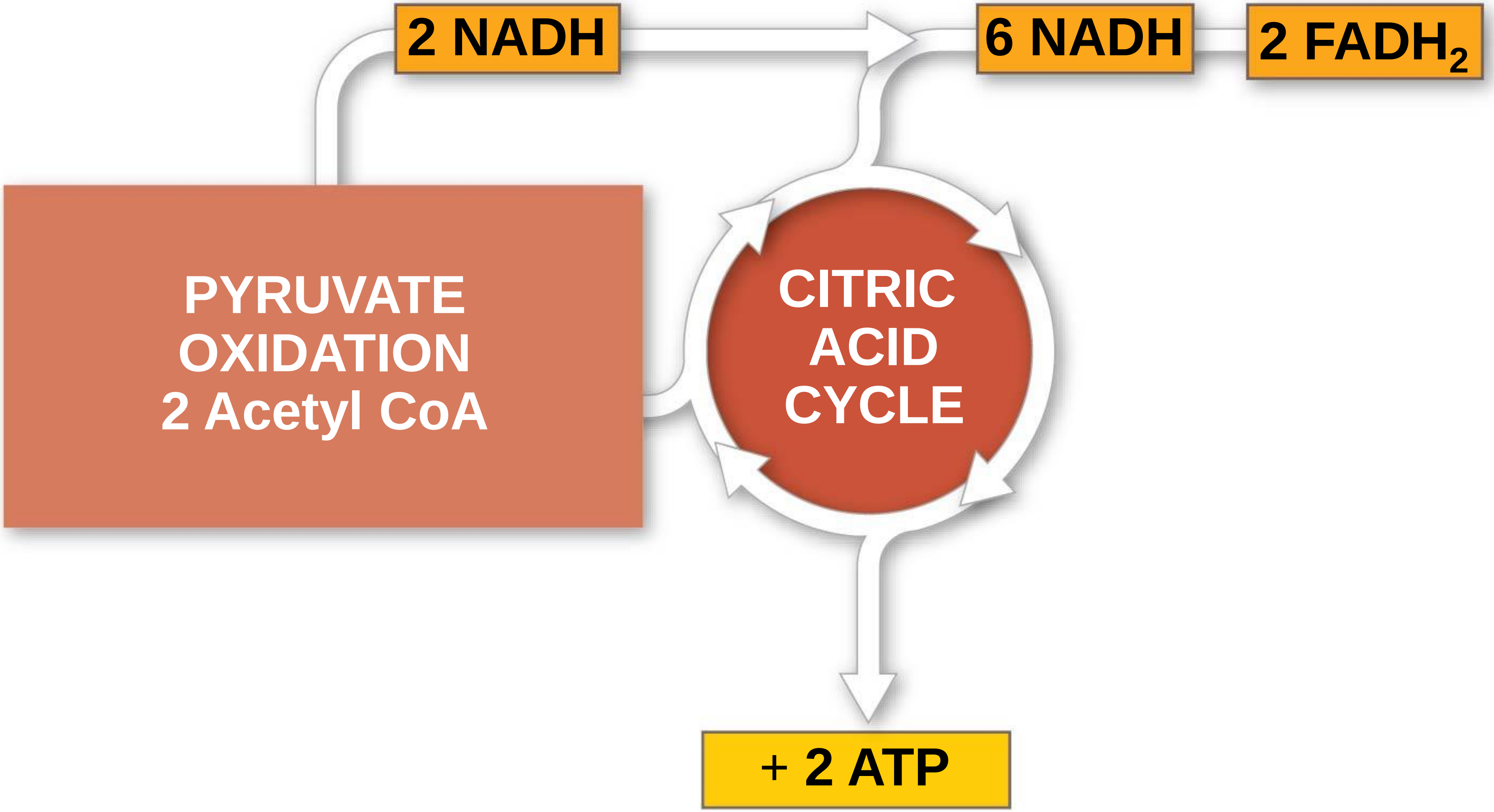


Figure 10.16c

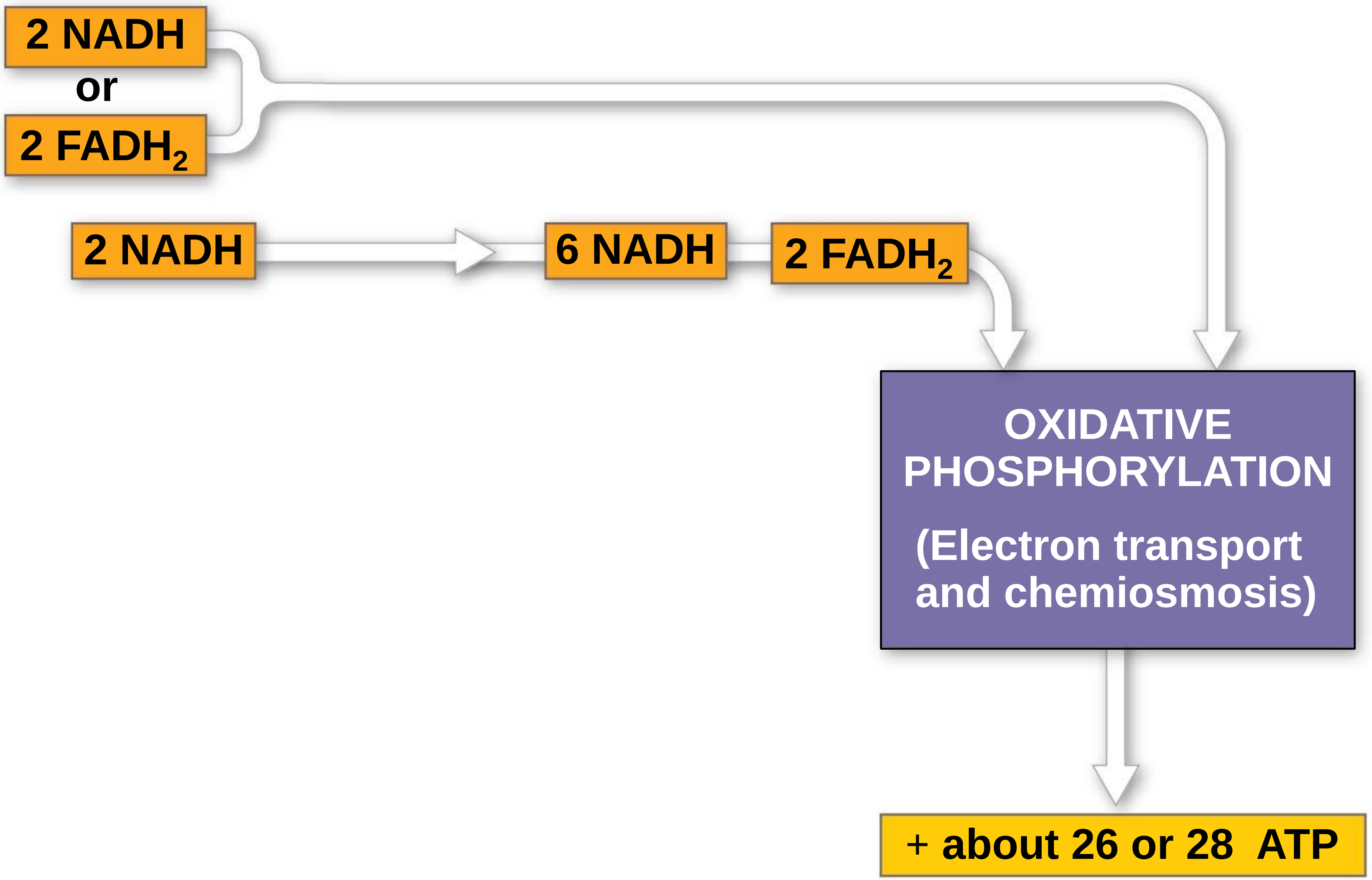


Figure 10.16d

Maximum per glucose:

About
30 or 32 ATP

- There are three reasons why the number of ATP is not known exactly
  1. Photophosphorylation and the redox reactions are not directly coupled; the ratio of NADH to ATP molecules is not a whole number
  2. ATP yield varies depending on whether electrons are passed to NAD^+ or FAD in the mitochondrial matrix
  3. The proton-motive force is also used to drive other kinds of work

Concept 10.5: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- Most cellular respiration depends on electronegative oxygen to pull electrons down the transport chain
- Without oxygen, the electron transport chain will cease to operate
- In that case, glycolysis couples with anaerobic respiration or fermentation to produce ATP

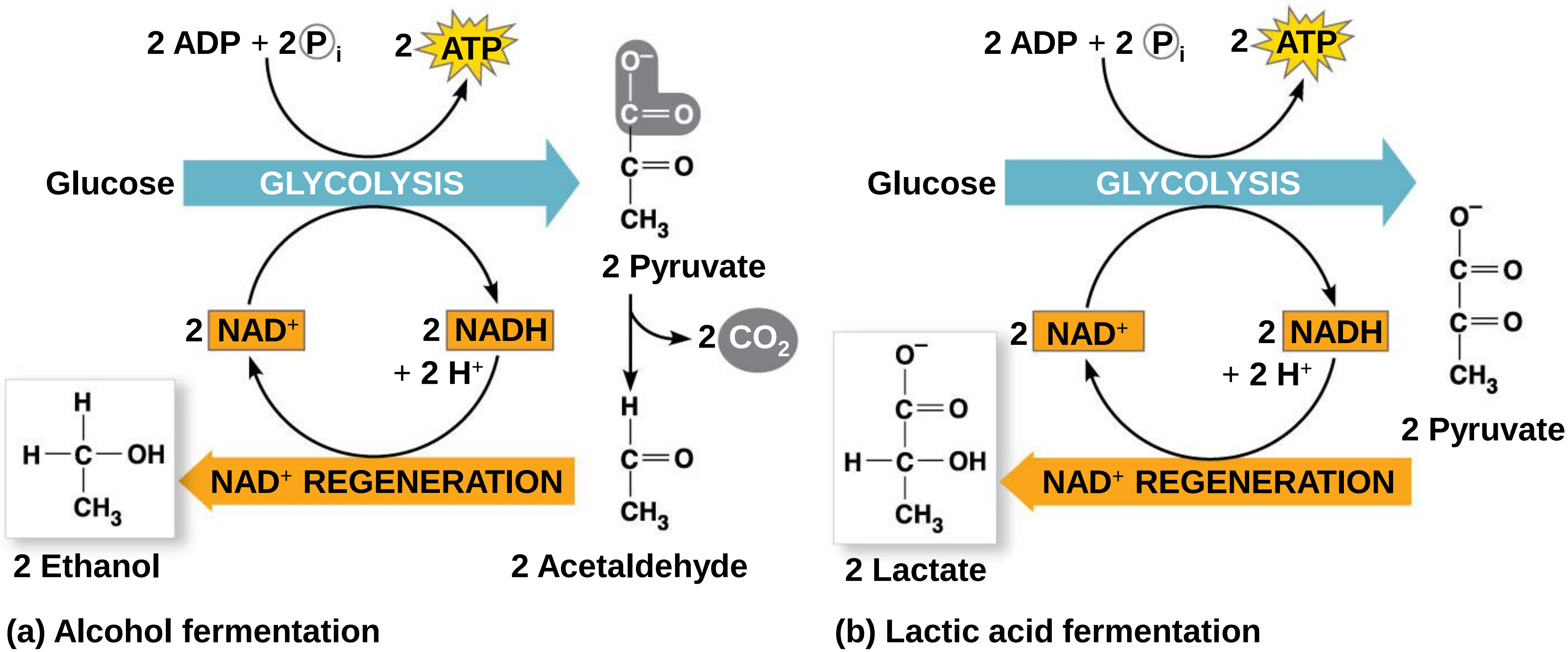
- Anaerobic respiration uses an electron transport chain with a final electron acceptor other than oxygen, for example, sulfate
- Fermentation uses substrate-level phosphorylation instead of an electron transport chain to generate ATP

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

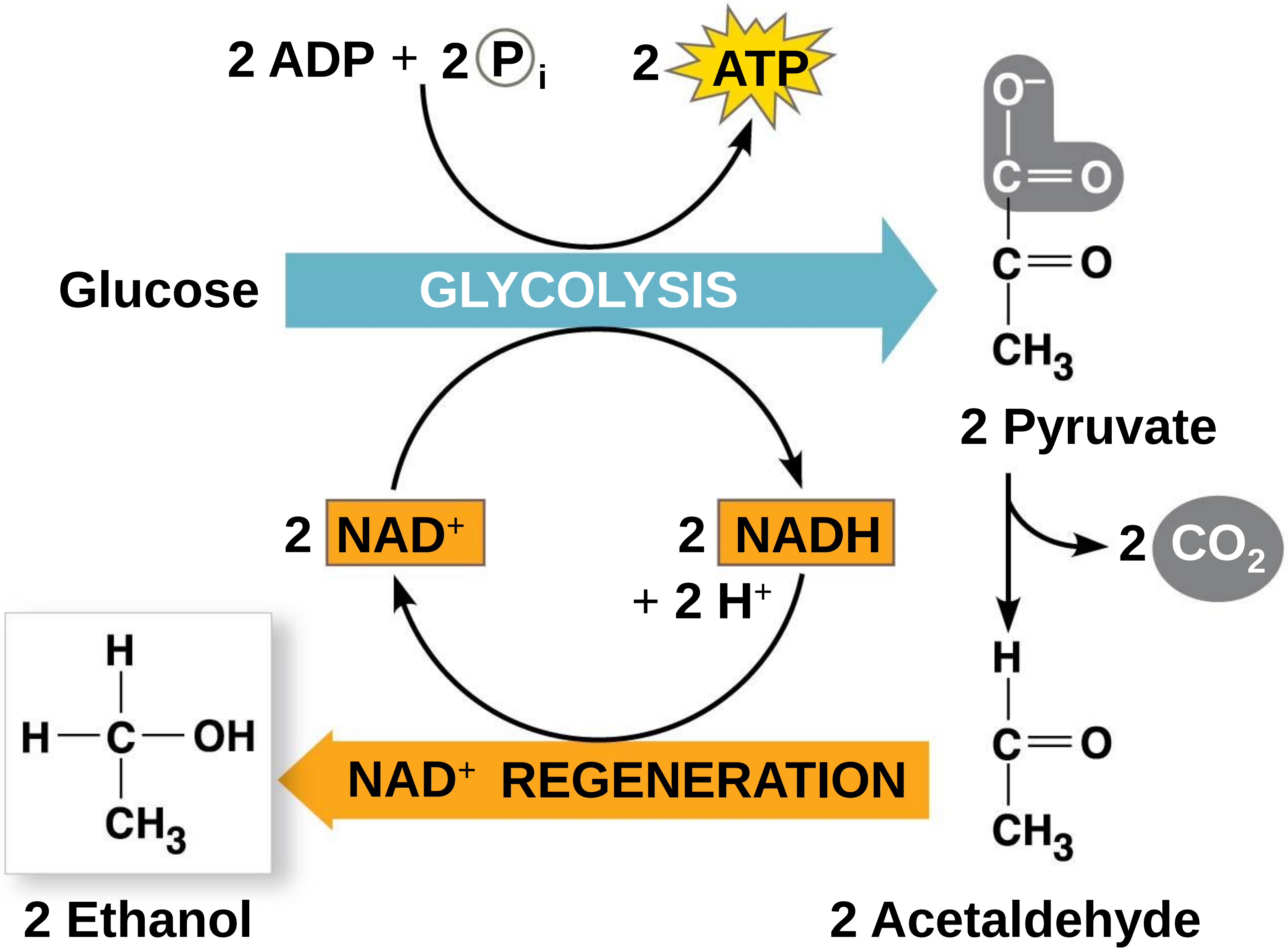
- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps
  - The first step releases CO_2 from pyruvate
  - The second step produces NAD^+ and ethanol
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking

Figure 10.17



2 ADP + 2 (P)i
2 ATP
Glucose
GLYCOLYSIS
O−
C=O
C=O
CH3
2 Pyruvate
2 NAD+
2 NADH
+ 2 H+
2 CO2
H
C=O
CH3
2 Acetaldehyde
H
H—C—OH
H
CH3
NAD+ REGENERATION
2 Ethanol
(a) Alcohol fermentation
2 ADP + 2 (P)i
2 ATP
Glucose
GLYCOLYSIS
O−
C=O
C=O
CH3
2 Pyruvate
2 NAD+
2 NADH
+ 2 H+
O−
C=O
H—C—OH
CH3
NAD+ REGENERATION
2 Lactate
(b) Lactic acid fermentation

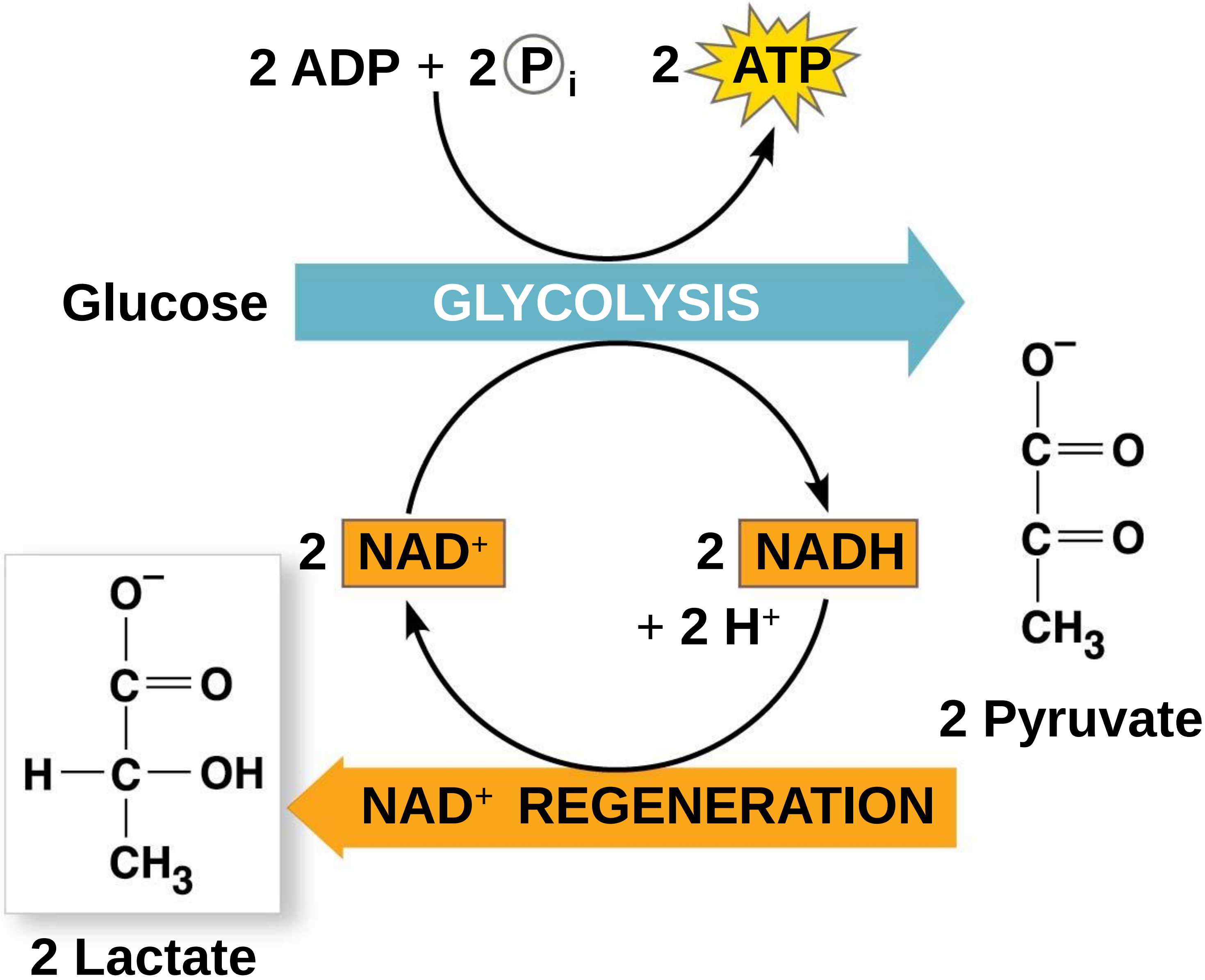
Figure 10.17a



(a) Alcohol fermentation

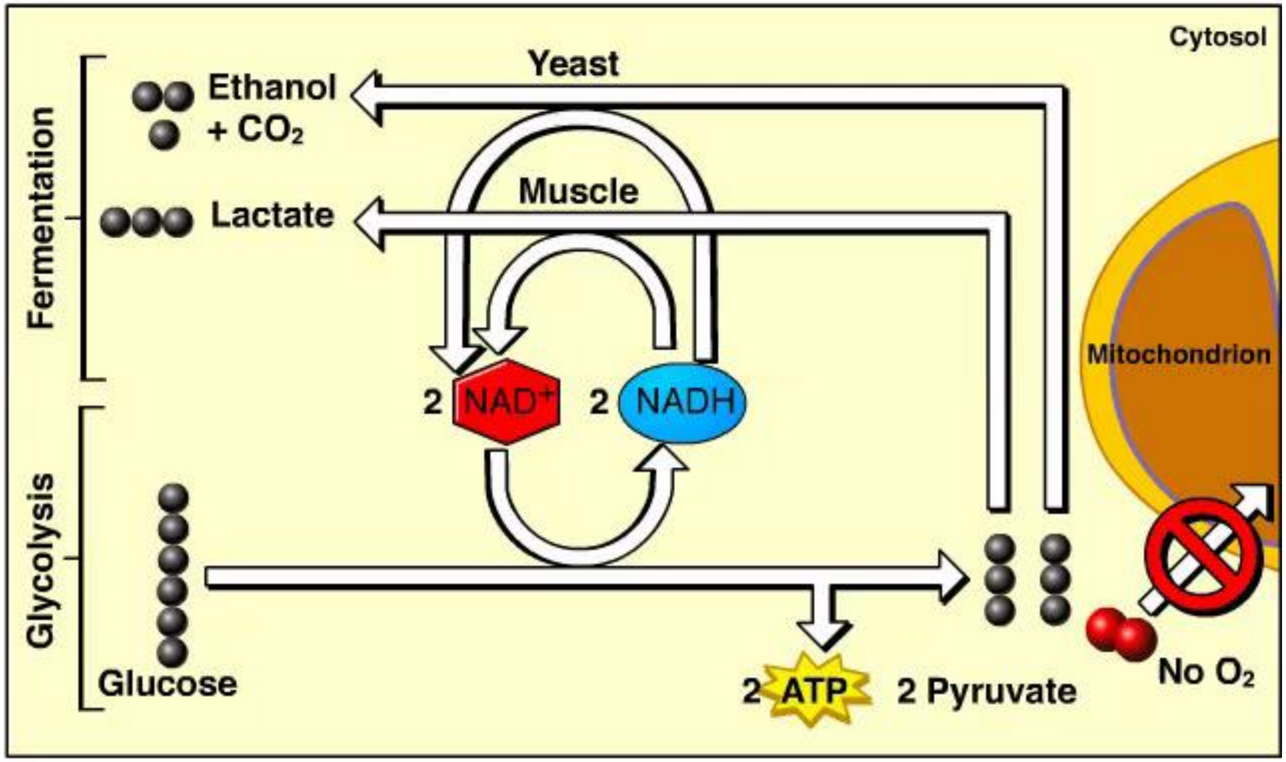
- In **lactic acid fermentation**, pyruvate is reduced by NADH, forming NAD^+ and lactate as end products, with no release of CO_2
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
- Human muscle cells use lactic acid fermentation to generate ATP during strenuous exercise when O_2 is scarce

Figure 10.17b



(b) Lactic acid fermentation

Animation: Fermentation Overview



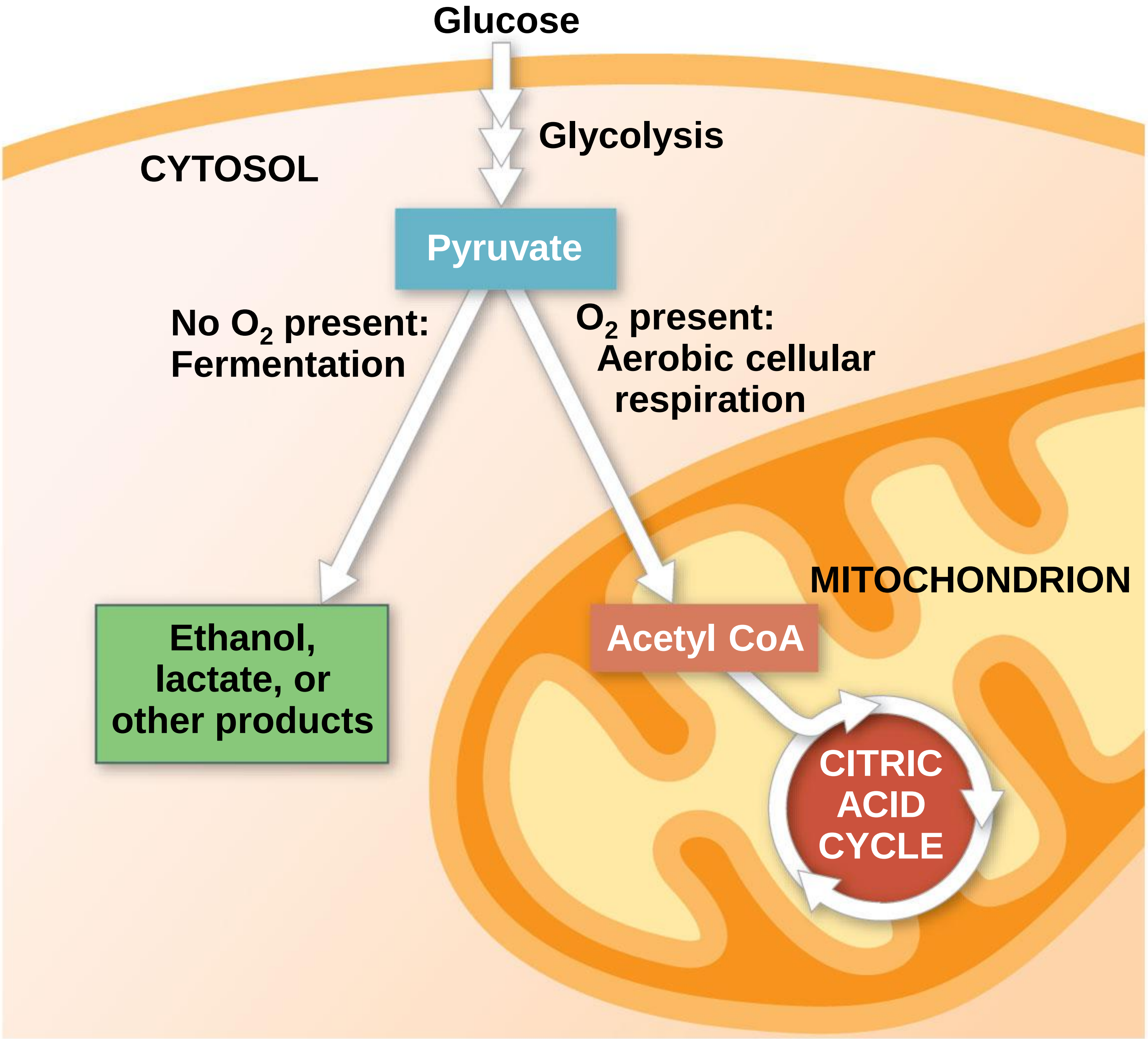
Comparing Fermentation with Anaerobic and Aerobic Respiration

- All use glycolysis (net ATP = 2) to oxidize glucose and harvest the chemical energy of food
- In all three, NAD^+ is the oxidizing agent that accepts electrons during glycolysis

- The processes have different mechanisms for oxidizing NADH to NAD^+:
  - In fermentation, an organic molecule (such as pyruvate or acetaldehyde) acts as a final electron acceptor
  - In cellular respiration, electrons are transferred to the electron transport chain
- 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 10.18


Glucose
Glycolysis
CYTOSOL
Pyruvate
No O_2 present:
Fermentation
O_2 present:
Aerobic cellular
respiration
MITOCHONDRION
Ethanol,
lactate, or
other products
Acetyl CoA
CITRIC
ACID
CYCLE

The Evolutionary Significance of Glycolysis

- Glycolysis is an ancient process
- Early prokaryotes likely used glycolysis to produce ATP before O_2 accumulated in the atmosphere
- Used in both cellular respiration and fermentation, it is the most widespread metabolic pathway on Earth
- This pathway occurs in the cytosol so does not require the membrane-bound organelles of eukaryotic cells

Concept 10.6: 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 including starch, glycogen, and several disaccharides
- Proteins that are used for fuel must be digested to amino acids and their amino groups must be removed

- Fats are digested to glycerol (used to produce compounds needed for glycolysis) and fatty acids
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA, NADH, and $FADH_2$
- An oxidized gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate

Figure 10.19_1

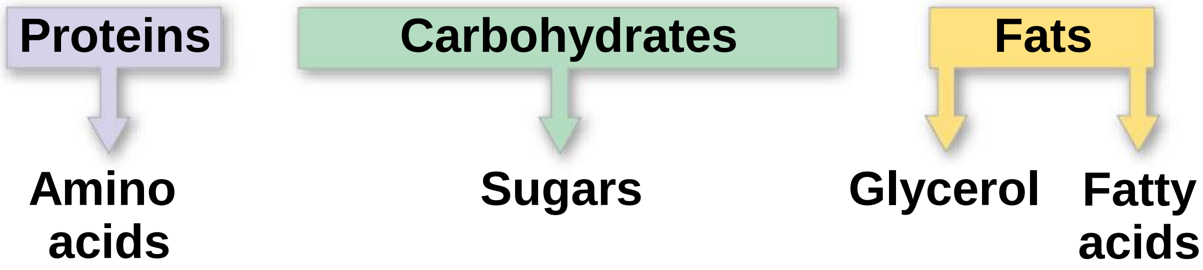


Figure 10.19_2

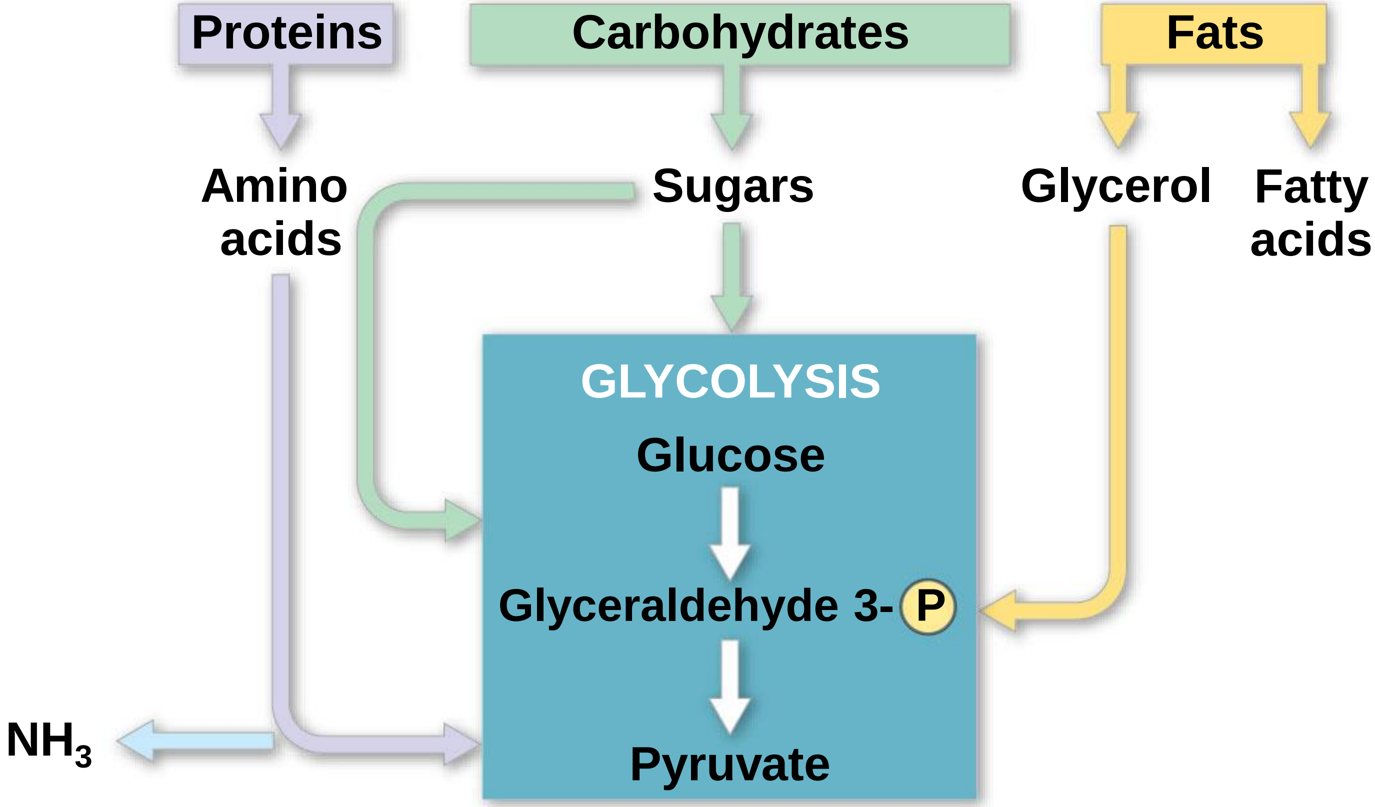


Figure 10.19_3

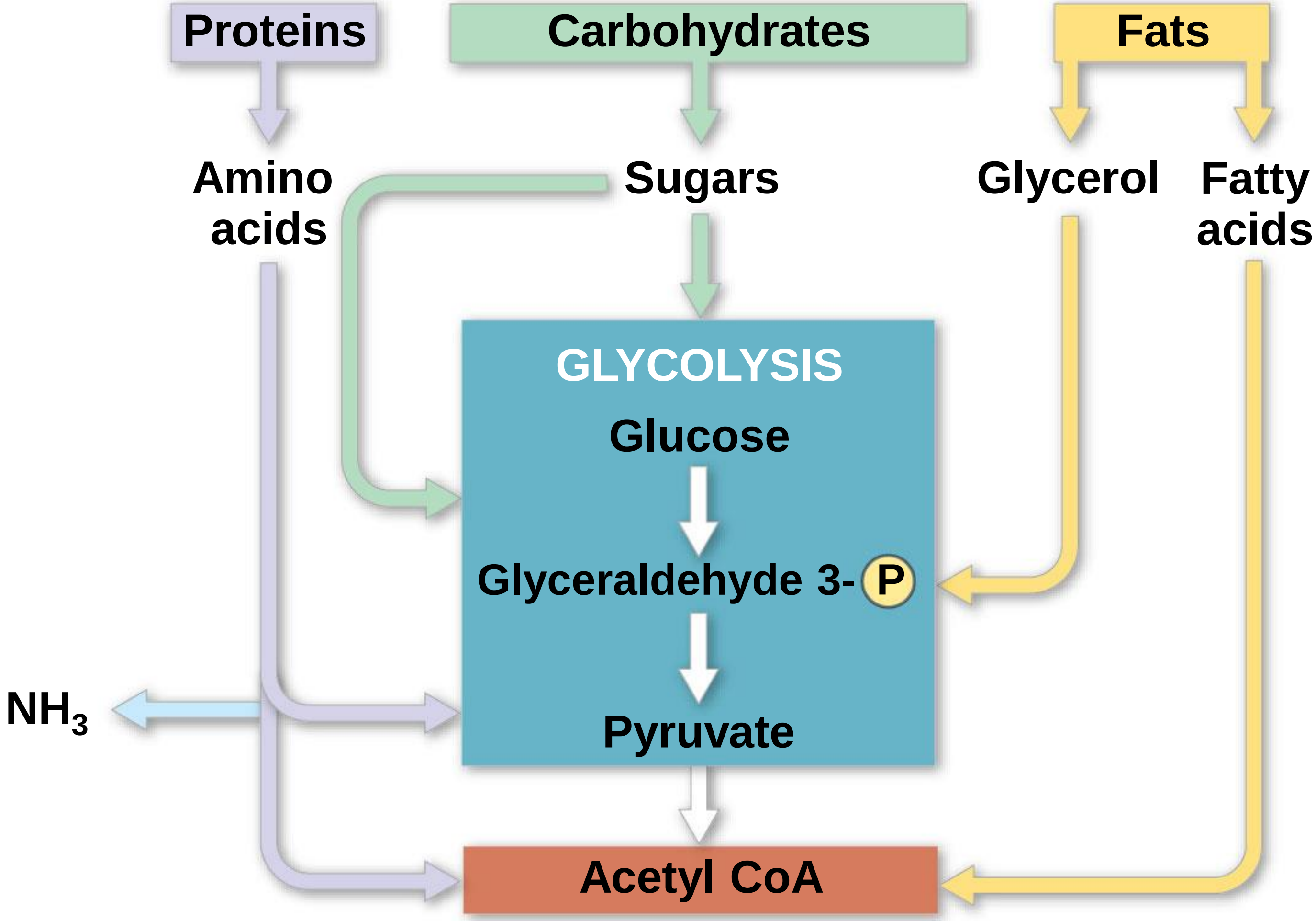


Figure 10.19_4

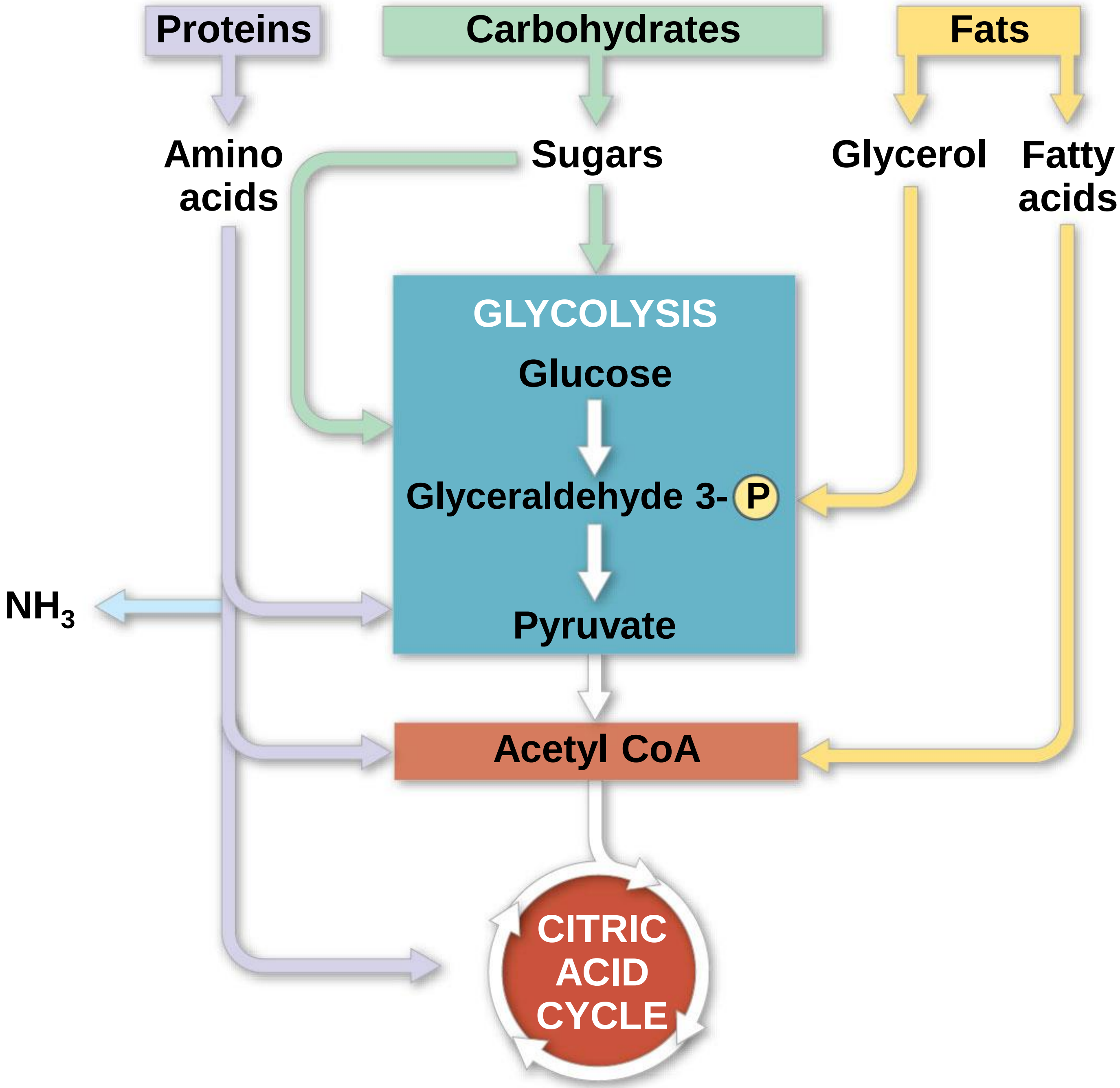
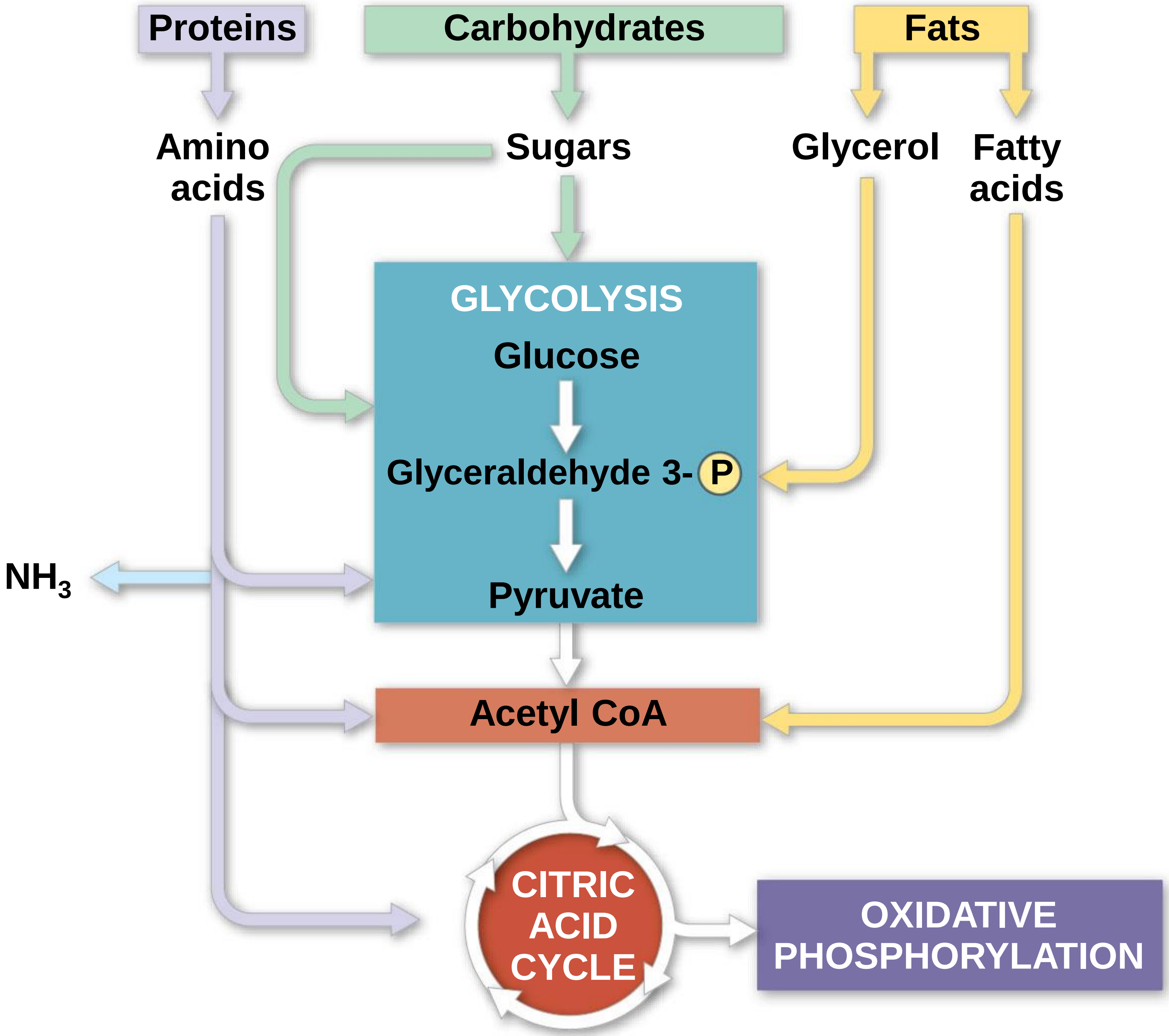


Figure 10.19_5



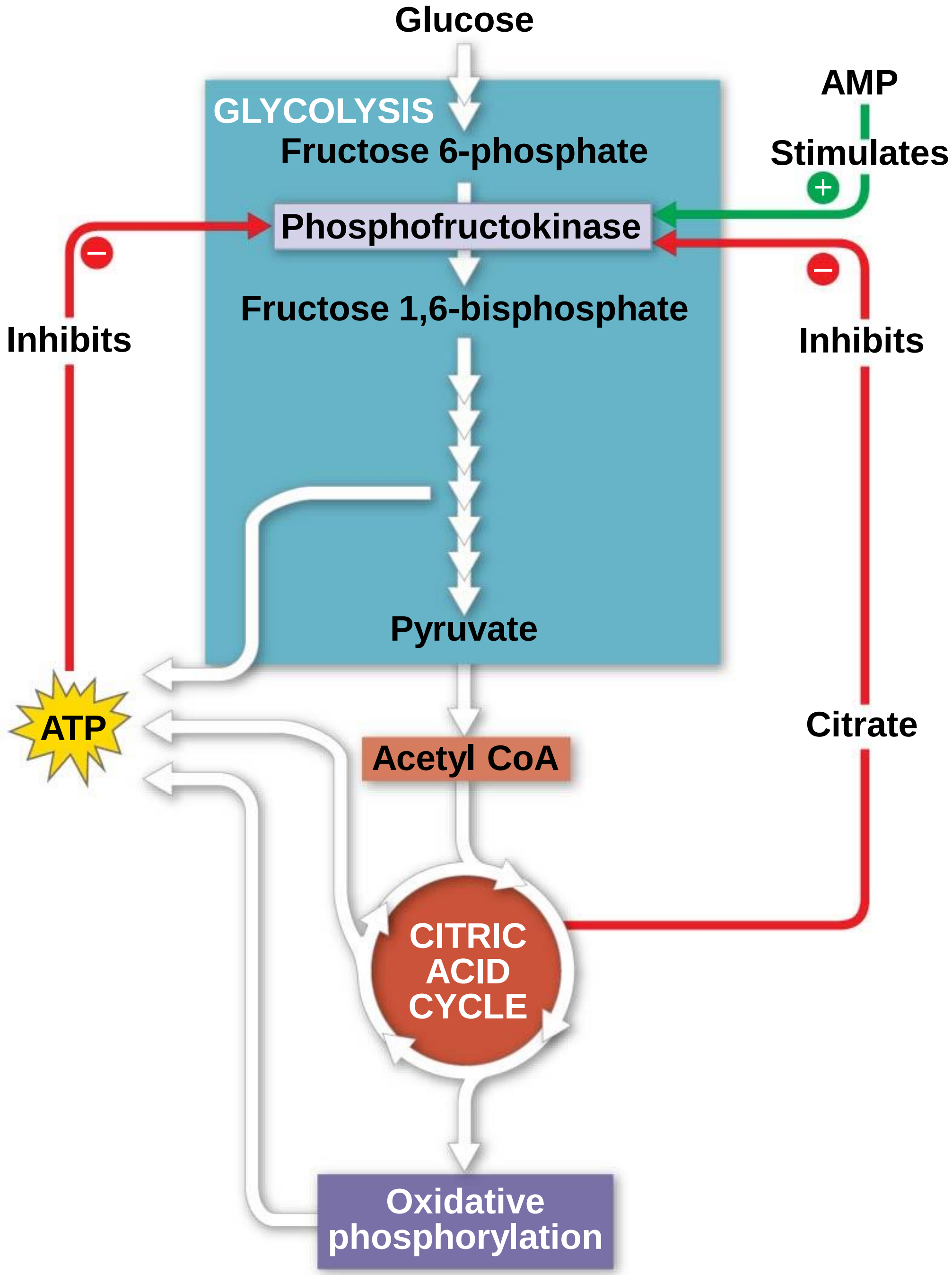
Biosynthesis (Anabolic Pathways)

- The body uses small molecules from food to build other their own molecules such as proteins
- 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 metabolic 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 10.20



Glucose
GLYCOLYSIS
Fructose 6-phosphate
AMP
Stimulates
Phosphofructokinase
Inhibits
Fructose 1,6-bisphosphate
Inhibits
Pyruvate
ATP
Acetyl CoA
Citrate
CITRIC
ACID
CYCLE
Oxidative
phosphorylation

Figure 10.UN10a

Data from the Experiment

Thyroid Hormone Level	Oxygen Consumption Rate [nmol O_2/(min · mg cells)]
Low	4.3
Normal	4.8
Elevated	8.7

Data from M. E. Harper and M. D. Brand, The quantitative contributions of mitochondrial proton leak and ATP turnover reactions to the changed respiration rates of hepatocytes from rats of different thyroid status, *Journal of Biological Chemistry* 268:14850–14860 (1993).

Figure 10.UN10b

Figure 10.UN11

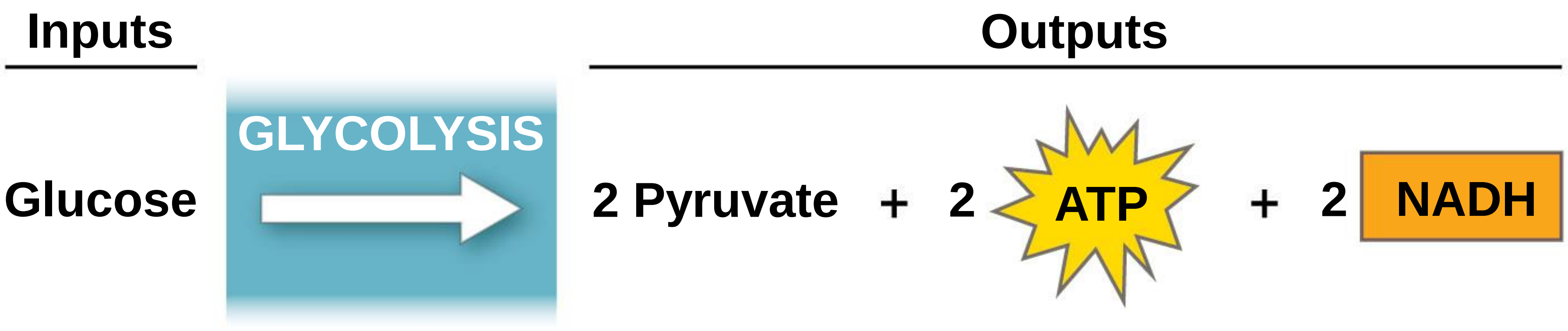


Figure 10.UN12

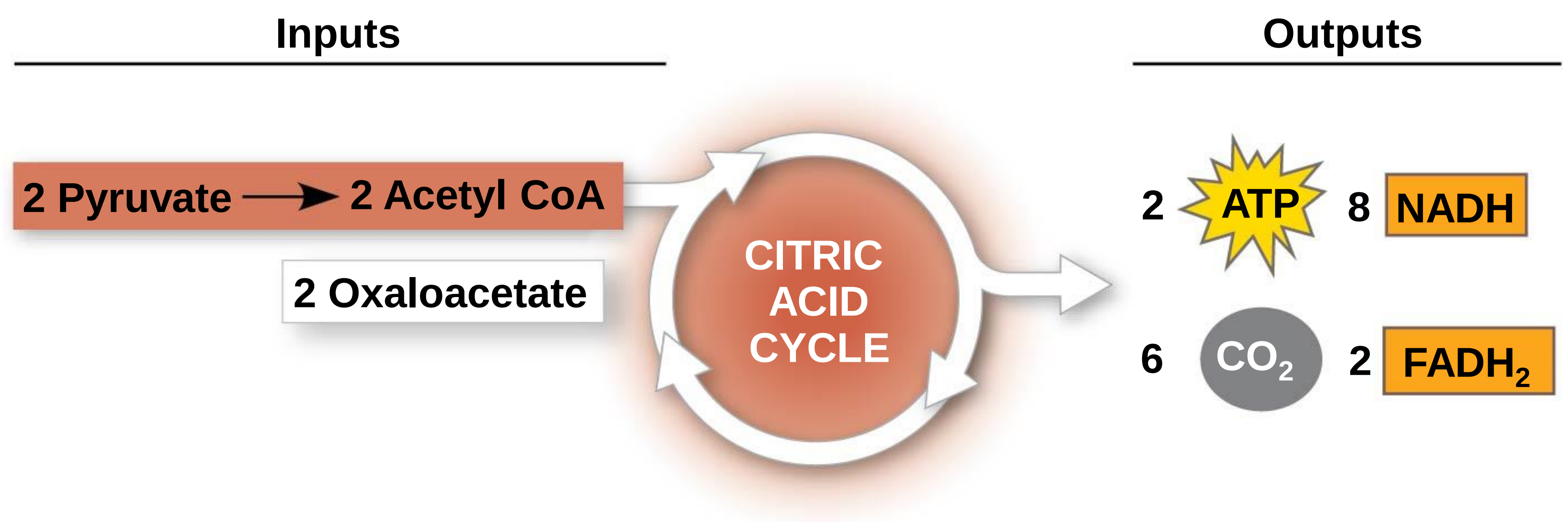


Figure 10.UN13

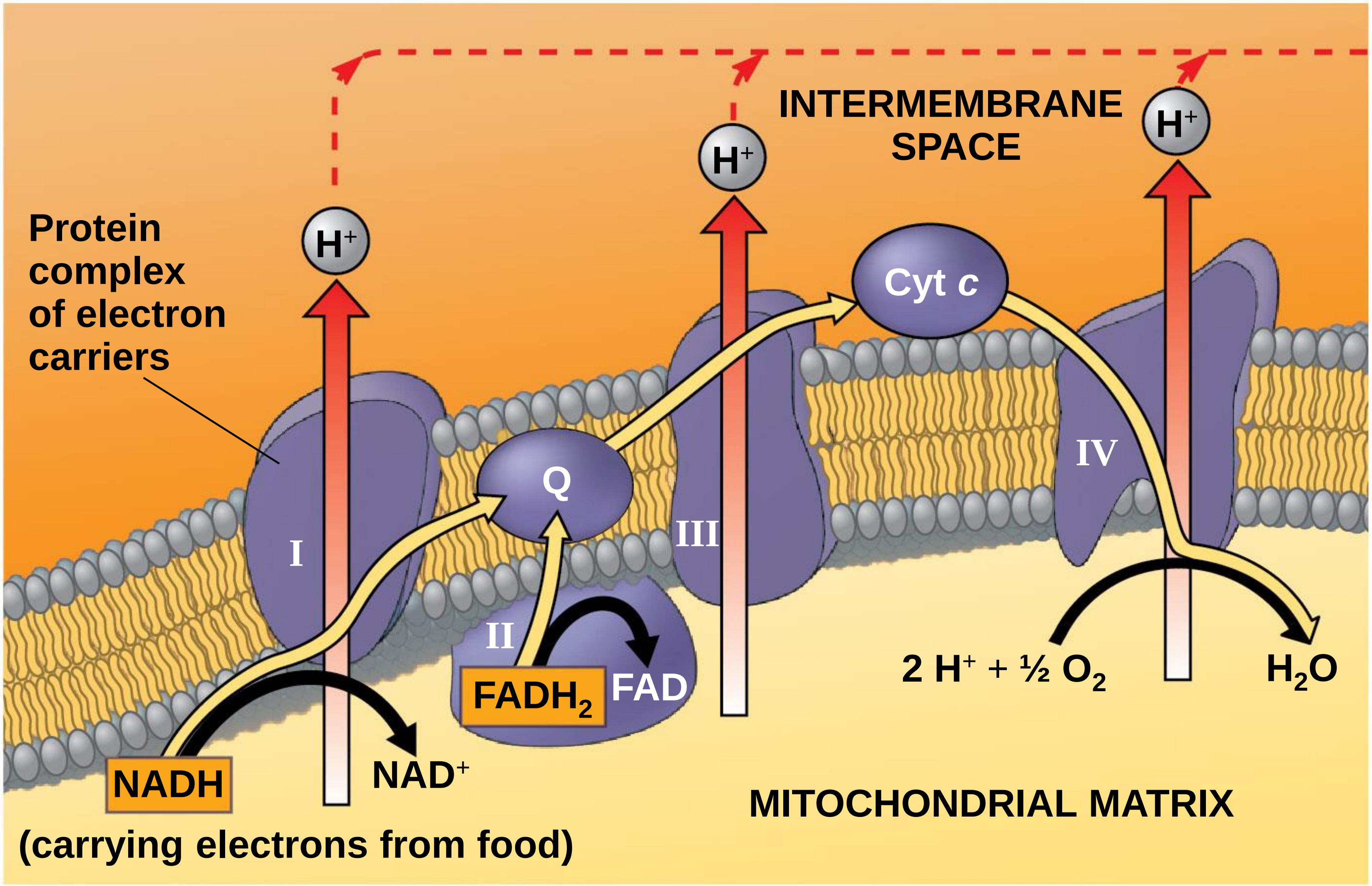


Figure 10.UN14

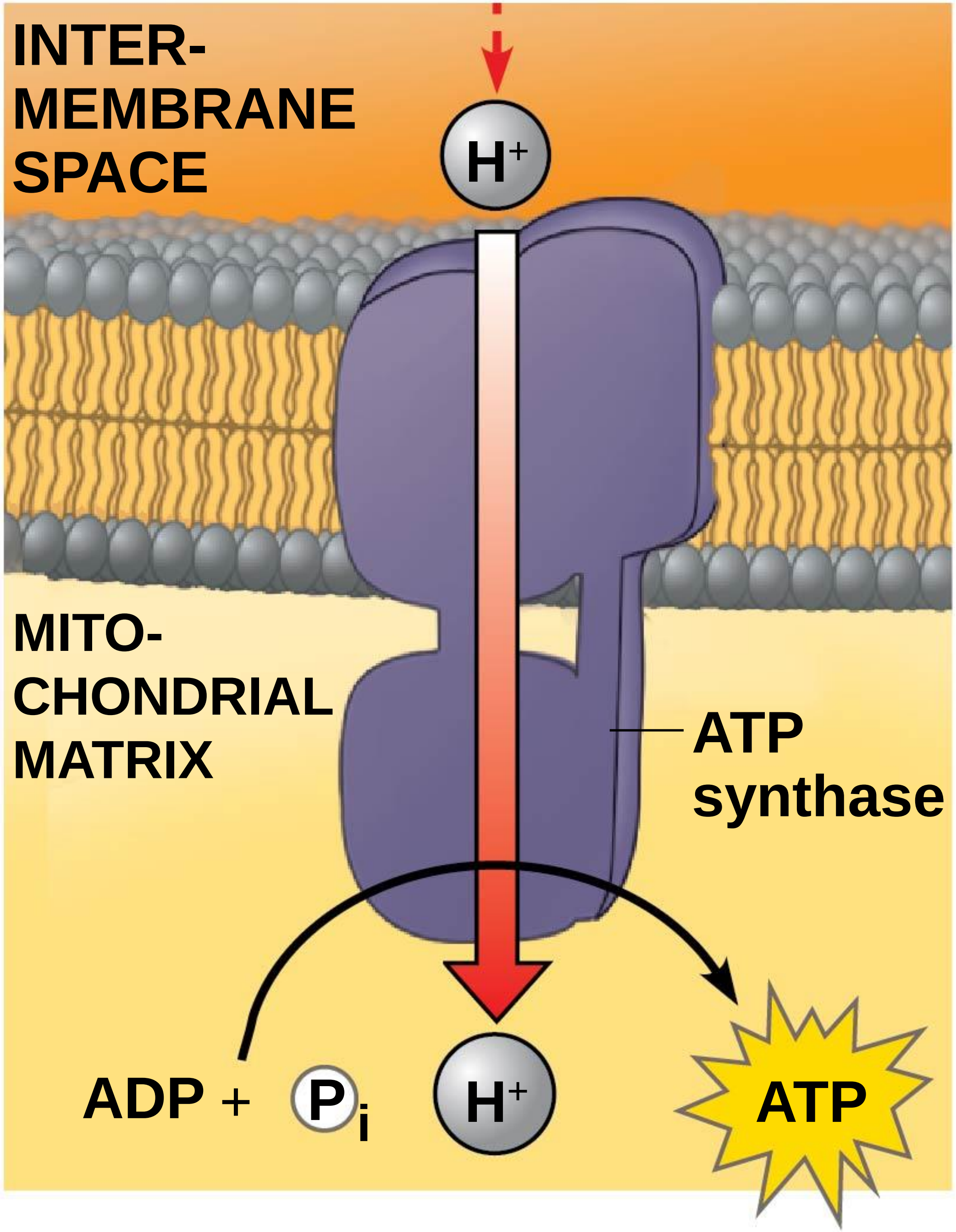


Figure 10.UN15

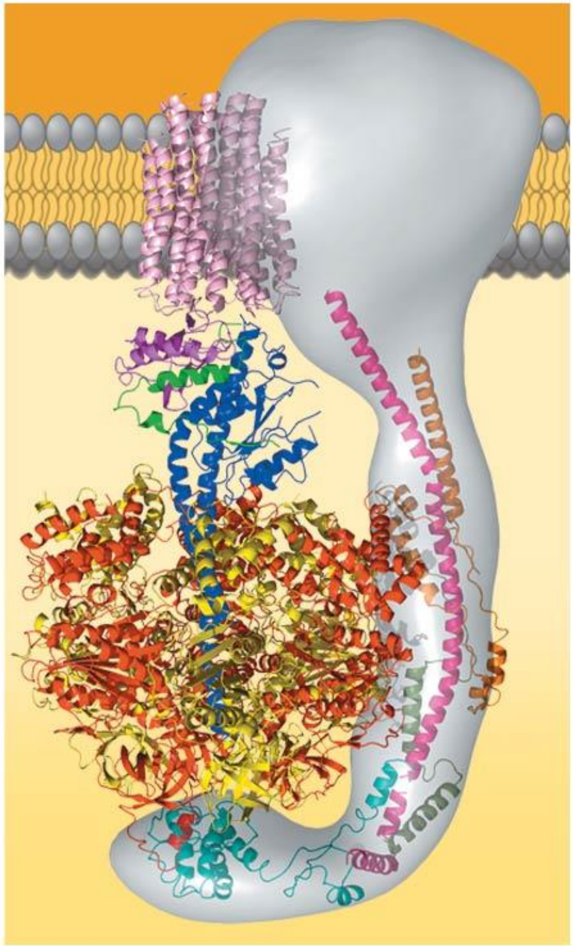


Figure 10.UN16

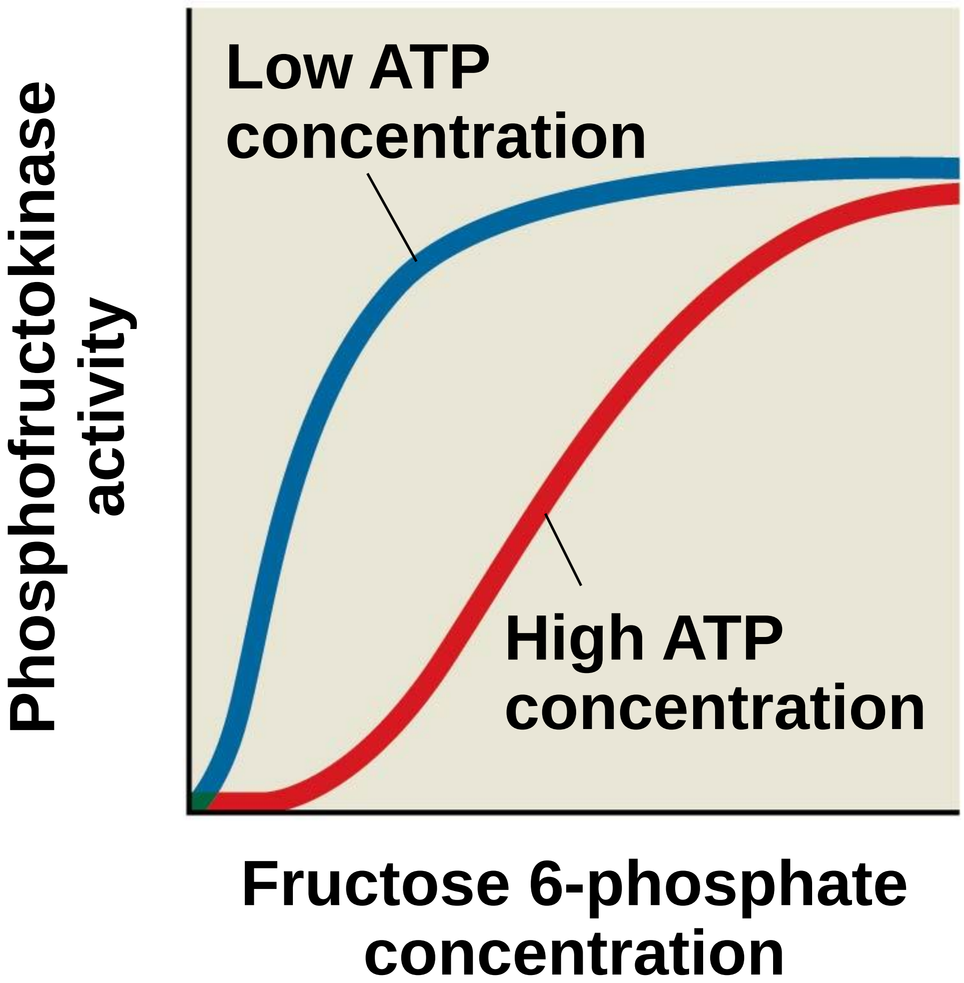


Figure 10.UN17

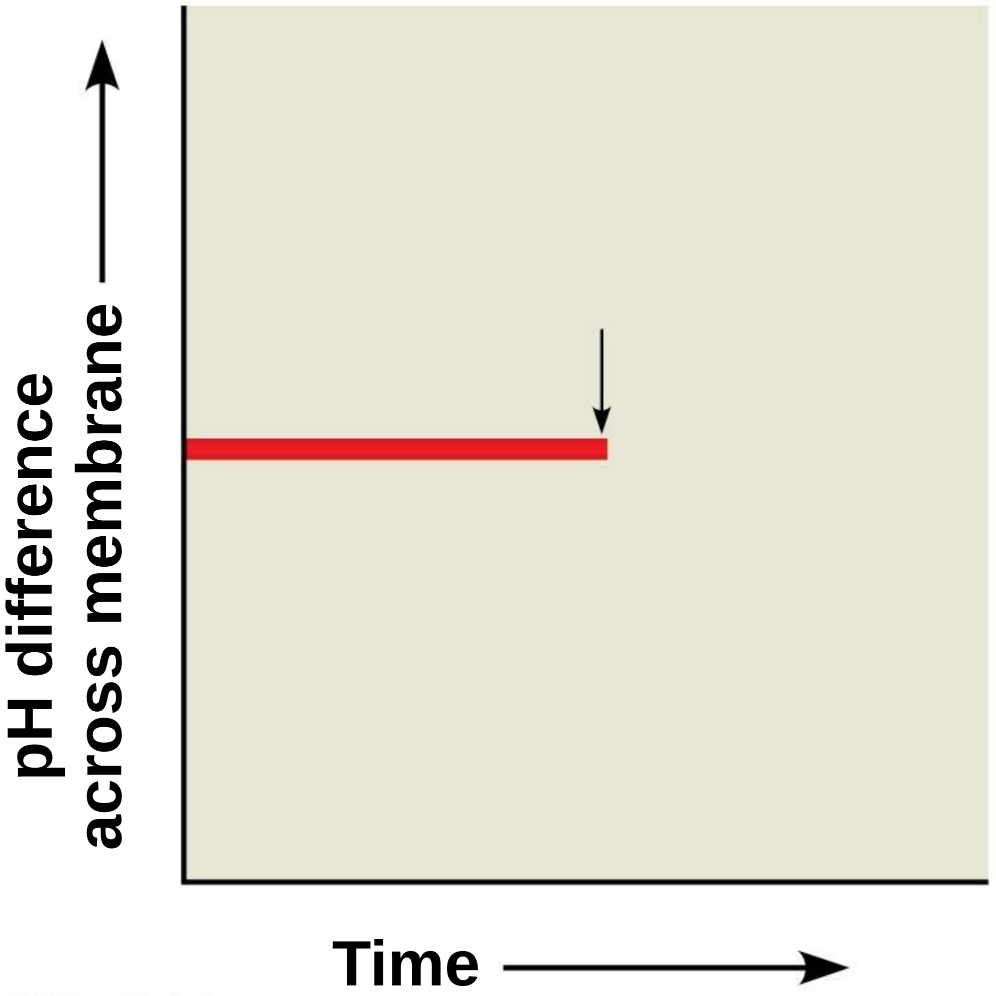


Figure 10.UN18