LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
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Chapter 9

Cellular Respiration and Fermentation

Lectures by
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Overview: Life Is Work

- **Living cells require energy from outside sources**

- **Some animals, such as the giant panda, obtain energy by eating plants, and some animals feed on other organisms that eat plants**

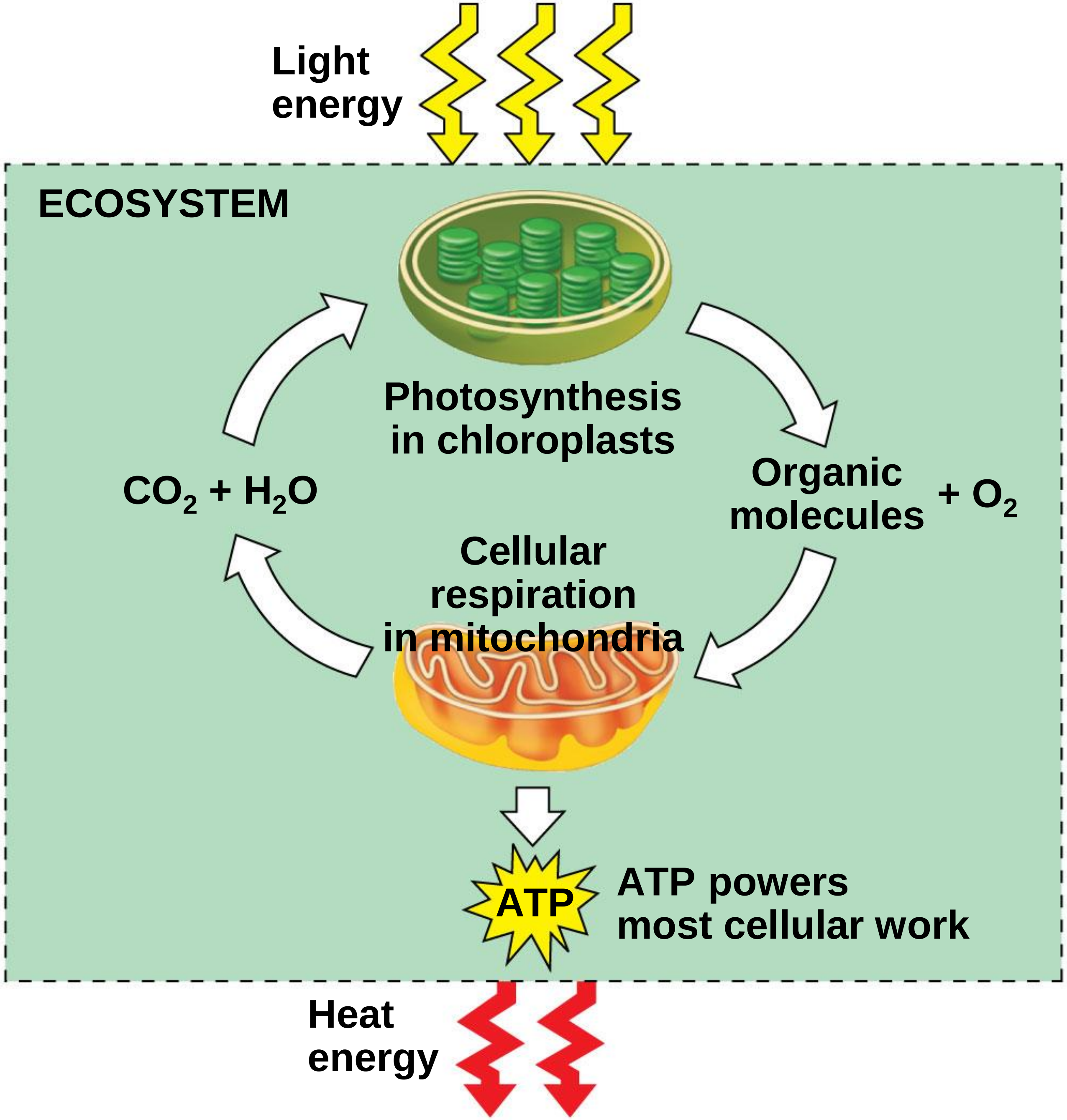
Figure 9.1

- **Energy flows into an ecosystem as sunlight and leaves as heat**

- **Photosynthesis generates O_2 and organic molecules, which are used in cellular respiration**

- **Cells use chemical energy stored in organic molecules to regenerate ATP, which powers work**

Figure 9.2


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

Concept 9.1: Catabolic pathways yield energy by oxidizing organic fuels

- 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

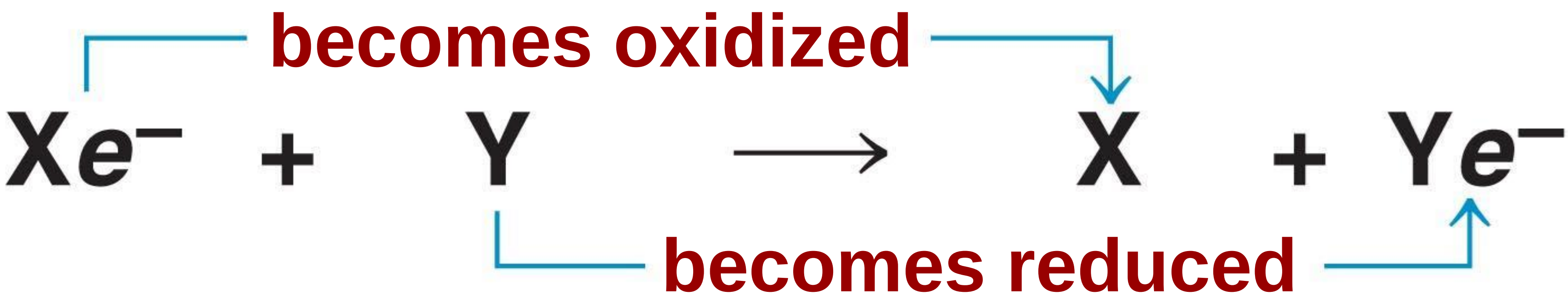
- **Chemical reactions that transfer electrons between reactants are called *oxidation-reduction reactions, or redox reactions***

- **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*)**

Fig. 9-UN2

Example: $Na + Cl$ □ $Na^+ + Cl^-$



The electron donor is called the
reducing agent

The electron receptor is called the
oxidizing agent

Oxidation of Organic Fuel Molecules During Cellular Respiration

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

Fig. 9-UN3

becomes oxidized

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

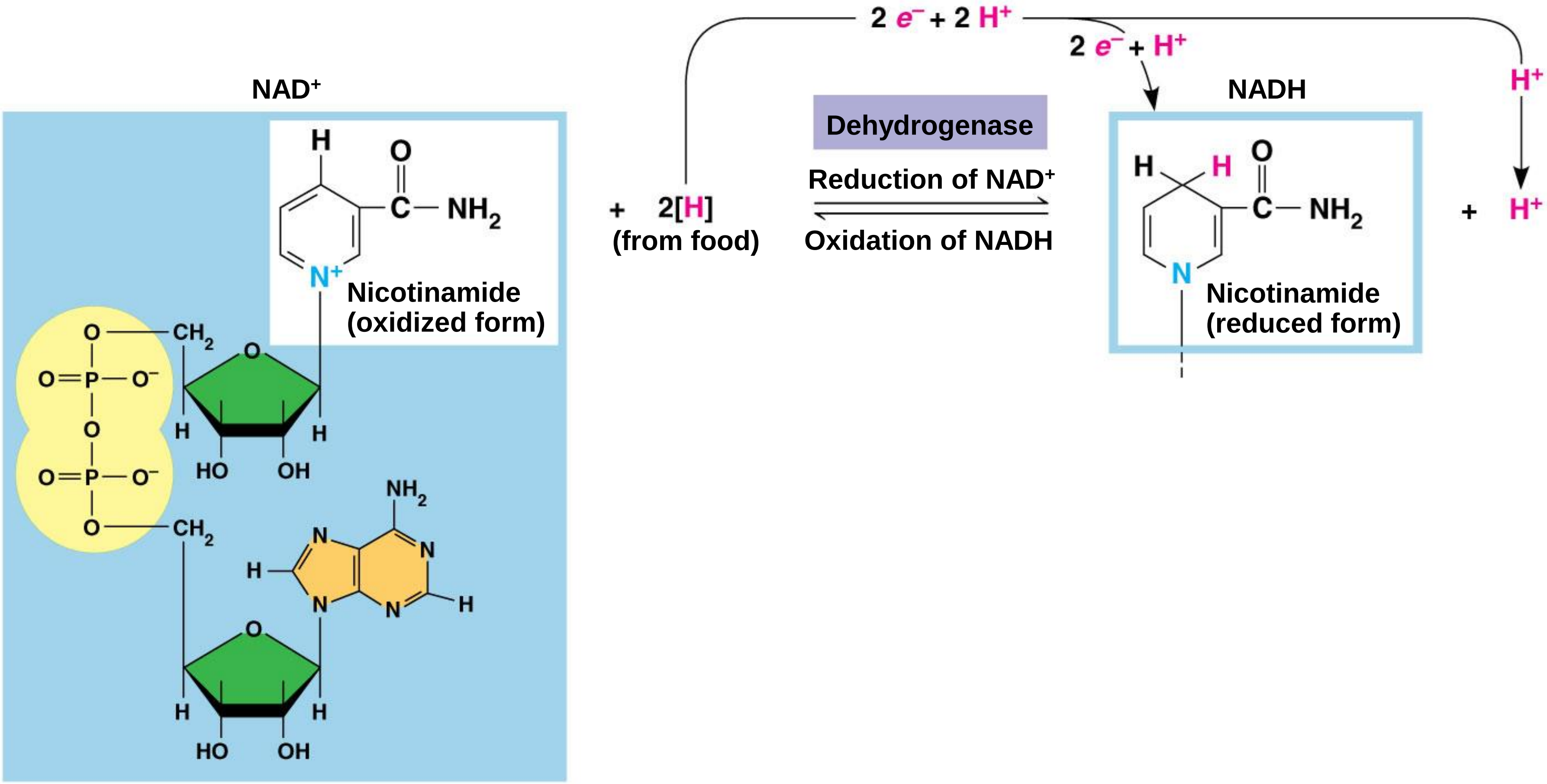
becomes reduced

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 <u>reduced form of NAD^+</u>) represents stored energy that is tapped to synthesize ATP**

Figure 9.4



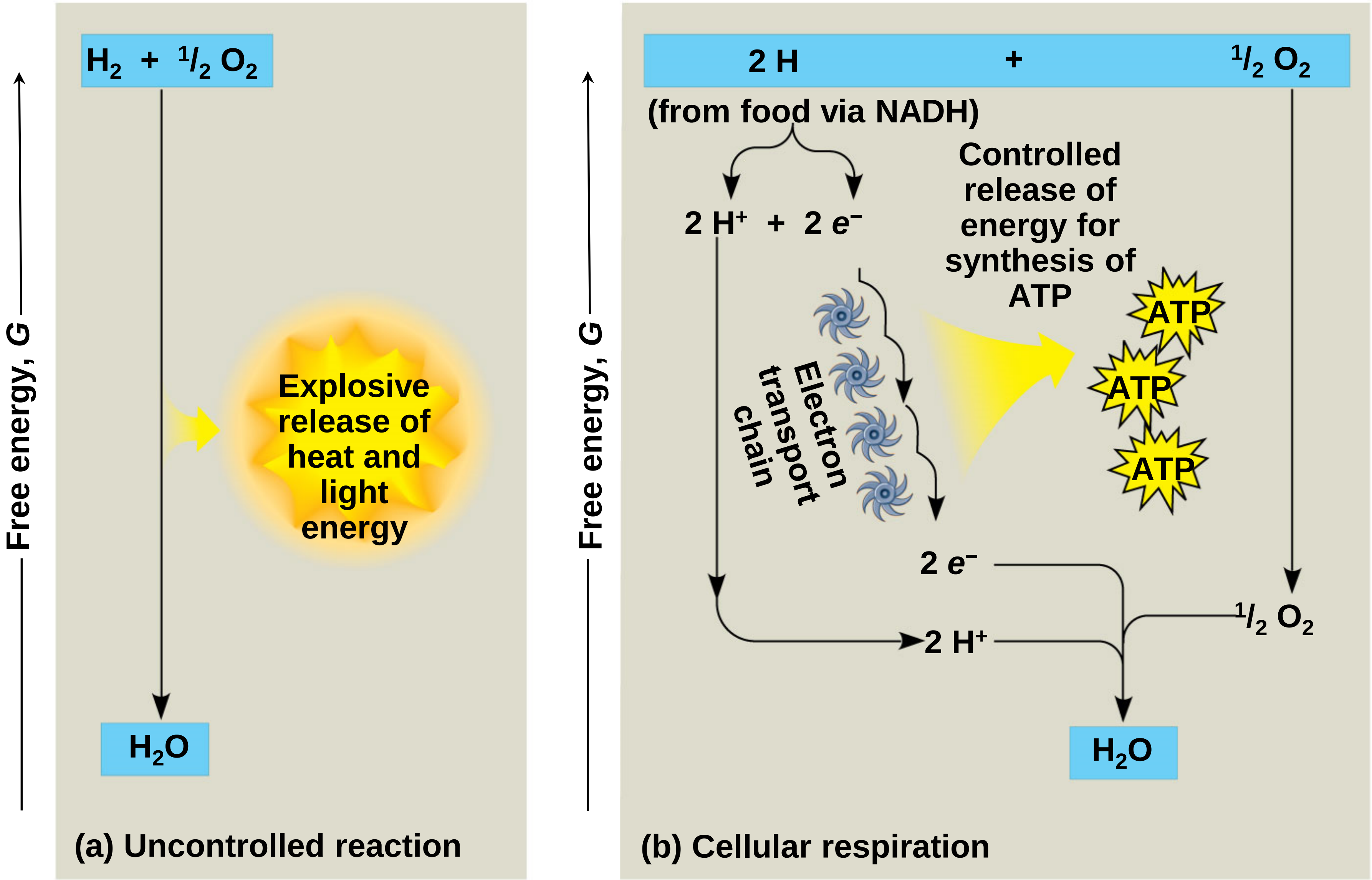
NAD+
NADH
Dehydrogenase
Reduction of NAD+
Oxidation of NADH
2 e− + 2 H+
2 e− + H+
H+
+ 2[H]
(from food)
+ H+
Nicotinamide
(oxidized form)
Nicotinamide
(reduced form)

- **NADH passes the electrons to the electron transport chain**

- **Unlike an uncontrolled reaction, *the electron transport chain <u>passes electrons in a series of steps</u> instead of one explosive reaction***

- <u>O_2 pulls electrons down the chain</u> in an energy-yielding **tumble**
- The energy yielded is used to **regenerate ATP**

Figure 9.5



Free energy, G
H2 + 1/2 O2
Explosive release of heat and light energy
H2O
(a) Uncontrolled reaction
Free energy, G
2 H + 1/2 O2
(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 O2
2 H+
H2O
(b) Cellular respiration

Stages of Cellular Respiration: *A Preview*

- Cellular respiration has <u>three stages:</u>
  - **Glycolysis** (breaks down <u>glucose into two</u> molecules of pyruvate)
  - The **citric acid cycle** (completes the breakdown of glucose)
  - **Oxidative phosphorylation** (accounts for most of the ATP synthesis)

Figure 9.6-1

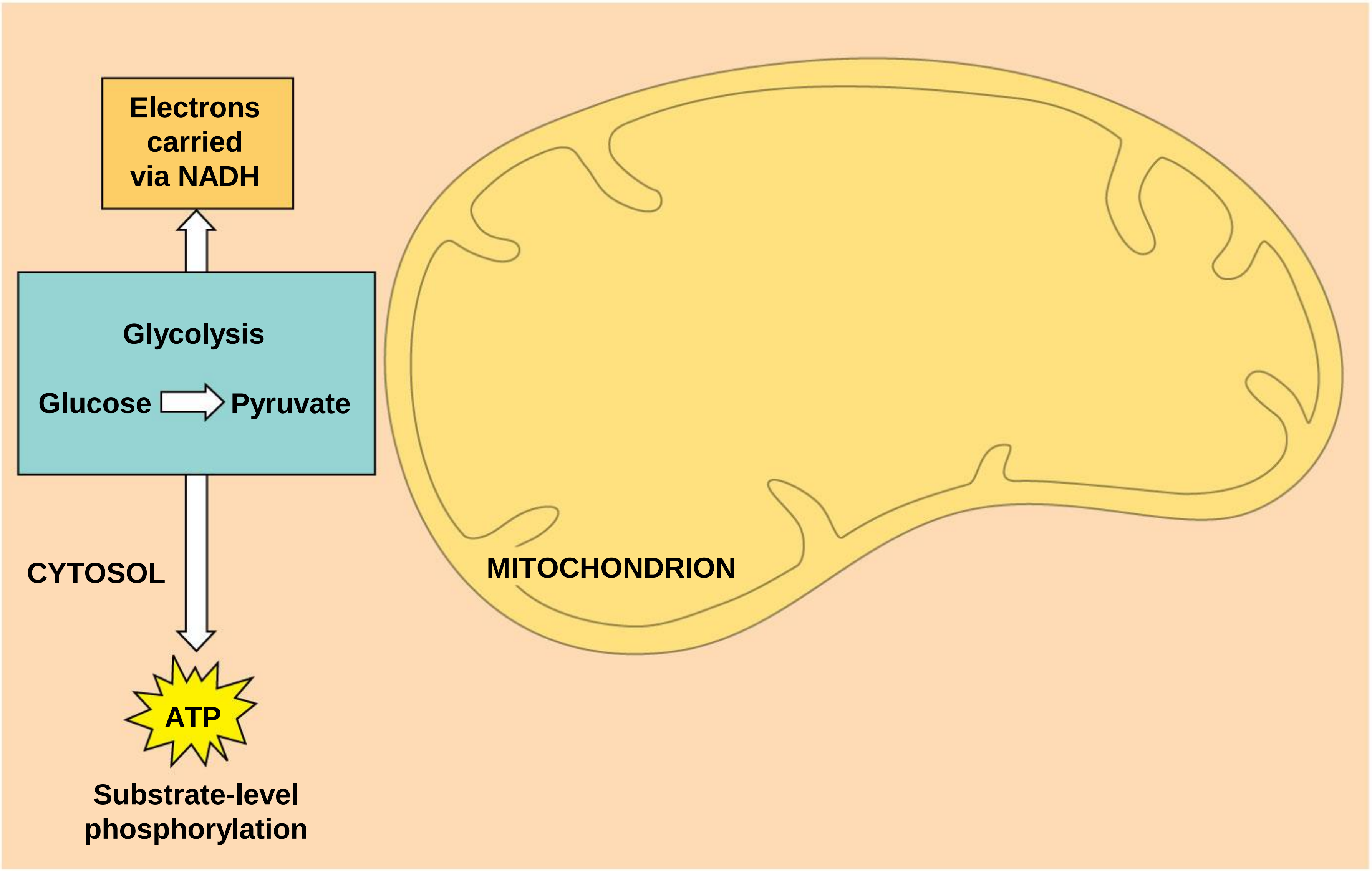
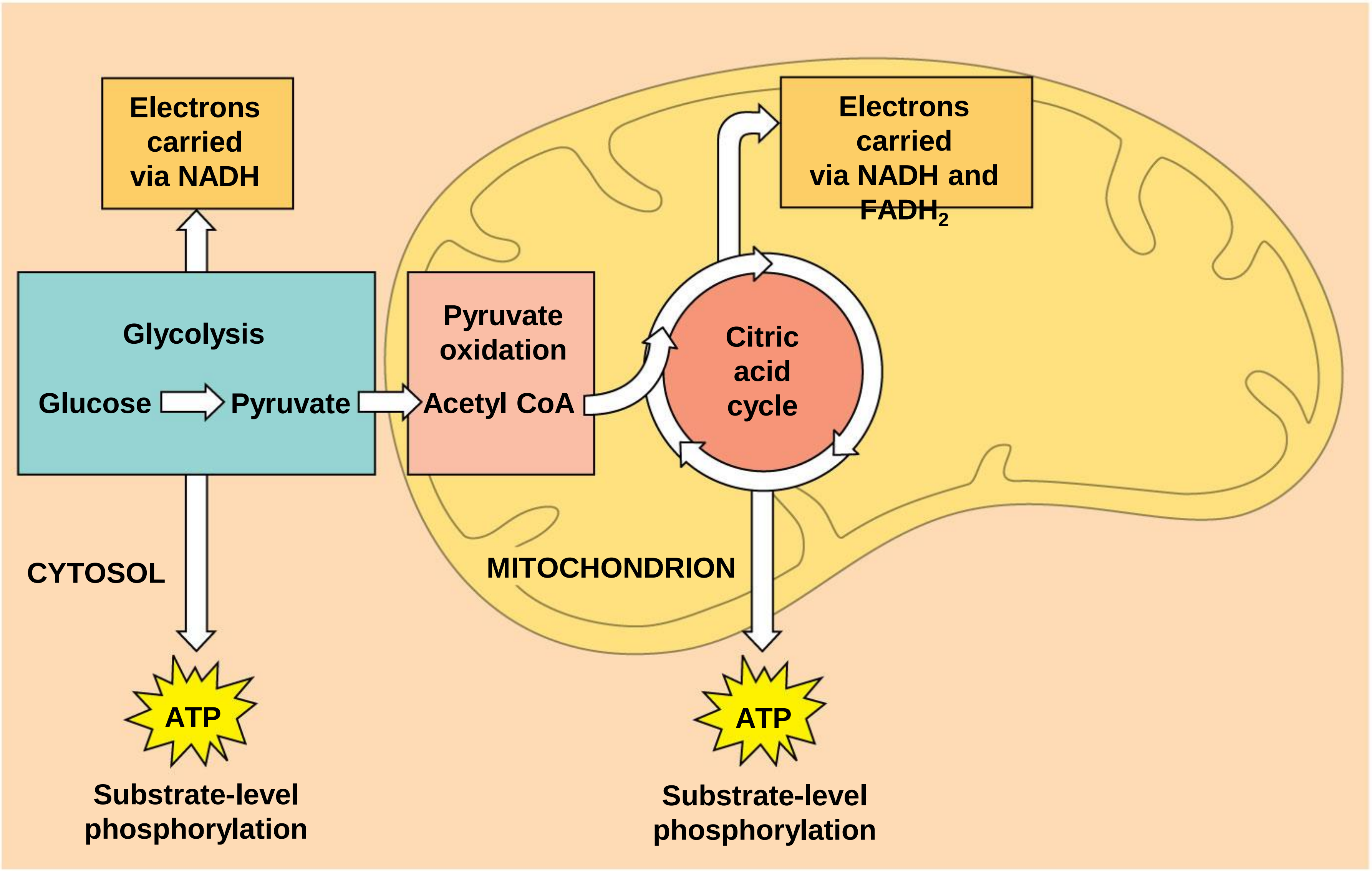
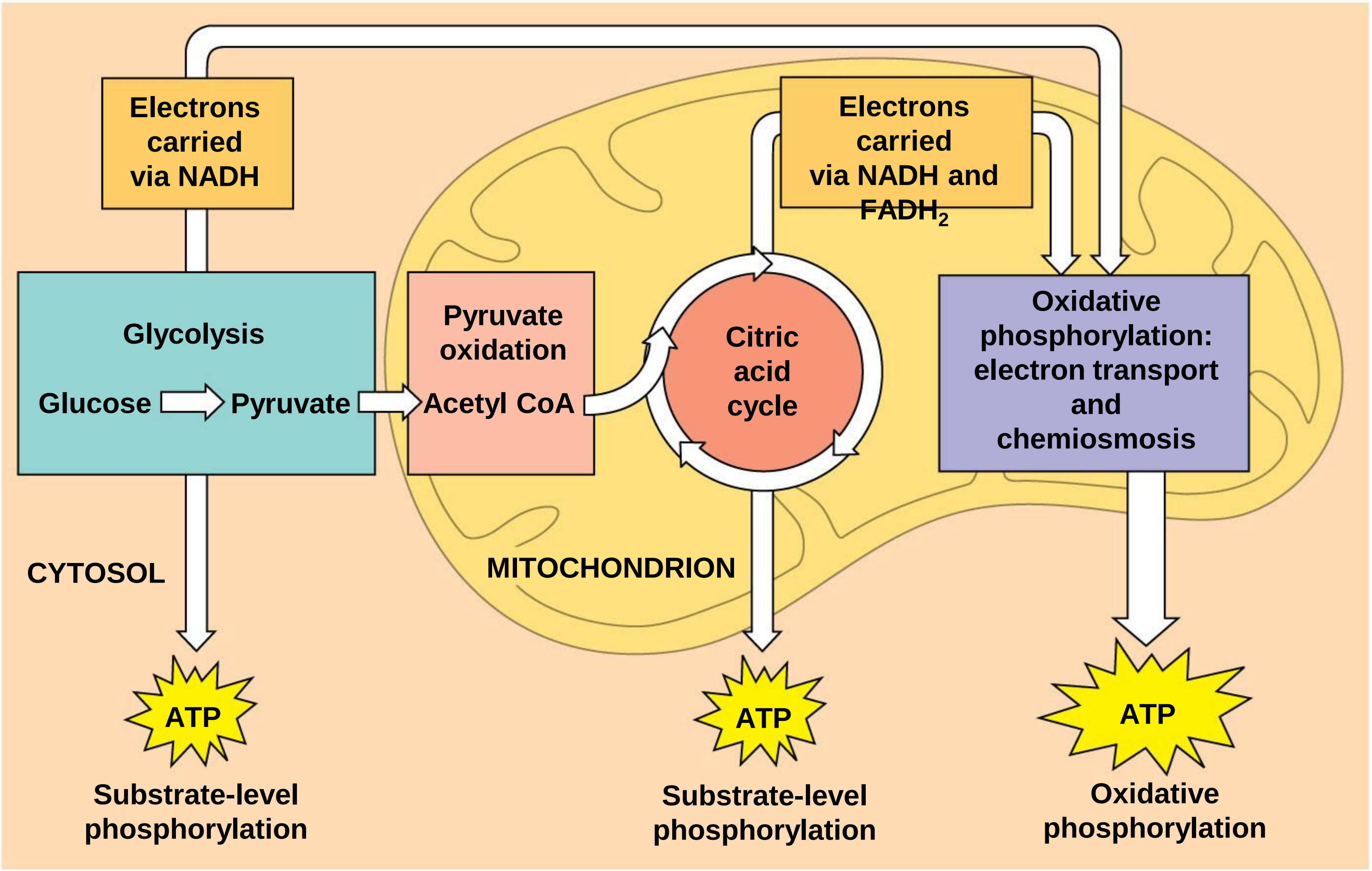

Electrons carried via NADH
Glycolysis
Glucose
Pyruvate
CYTOSOL
MITOCHONDRION
ATP
Substrate-level phosphorylation

Figure 9.6-2



Electrons carried via NADH
Glycolysis
Glucose
Pyruvate
Pyruvate oxidation
Acetyl CoA
Citric acid cycle
Electrons carried via NADH and $FADH_2$
CYTOSOL
MITOCHONDRION
ATP
Substrate-level phosphorylation
ATP
Substrate-level phosphorylation

Figure 9.6-3


Electrons carried via NADH
Electrons carried 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 phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation

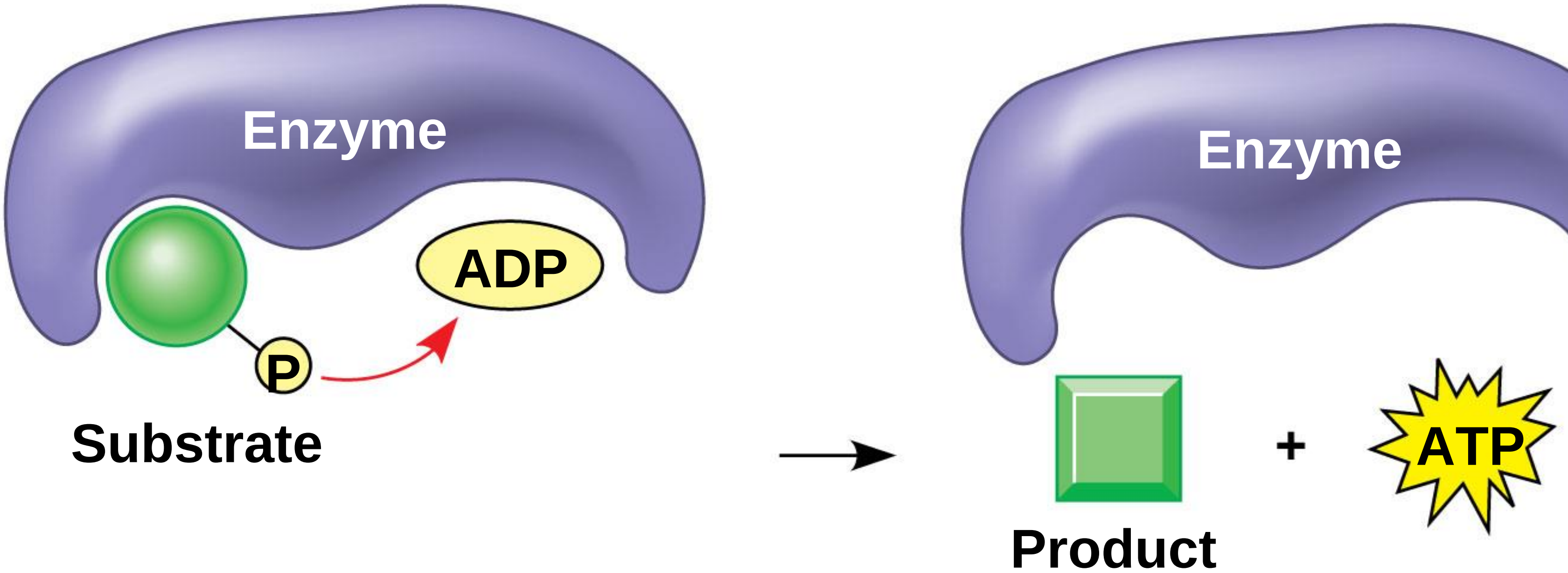
- **The process that generates most of the ATP is called oxidative phosphorylation.**

- **Oxidative phosphorylation accounts for almost 90% of the ATP generated by cellular respiration**

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

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

Figure 9.7

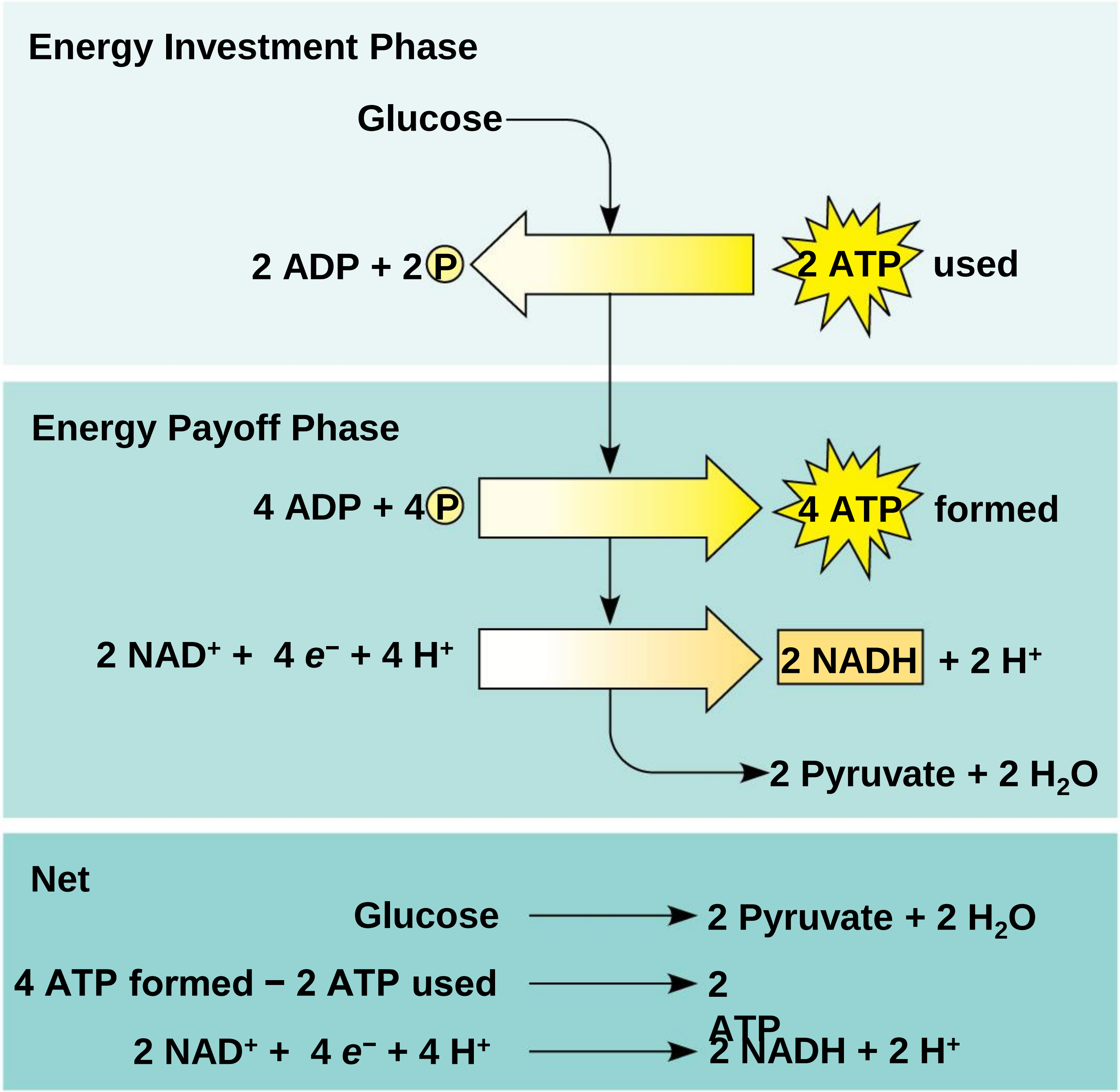


Concept 9.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- **Glycolysis** (**"splitting of sugar"**) **breaks down glucose into two molecules of pyruvate**

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

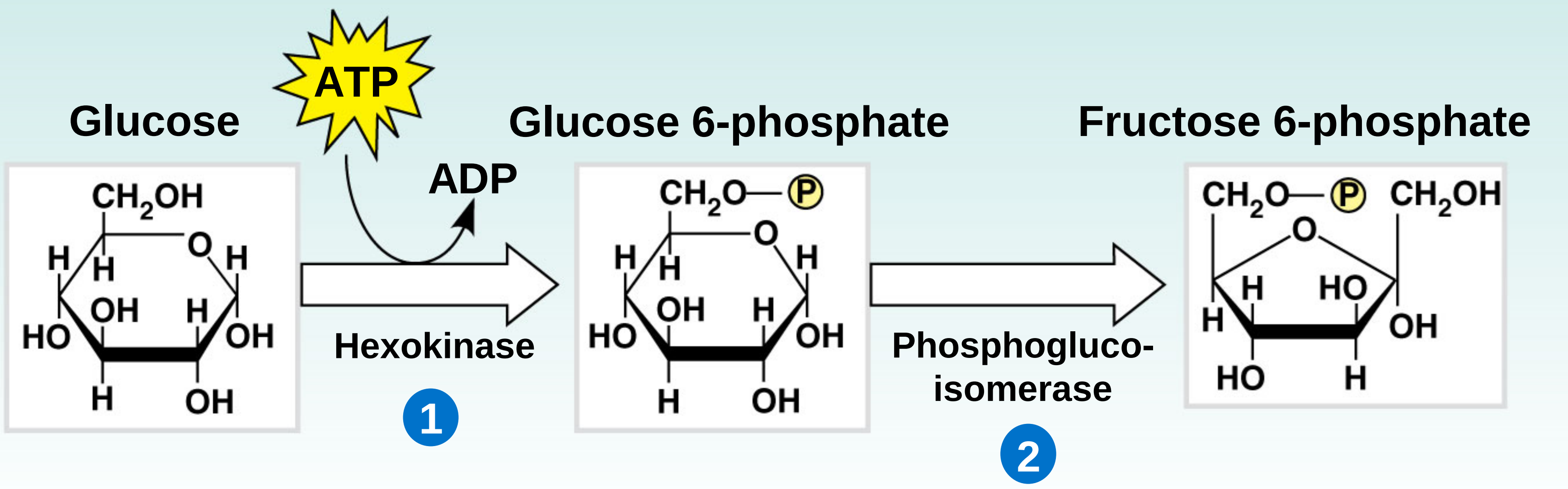
Figure 9.8



Energy Investment Phase
Glucose
2 ADP + 2 P
2 ATP
used
Energy Payoff Phase
4 ADP + 4 P
4 ATP
formed
2 NAD+ + 4 e− + 4 H+
2 NADH
+ 2 H+
2 Pyruvate + 2 H2O
Net
Glucose
2 Pyruvate + 2 H2O
4 ATP formed − 2 ATP used
2 ATP
2 NAD+ + 4 e− + 4 H+
2 NADH + 2 H+

Figure 9.9a

Glycolysis: Energy Investment Phase



Glycolysis: Energy Investment Phase

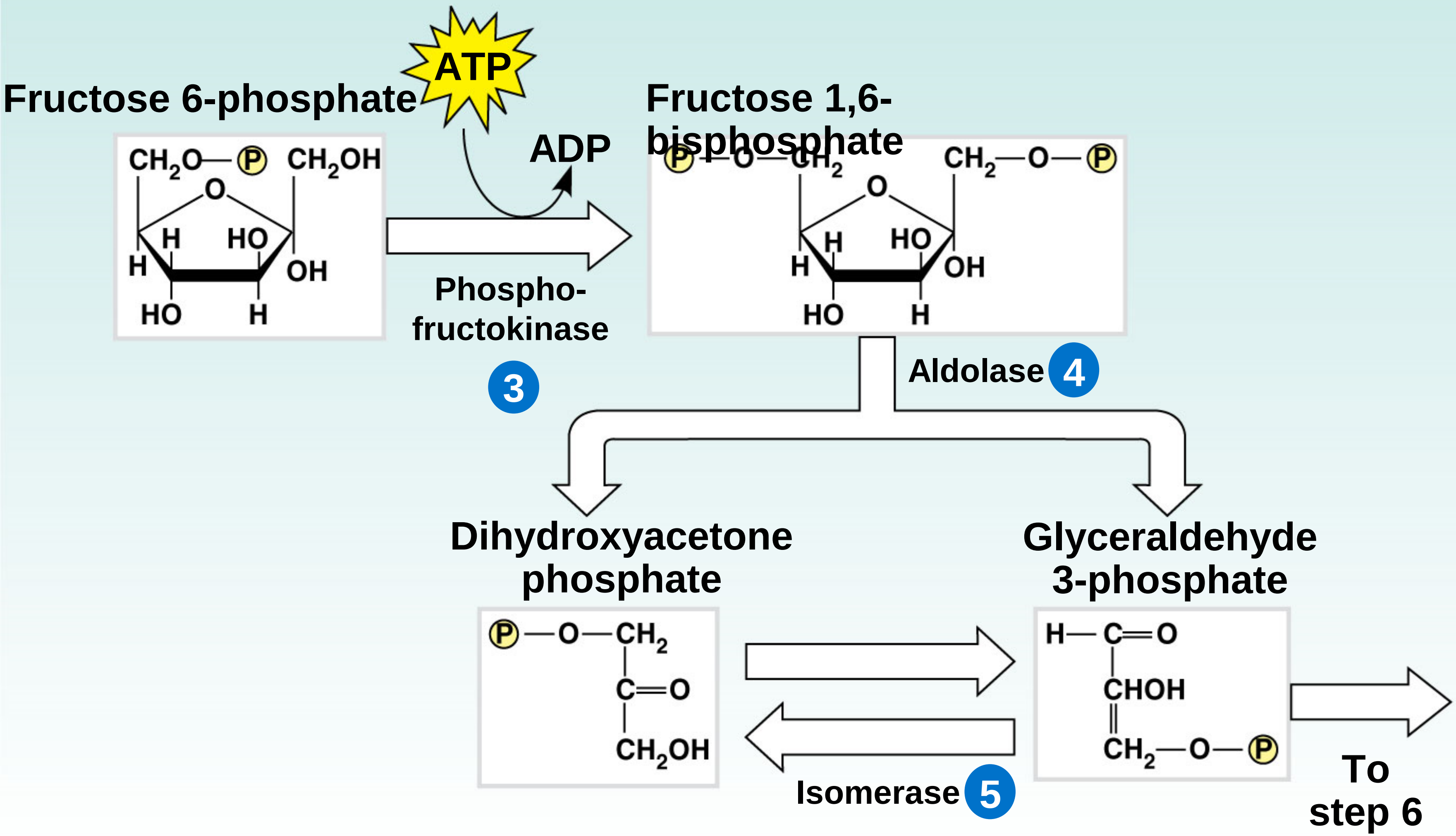


Figure 9.9c

Glycolysis: Energy Payoff Phase

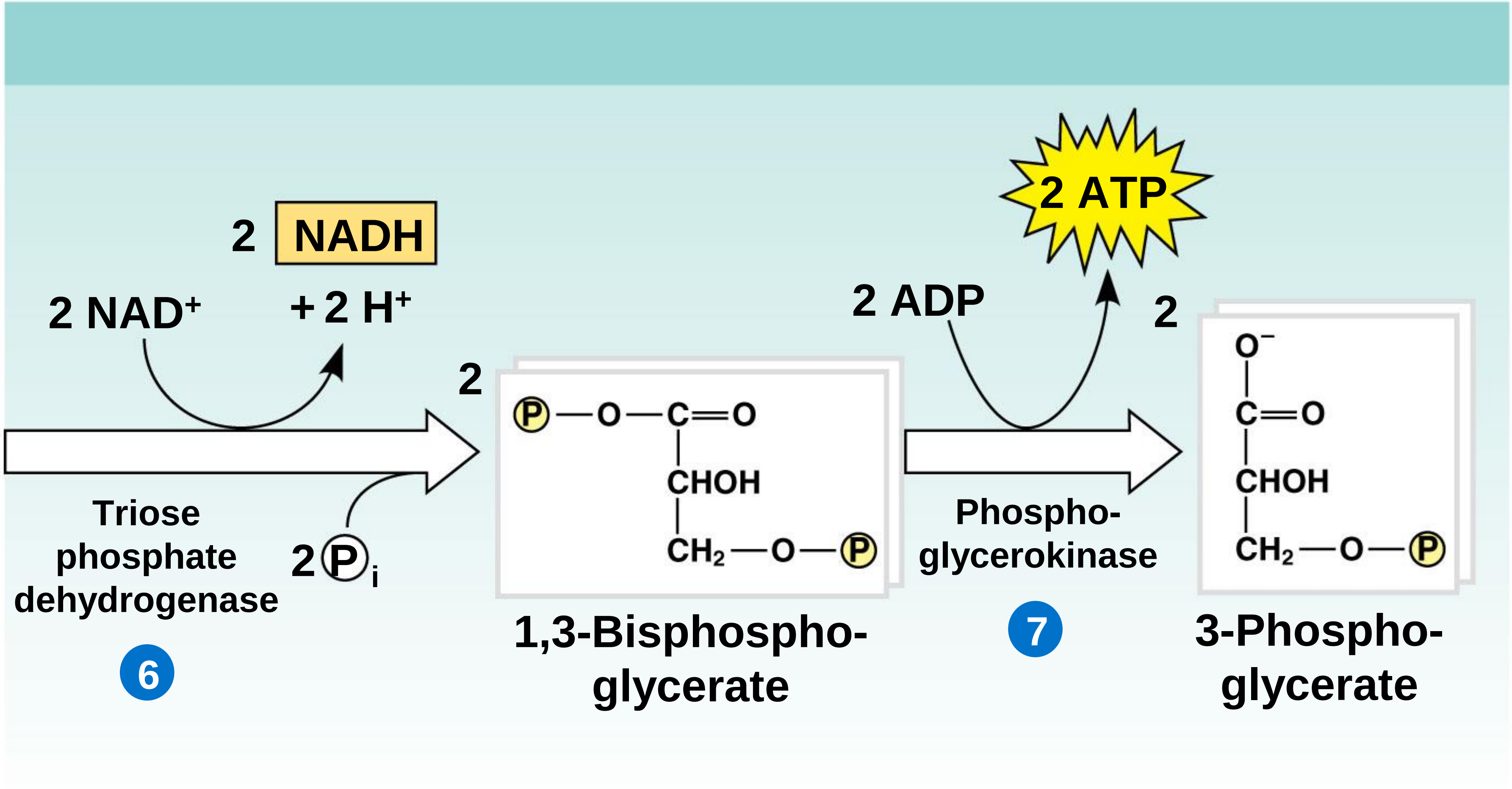
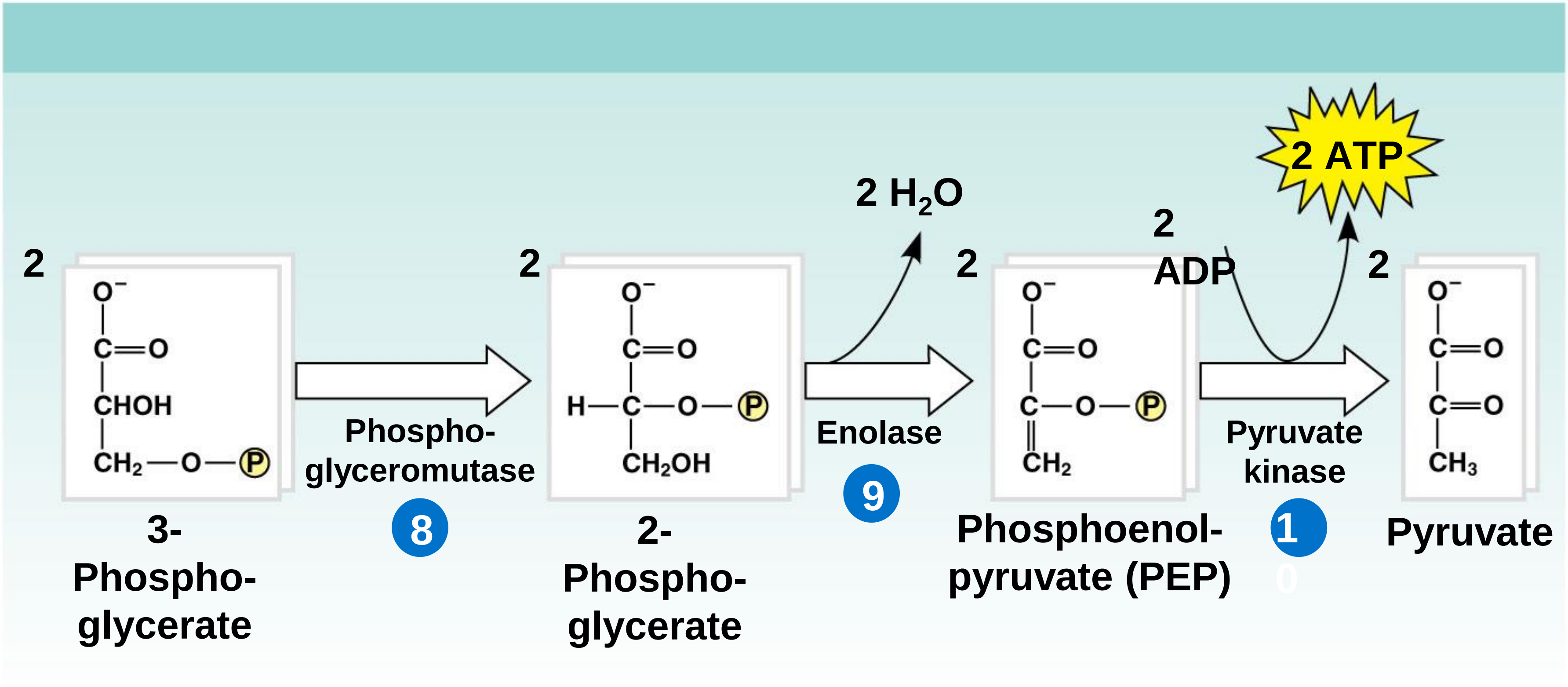


Figure 9.9d

Glycolysis: Energy Payoff Phase



Concept 9.3: The citric acid cycle completes the energy-yielding oxidation of organic molecules

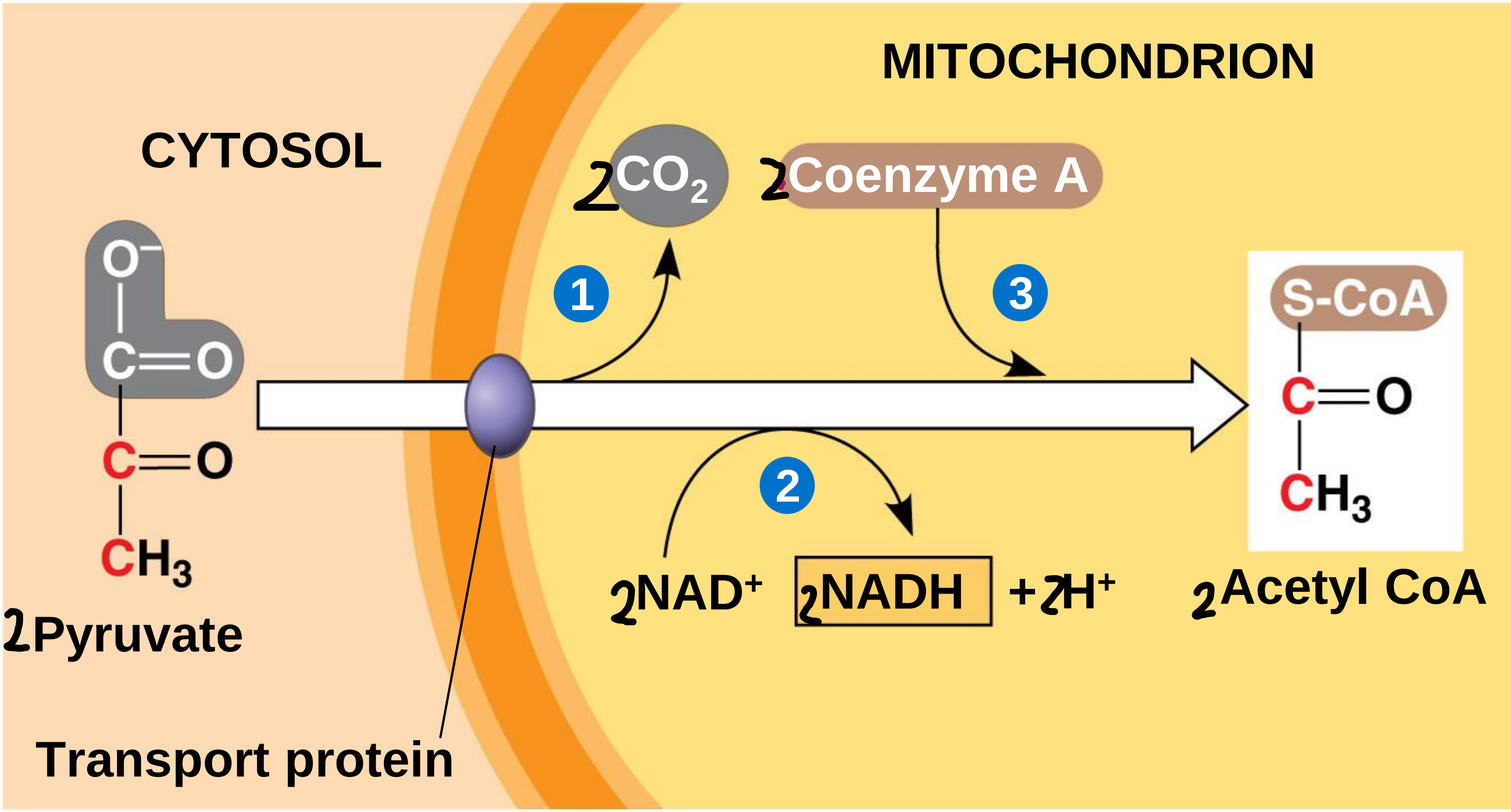
- **In the presence of O_2, pyruvate enters the mitochondrion**

Oxidation of Pyruvate to Acetyl CoA

- Before the citric acid cycle can begin, pyruvate must be converted to acetyl Coenzyme A (acetyl CoA, abbreviated a S-CoA to emphasize it sulfur atom), which links glycolysis to the citric acid cycle

- This step is carried out by a multienzyme complex (The Pyruvate Dehydrogenase complex) that catalyses three reactions

Figure 9.10

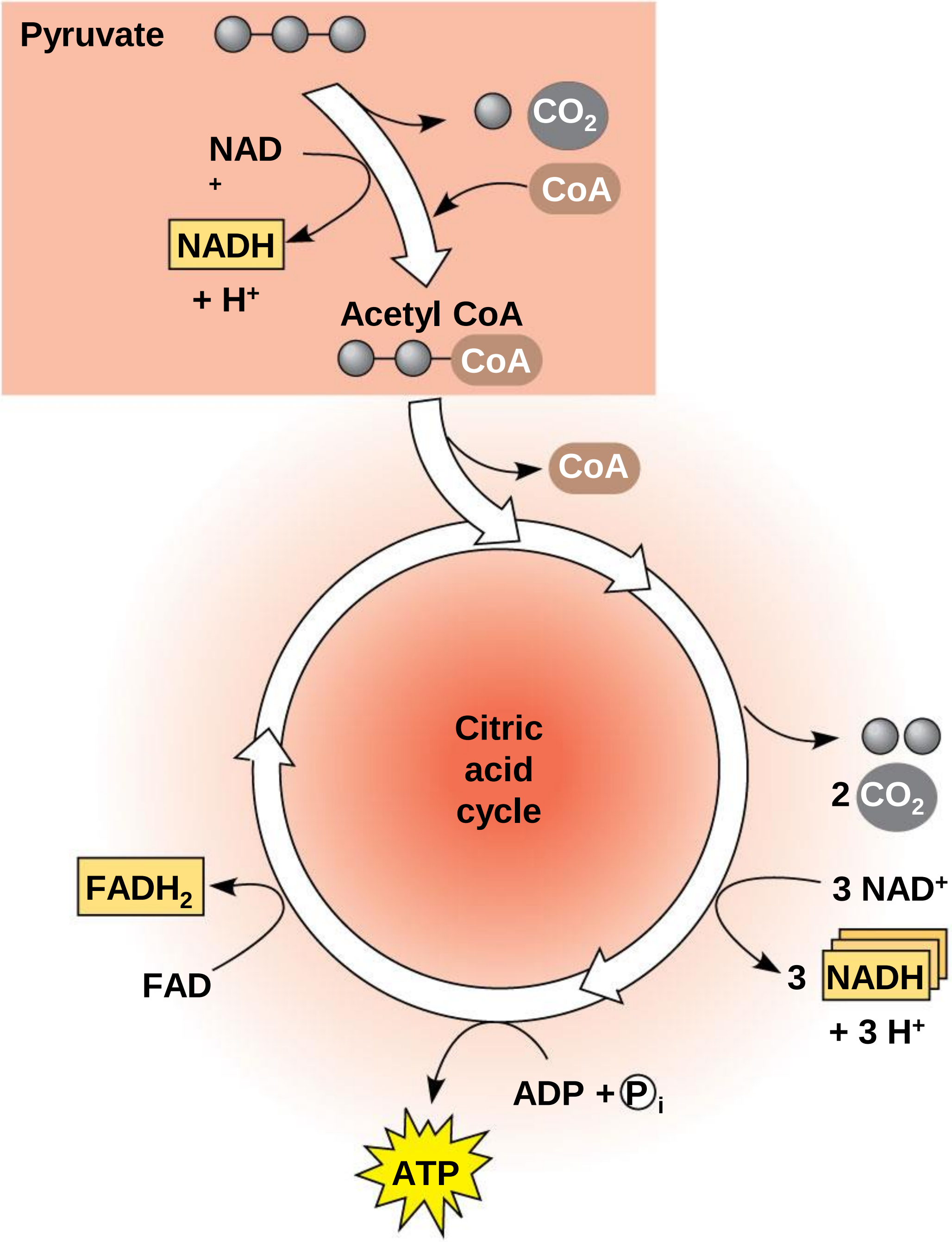


MITOCHONDRION
CYTOSOL
2 CO_2
2 Coenzyme A
1
3
2
O^-
C=O
C=O
CH_3
2 Pyruvate
S-CoA
C=O
CH_3
2 NAD^+
2 NADH
+ 2 H^+
2 Acetyl CoA
Transport protein

The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, takes place within the mitochondrial matrix
- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn (*Each glucose makes 2 turns*)

Figure 9.11


Pyruvate
CO2
NAD
+
CoA
NADH
+ H+
Acetyl CoA
CoA
CoA
Citric
acid
cycle
2 CO2
3 NAD+
FADH2
3 NADH
+ 3 H+
FAD
ADP + P i
ATP

- **In the first step, acetyl group of acetyl CoA <u>joins</u> 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 <u>electron transport chain</u>**

Figure 9.12-1

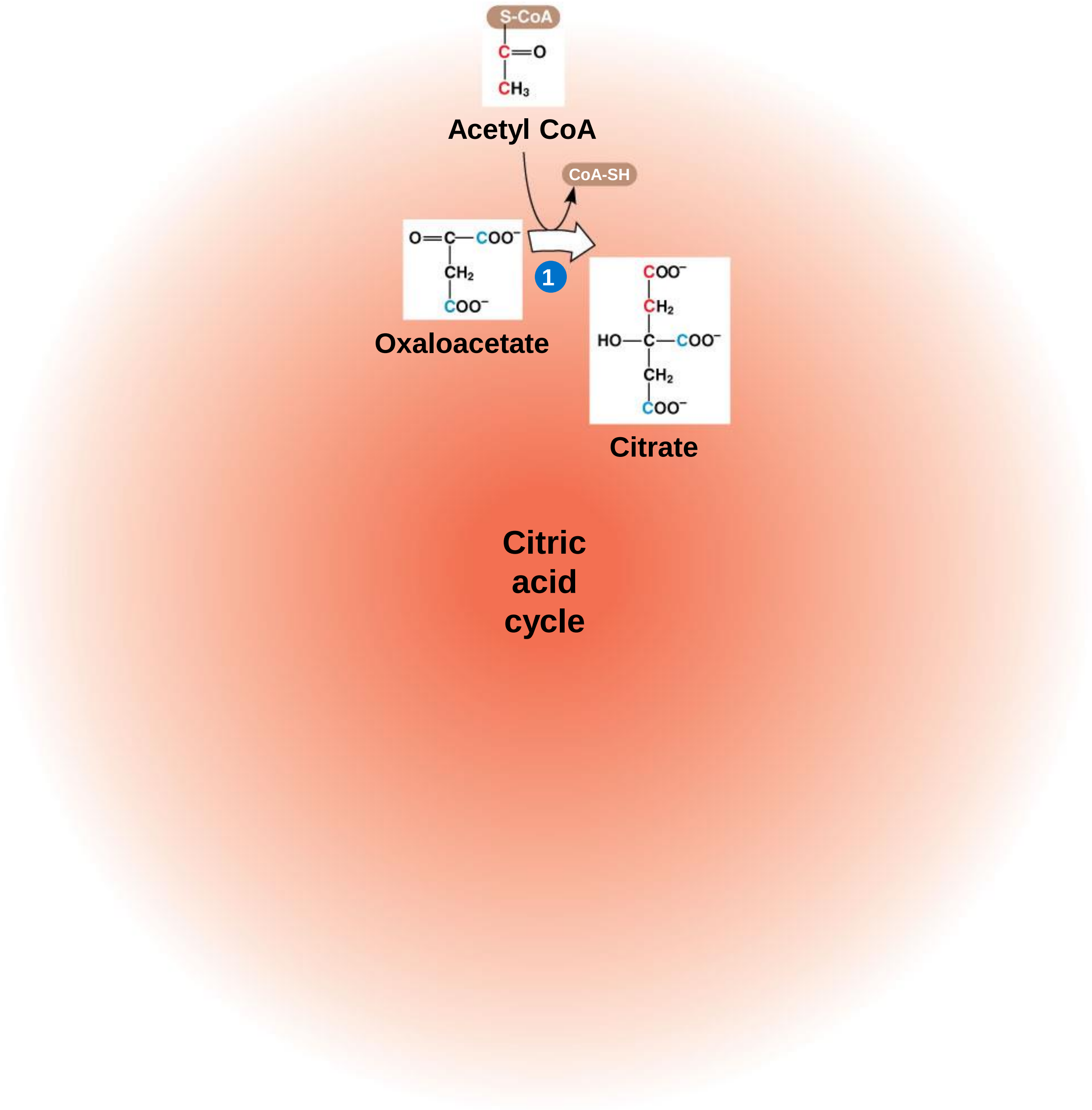

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
Citric
acid
cycle

Figure 9.12-2

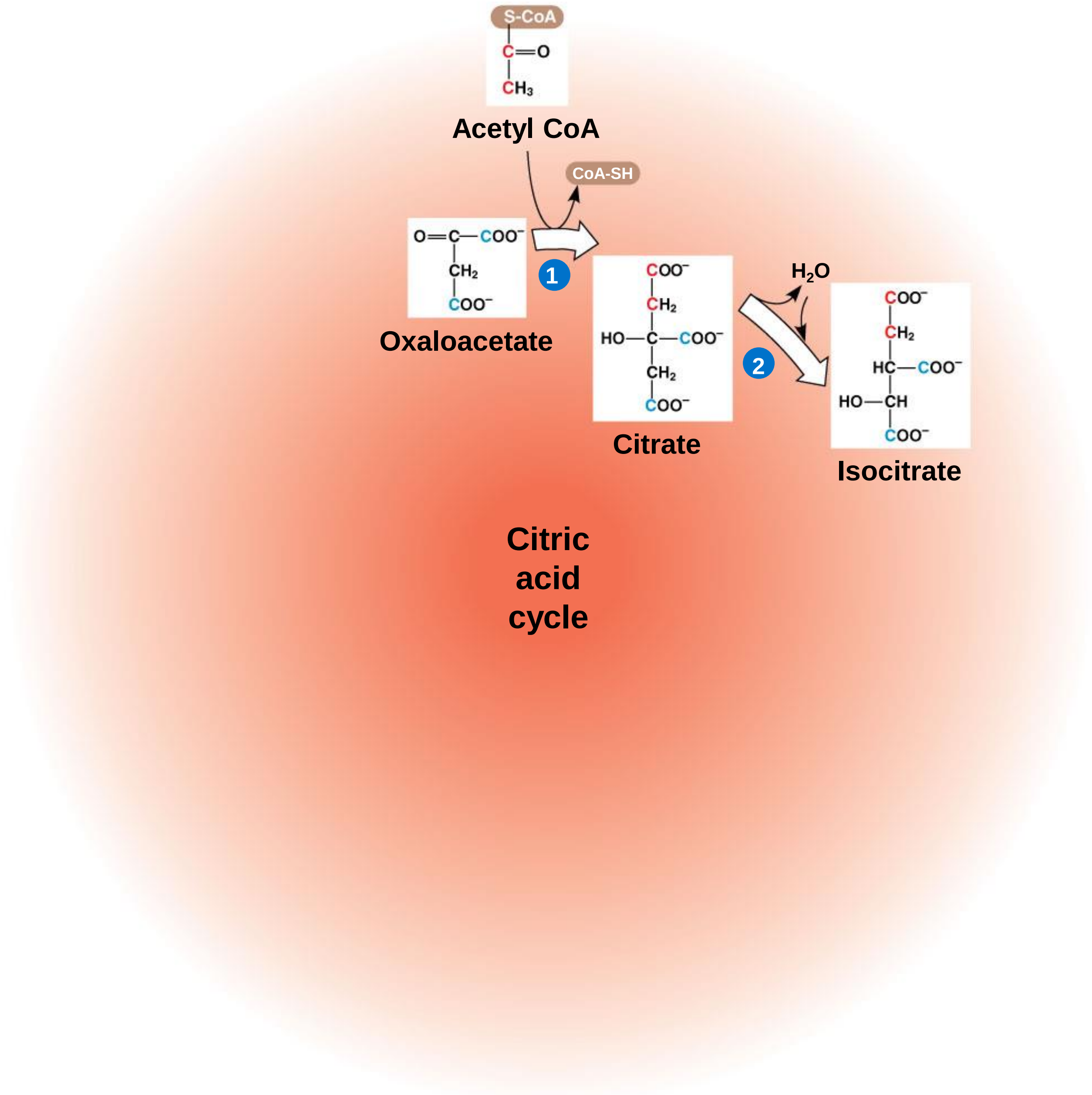

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
Citric
acid
cycle

Figure 9.12-3

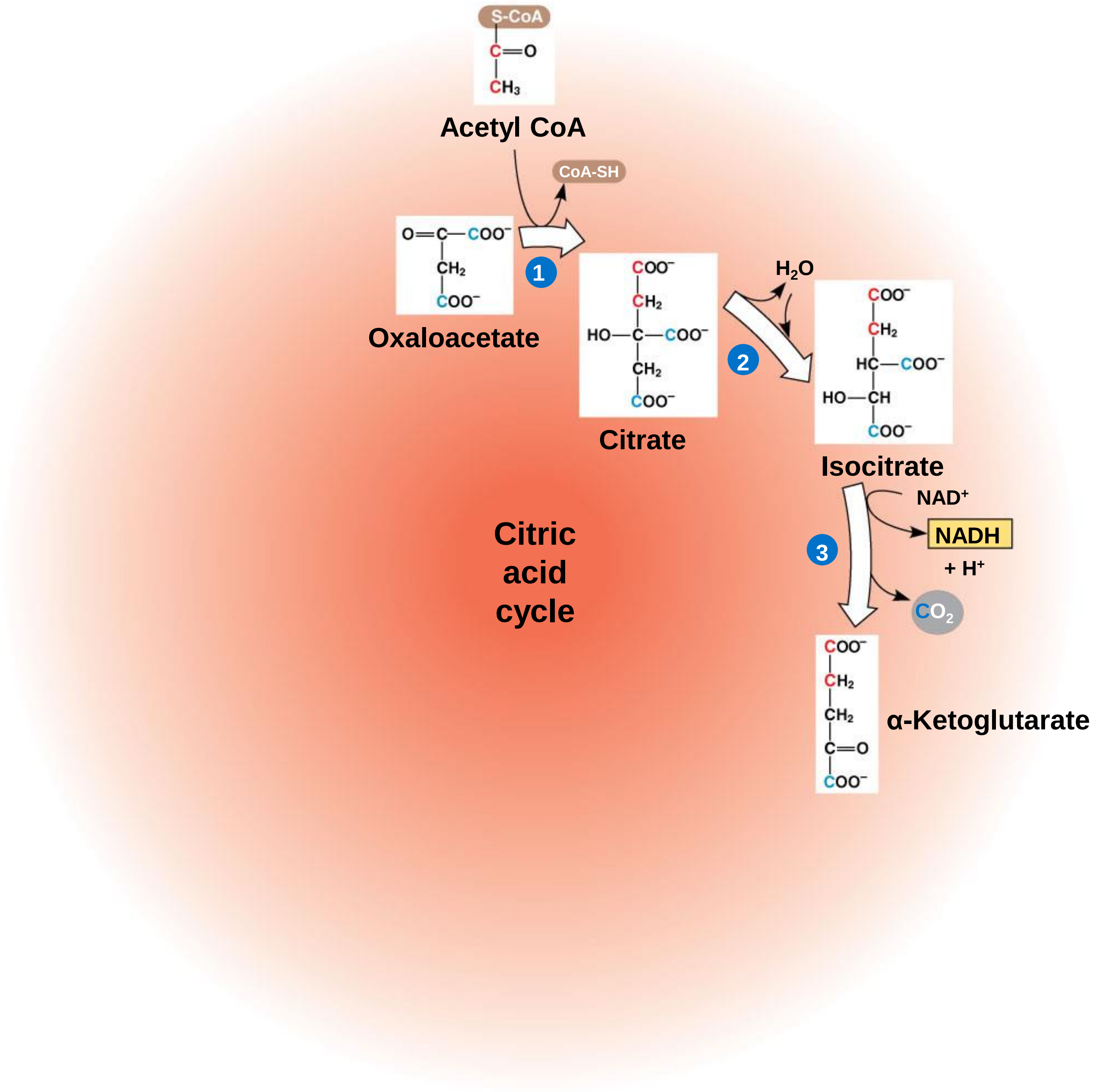
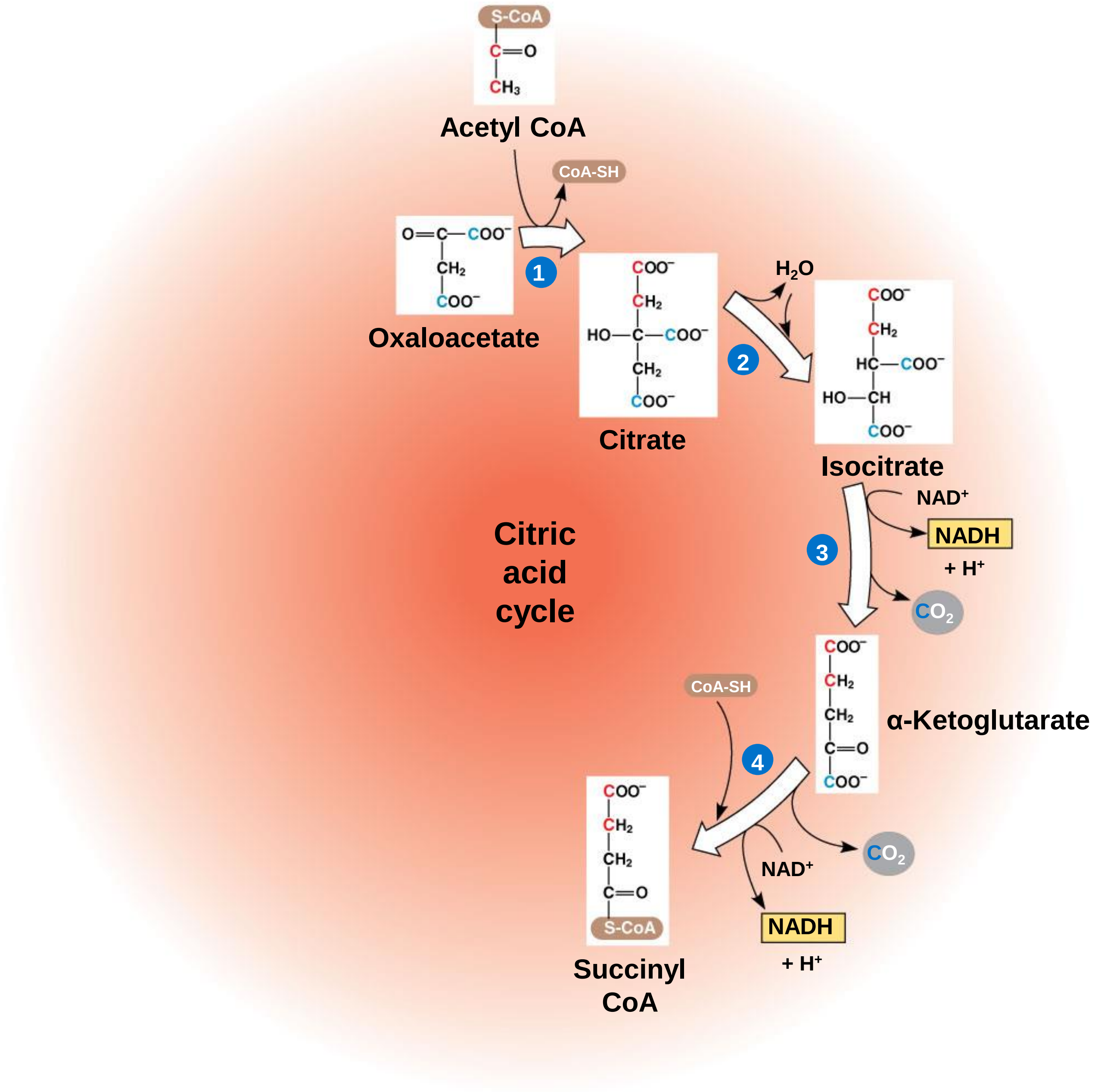
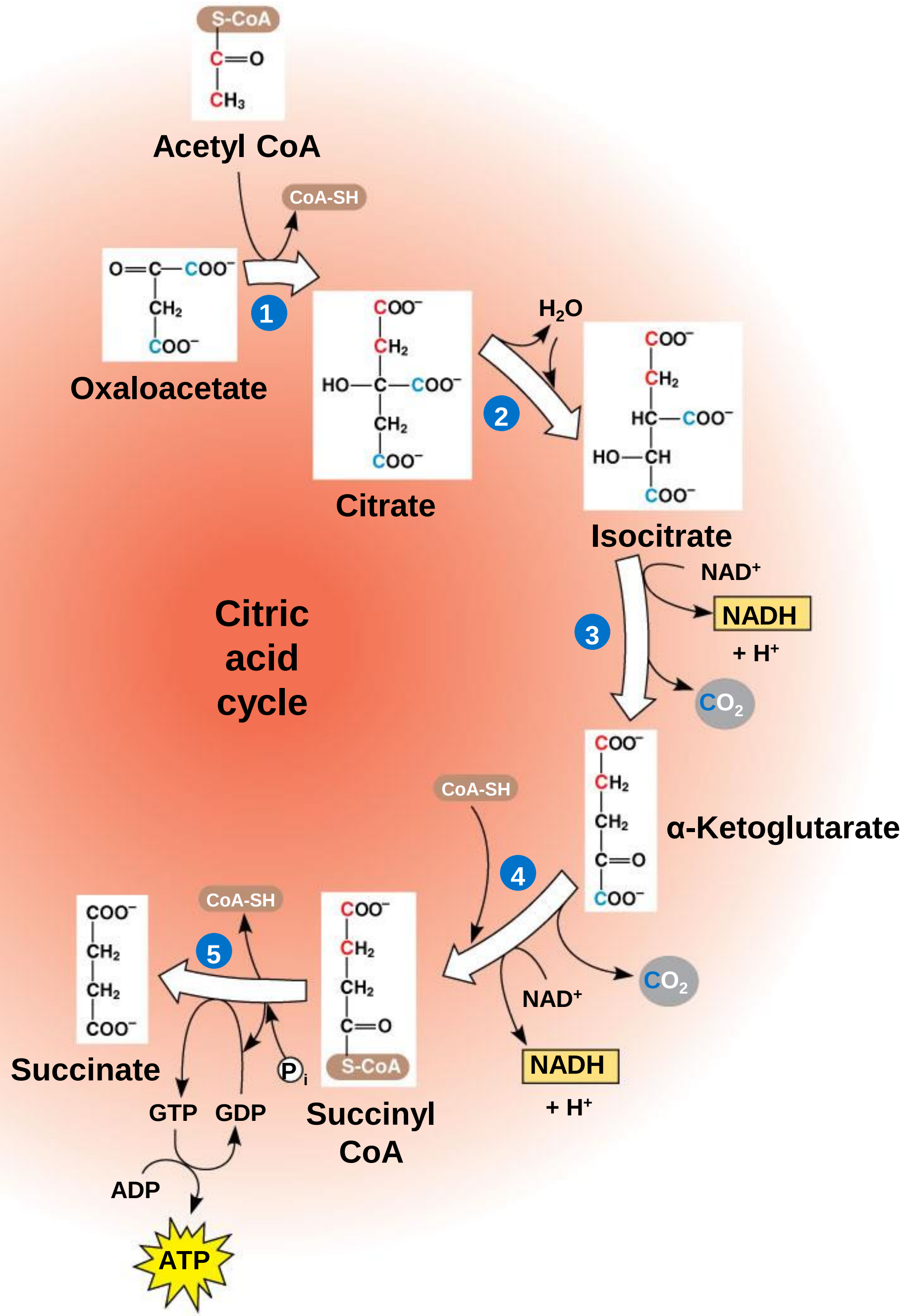

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
COO⁻
CH2
CH2
C=O
COO⁻
α-Ketoglutarate
Citric
acid
cycle

Figure 9.12-4



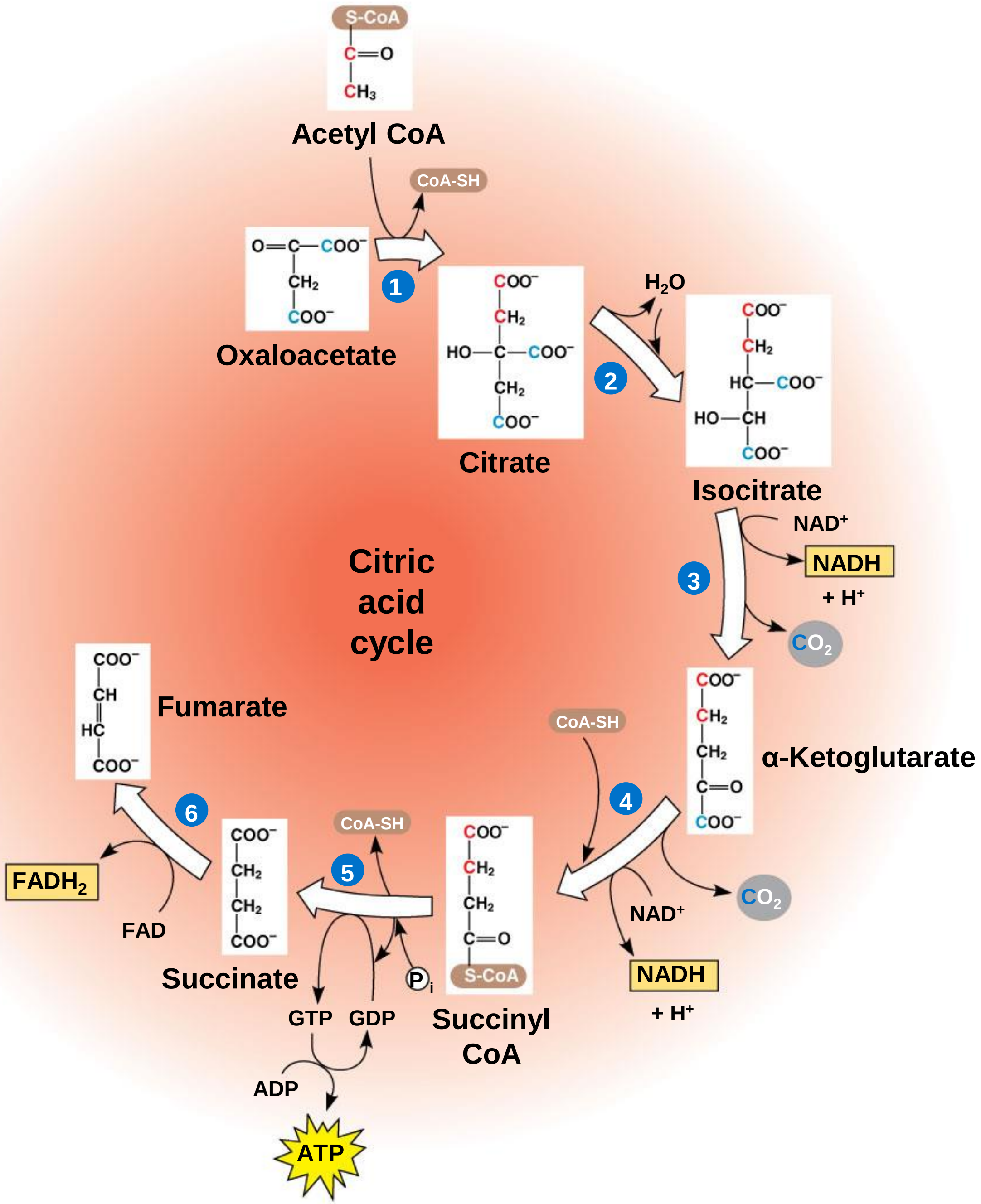
S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
Citric
acid
cycle
COO⁻
CH2
CH2
C=O
COO⁻
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
COO⁻
CH2
CH2
C=O
S-CoA
Succinyl
CoA

Figure 9.12-5



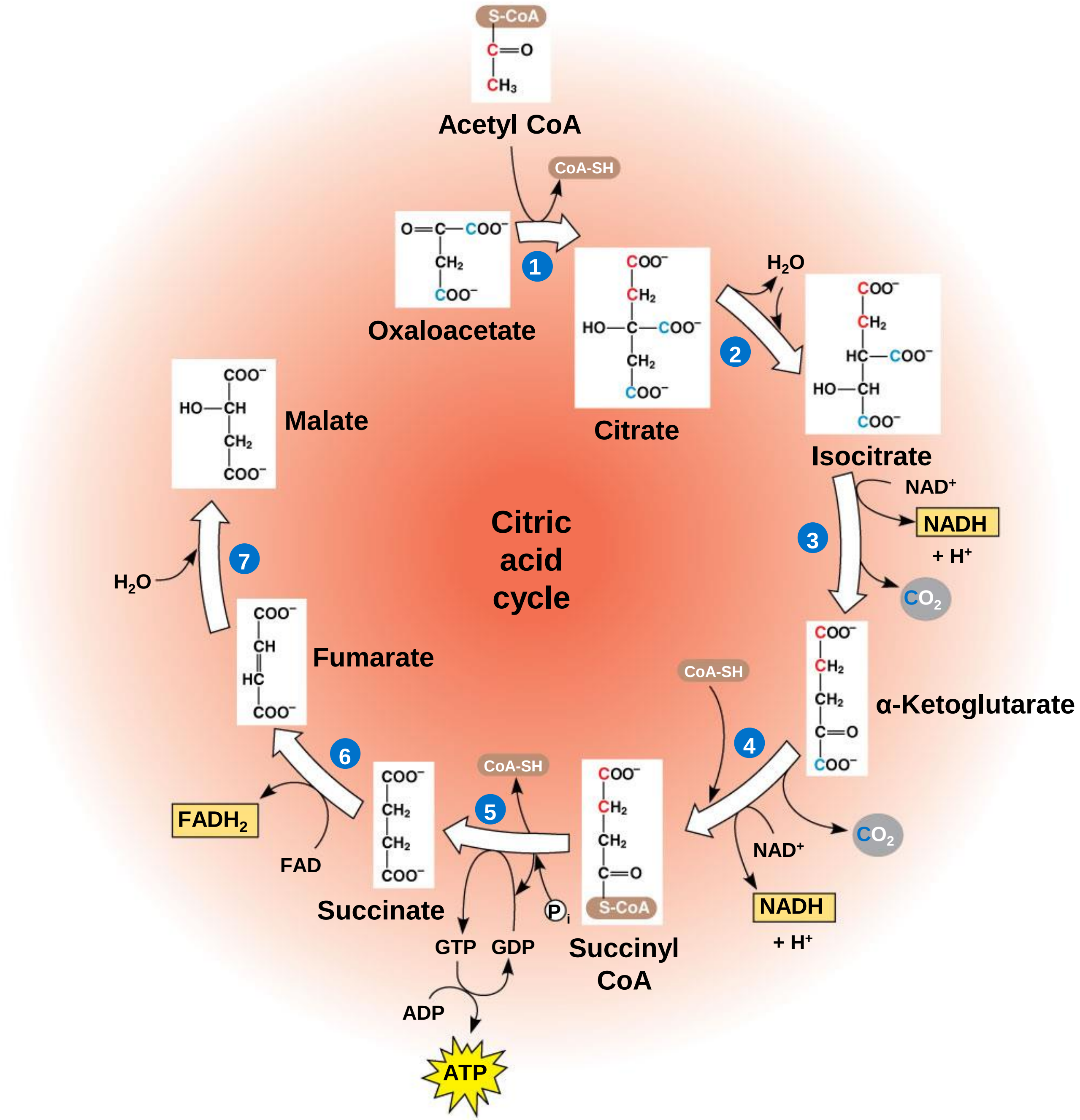
S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
Citric
acid
cycle
COO⁻
CH2
CH2
C=O
COO⁻
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
COO⁻
CH2
CH2
C=O
S-CoA
Succinyl
CoA
CoA-SH
5
Pi
COO⁻
CH2
CH2
COO⁻
Succinate
GTP
GDP
ADP
ATP

Figure 9.12-6



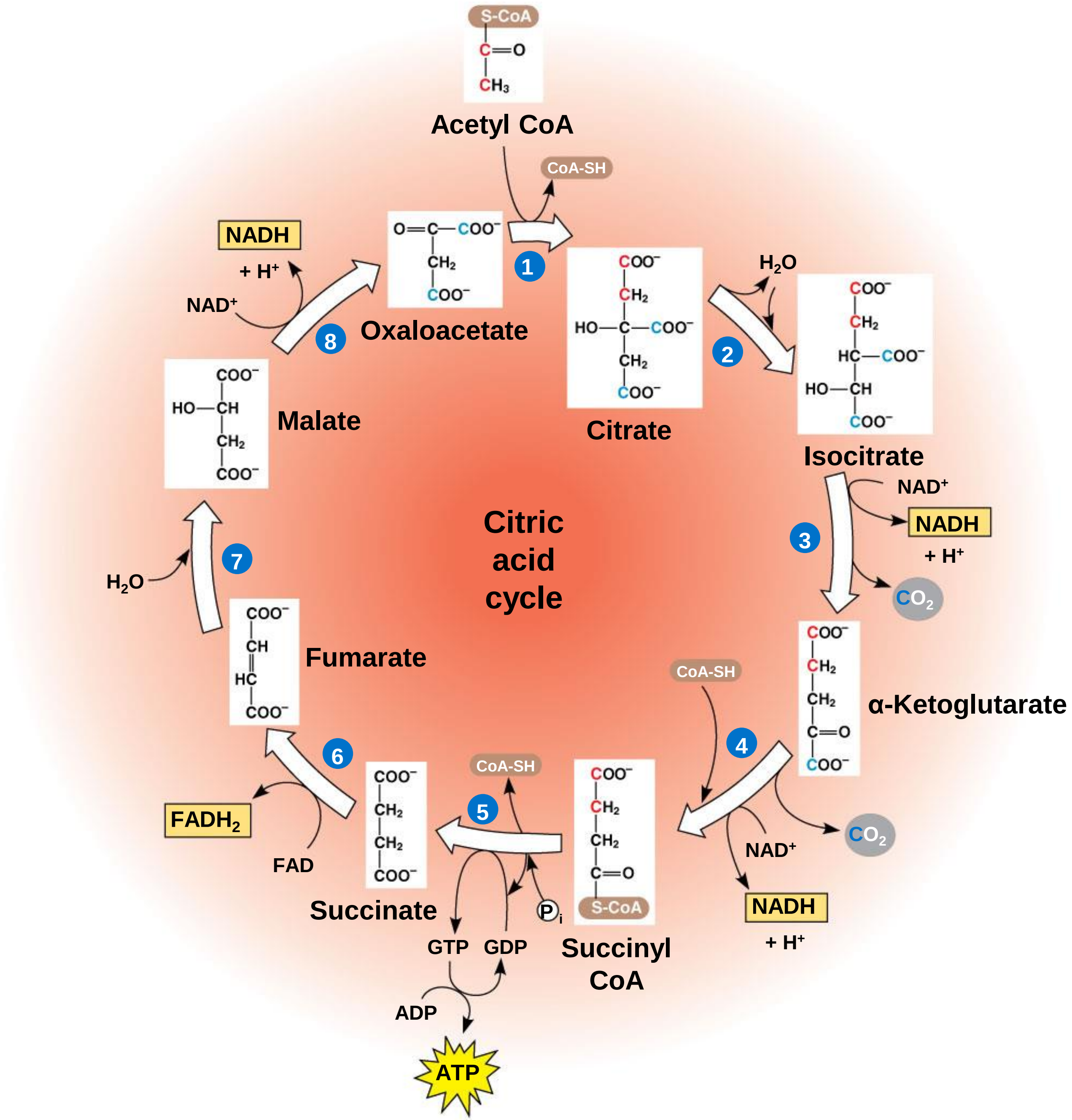
S-CoA
Acetyl CoA
CoA-SH
Oxaloacetate
1
Citrate
H_2O
2
Isocitrate
NAD^+
NADH
$+ H^+$
3
CO_2
Citric acid cycle
α-Ketoglutarate
CoA-SH
4
CO_2
NAD^+
NADH
$+ H^+$
Succinyl CoA
S-CoA
CoA-SH
5
P_i
GTP
GDP
ADP
ATP
Succinate
6
$FADH_2$
FAD
Fumarate

Figure 9.12-7



S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
1
Oxaloacetate
Citrate
H2O
2
Isocitrate
NAD+
NADH
+ H+
3
CO2
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
Succinyl CoA
S-CoA
CoA-SH
5
Pi
GTP
GDP
ADP
ATP
Succinate
6
FADH2
FAD
Fumarate
7
H2O
Malate
Citric acid cycle

Figure 9.12-8



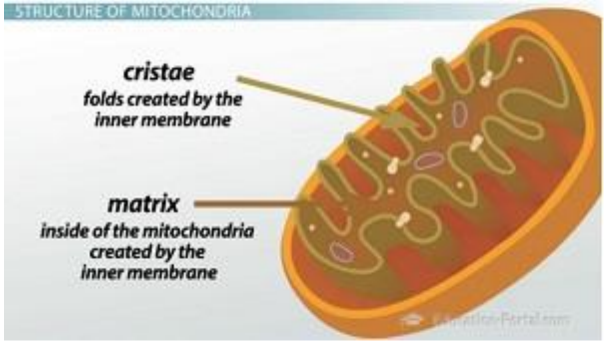
S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
Oxaloacetate
Citrate
Isocitrate
α-Ketoglutarate
Succinyl CoA
Succinate
Fumarate
Malate
Citric acid cycle
1
2
3
4
5
6
7
8
H2O
NAD+
NADH
+ H+
CO2
GTP
GDP
ADP
ATP
Pi
FAD
FADH2

Concept 9.4: 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 ***cristae*** of the mitochondrion

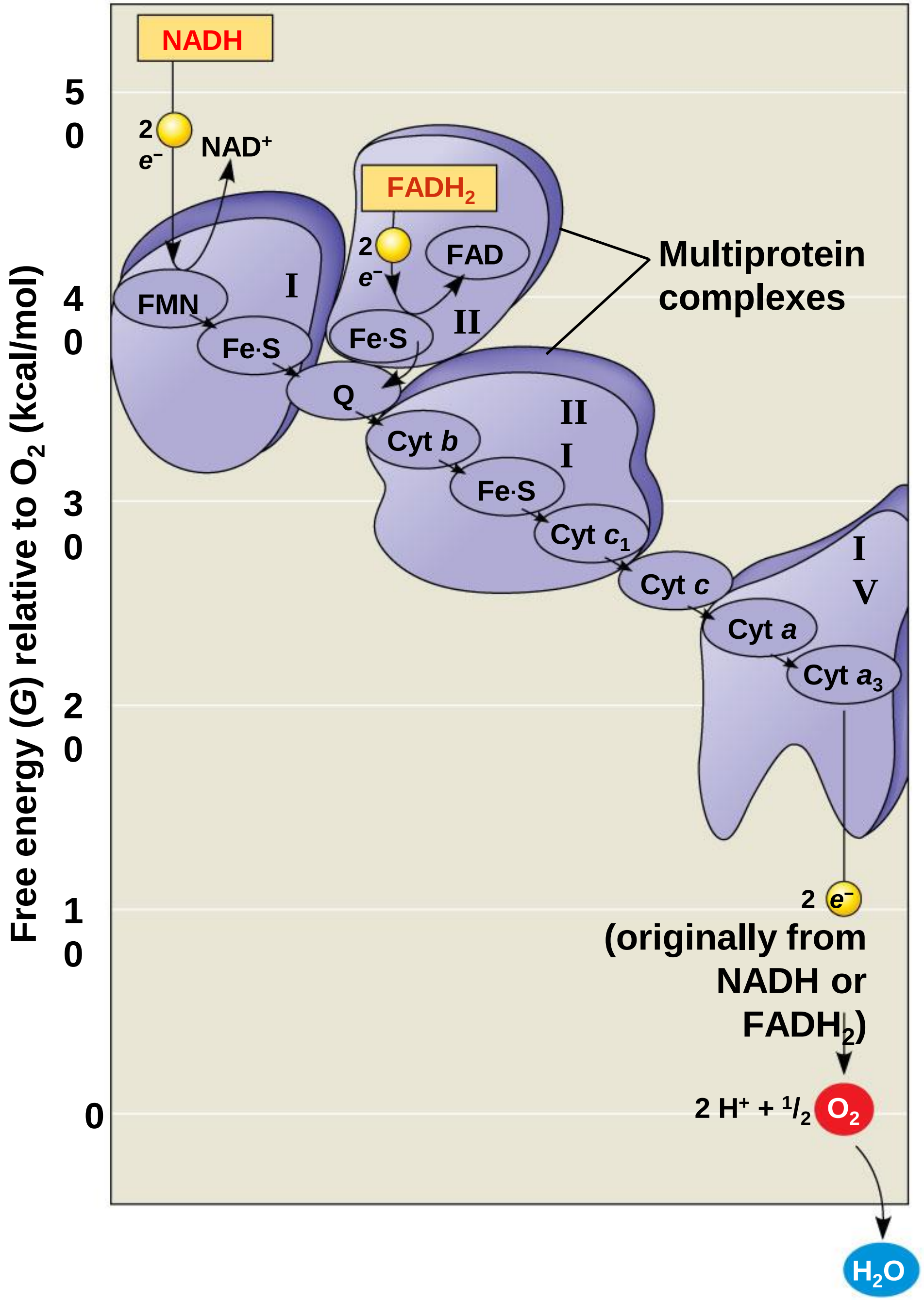


- Most of the chain's components are proteins, which exist in multiprotein complexes

- ***<u>The electron transport chain generates no ATP</u>***

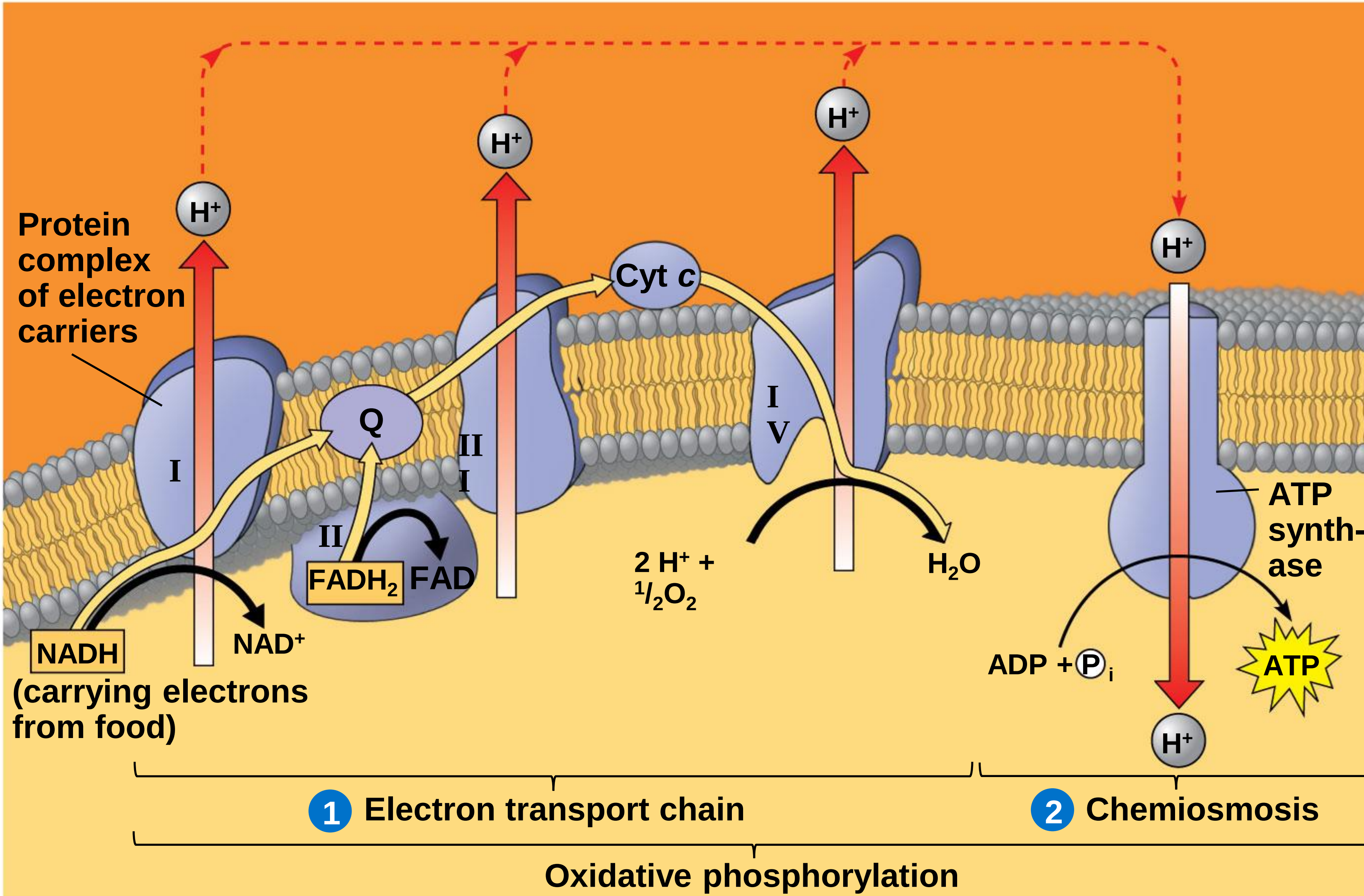
- **<u>Electrons drop</u> in free energy as they go <u>down</u> the chain and are <u>finally passed to O_2, forming H_2O</u>**

Figure 9.13



NADH
2 e^-
NAD^+
FADH$_2$
2 e^-
FAD
FMN
Fe·S
I
Fe·S
II
Q
III
Cyt b
Fe·S
Cyt c_1
Cyt c
IV
Cyt a
Cyt a_3
Multiprotein complexes
2 e^-
(originally from NADH or FADH$_2$)
2 H^+ + $^1/_2$ O_2
H_2O
Free energy (G) relative to O_2 (kcal/mol)
50
40
30
20
10
0

Figure 9.15



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

- **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**

- **It breaks the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts**

Chemiosmosis: The Energy-Coupling Mechanism

- Electron transfer in the electron transport chain causes proteins to pump H^+ from the mitochondrial matrix to the intermembrane space

- H^+ then moves back across the membrane, passing through 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**

Figure 9.14

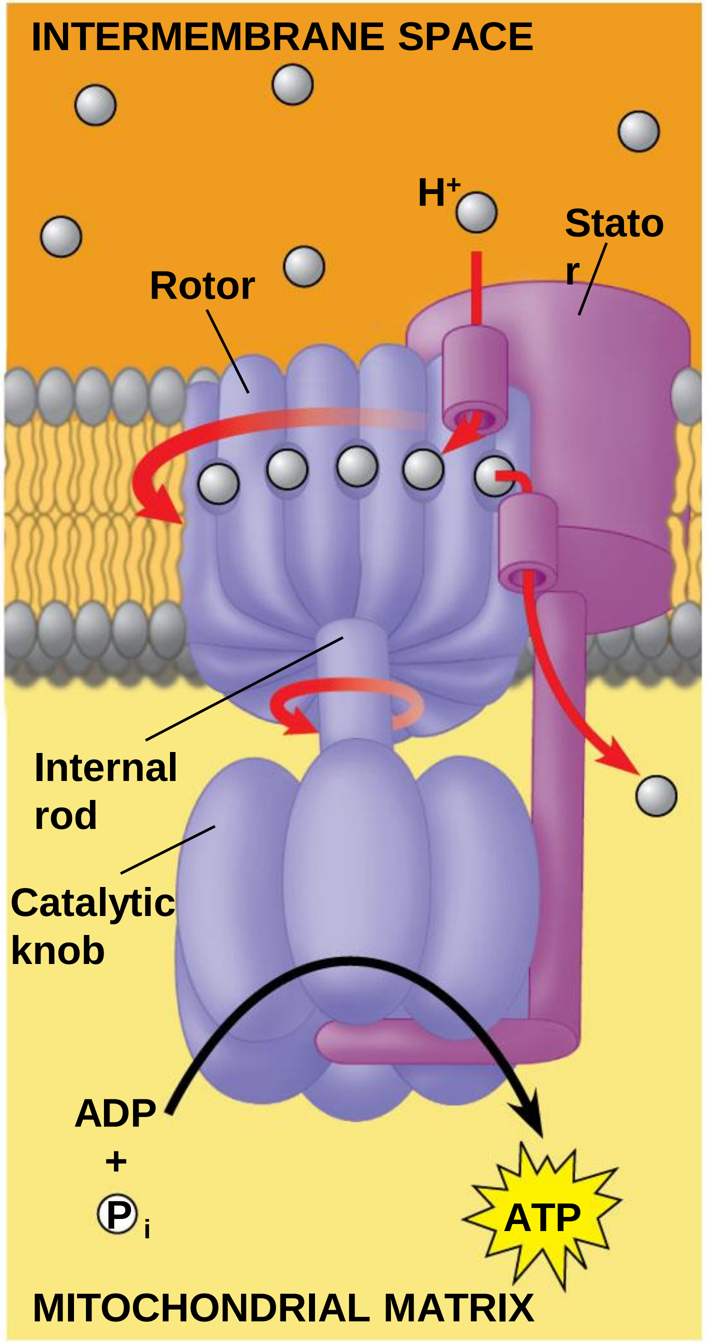
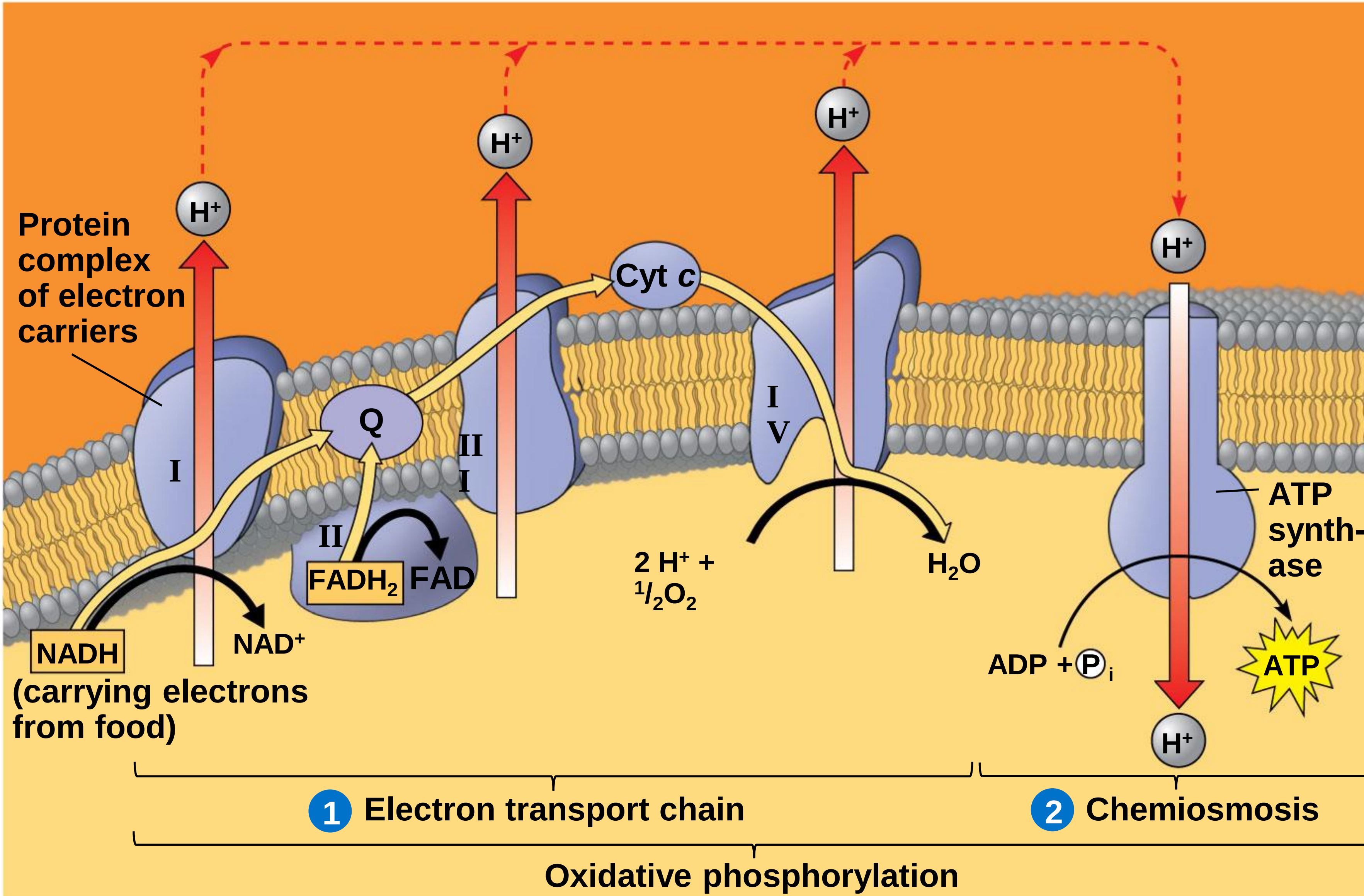

INTERMEMBRANE SPACE
H+
Stato
r
Rotor
Internal
rod
Catalytic
knob
ADP
+
P i
ATP
MITOCHONDRIAL MATRIX

Figure 9.15



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

- **The energy stored in a <u>H^+ gradient</u> across a membrane couples the redox reactions of the electron transport chain to ATP synthesis**

- **The H^+ gradient is referred to as a proton-motive force, emphasizing its capacity to do work**

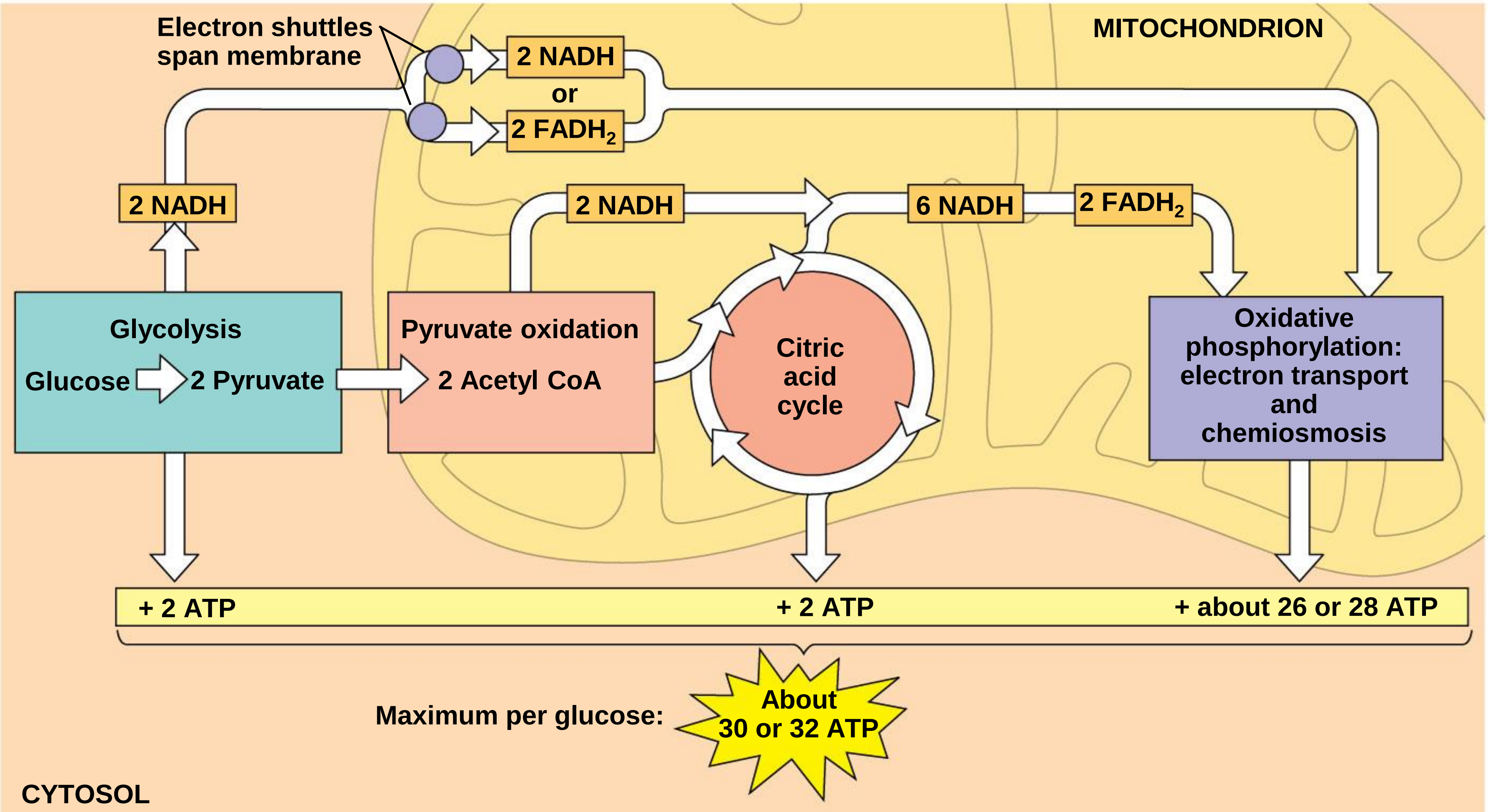
An Accounting of ATP Production by Cellular Respiration

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

glucose → NADH → electron transport chain → proton-motive force → ATP

- **About <u>34%</u> of the energy in a glucose molecule is transferred to ATP during cellular respiration, <u>making about 32 ATP</u>**
- **There are several reasons why the number of ATP is not known exactly**

Figure 9.16



Electron shuttles span membrane
MITOCHONDRION
2 NADH
or
2 $FADH_2$
2 NADH
2 NADH
6 NADH
2 $FADH_2$
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
CYTOSOL

Concept 9.5: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- **Most cellular respiration requires O_2 to produce ATP**

- **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**

- **Anaerobic respiration uses an electron transport chain with a final electron acceptor other than O_2 (e.g. sulfate)**

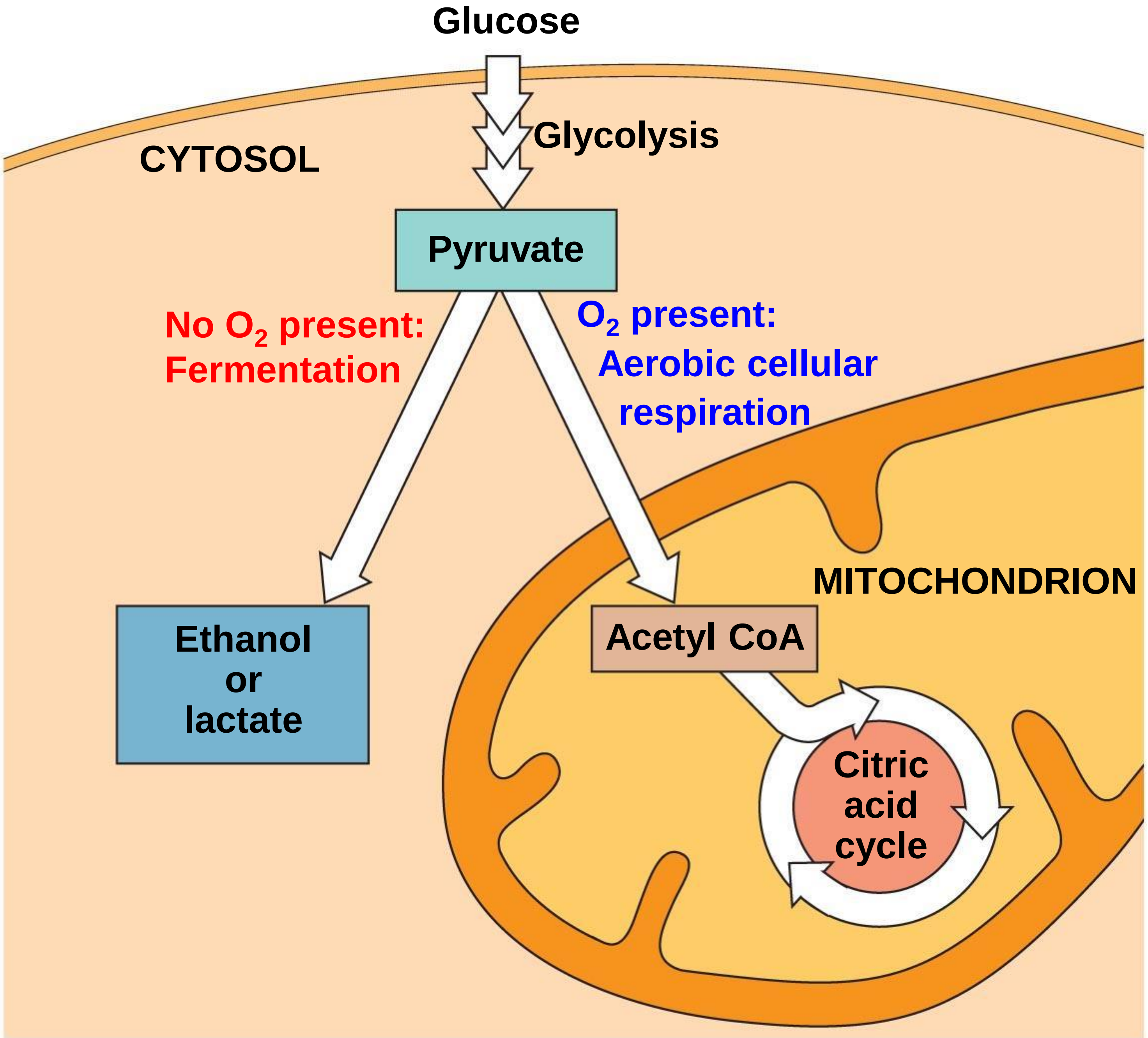
- **Fermentation uses substrate-level phosphorylation instead of an electron transport chain to generate ATP**

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

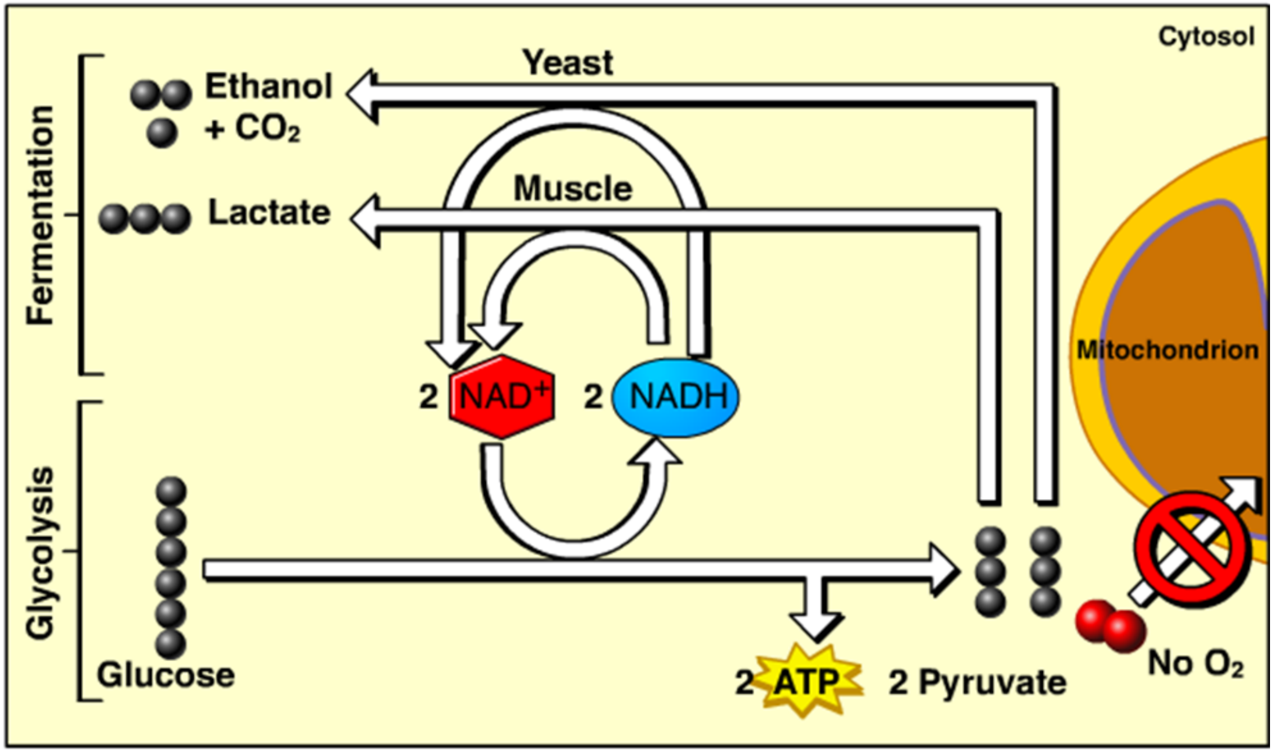
Fig. 9-19



Glucose
Glycolysis
CYTOSOL
Pyruvate
No O_2 present:
Fermentation
O_2 present:
Aerobic cellular
respiration
MITOCHONDRION
Ethanol
or
lactate
Acetyl CoA
Citric
acid
cycle

- **In alcohol fermentation, <u>pyruvate</u> is converted to <u>ethanol</u> in two steps, with the <u>first releasing CO_2</u>**

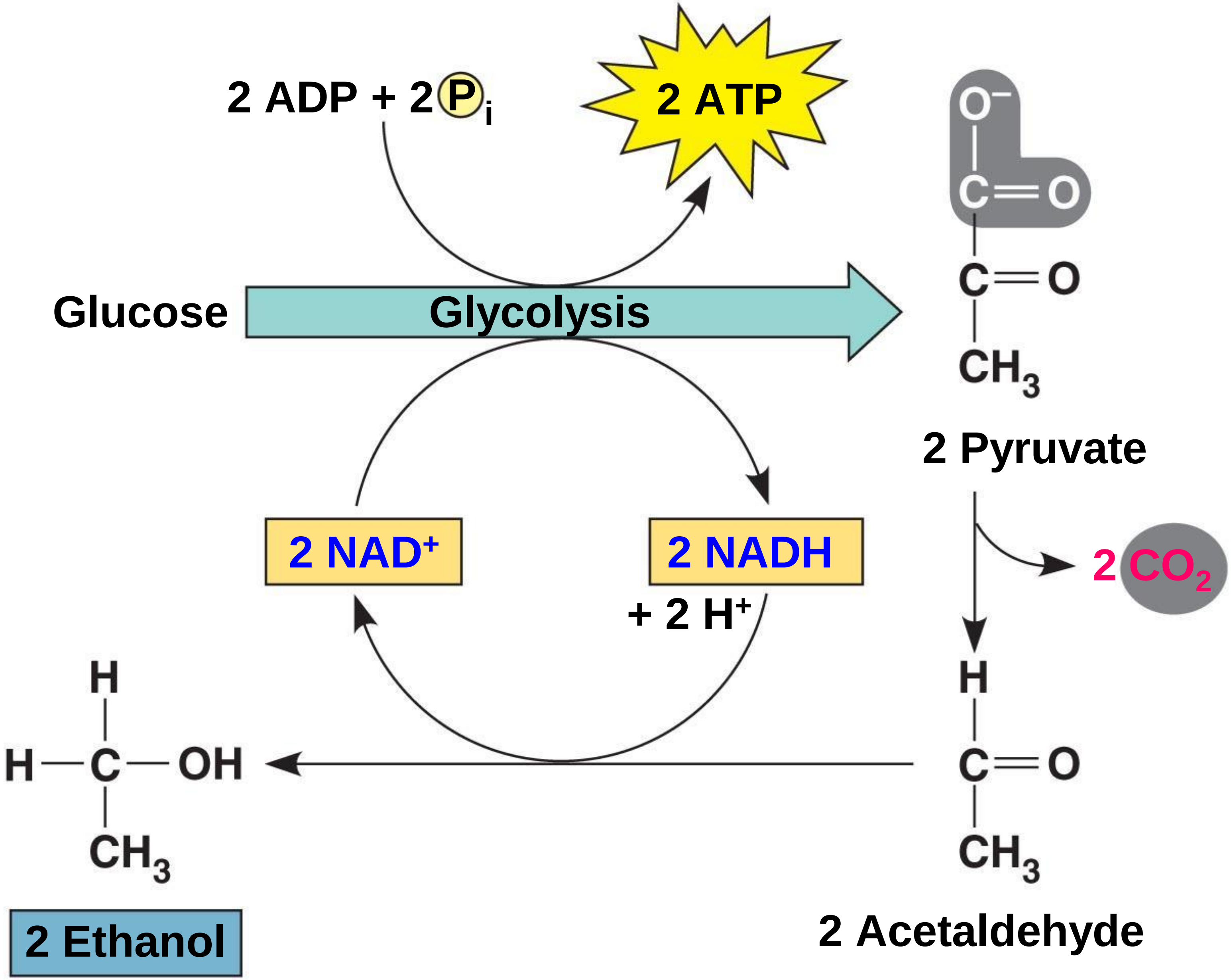
- **Alcohol fermentation by yeast is used in brewing, winemaking, and baking**



Animation: Fermentation Overview

Right-click slide / select “Play”

Fig. 9-18a



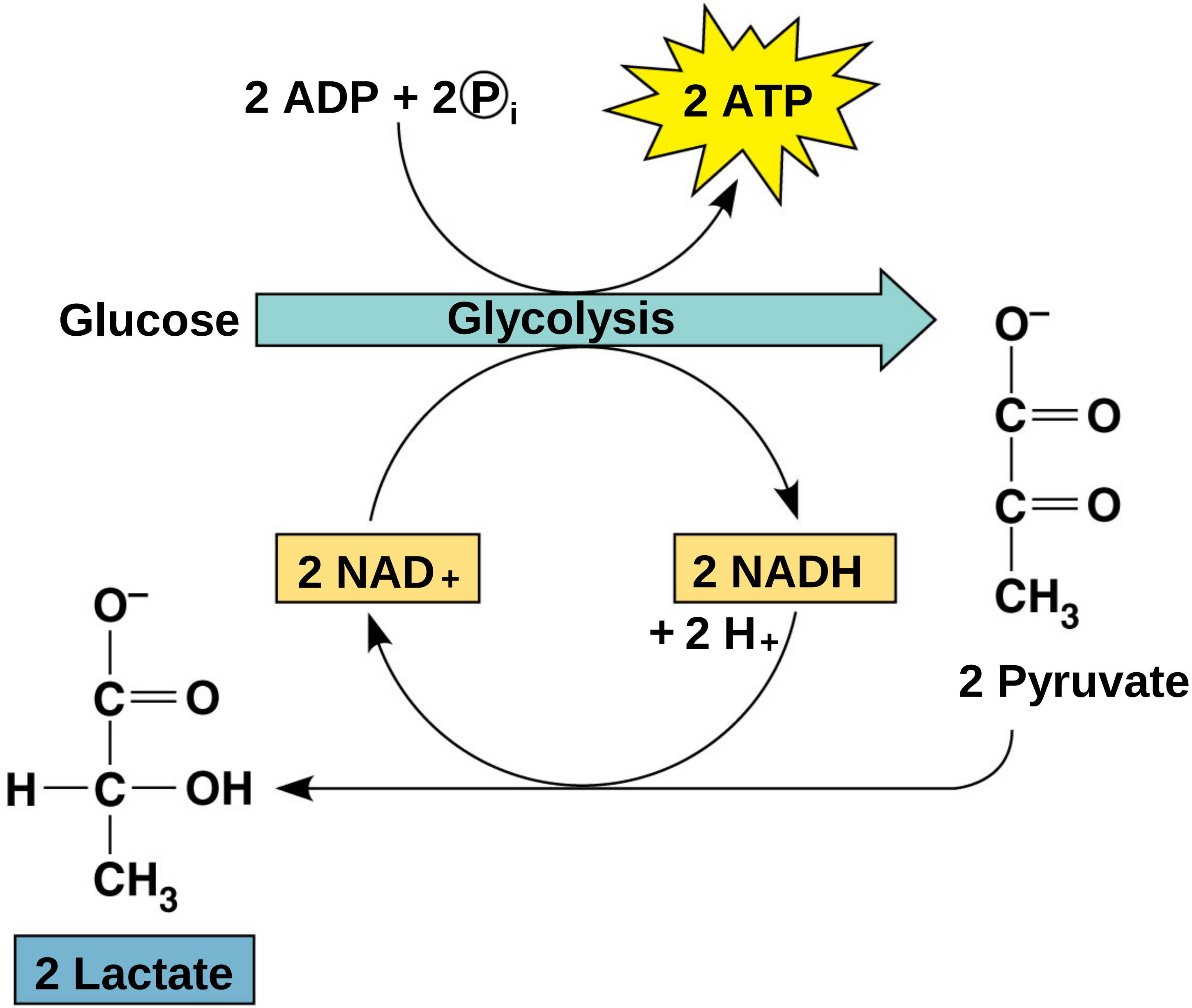
(a) Alcohol fermentation

- **In lactic acid fermentation, pyruvate is reduced to NADH, forming lactate as an end product, with no release of CO_2**

- **Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt**

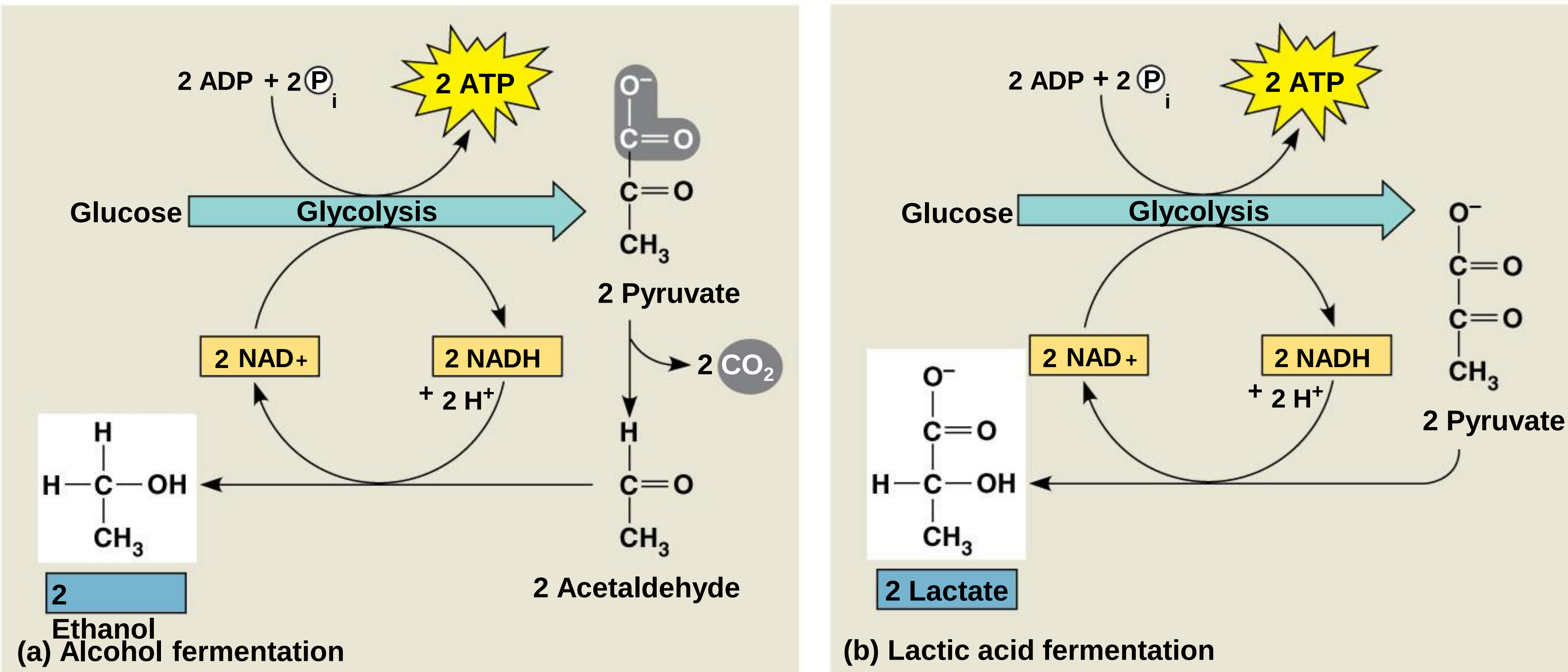
- **Human muscle cells use lactic acid fermentation to generate ATP when O_2 is scarce**

Figure 9.17b



(b) Lactic acid fermentation

Figure 9.17



2 ADP + 2 Ⓟi
2 ATP
Glucose
Glycolysis
2 Pyruvate
2 NAD+
2 NADH
+ 2 H+
2 CO2
2 Acetaldehyde
2 Ethanol
(a) Alcohol fermentation
2 ADP + 2 Ⓟi
2 ATP
Glucose
Glycolysis
2 Pyruvate
2 NAD+
2 NADH
+ 2 H+
2 Lactate
(b) Lactic acid fermentation

Concept 9.6: Glycolysis and the citric acid cycle connect to many other metabolic pathways

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

The Versatility of Catabolism

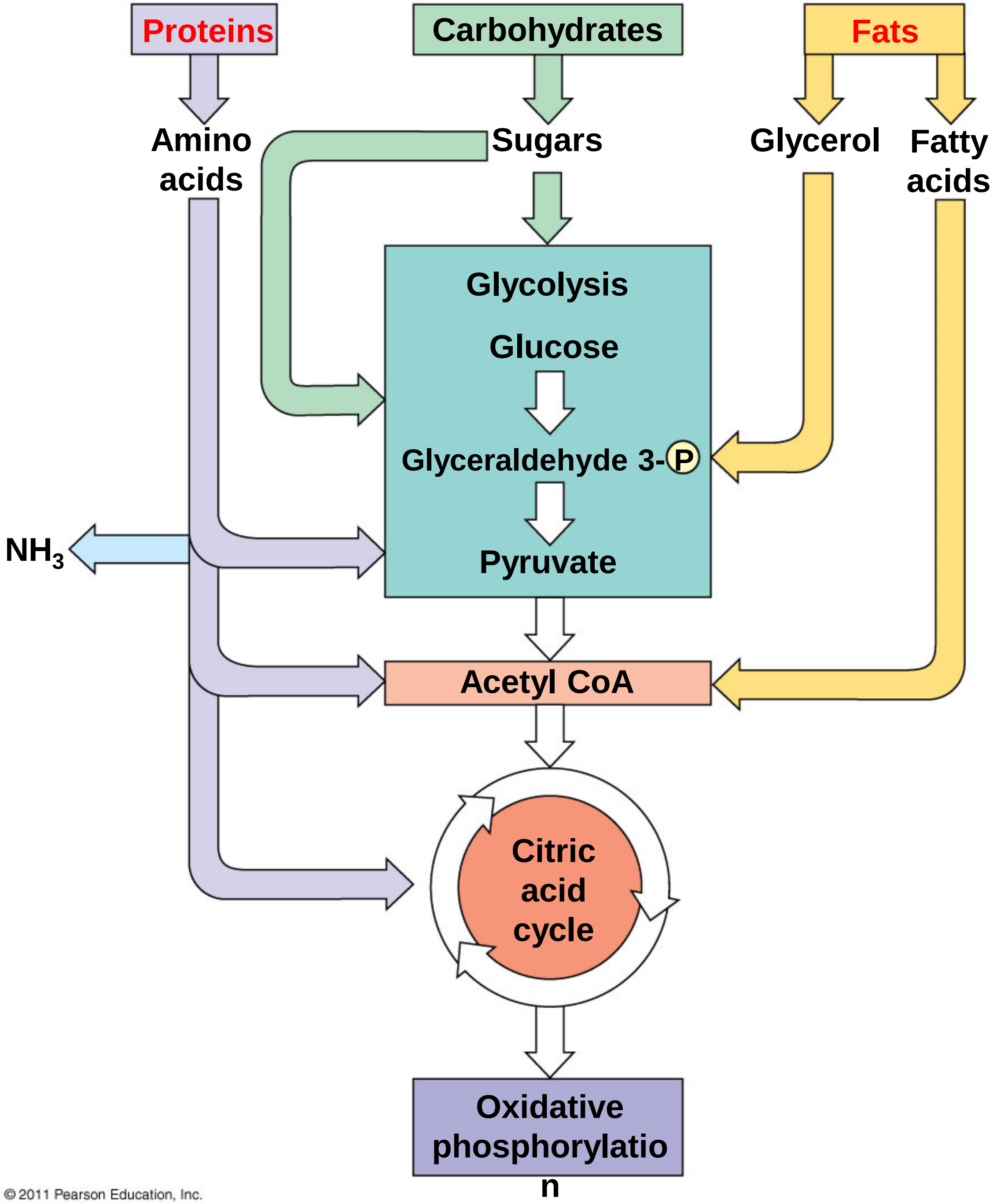
- **Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration**

- **Glycolysis accepts a wide range of carbohydrates**

- **Proteins must be digested to amino acids; amino groups can feed glycolysis or the citric acid cycle**

- Fats are digested to glycerol (**used in glycolysis**) and **fatty acids** (**used in generating acetyl CoA)**
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA
- An oxidized **gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate**

Figure 9.19



Proteins
Carbohydrates
Fats
Amino acids
Sugars
Glycerol
Fatty acids
Glycolysis
Glucose
Glyceraldehyde 3-P
NH_3
Pyruvate
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

Biosynthesis (Anabolic Pathways)

- The body **uses small molecules to build other substances**
- These small molecules may **come directly from food, from glycolysis**, or **from the citric acid cycle**
- **Humans can make more than half of the 20 amino acids by modifying compounds siphoned away from citric acid cycle**
- **Glucose can be synthesized from pyruvate**
- **Fats can be synthesized from Acetyl-CoA**

Metabolism

- **Metabolism is remarkably versatile (able to adapt) and adaptable!!**

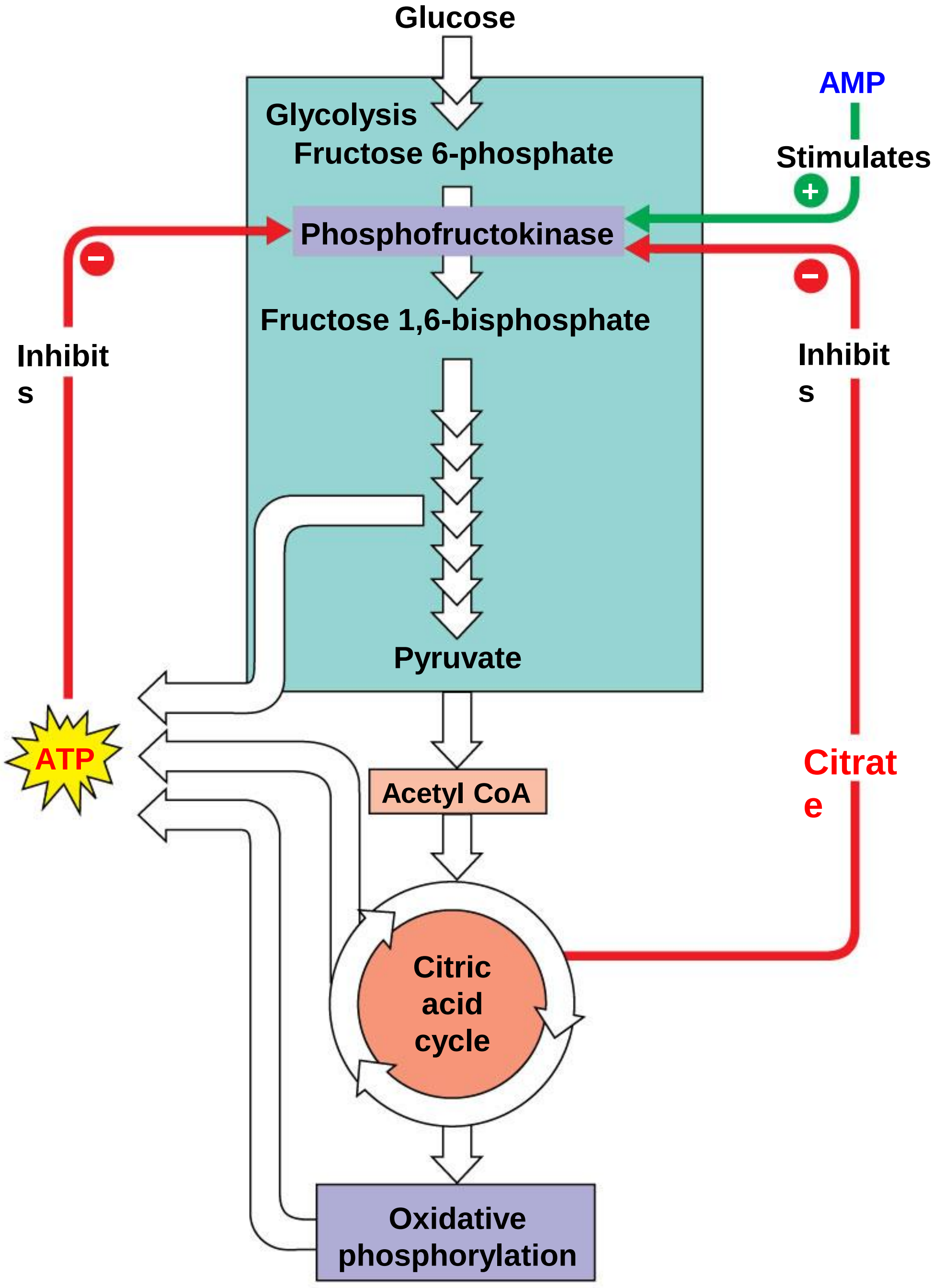
Regulation of Cellular Respiration via Feedback Mechanisms

- **Feedback inhibition is the most common mechanism for control**

- **If ATP concentration begins to drop, respiration speeds up; when there is plenty of ATP, respiration slows down**

- **Control of catabolism is based mainly on regulating the activity of enzymes at strategic points in the catabolic pathway**

Figure 9.20



Glucose
Glycolysis
Fructose 6-phosphate
AMP
Stimulates
+
Phosphofructokinase
–
–
Fructose 1,6-bisphosphate
Inhibit
s
Inhibit
s
Pyruvate
ATP
Citrat
e
Acetyl CoA
Citric
acid
cycle
Oxidative
phosphorylation