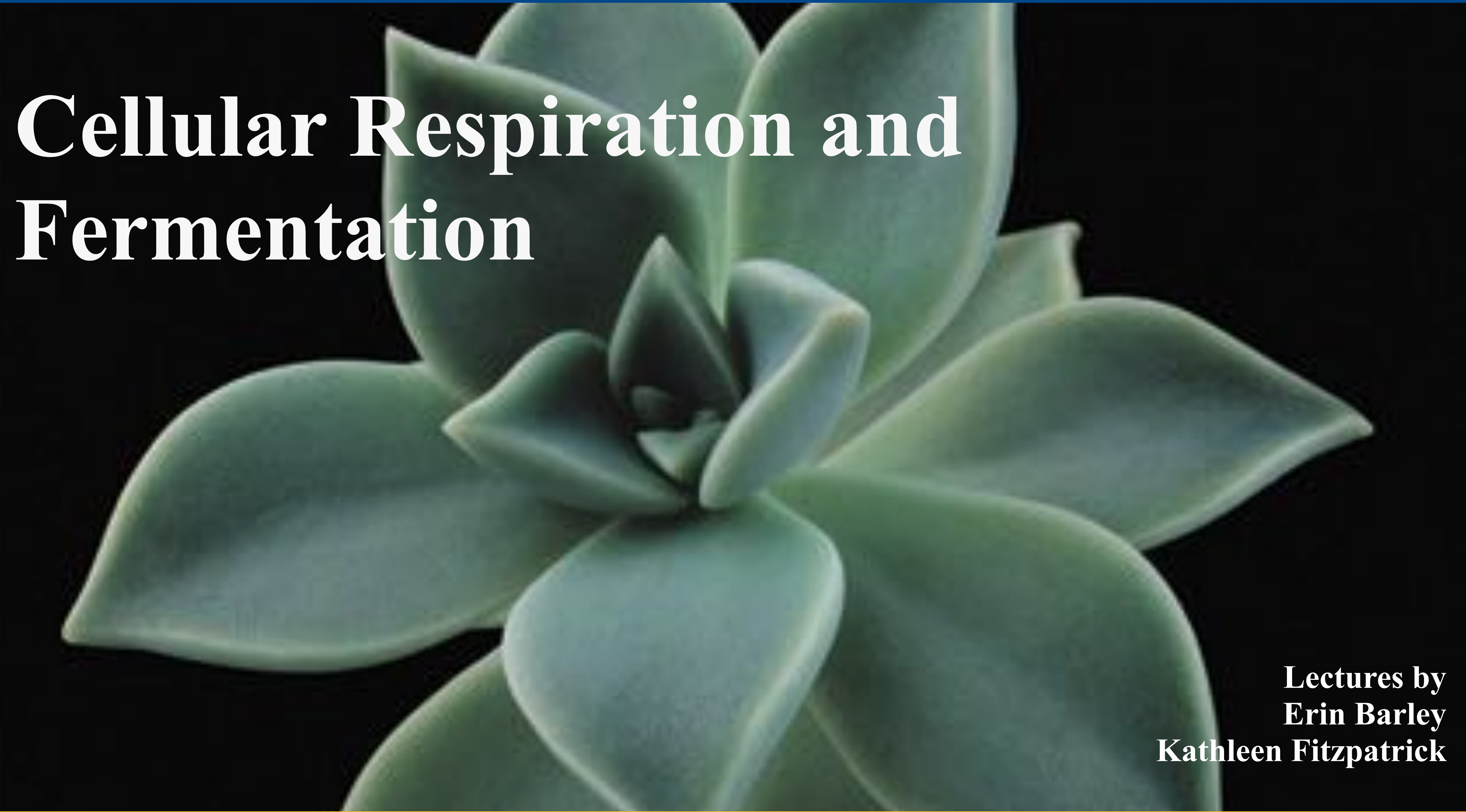
LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 9



Cellular Respiration and Fermentation

Lectures by
Erin Barley
Kathleen Fitzpatrick

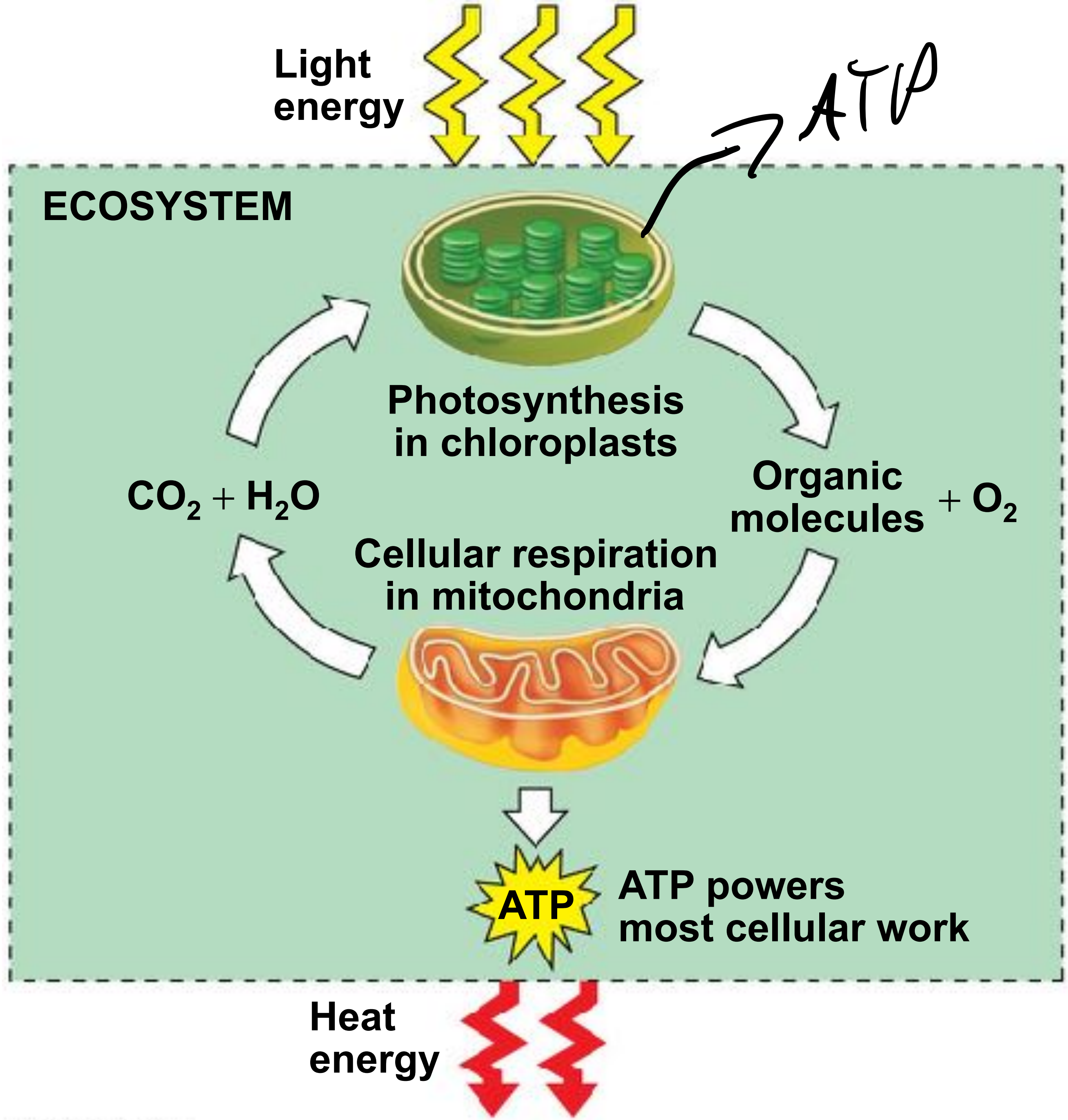
Overview: Life Is Work

- Living cells require energy from outside sources
- Some animals, such as the chimpanzee, 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
ATP
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

- Several processes are central to cellular respiration and related pathways

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 9.UN01

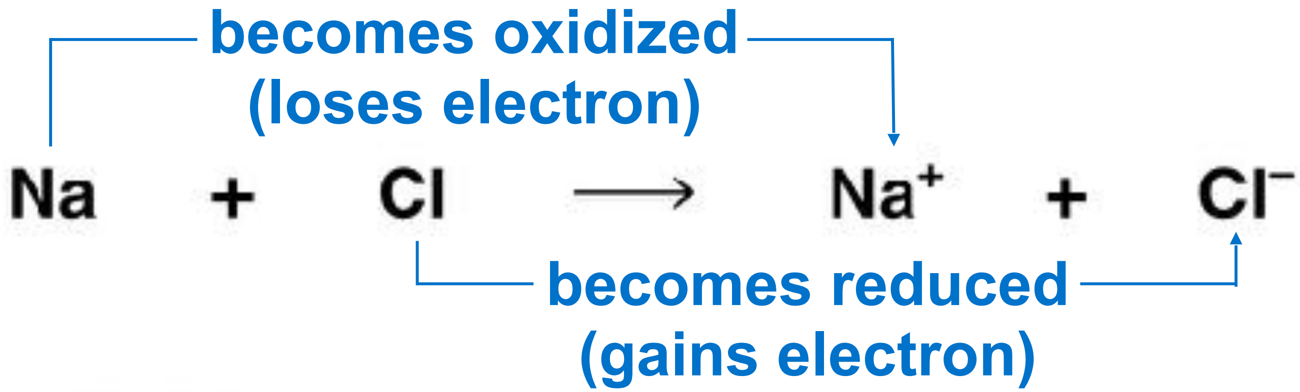
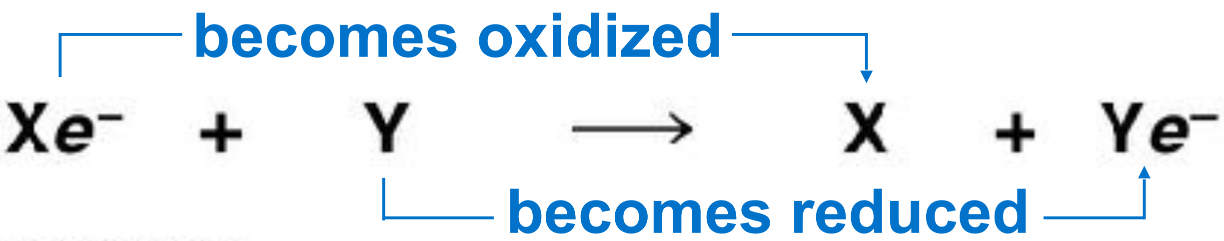
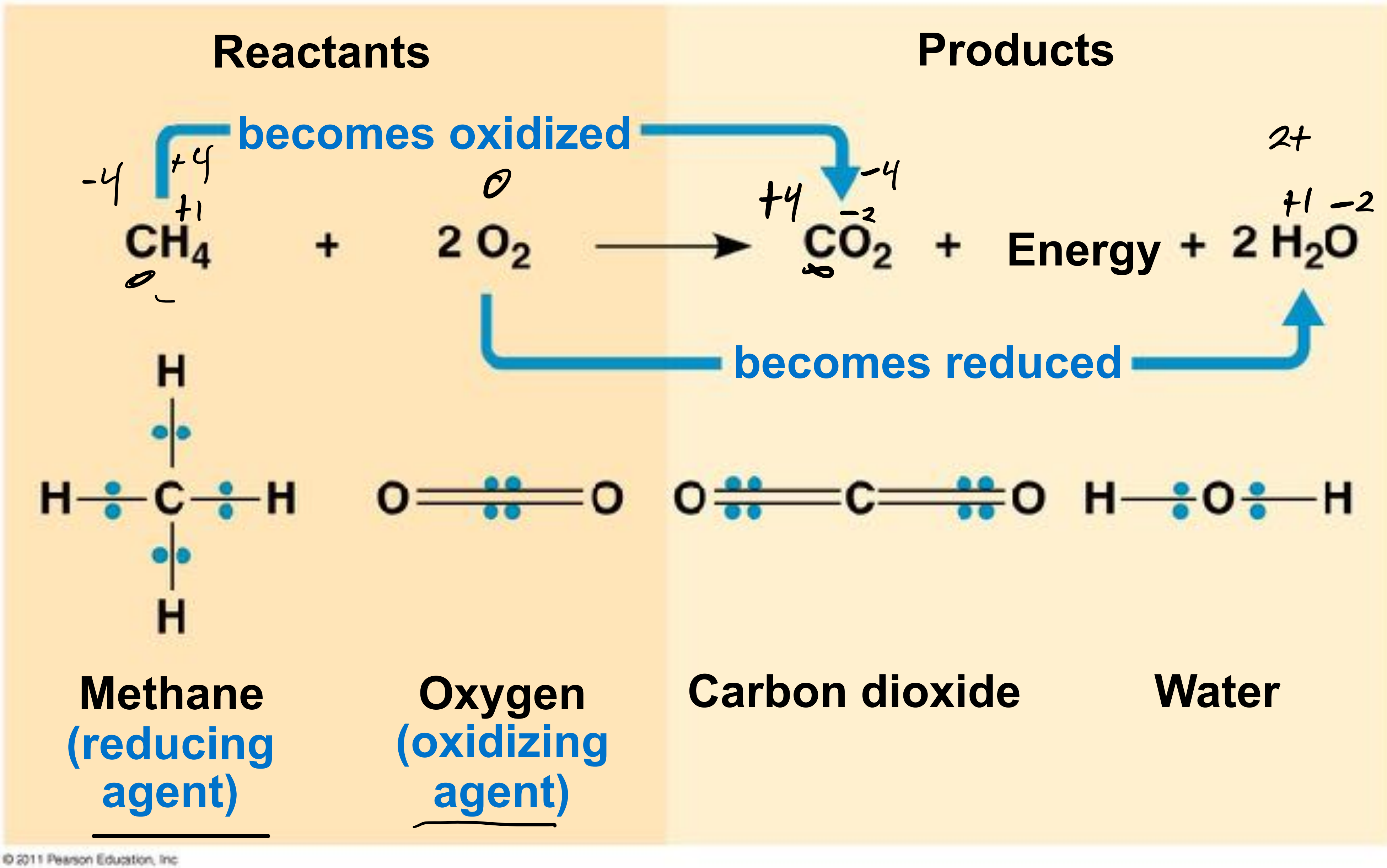


Figure 9.UN02



- 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 9.3


Reactants
Products
becomes oxidized
CH4 + 2 O2 → CO2 + Energy + 2 H2O
becomes reduced
Methane
(reducing agent)
Oxygen
(oxidizing agent)
Carbon dioxide
Water
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Oxidation of Organic Fuel Molecules During Cellular Respiration

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

Figure 9.UN03

becomes oxidized

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

becomes reduced

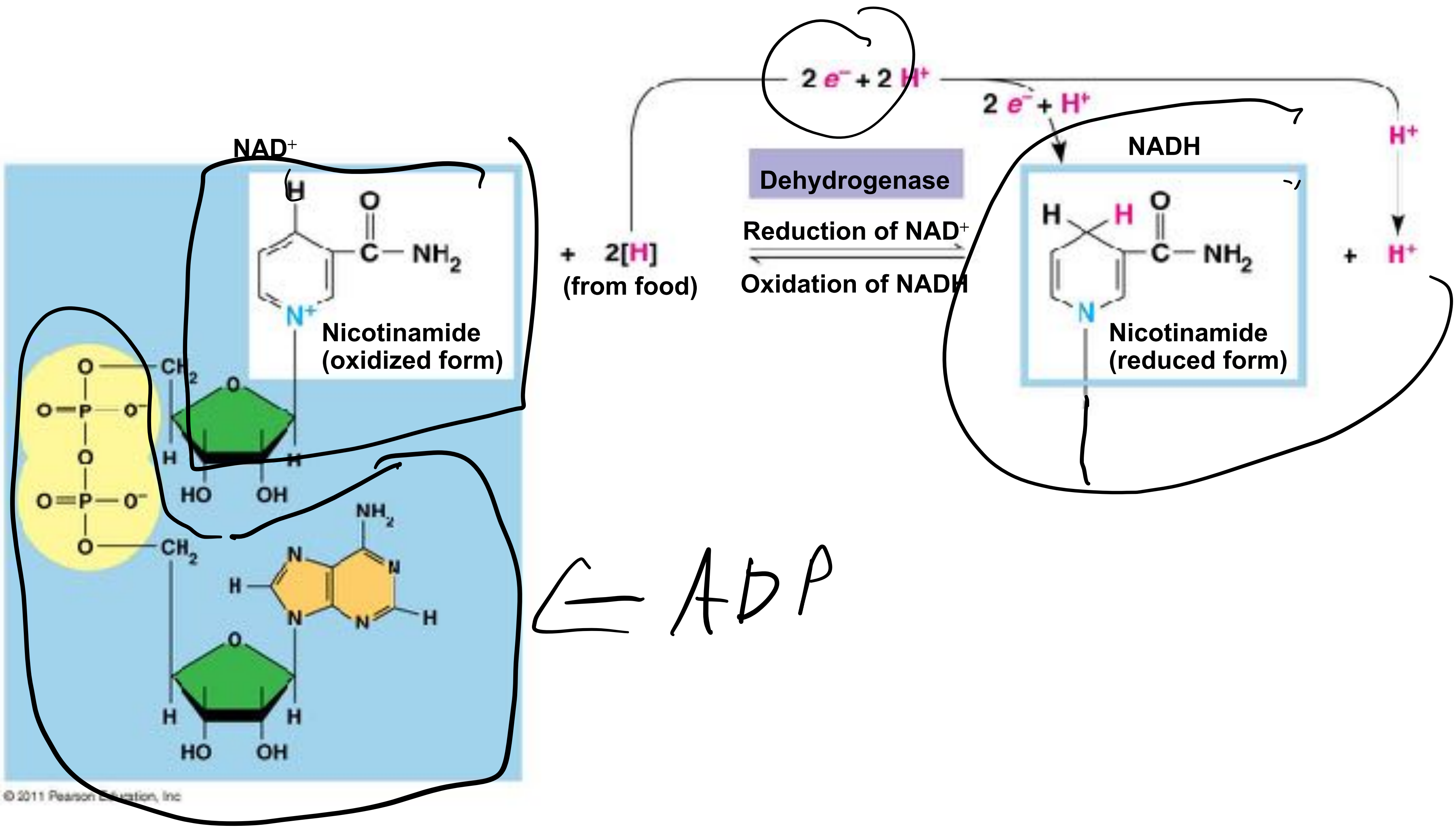
Stepwise Energy Harvest via NAD$^+$ and the Electron Transport Chain

- 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

  oxidized $+2e^-$ → NADH (Reduced)

- 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 9.4



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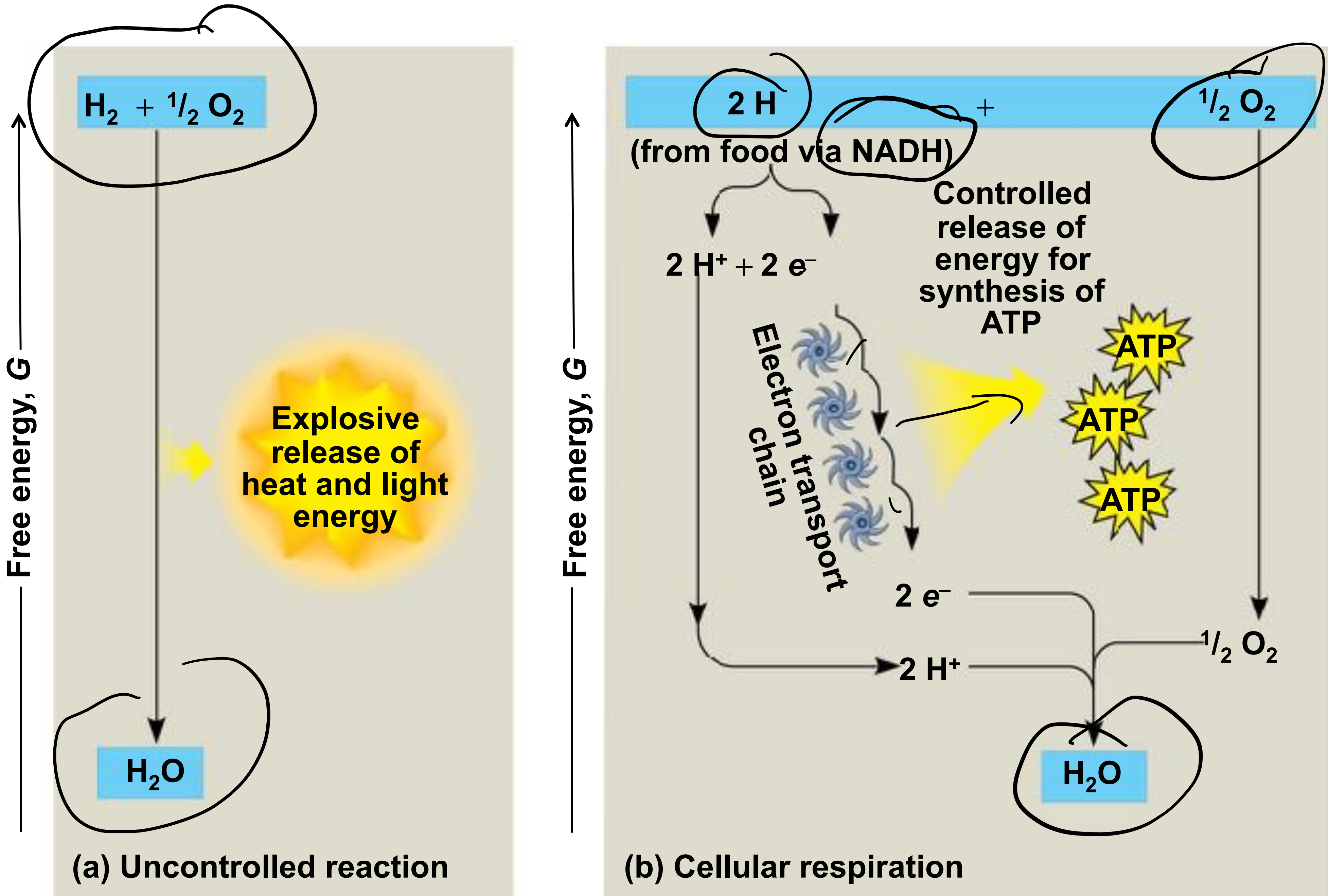
ADP

Figure 9.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 9.5



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

The Stages of Cellular Respiration: *A Preview*

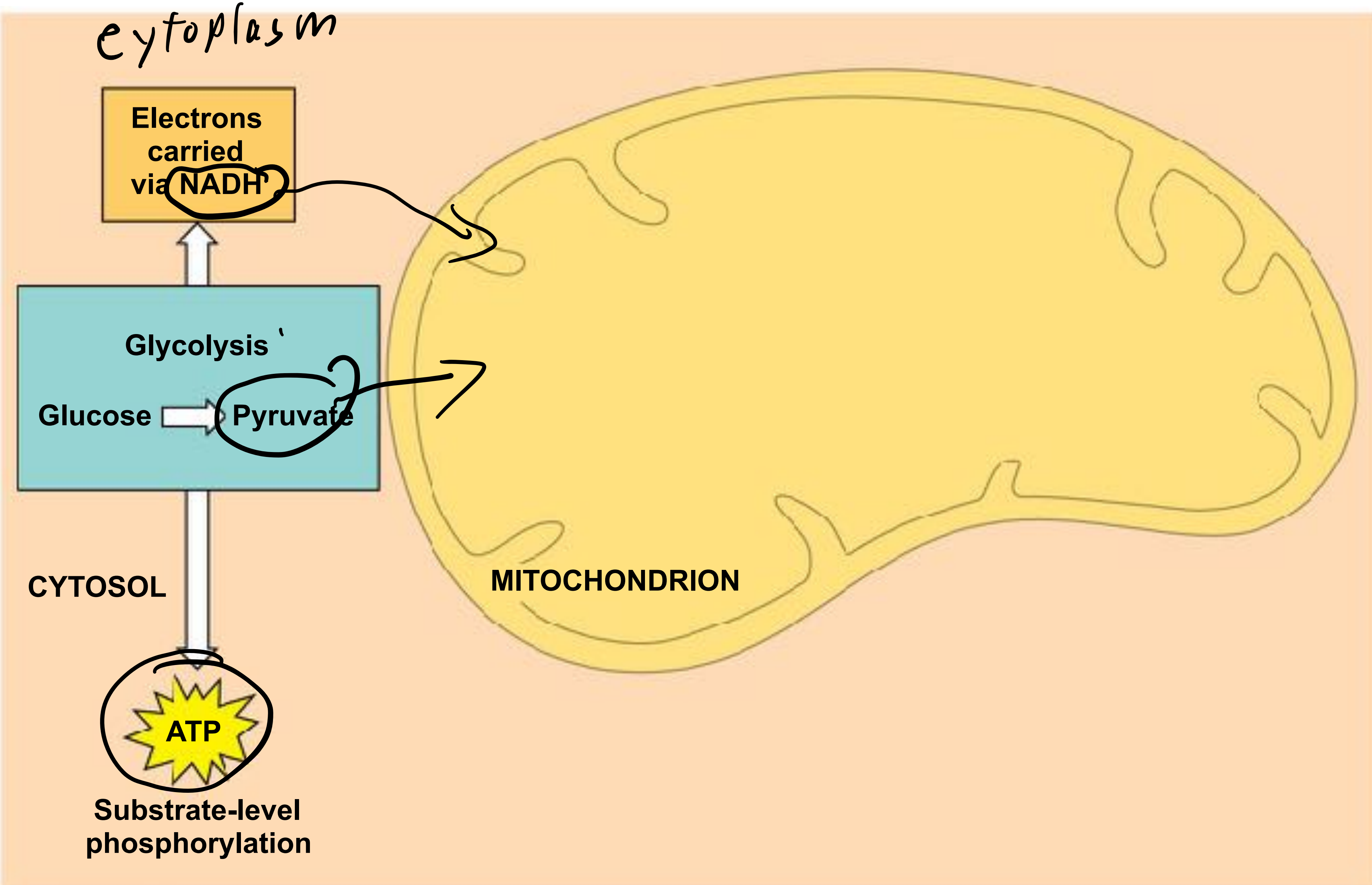
- Harvesting of energy from glucose has three stages
  - **Glycolysis** (breaks down glucose into two molecules of pyruvate)
  - The **citric acid cycle** (completes the breakdown of glucose)
  - **Oxidative phosphorylation** (accounts for most of the ATP synthesis)

Figure 9.UN05

fermentation.

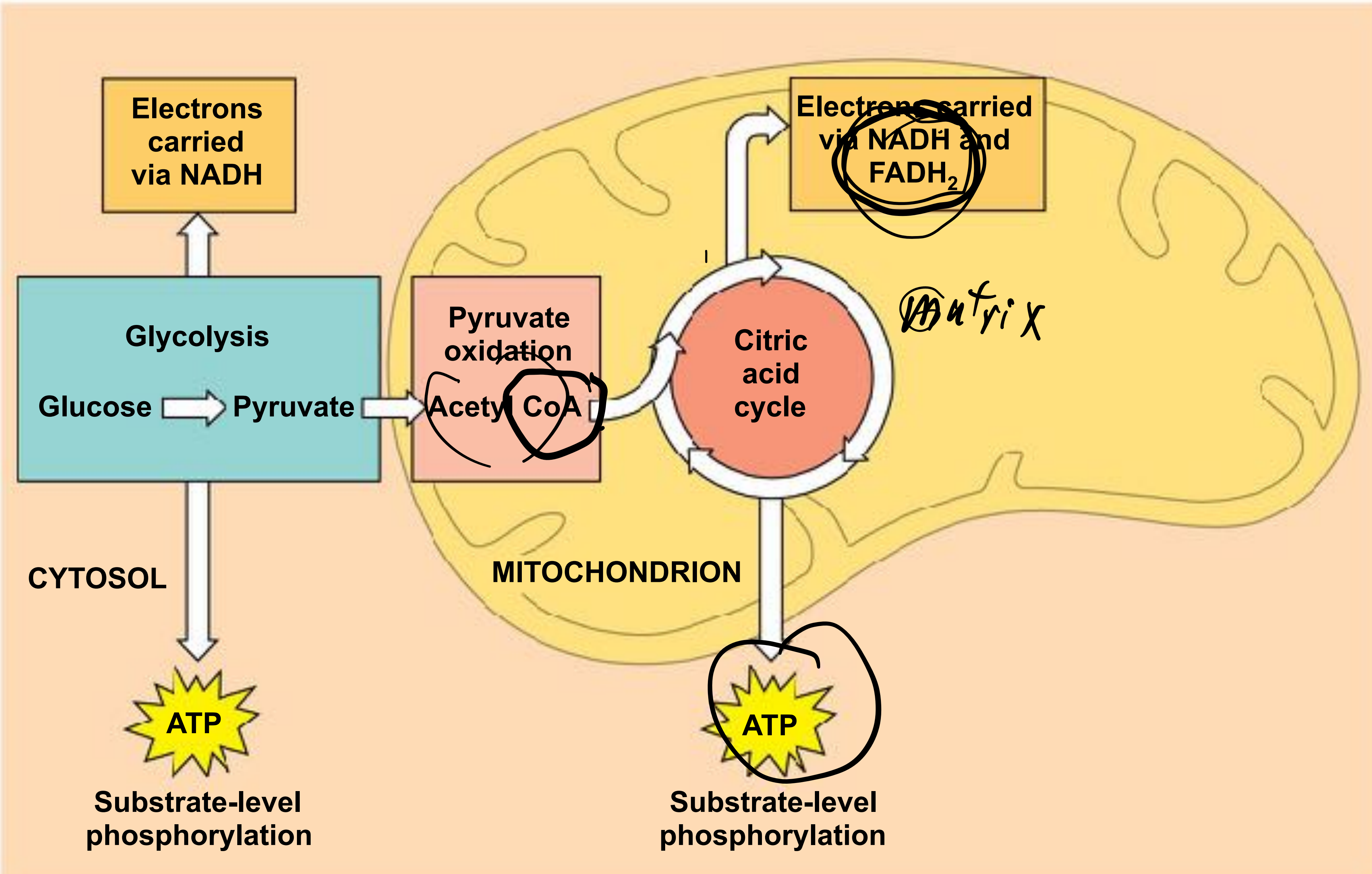
1. Glycolysis (color-coded teal throughout the chapter)
2. Pyruvate oxidation and the citric acid cycle (color-coded salmon)
3. Oxidative phosphorylation: electron transport and chemiosmosis (color-coded violet)

Figure 9.6-1



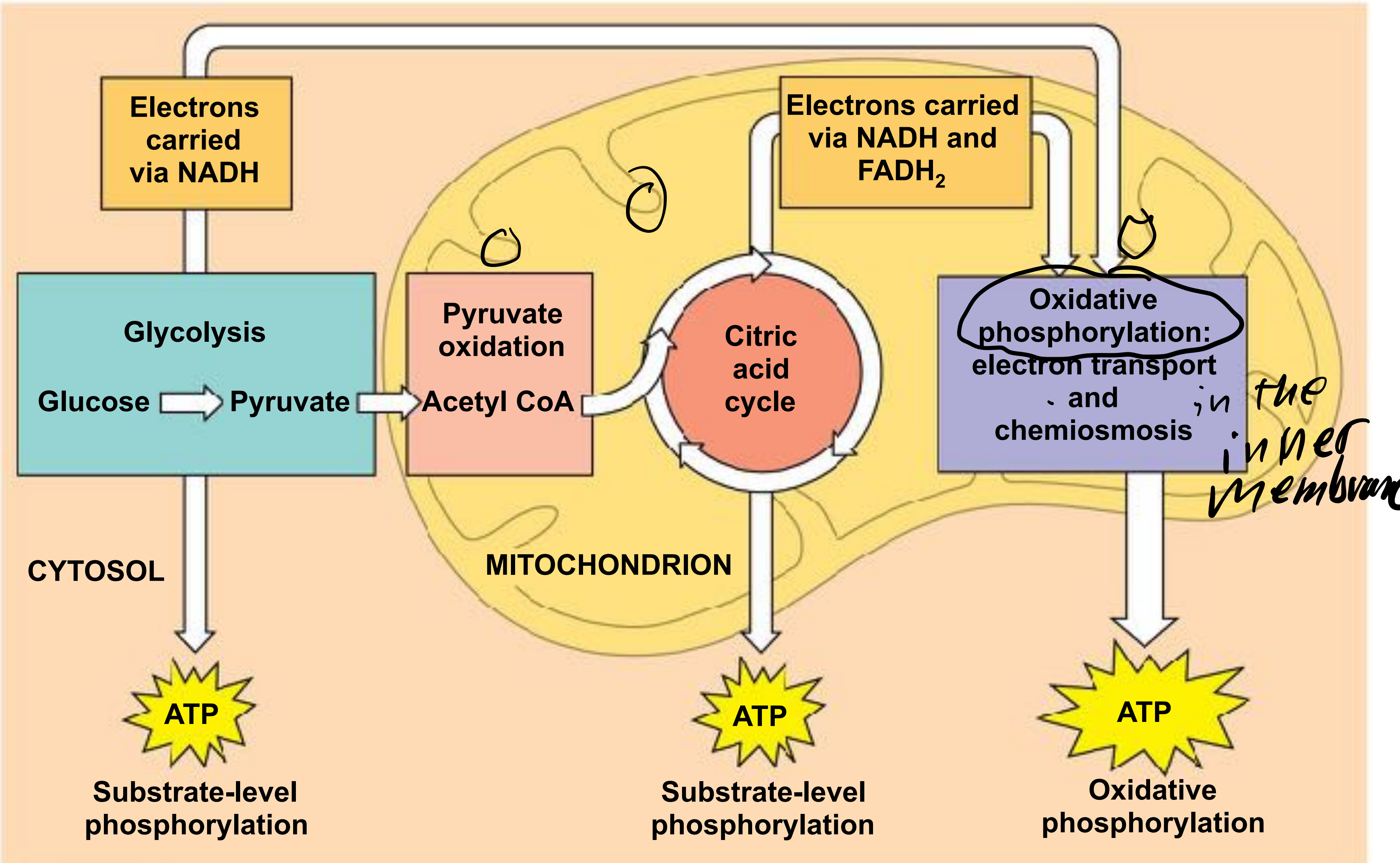
cytoplasm
Electrons carried via NADH
Glycolysis
Glucose
Pyruvate
CYTOSOL
MITOCHONDRION
ATP
Substrate-level phosphorylation

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
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation

Figure 9.6-3

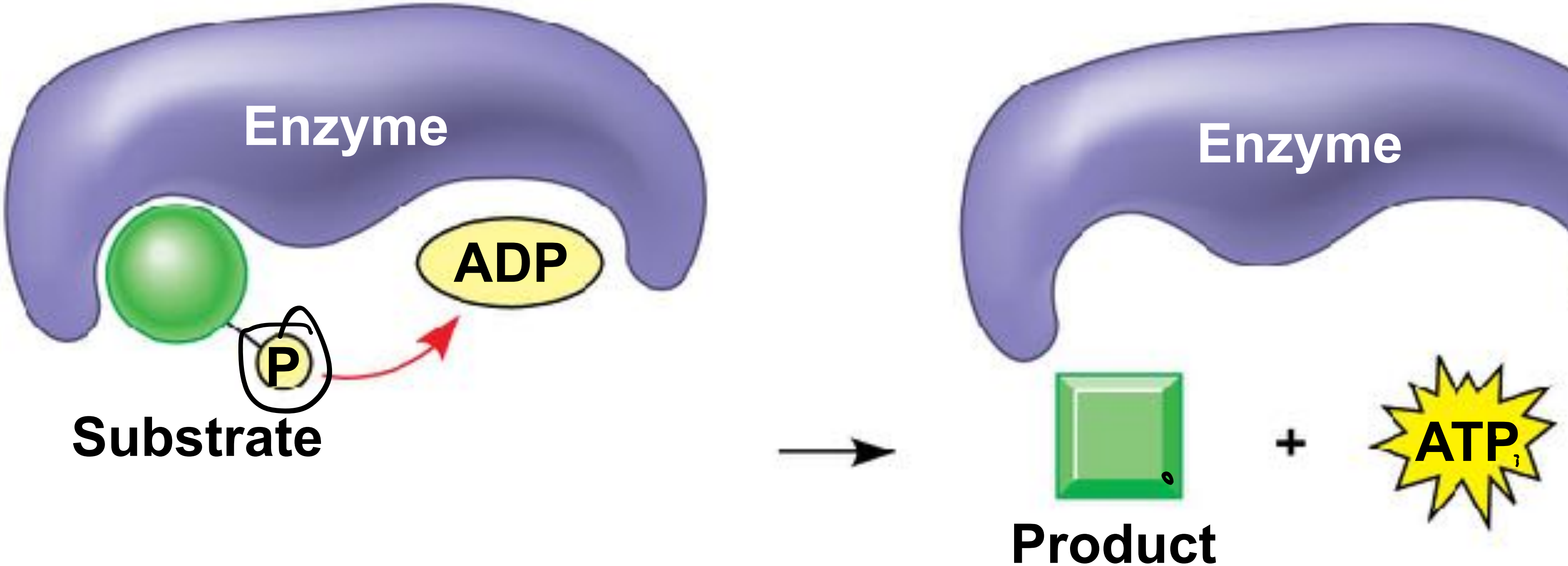

Electrons carried via NADH
Electrons carried via NADH and FADH2
Glycolysis
Glucose
Pyruvate
Pyruvate oxidation
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation: electron transport and chemiosmosis
in the inner membrane
CYTOSOL
MITOCHONDRION
ATP
Substrate-level phosphorylation
ATP
Substrate-level phosphorylation
ATP
Oxidative phosphorylation

- The process that generates most of the ATP is called oxidative phosphorylation because it is powered by redox reactions

PLAY BioFlix: Cellular Respiration

- 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

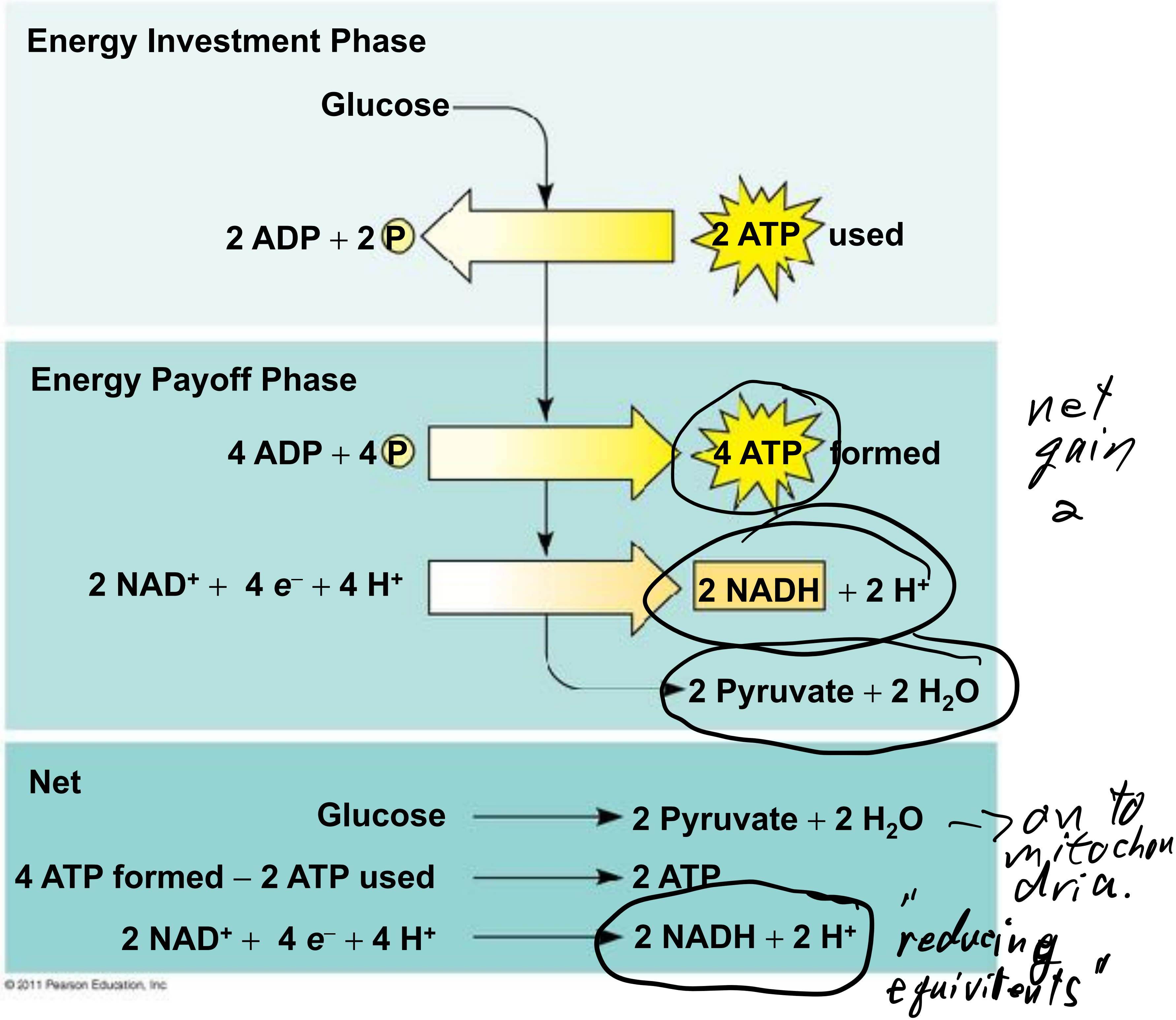


Concept 9.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- 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
- Glycolysis occurs whether or not O_2 is present

net gain of 2 ATP

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⁺
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net gain 2
on to mitochondria.
"reducing equivitents"

Glycolysis: Energy Investment Phase

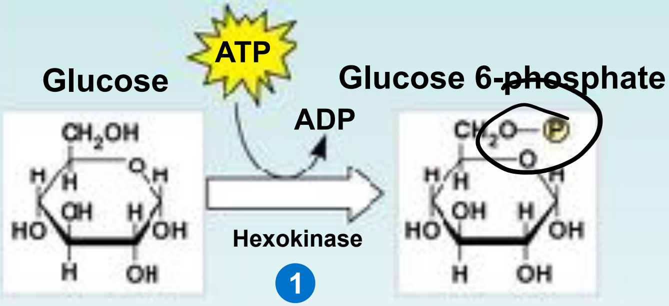
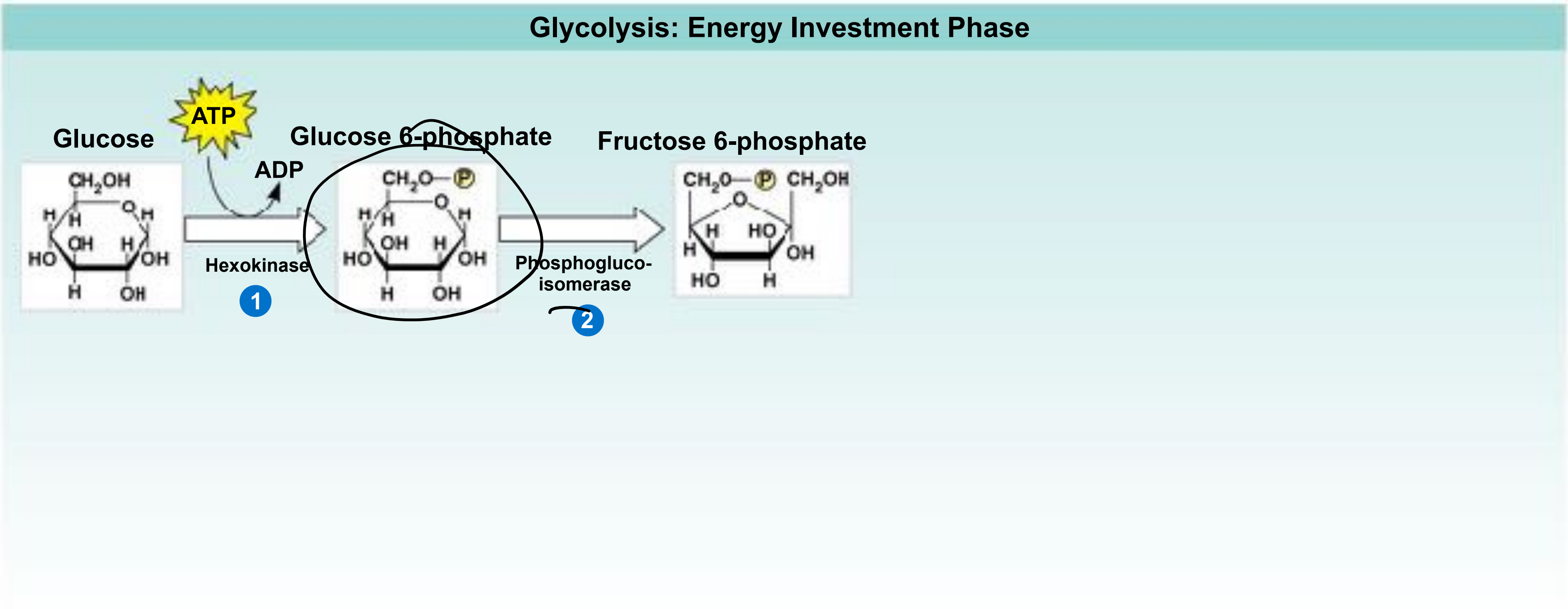
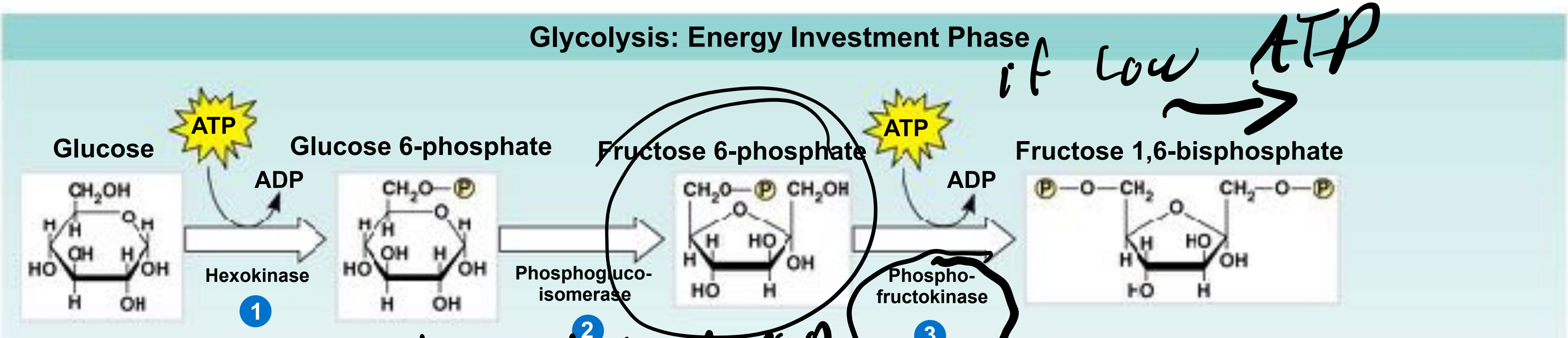


Figure 9.9-2



Glycolysis: Energy Investment Phase
ATP
Glucose
ADP
Glucose 6-phosphate
Fructose 6-phosphate
CH2OH
HO
OH
H
Hexokinase
1
Phosphogluco-
isomerase
2

Figure 9.9-3



if low ATP →

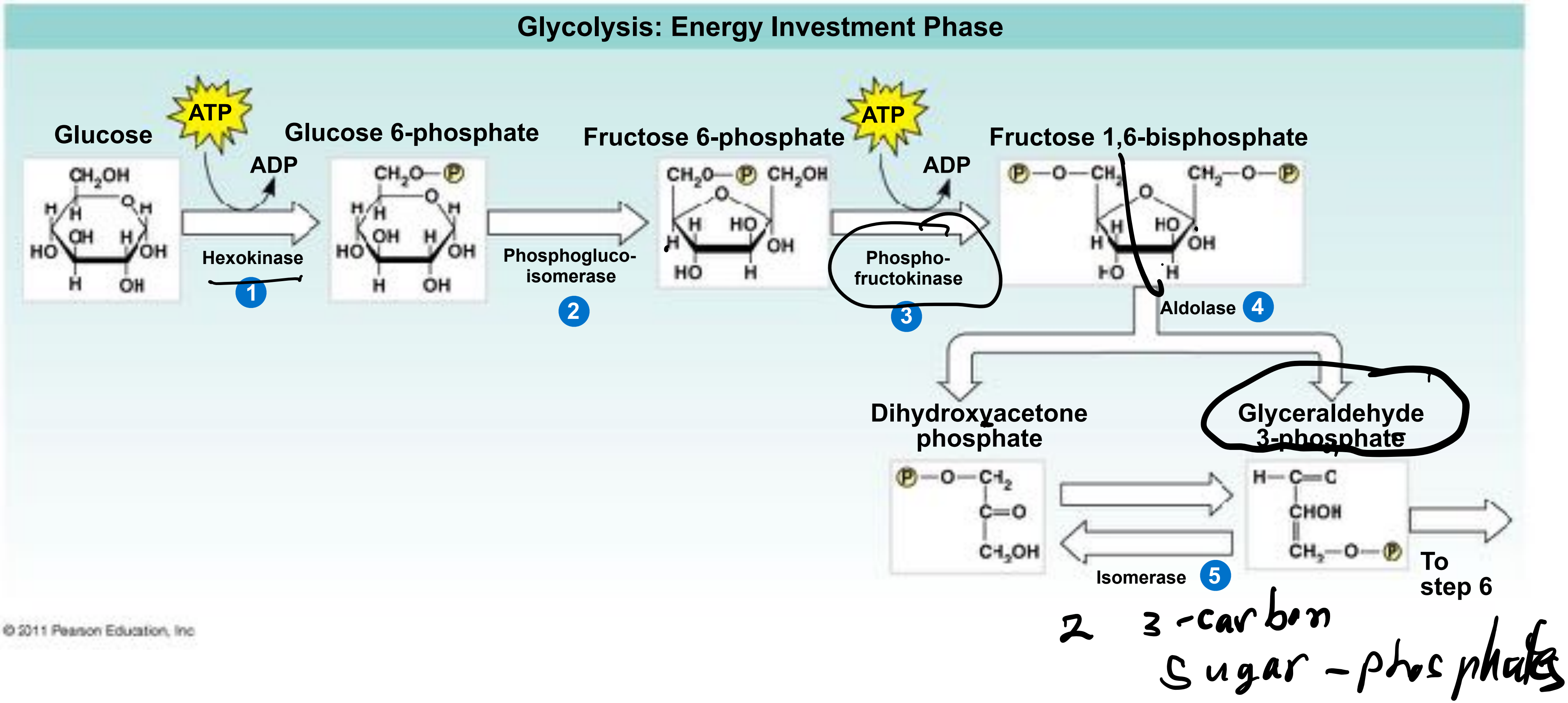
if high ATP
+ citrate

inhibited by later products.

Build starch (plant)
or
glycogen (animal)

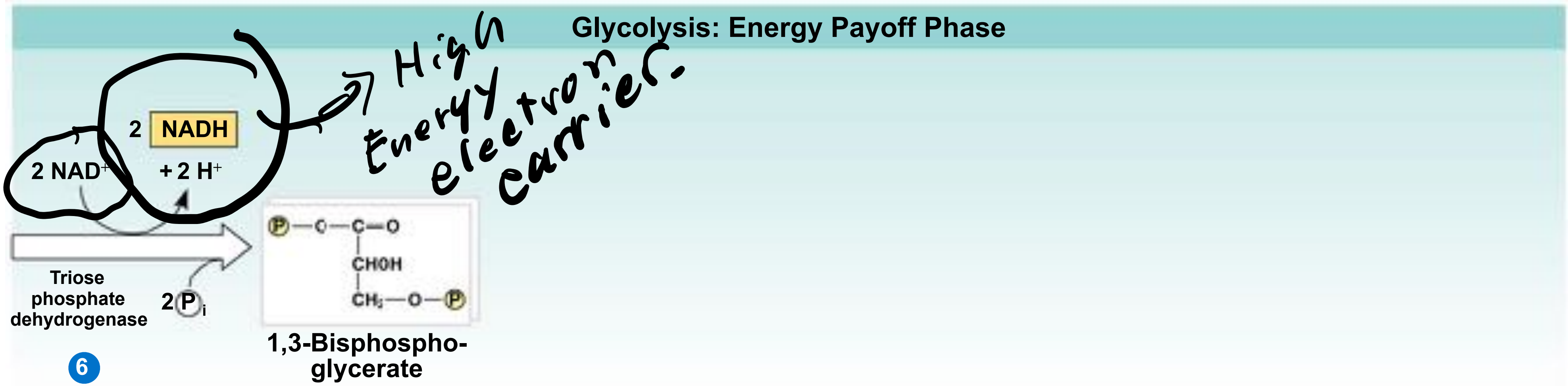
inhibited by
citrate
+
ATP high
concentration

Figure 9.9-4



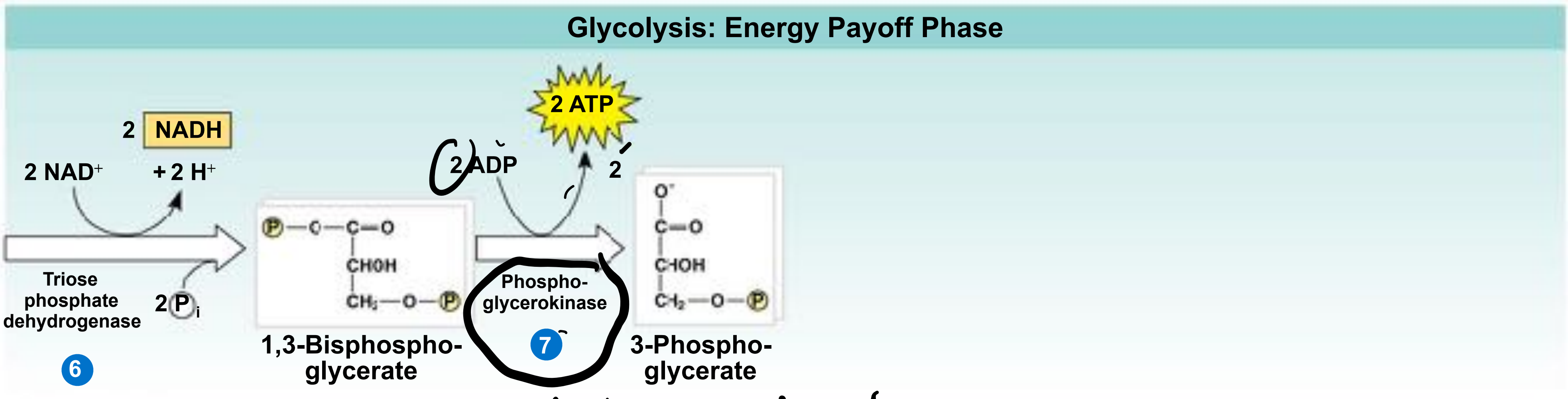
Glycolysis: Energy Investment Phase
Glucose
ATP
ADP
Hexokinase
1
Glucose 6-phosphate
Phosphogluco-
isomerase
2
Fructose 6-phosphate
ATP
ADP
Phospho-
fructokinase
3
Fructose 1,6-bisphosphate
Aldolase
4
Dihydroxyacetone
phosphate
Glyceraldehyde
3-phosphate
Isomerase
5
To
step 6
2 3-carbon
sugar-phosphate

Figure 9.9-5



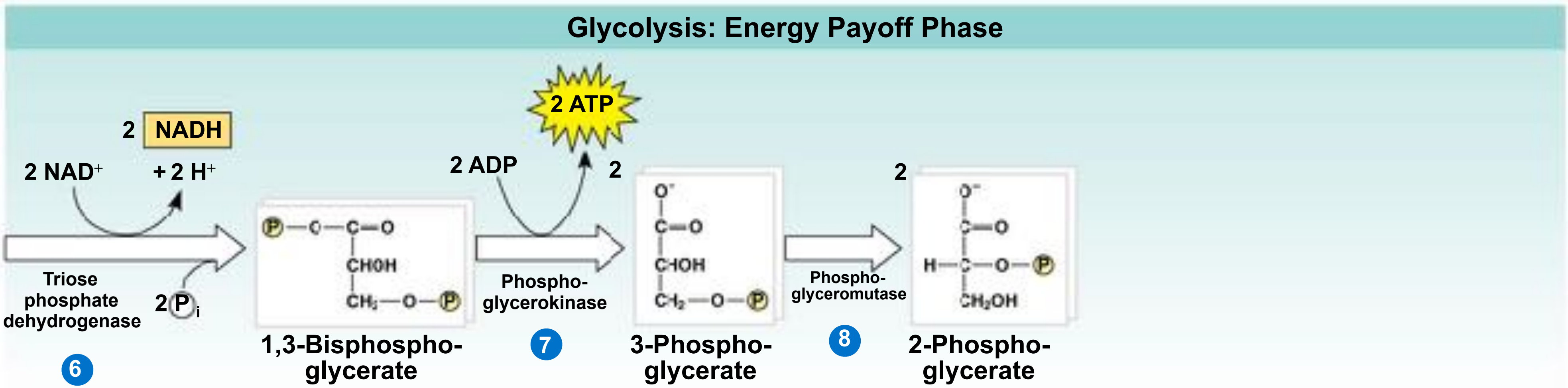
Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
Triose phosphate dehydrogenase
2 P i
P—C—C=O
CHOH
CH2—O—P
1,3-Bisphosphoglycerate
6
High Energy electron carrier.

Figure 9.9-6



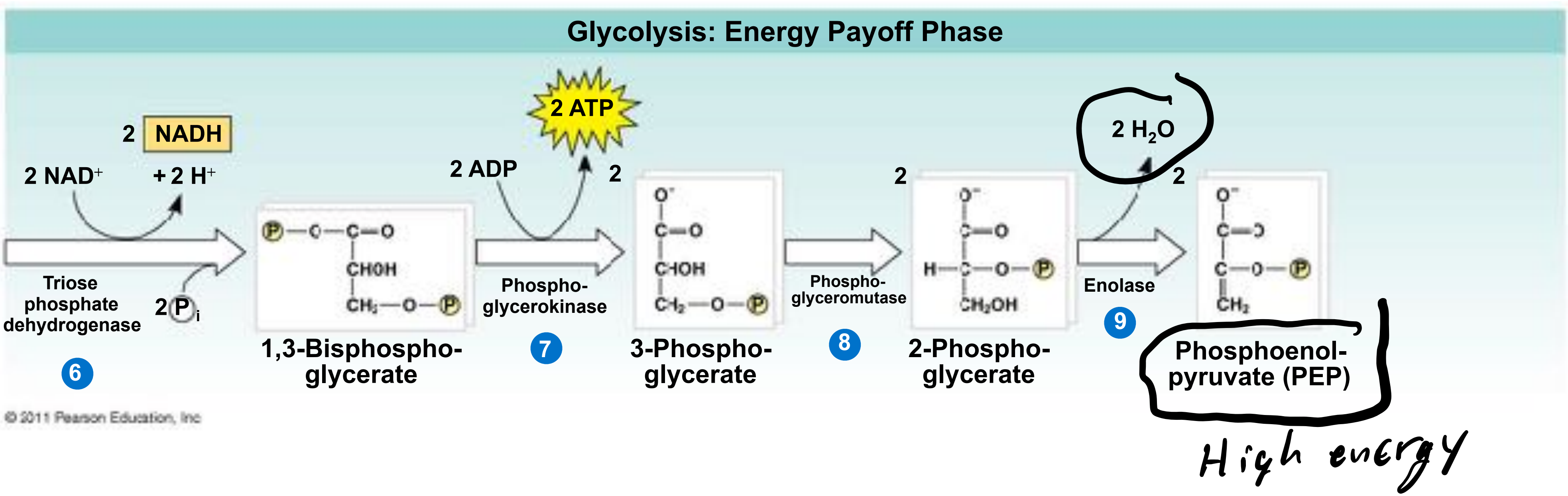
substrate -level phosphorylation

Figure 9.9-7



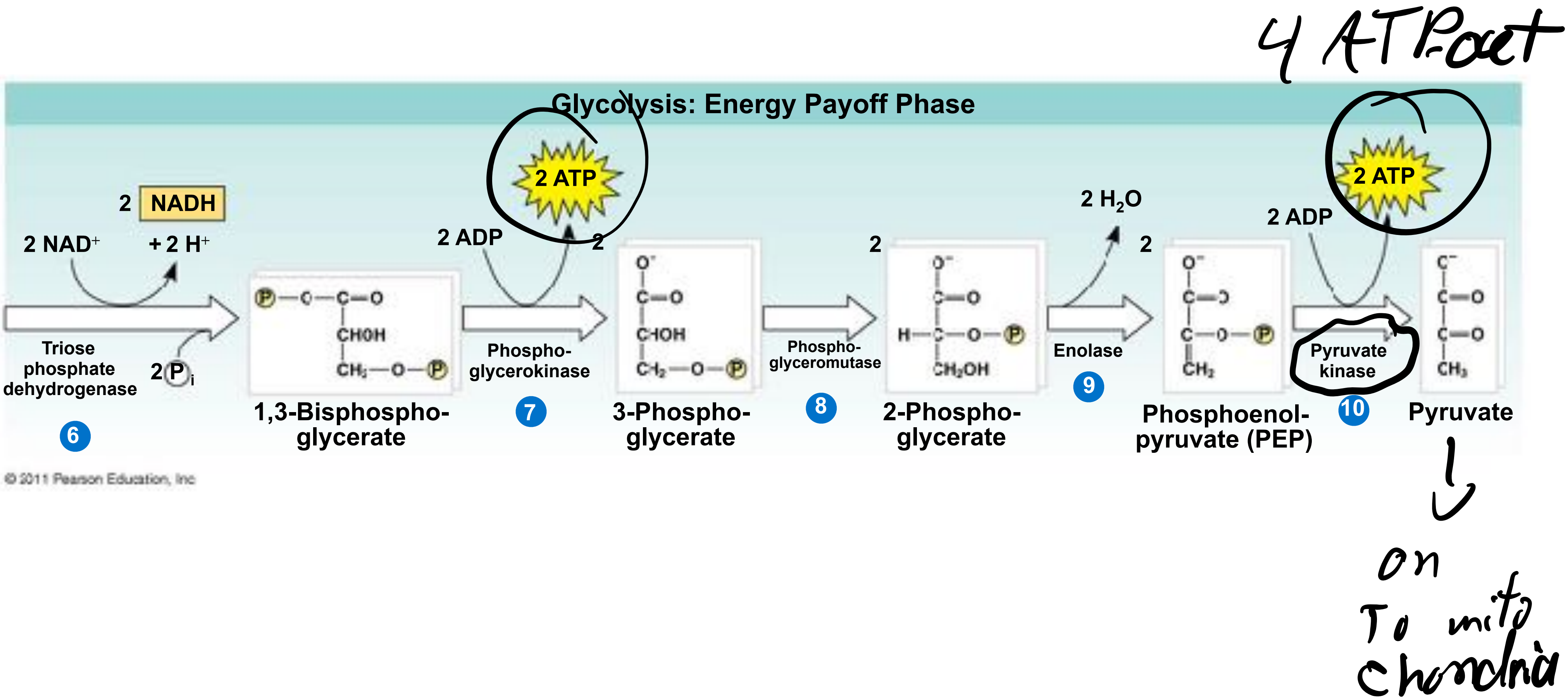
Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
2 ATP
2 ADP
2
2
Triose phosphate dehydrogenase
2 Pi
6
P—O—C—O
CHOH
CH2—O—P
1,3-Bisphospho-glycerate
Phospho-glycerokinase
7
O-
C—O
CHOH
CH2—O—P
3-Phospho-glycerate
Phospho-glyceromutase
8
O-
C—O
H—C—O—P
CH2OH
2-Phospho-glycerate

Figure 9.9-8



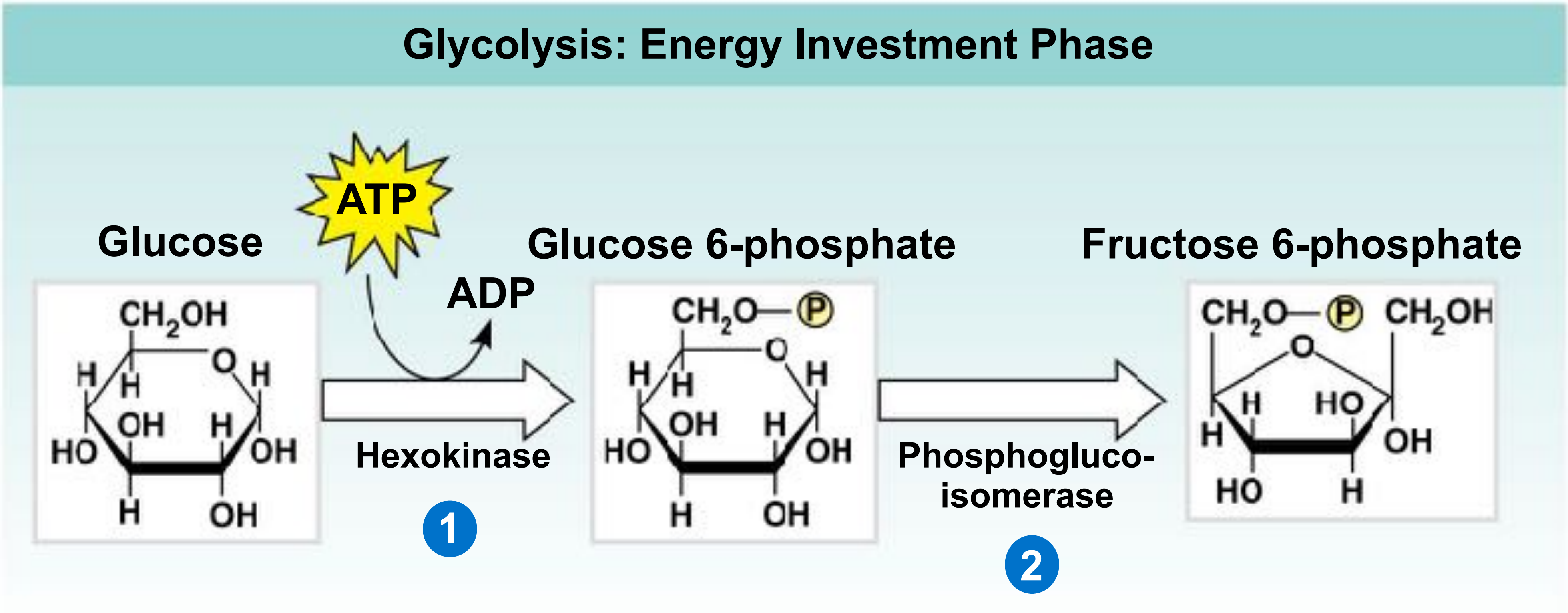
Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
Triose phosphate dehydrogenase
2 Pi
6
1,3-Bisphospho-glycerate
2 ATP
2 ADP
2
Phospho-glycerokinase
7
3-Phospho-glycerate
2
Phospho-glyceromutase
8
2-Phospho-glycerate
2 H2O
2
Enolase
9
Phosphoenol-pyruvate (PEP)
High energy

Figure 9.9-9



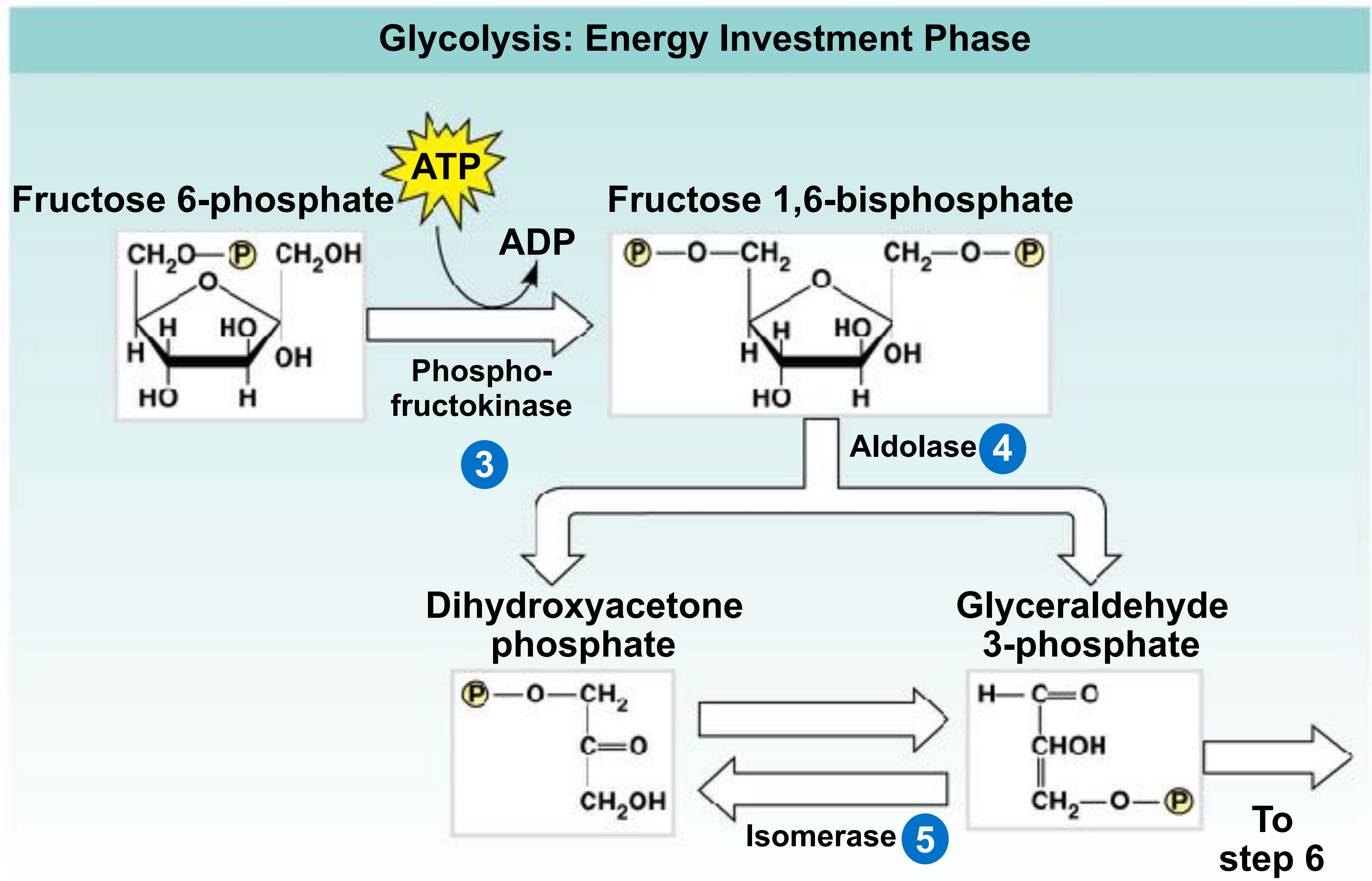
Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
Triose phosphate dehydrogenase
2 P i
1,3-Bisphospho-glycerate
2 ADP
2 ATP
2
Phospho-glycerokinase
3-Phospho-glycerate
2
Phospho-glyceromutase
2-Phospho-glycerate
2 H2O
2
Enolase
Phosphoenol-pyruvate (PEP)
2 ADP
2 ATP
Pyruvate kinase
Pyruvate
6
7
8
9
10
4 ATP out
on To mitochondria

Figure 9.9a



Glycolysis: Energy Investment Phase
ATP
Glucose
Glucose 6-phosphate
Fructose 6-phosphate
ADP
CH2OH
CH2O—P
CH2OH
Hexokinase
1
Phosphogluco-
isomerase
2

Figure 9.9b



Glycolysis: Energy Investment Phase
Fructose 6-phosphate
ATP
ADP
Fructose 1,6-bisphosphate
CH2O—P CH2OH
O
H HO
H OH
HO H
P—O—CH2 CH2—O—P
Phospho-
fructokinase
3
Aldolase
4
Dihydroxyacetone
phosphate
Glyceraldehyde
3-phosphate
P—O—CH2
C═O
CH2OH
H—C═O
CHOH
CH2—O—P
Isomerase
5
To
step 6

Figure 9.9c

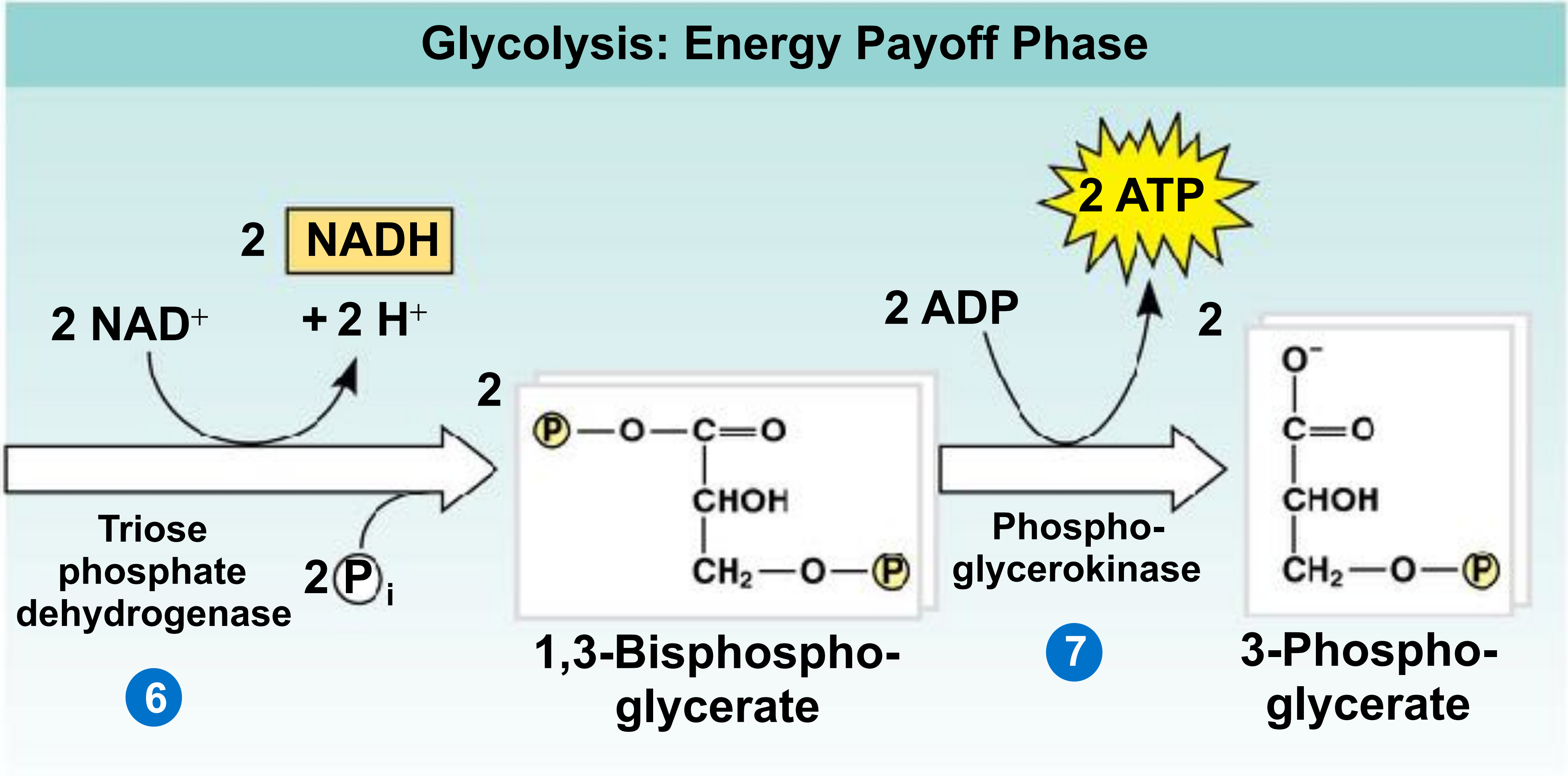
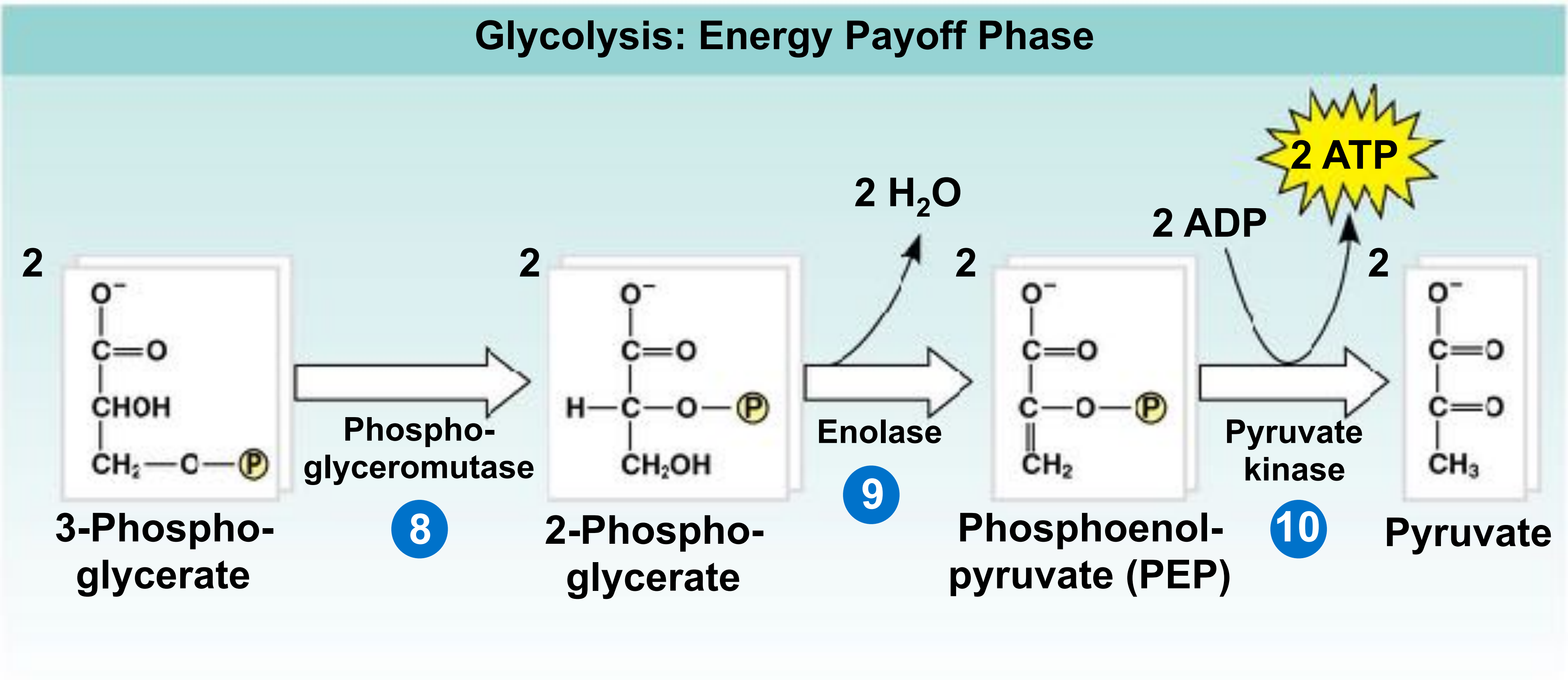

Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
2
2 ATP
2 ADP
2
P—O—C=O
CHOH
CH2—O—P
O−
C=O
CHOH
CH2—O—P
Triose phosphate dehydrogenase
2 Pi
6
1,3-Bisphospho-glycerate
Phospho-glycerokinase
7
3-Phospho-glycerate

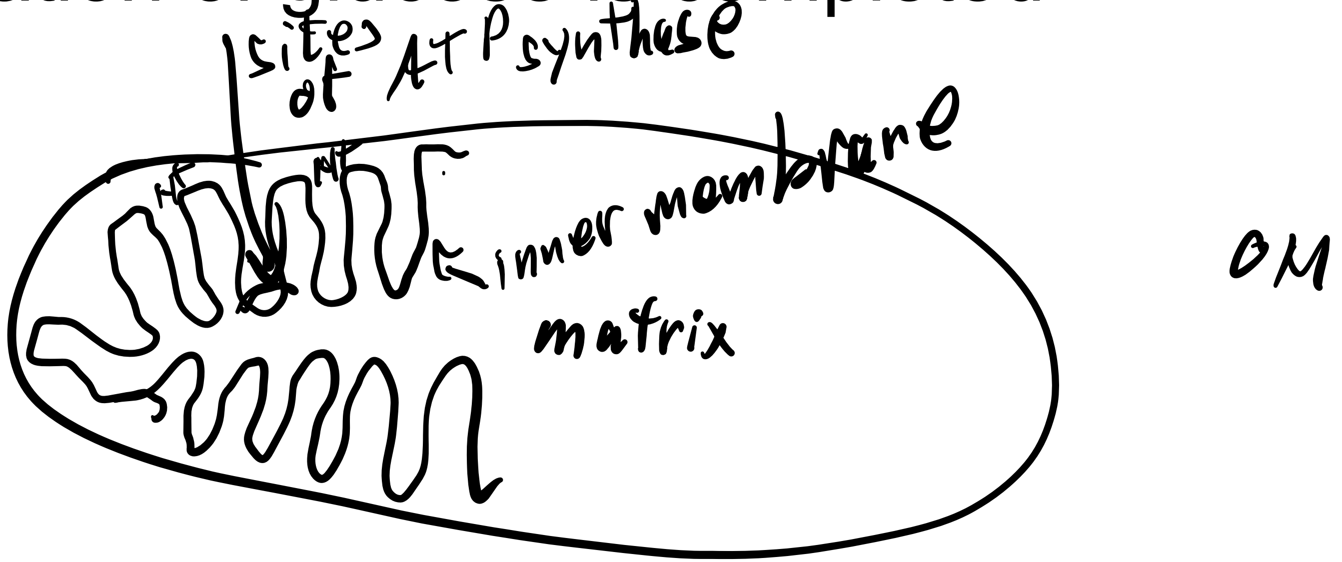
Figure 9.9d



Glycolysis: Energy Payoff Phase
2
O⁻
C=O
CHOH
CH₂—O—P
3-Phospho-
glycerate
Phospho-
glyceromutase
8
2
H—C—O—P
CH₂OH
2-Phospho-
glycerate
2 H₂O
Enolase
9
2
CH₂
Phosphoenol-
pyruvate (PEP)
2 ADP
2 ATP
Pyruvate
kinase
10
2
CH₃
Pyruvate

Concept 9.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

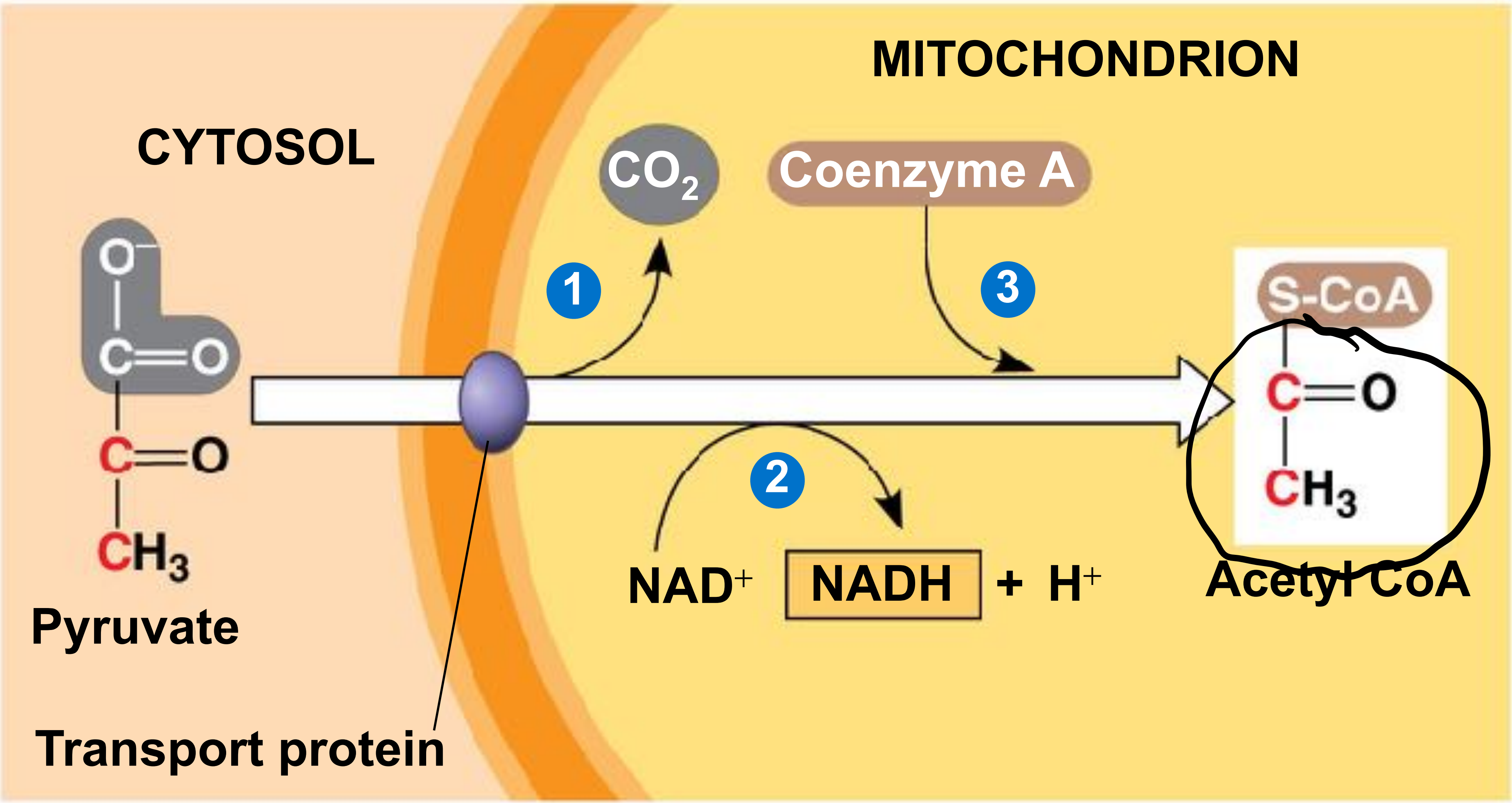
- In the presence of O_2, pyruvate enters the mitochondrion (in eukaryotic cells) where the oxidation of glucose is completed



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 catalyses three reactions

Figure 9.10

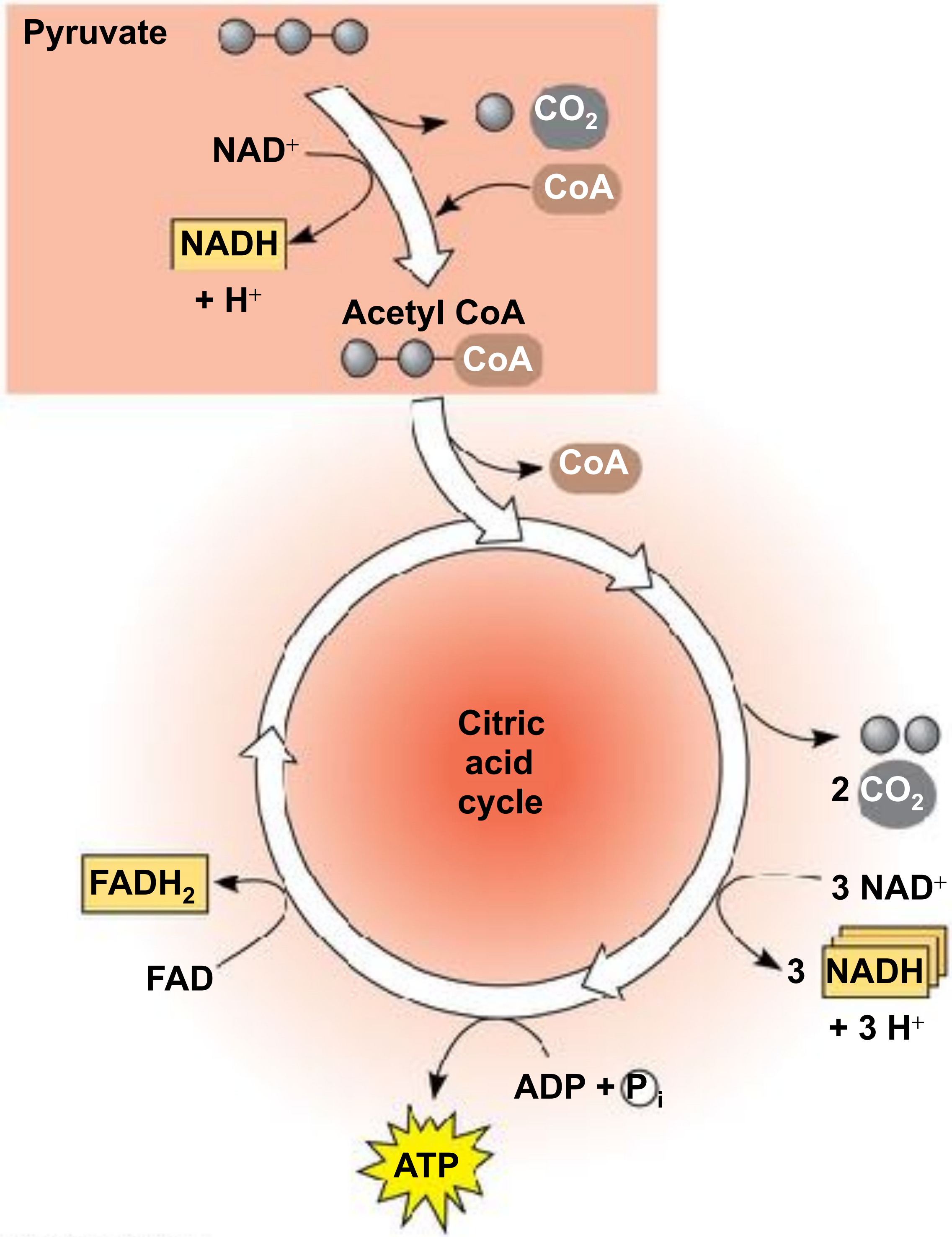


MITOCHONDRION
CYTOSOL
CO2
Coenzyme A
1
3
S-CoA
C=O
CH3
O⁻
C=O
C=O
CH3
Pyruvate
2
NAD+
NADH
+ H+
Acetyl CoA
Transport protein

The Citric Acid Cycle

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

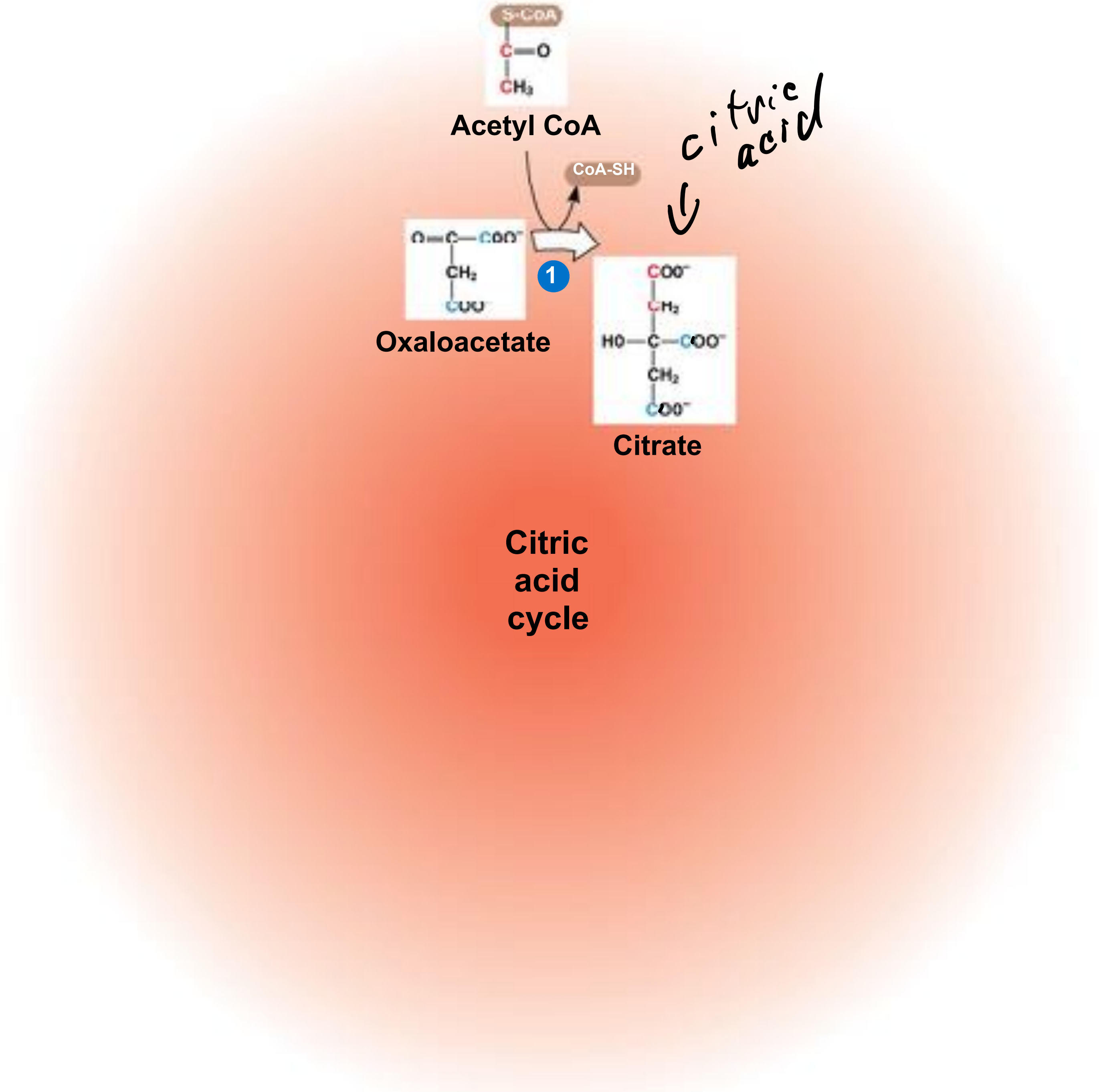
Figure 9.11



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

- 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 9.12-1



Acetyl CoA
CoA-SH
citric acid
1
Oxaloacetate
Citrate
Citric
acid
cycle

Figure 9.12-2

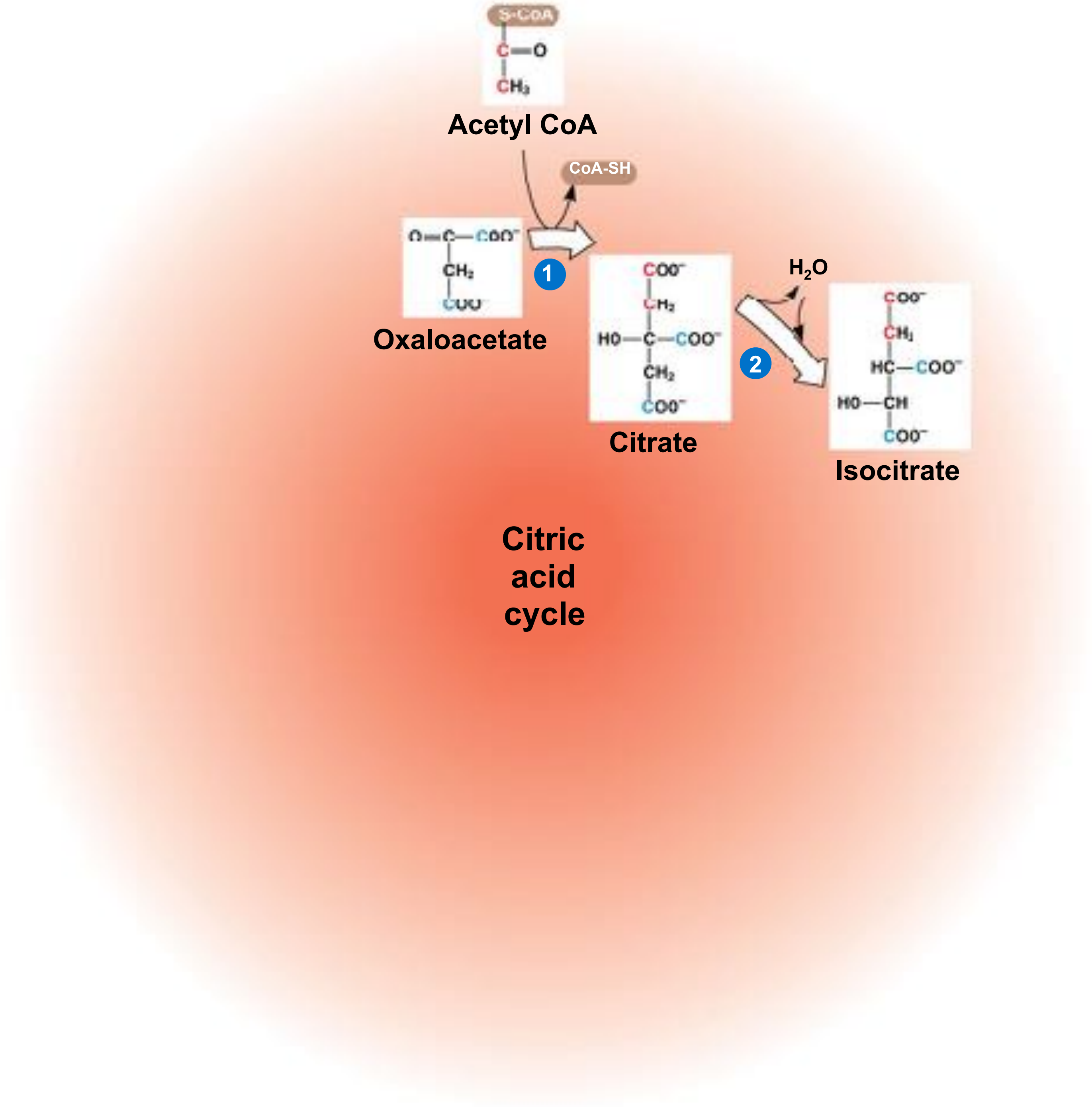
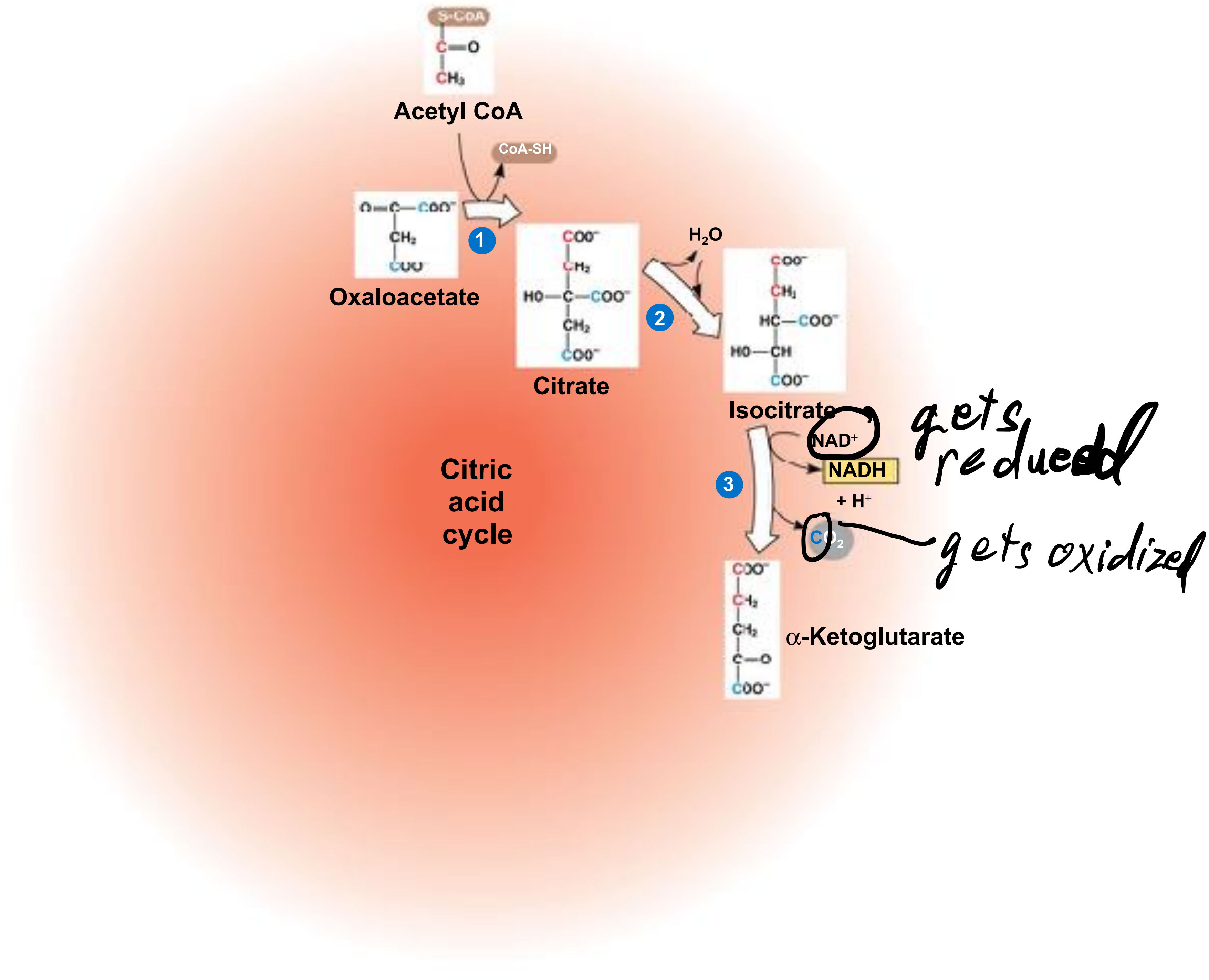
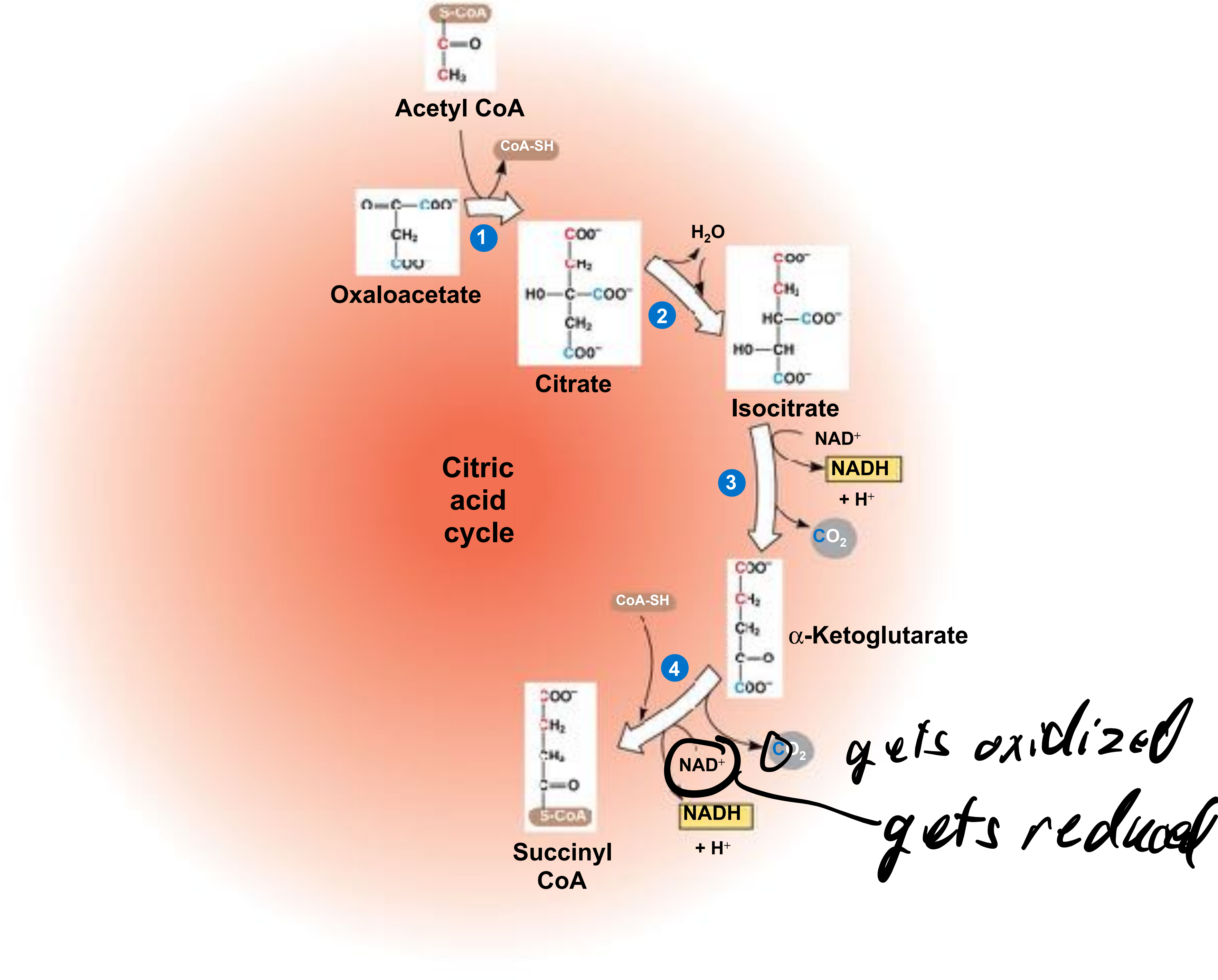

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
Citric acid cycle

Figure 9.12-3



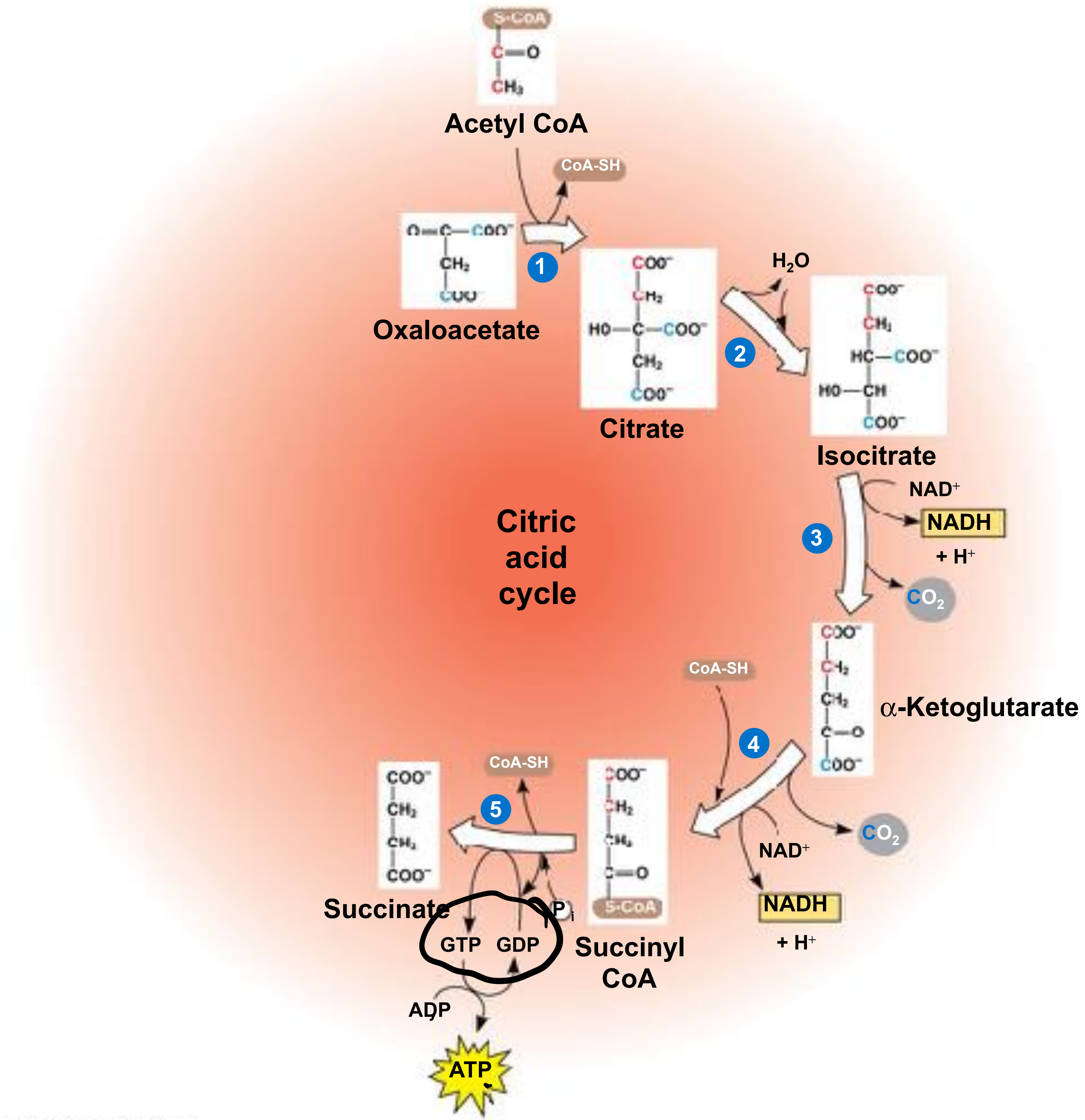
Acetyl CoA
CoA-SH
Oxaloacetate
1
Citrate
H_2O
2
Isocitrate
NAD^+
NADH
$+ H^+$
3
CO_2
α-Ketoglutarate
Citric acid cycle
gets reduced
gets oxidized

Figure 9.12-4



S-CoA
Acetyl CoA
CoA-SH
Oxaloacetate
1
Citrate
H2O
2
Isocitrate
NAD+
NADH
+ H+
3
CO2
Citric acid cycle
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
S-CoA
Succinyl CoA
gets oxidized
gets reduced

Figure 9.12-5



Acetyl CoA
CoA-SH
Oxaloacetate
Citrate
H_2O
Isocitrate
Citric acid cycle
NAD+
NADH
+ H+
CO_2
CoA-SH
α-Ketoglutarate
CoA-SH
CO_2
NAD+
NADH
+ H+
Succinate
P_i
GTP
GDP
Succinyl CoA
ADP
ATP

Figure 9.12-6

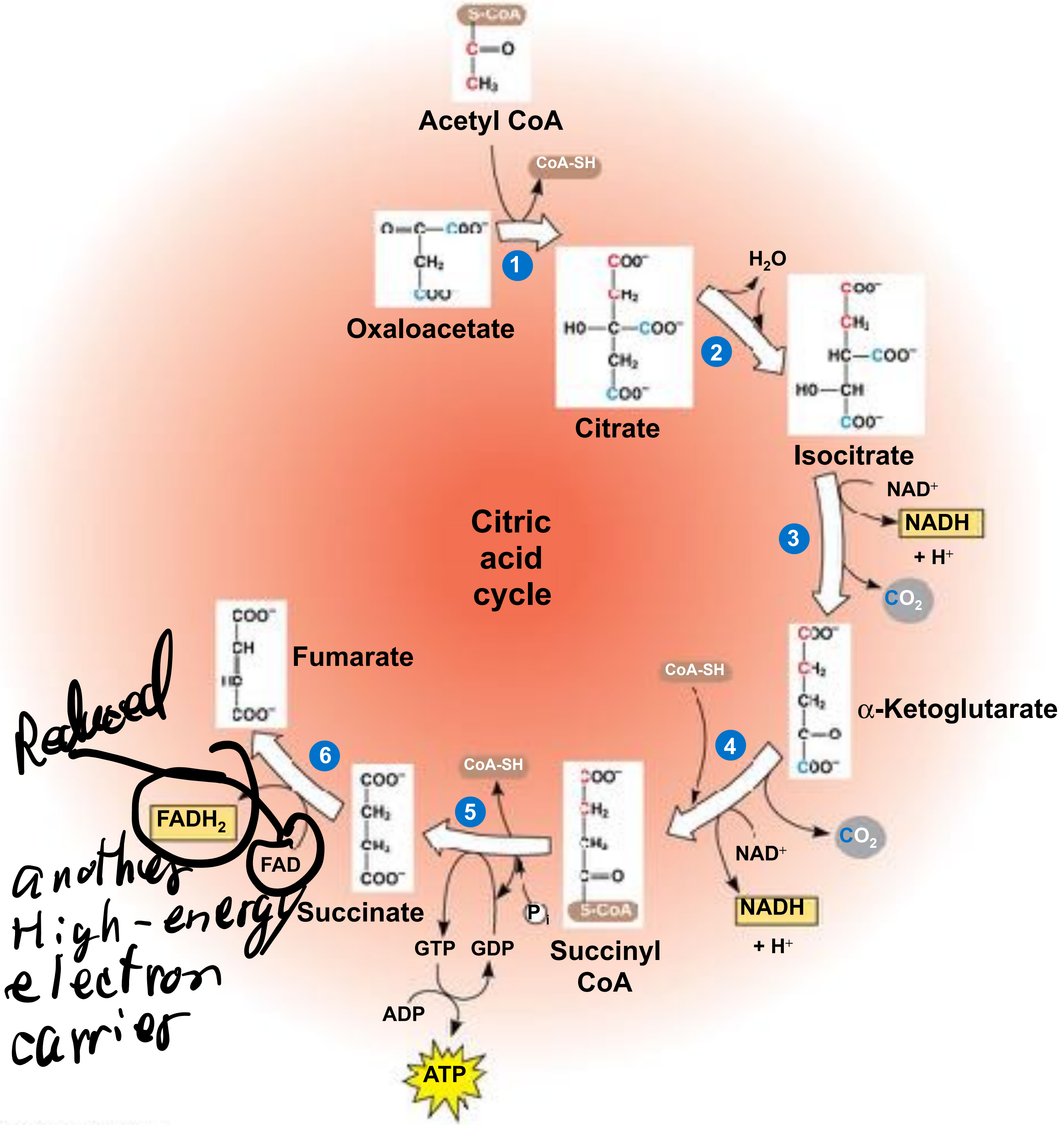
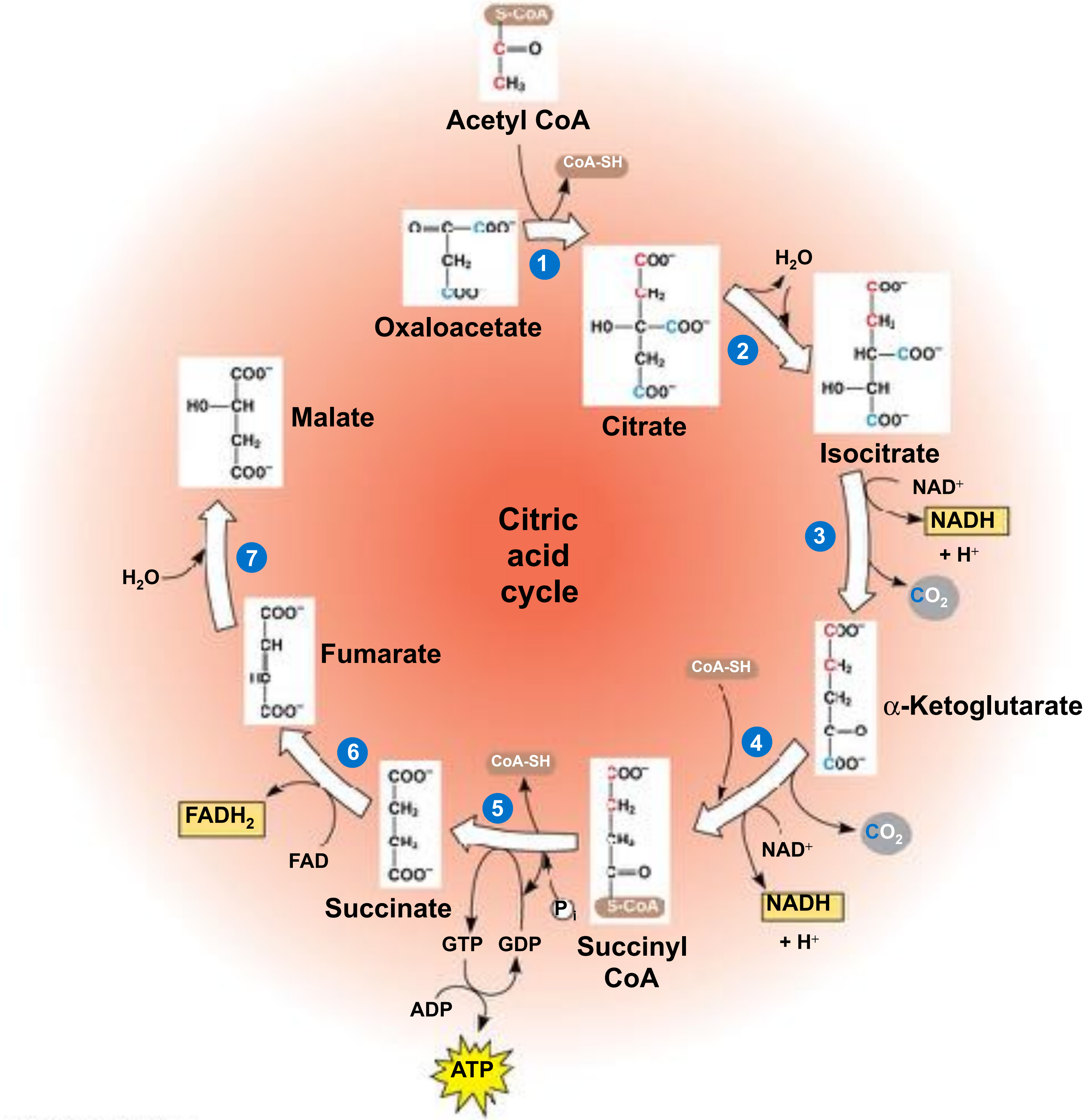
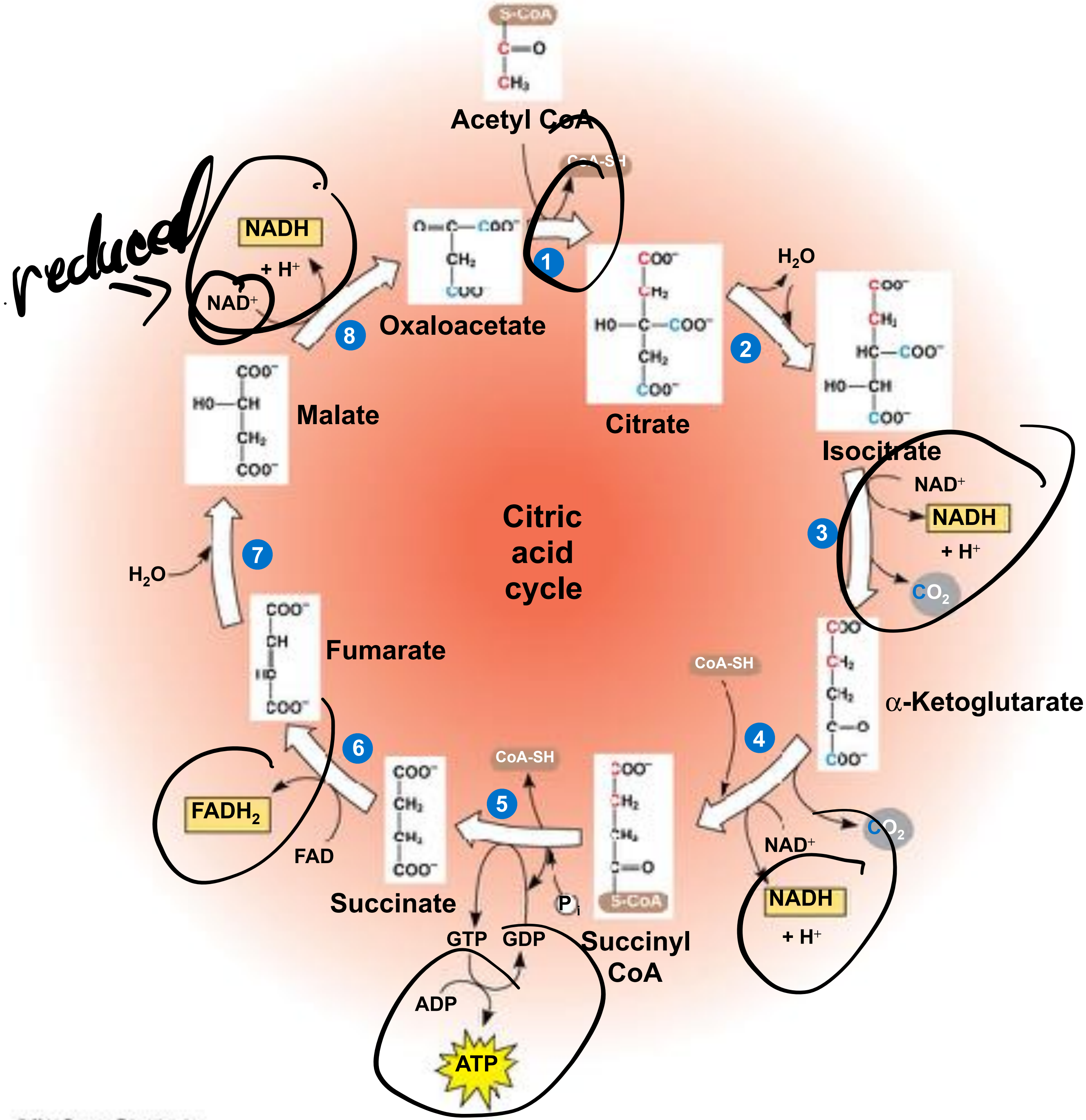

S-CoA
Acetyl CoA
CoA-SH
Oxaloacetate
1
Citrate
H_2O
2
Isocitrate
3
NAD^+
NADH
$+ H^+$
CO_2
α-Ketoglutarate
4
CoA-SH
CO_2
NAD^+
NADH
$+ H^+$
Succinyl CoA
S-CoA
5
CoA-SH
P_i
GTP
GDP
ADP
ATP
Succinate
6
FAD
$FADH_2$
Fumarate
Citric acid cycle
Reduced
another High-energy electron carrier

Figure 9.12-7



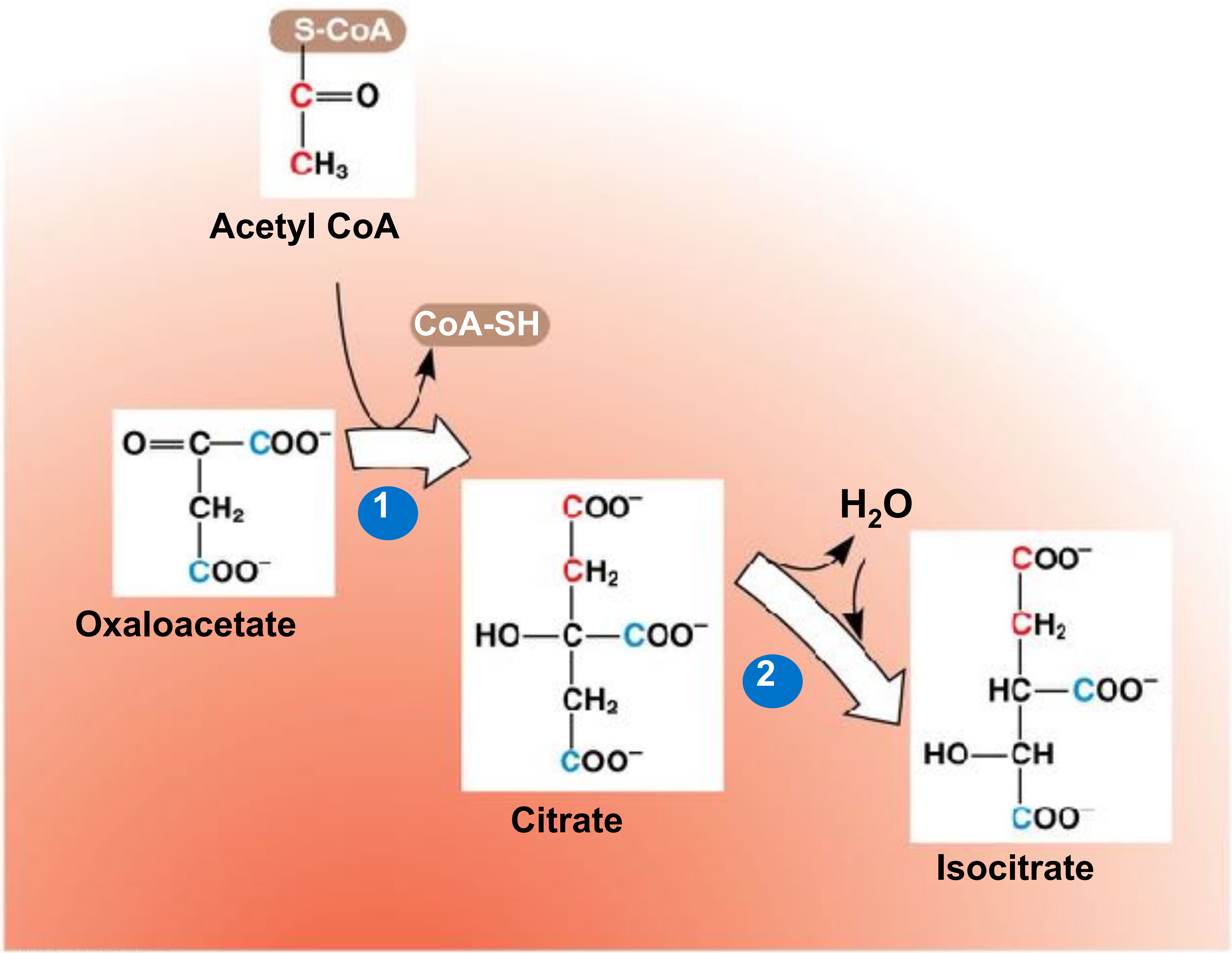
Acetyl CoA
CoA-SH
Oxaloacetate
1
Citrate
H2O
2
Isocitrate
NAD+
NADH
+ H+
3
CO2
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
Succinyl CoA
CoA-SH
5
Pi
GTP
GDP
ADP
ATP
Succinate
6
FADH2
FAD
Fumarate
7
H2O
Malate
Citric acid cycle

Figure 9.12-8



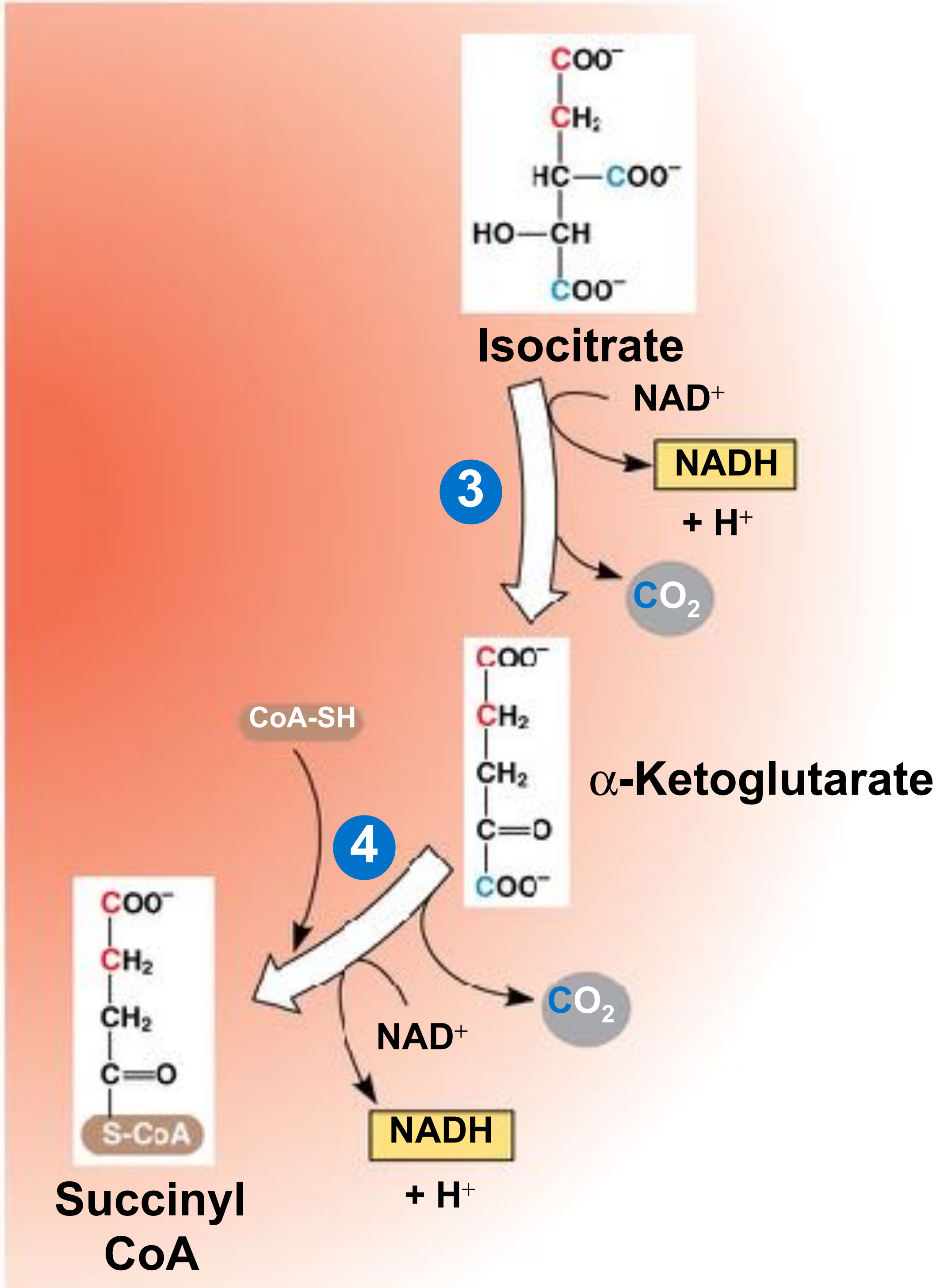
S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
1
Oxaloacetate
Citrate
H2O
2
Isocitrate
NAD+
NADH
+ H+
3
CO2
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
Succinyl CoA
S-CoA
CoA-SH
5
Pi
GDP
GTP
ADP
ATP
Succinate
6
FAD
FADH2
Fumarate
7
H2O
Malate
8
NAD+
NADH
+ H+
Citric acid cycle
reduced

Figure 9.12a



S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H_2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate

Figure 9.12b



COO⁻
CH₂
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
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 9.12c

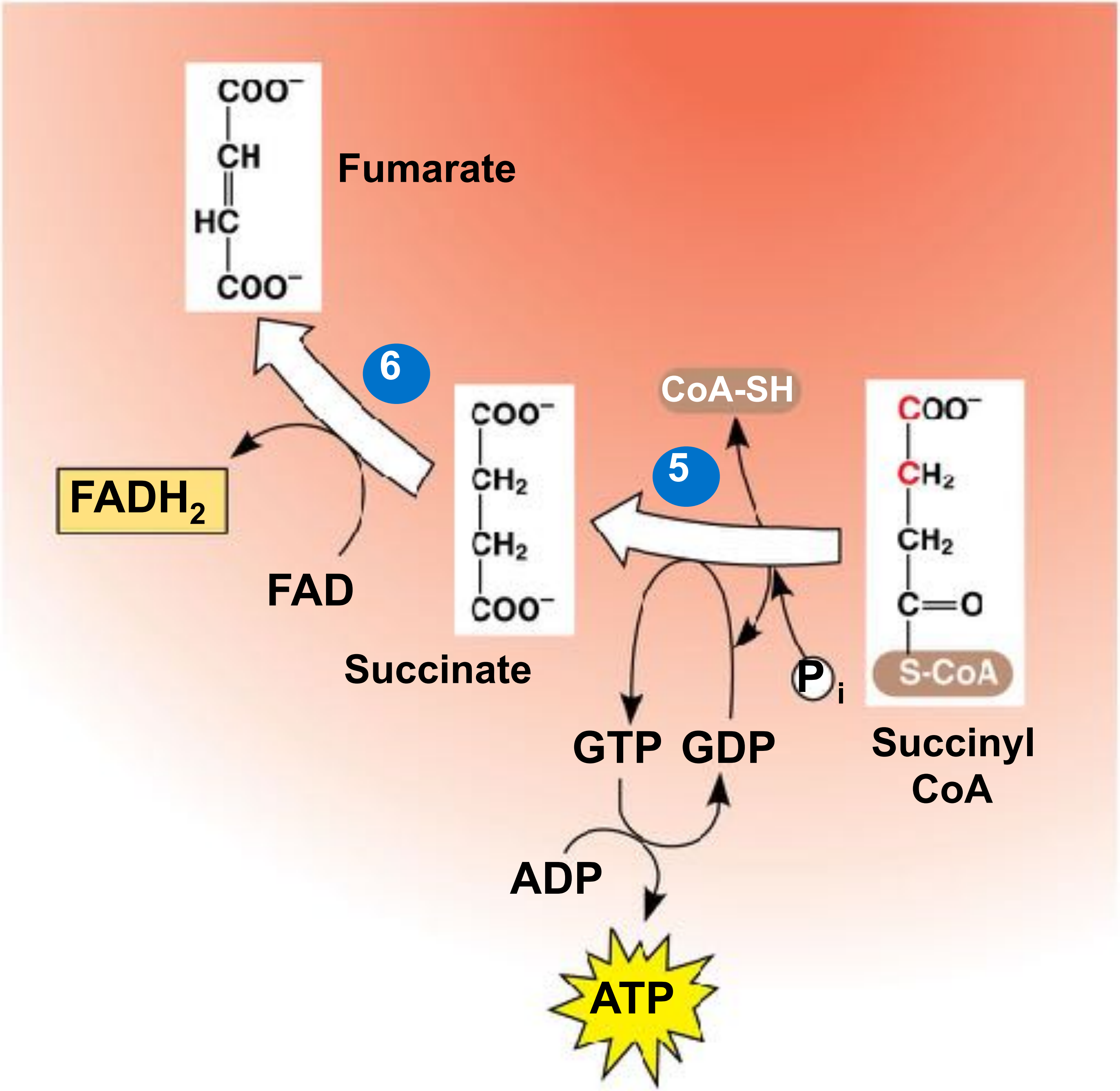
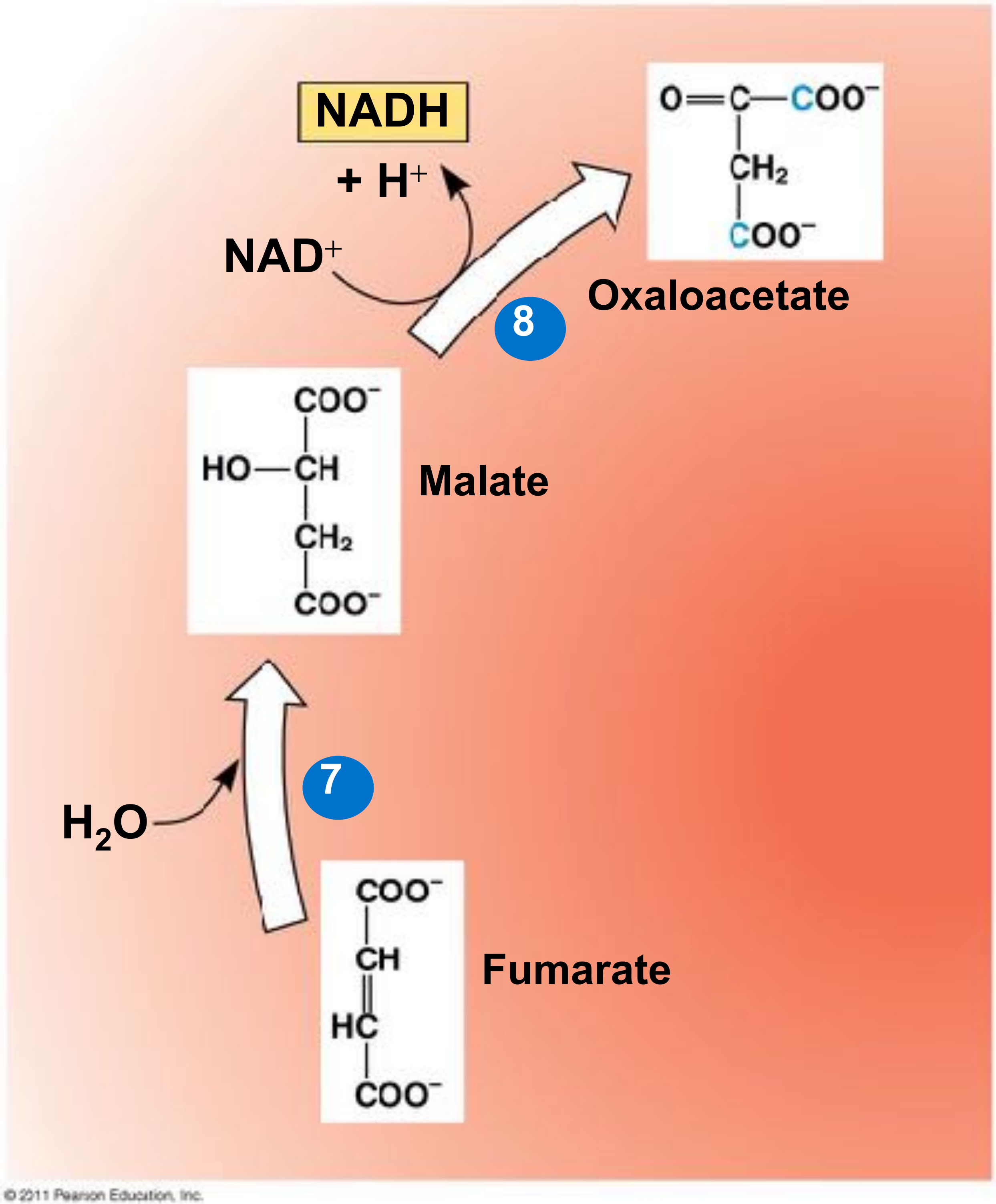

COO⁻
CH
HC
COO⁻
Fumarate
6
FADH2
FAD
COO⁻
CH2
CH2
COO⁻
Succinate
CoA-SH
5
COO⁻
CH2
CH2
C=O
S-CoA
Pi
GTP
GDP
Succinyl CoA
ADP
ATP

Figure 9.12d



NADH
+ H+
NAD+
O=C—COO−
CH2
COO−
Oxaloacetate
8
COO−
HO—CH
CH2
COO−
Malate
7
H2O
COO−
CH
HC
COO−
Fumarate
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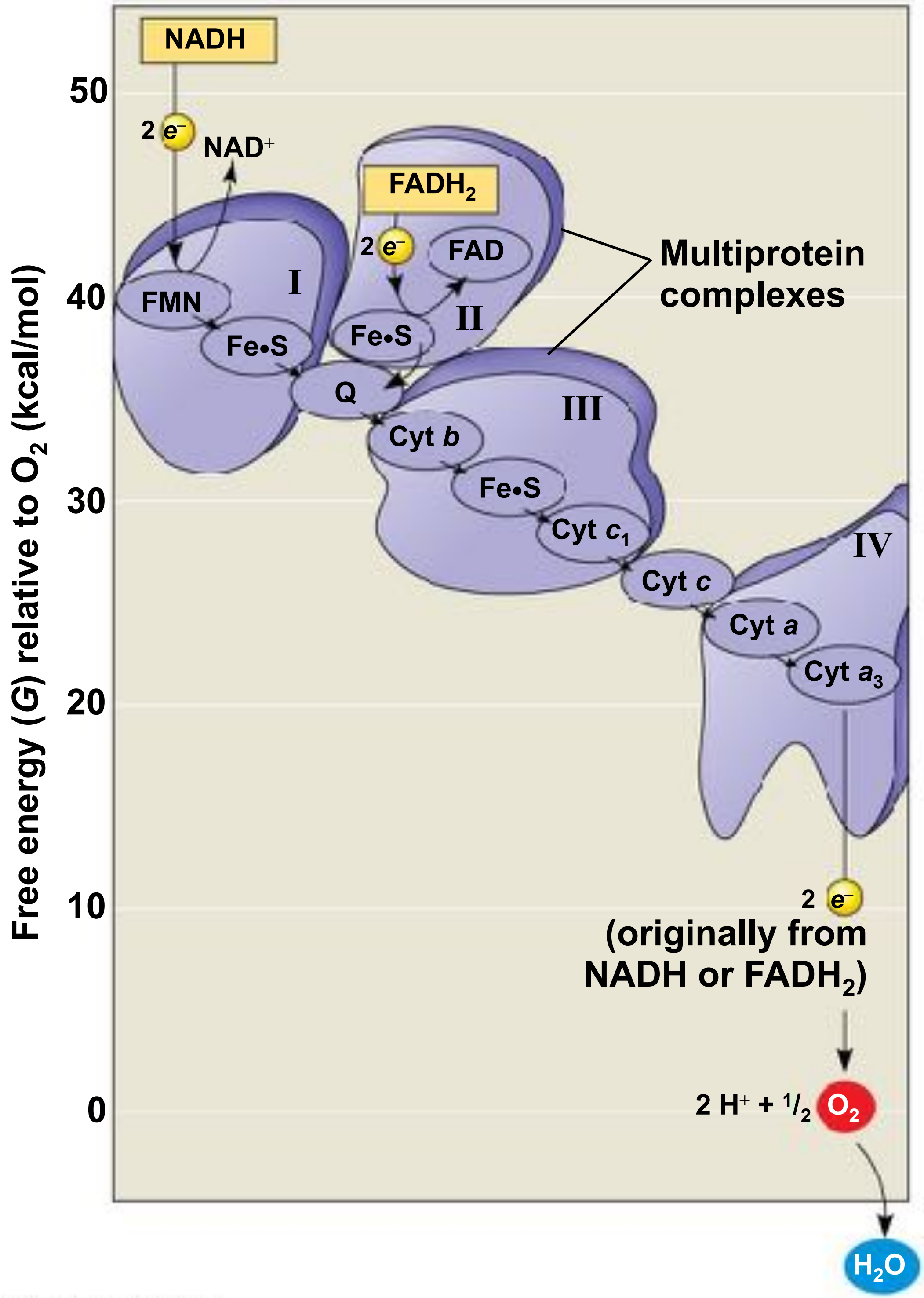
Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

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

Figure 9.13



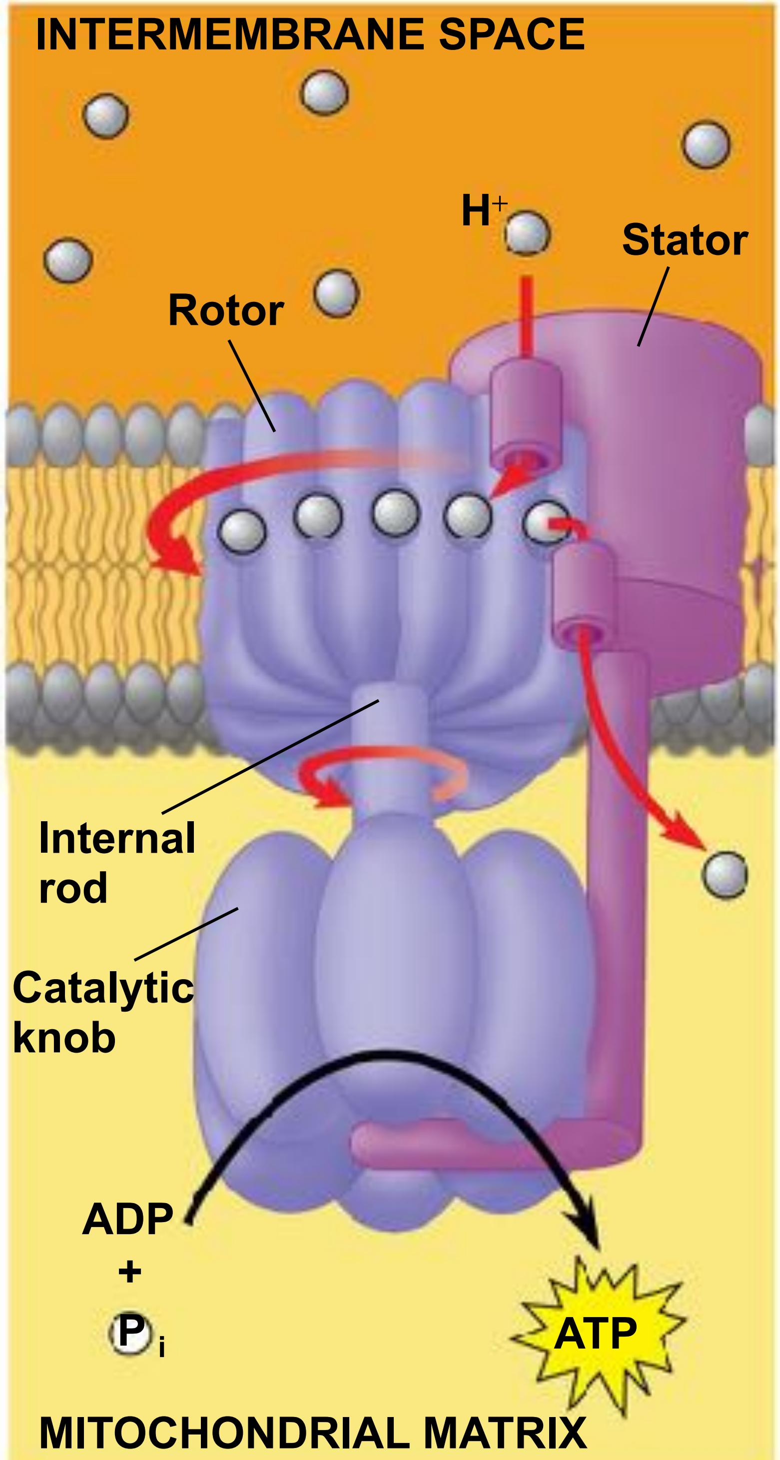
NADH
50
2 e⁻
NAD+
FADH2
2 e⁻
FAD
Multiprotein complexes
40
FMN
I
Fe•S
Fe•S
II
Q
III
Cyt b
30
Fe•S
Cyt c1
IV
Cyt c
Cyt a
Cyt a3
20
10
2 e⁻
(originally from NADH or FADH2)
0
2 H+ + 1/2 O2
H2O
Free energy (G) relative to O2 (kcal/mol)

- 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

Chemiosmosis: The Energy-Coupling Mechanism

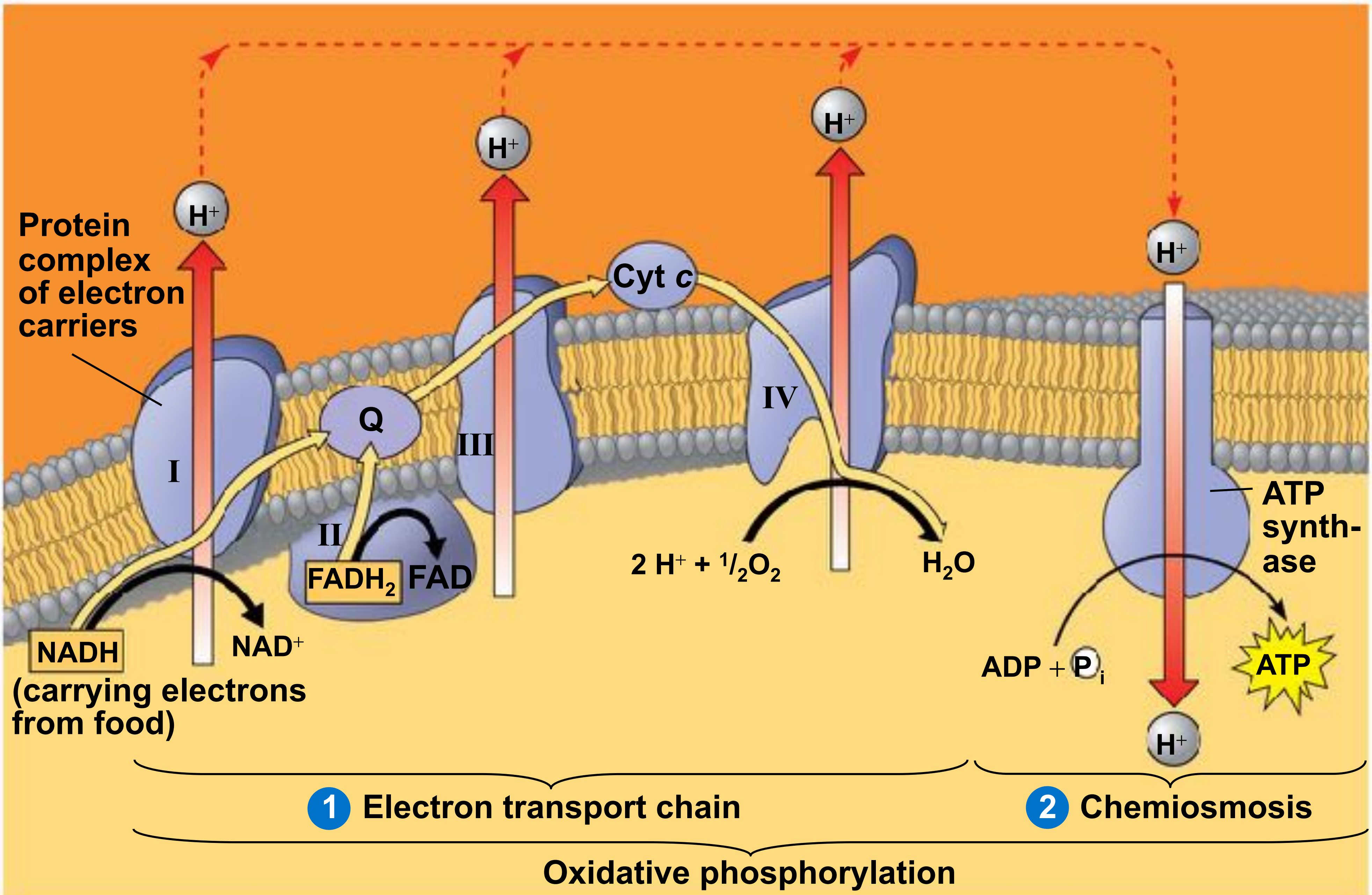
- Electron transfer in the electron transport chain causes proteins to pump H^+ from the mitochondrial matrix to the intermembrane space
- H^+ then moves back across the membrane, passing through the proton, **ATP synthase**
- ATP synthase uses the exergonic flow of H^+ to drive phosphorylation of ATP
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive cellular work

Figure 9.14



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

Figure 9.15



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

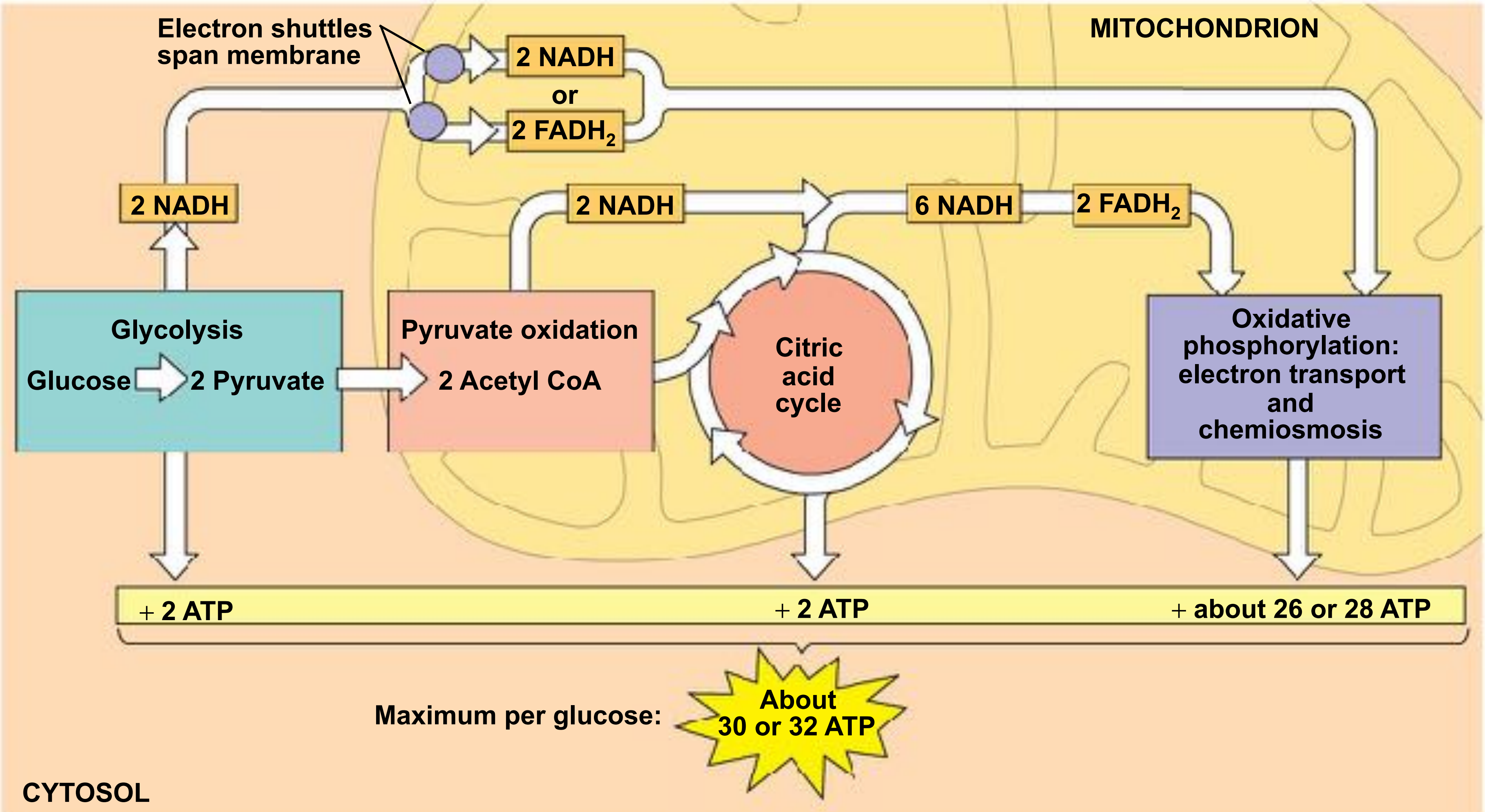
- The energy stored in a H^+ gradient across a membrane couples the redox reactions of the electron transport chain to ATP synthesis
- The H^+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

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
- 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 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
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
- 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

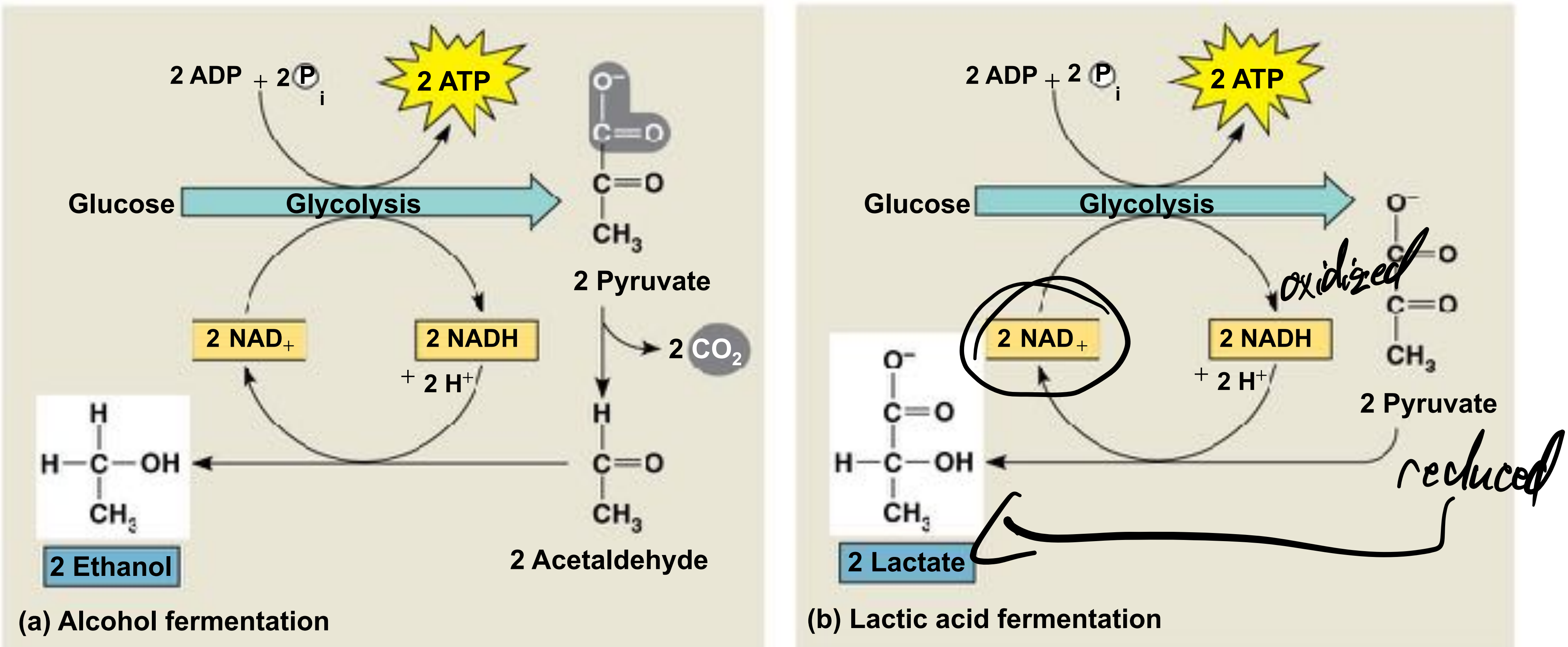
Types of Fermentation

- 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

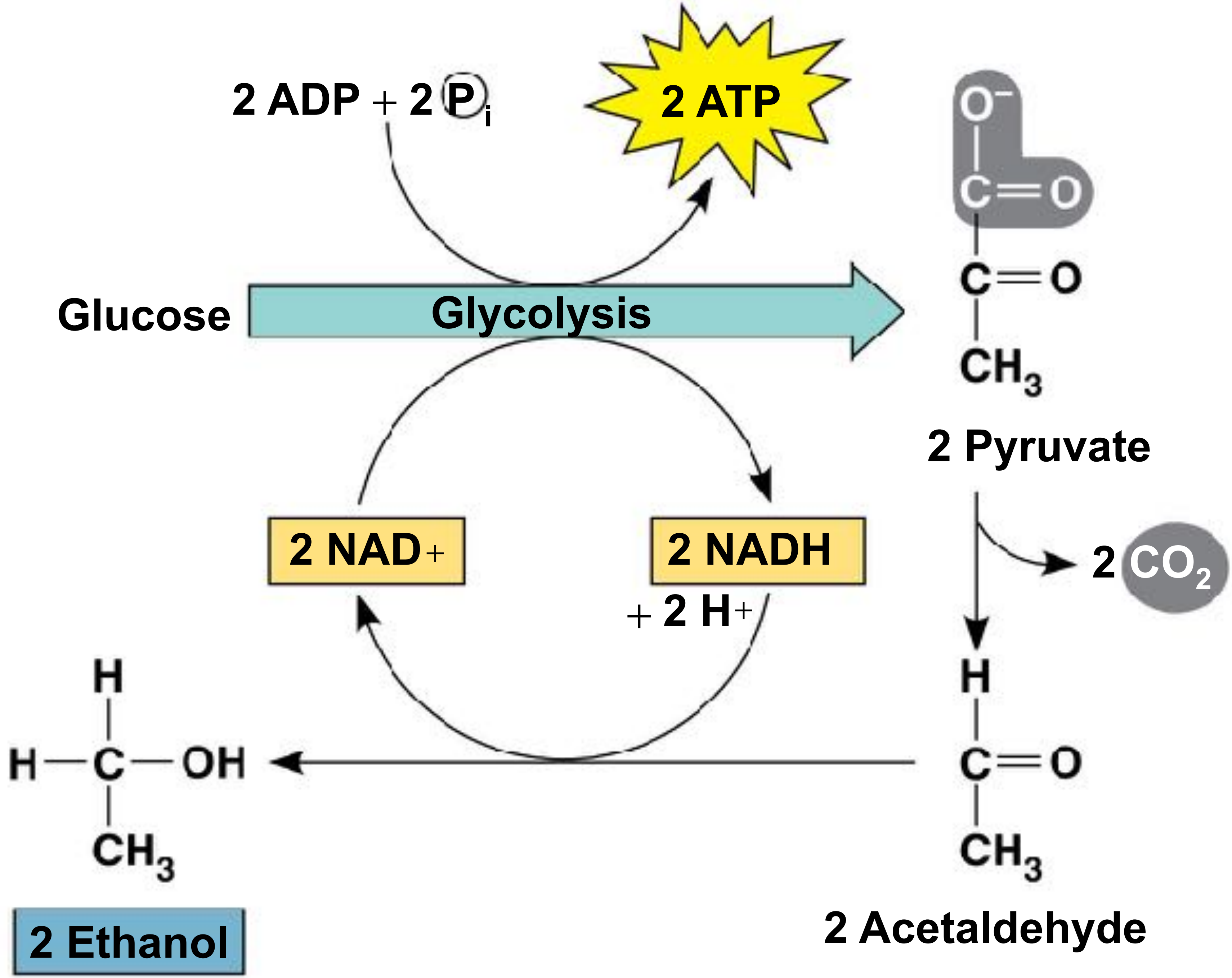
PLAY Animation: Fermentation Overview

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 NAD+
2 NADH
+ 2 H+
2 Pyruvate
2 Lactate
(b) Lactic acid fermentation
oxidized
reduced

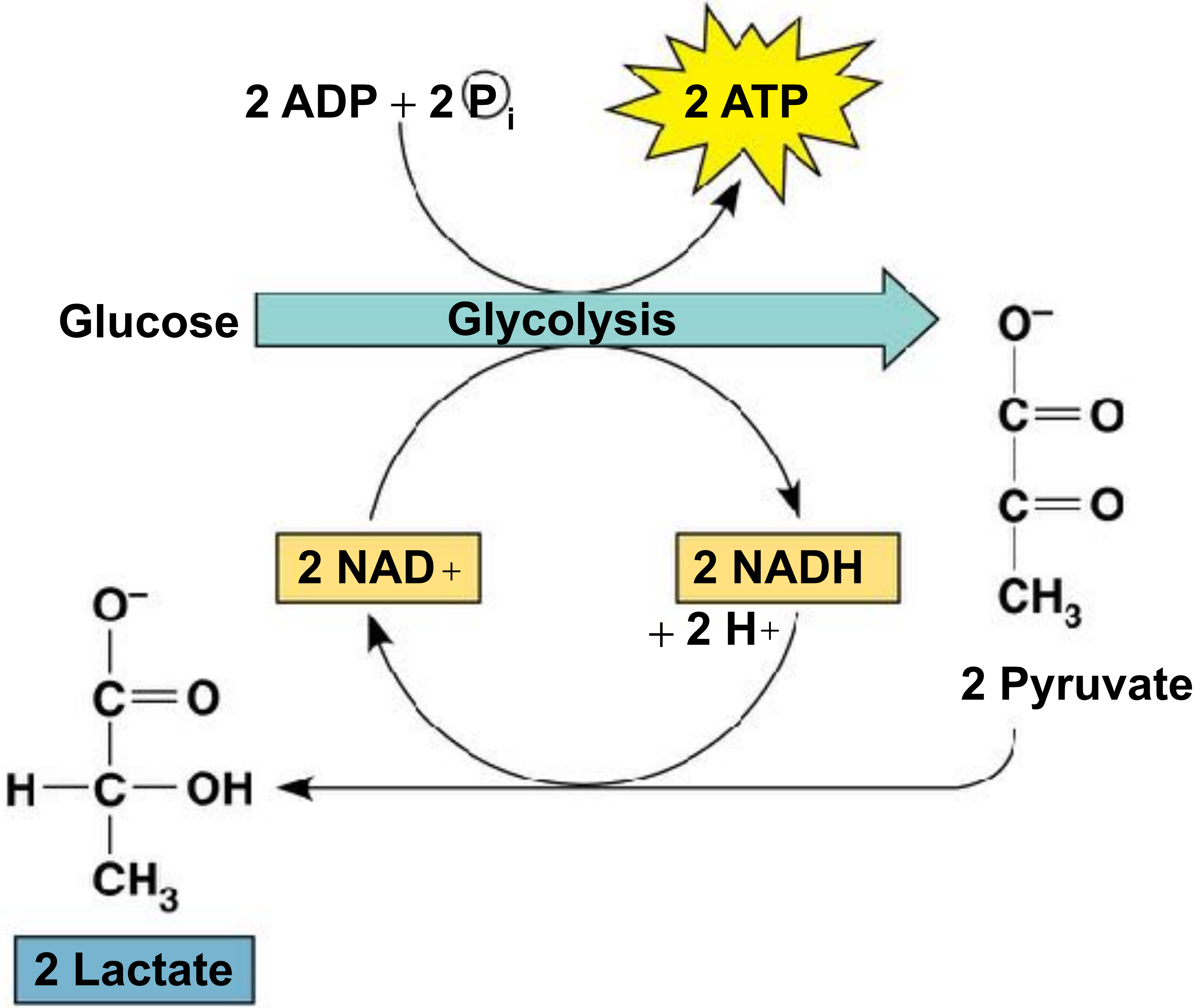
Figure 9.17a



(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



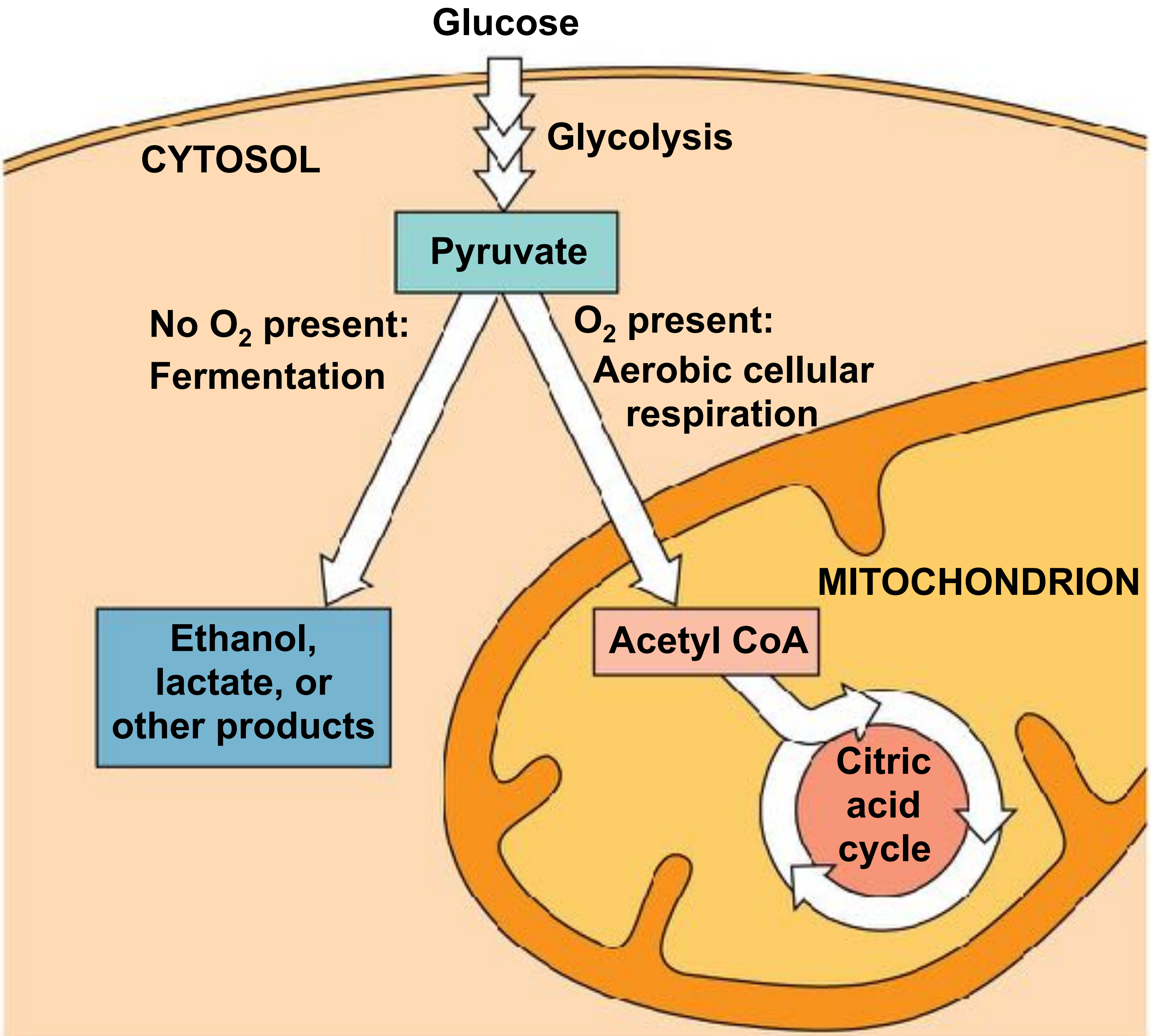
(b) Lactic acid fermentation

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

- **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 9.18



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

- 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 other oxidizers were used.
- Glycolysis is a very ancient process

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

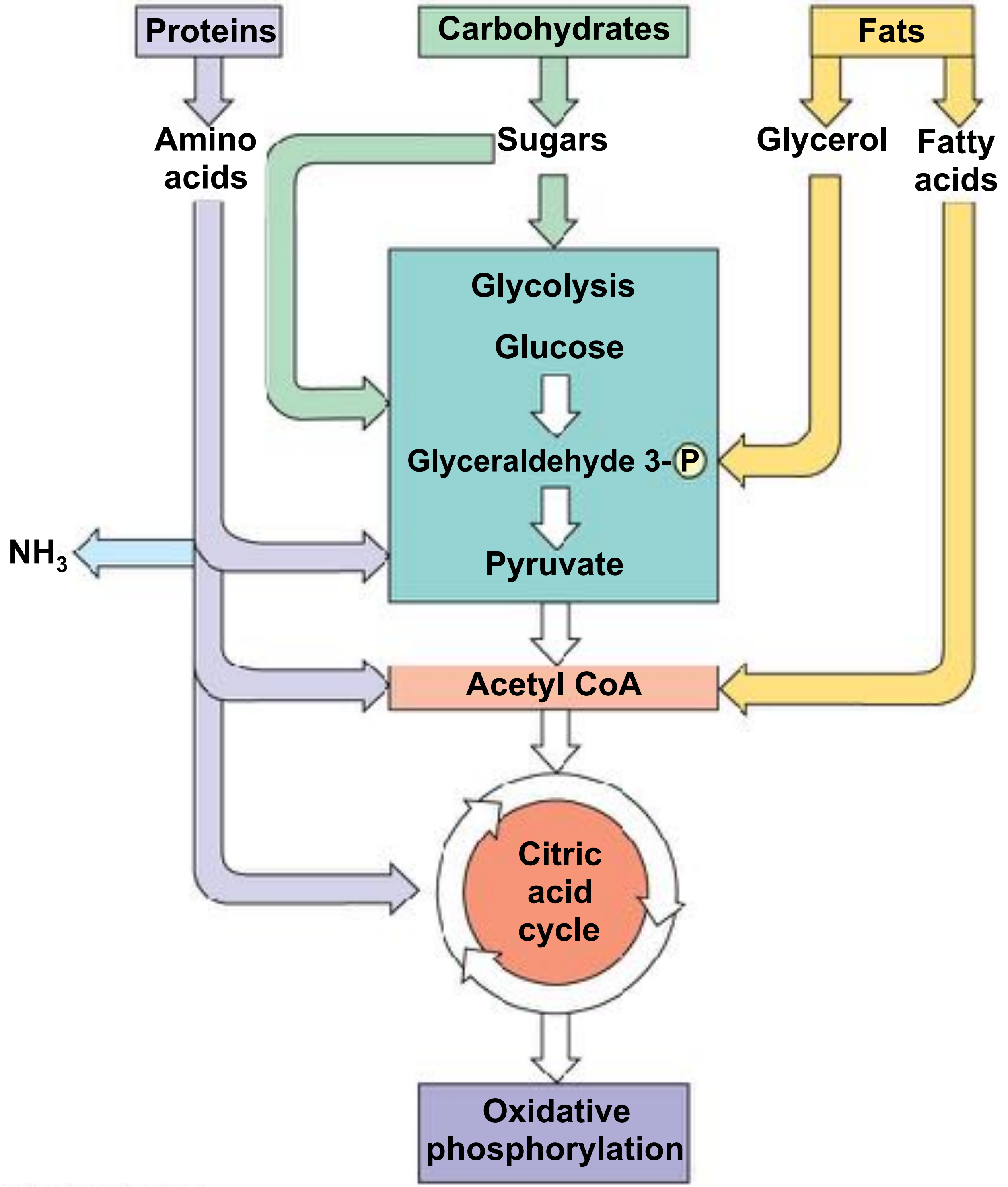
- Gycolysis and the citric acid cycle are major intersections to various catabolic and anabolic pathways

The Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
- Glycolysis accepts a wide range of carbohydrates
- 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
Pyruvate
NH3
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

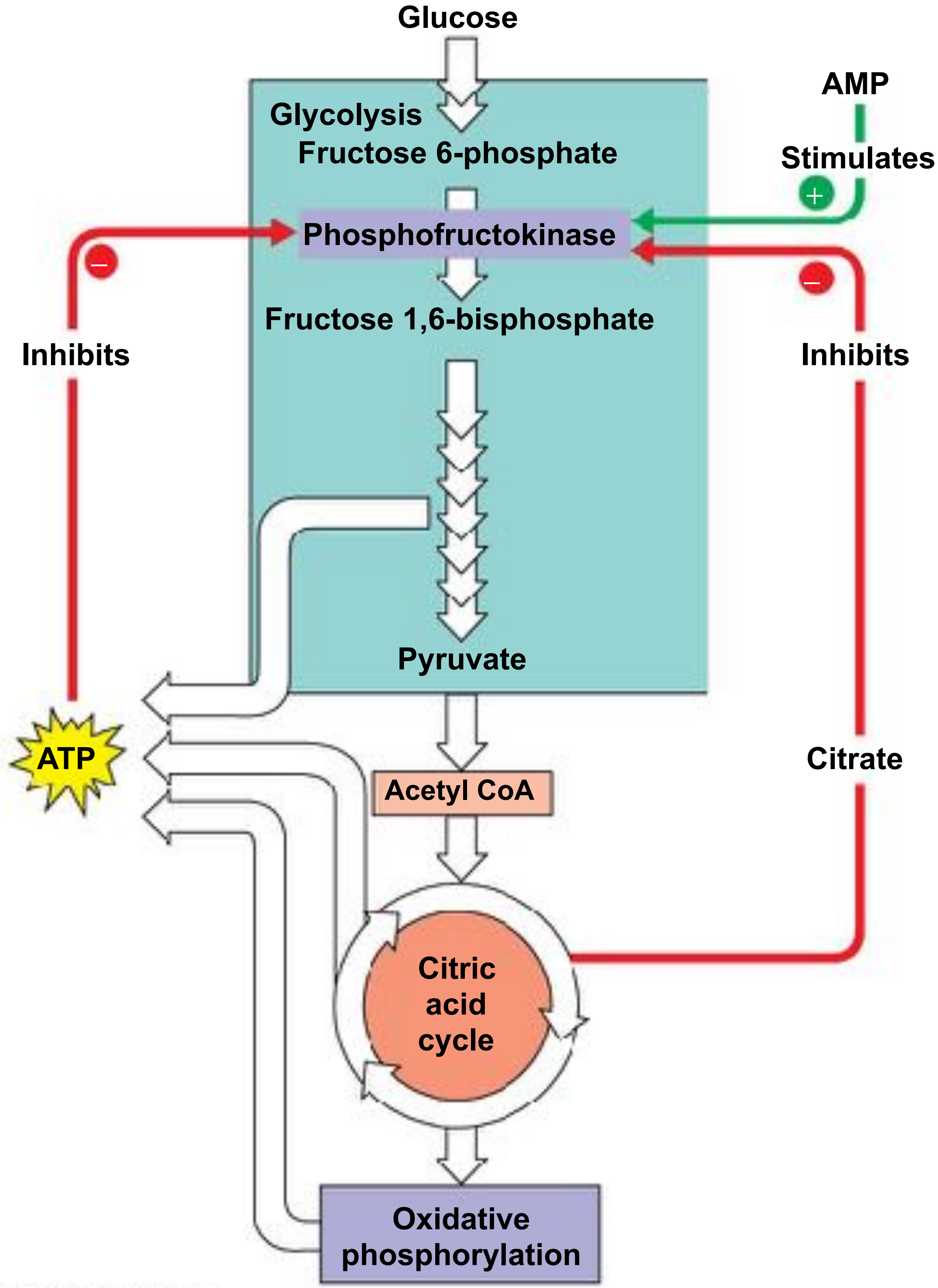
Biosynthesis (Anabolic Pathways)

- 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

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
Inhibits
Inhibits
Pyruvate
ATP
Citrate
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

Figure 9.UN06

Figure 9.UN07

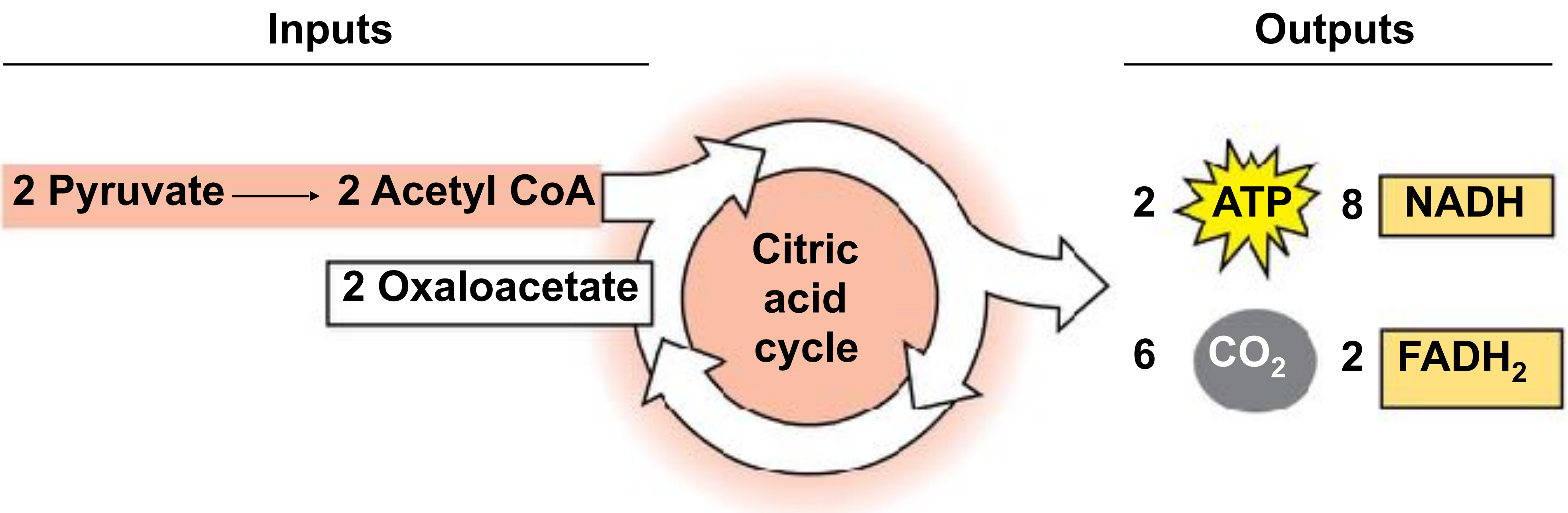


Figure 9.UN08

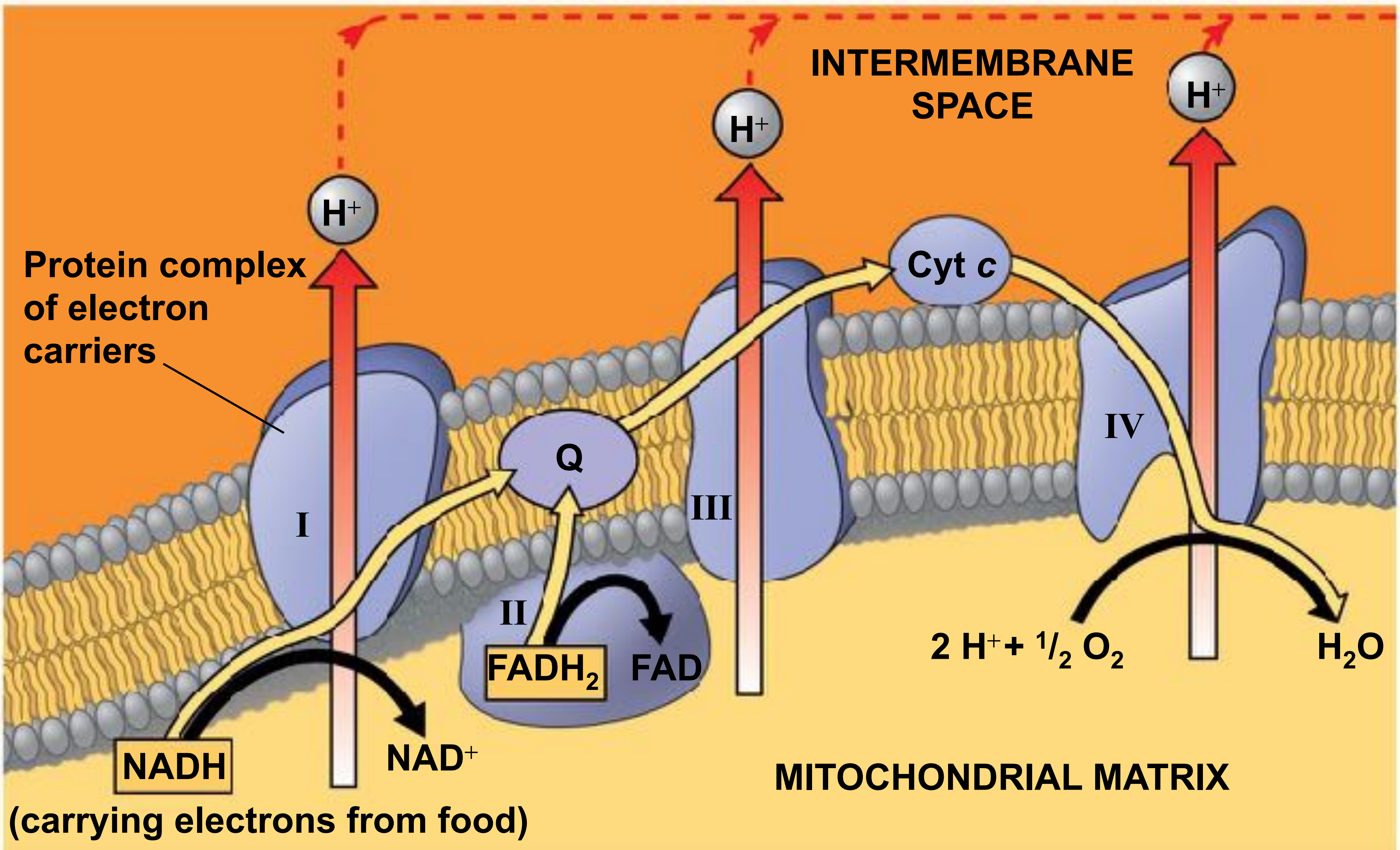


Figure 9.UN09

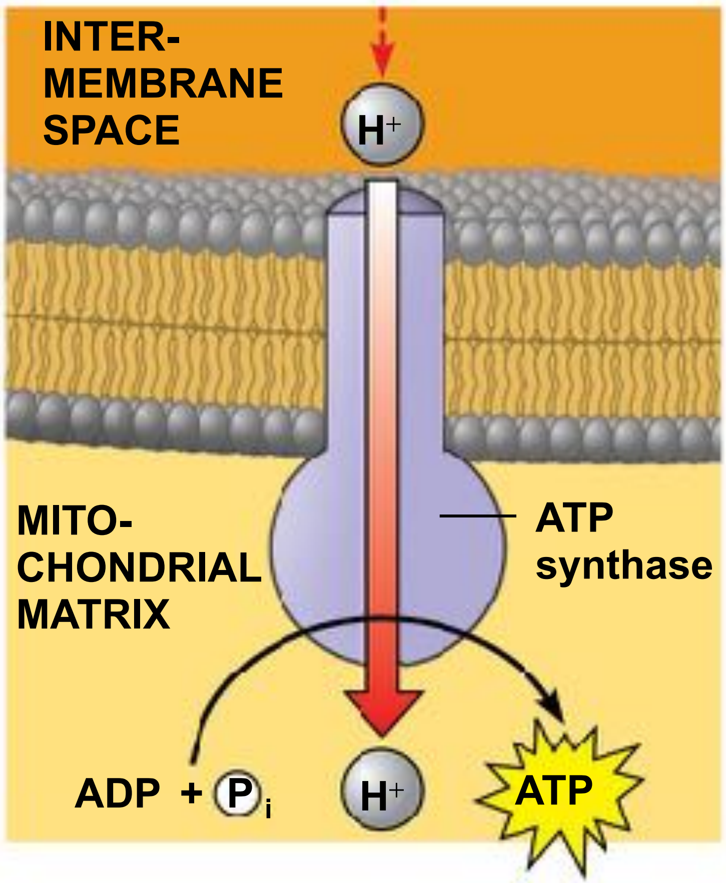


Figure 9.UN10

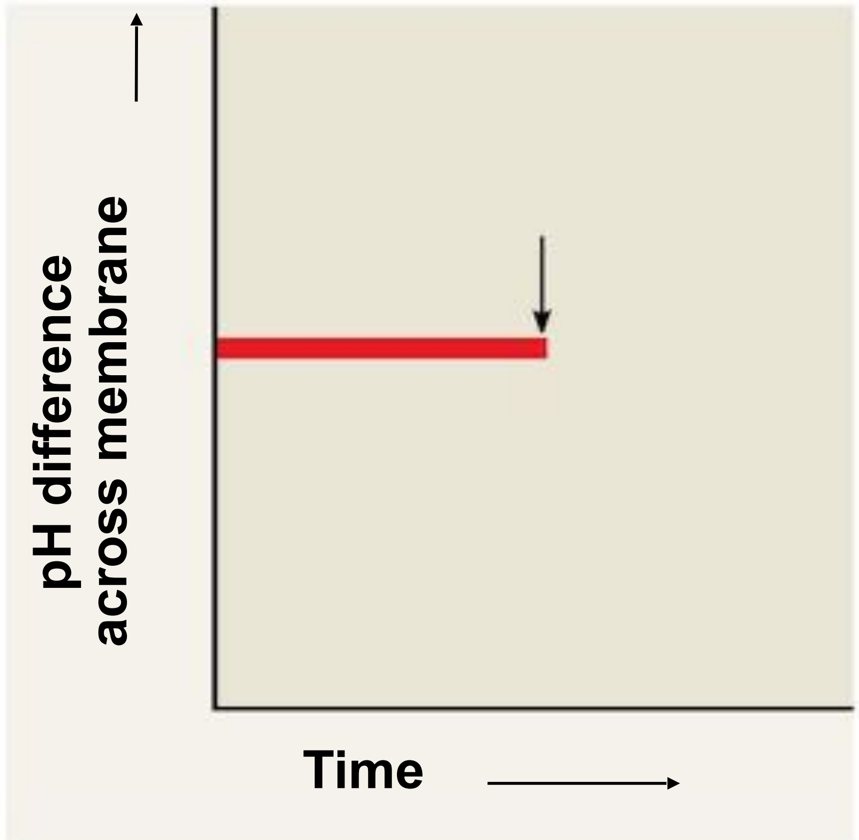


Figure 9.UN11