Chapter 9

Cellular Respiration: Harvesting Chemical Energy

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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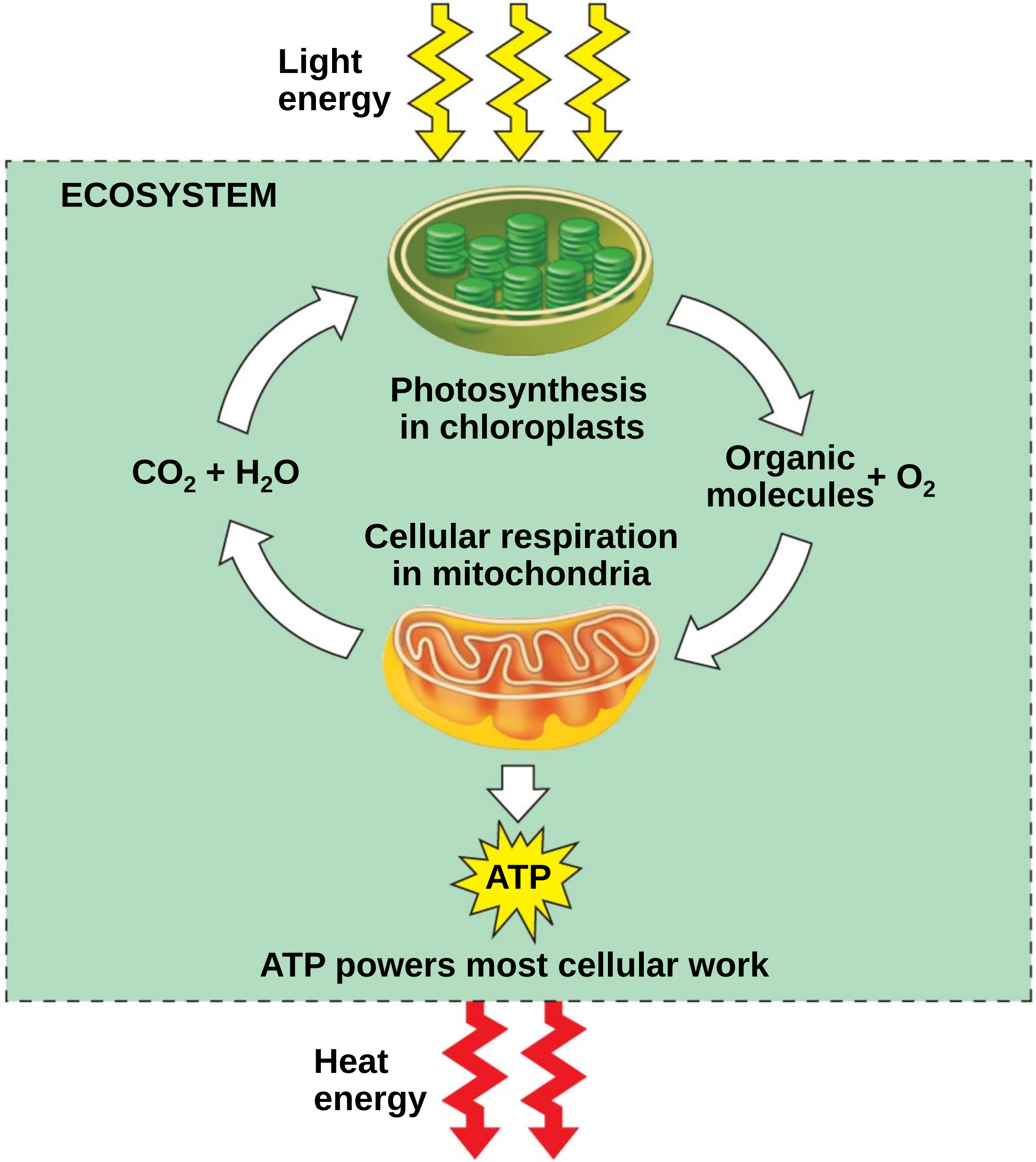
Overview: Life Is Work

- 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

- 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

Fig. 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

Catabolic Pathways and Production of ATP

- **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

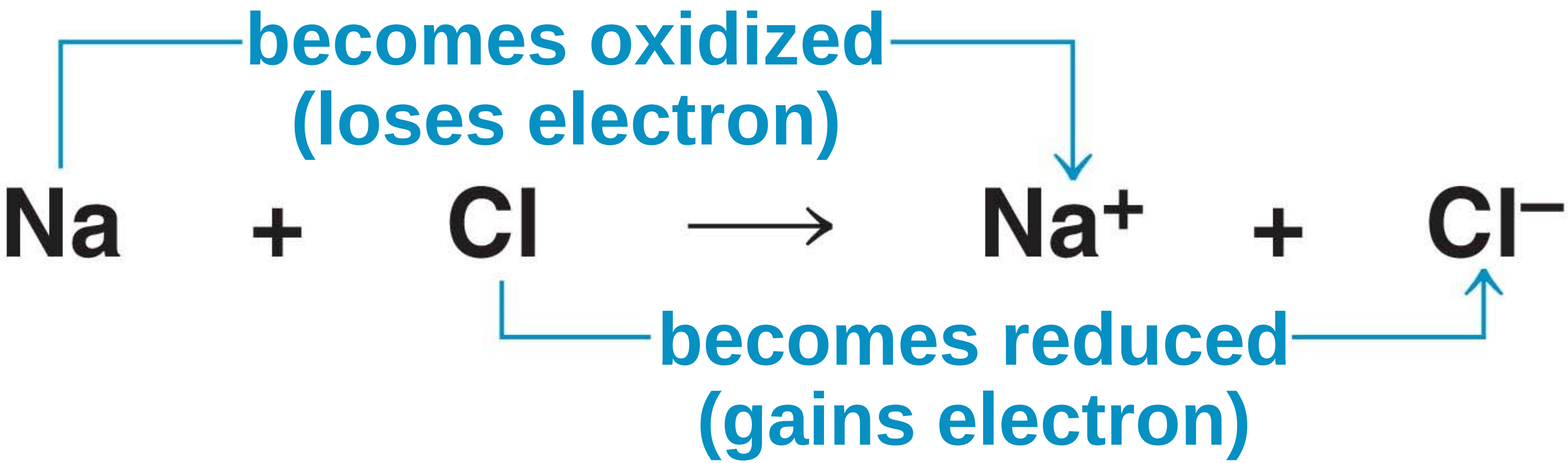
- The transfer of electrons during chemical reactions releases energy stored in organic molecules

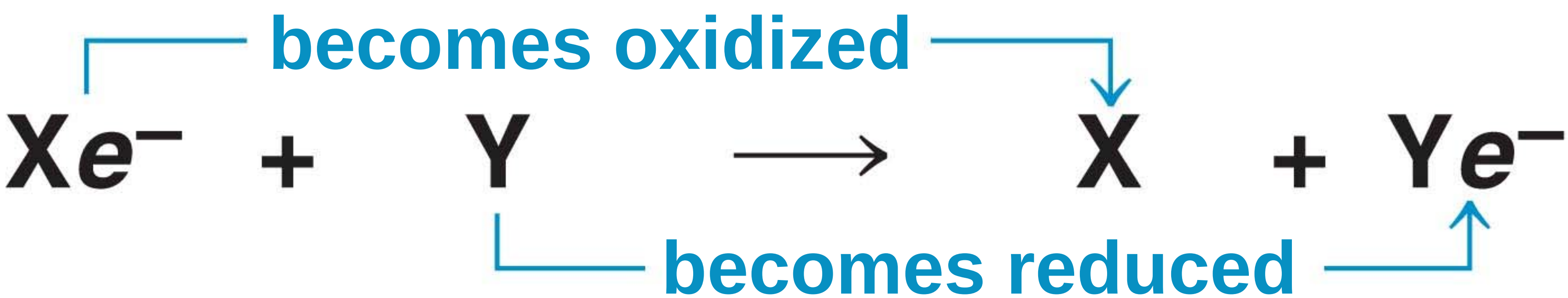
- This released energy is ultimately used to synthesize ATP

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-UN1

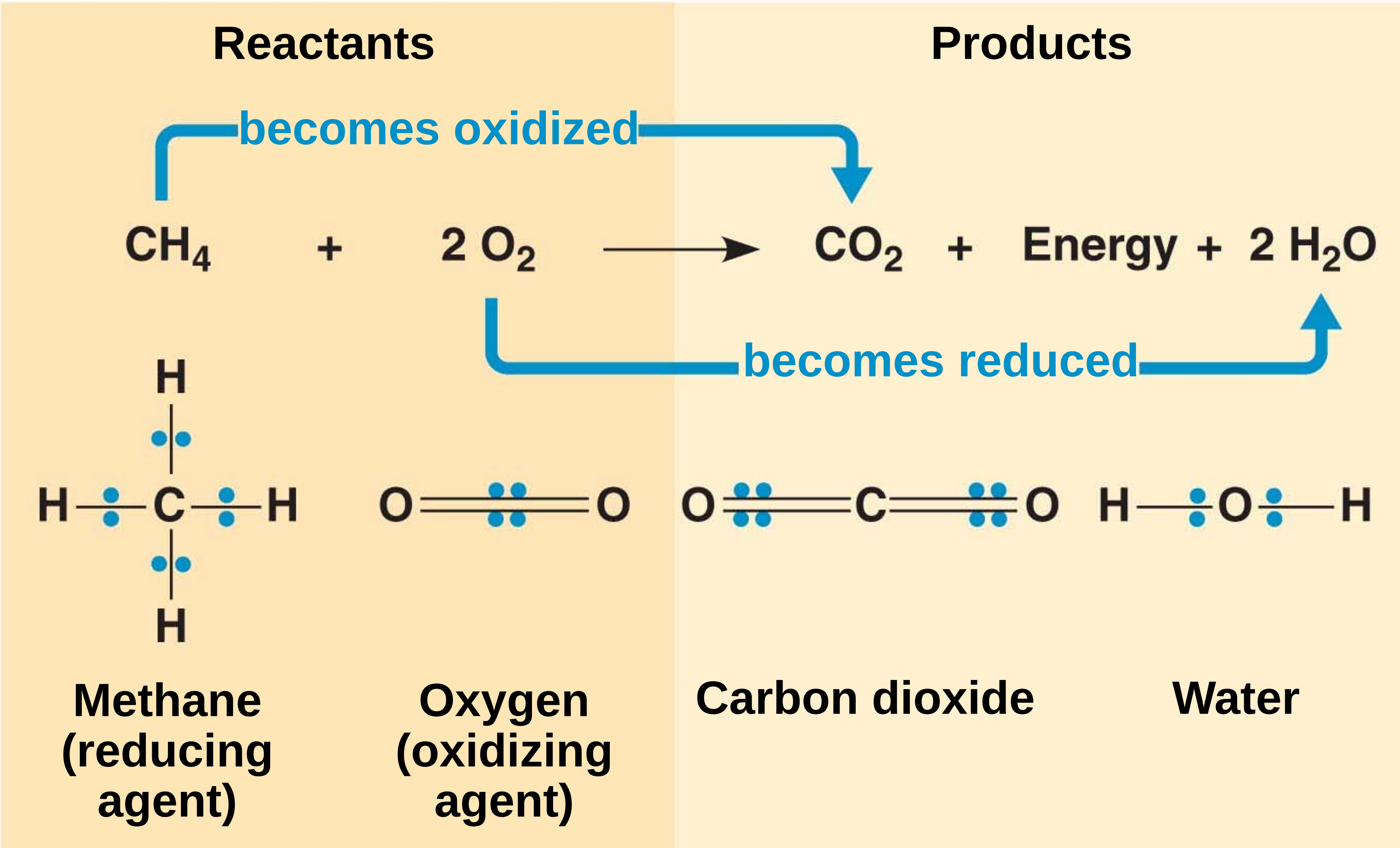

becomes oxidized
(loses electron)
Na + Cl → Na+ + Cl−
becomes reduced
(gains electron)


becomes oxidized
Xe− + Y → X + Ye−
becomes reduced

- 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

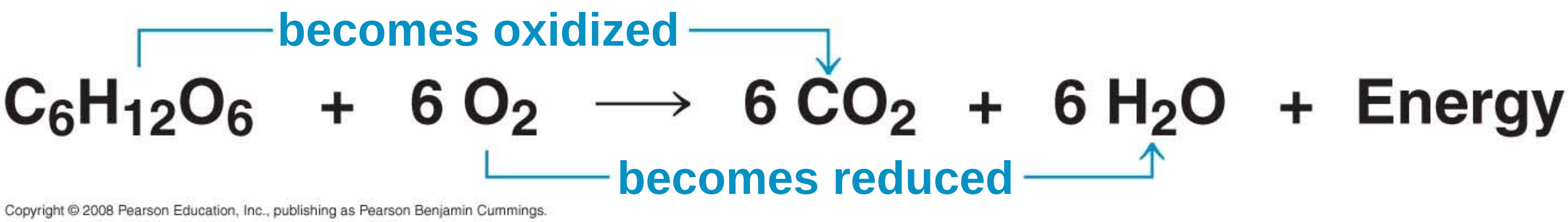
Fig. 9-3

Methane combustion as an energy-yielding redox reaction



Oxidation of Organic Fuel Molecules During Cellular Respiration

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

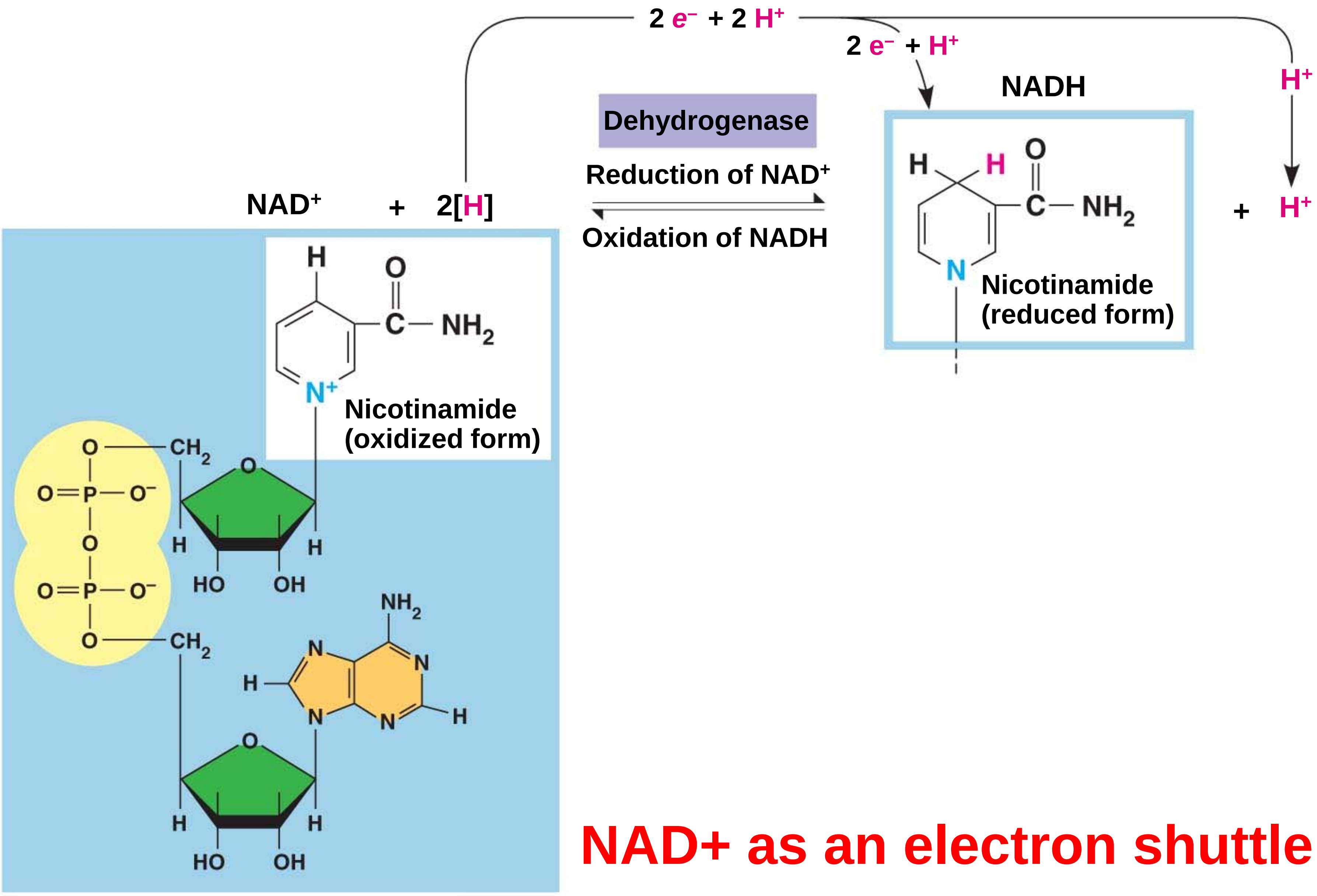


Stepwise Energy Harvest via NAD^+ and the Electron Transport Chain

- 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 reduced form of NAD^+) represents stored energy that is tapped to synthesize ATP

Fig. 9-UN4

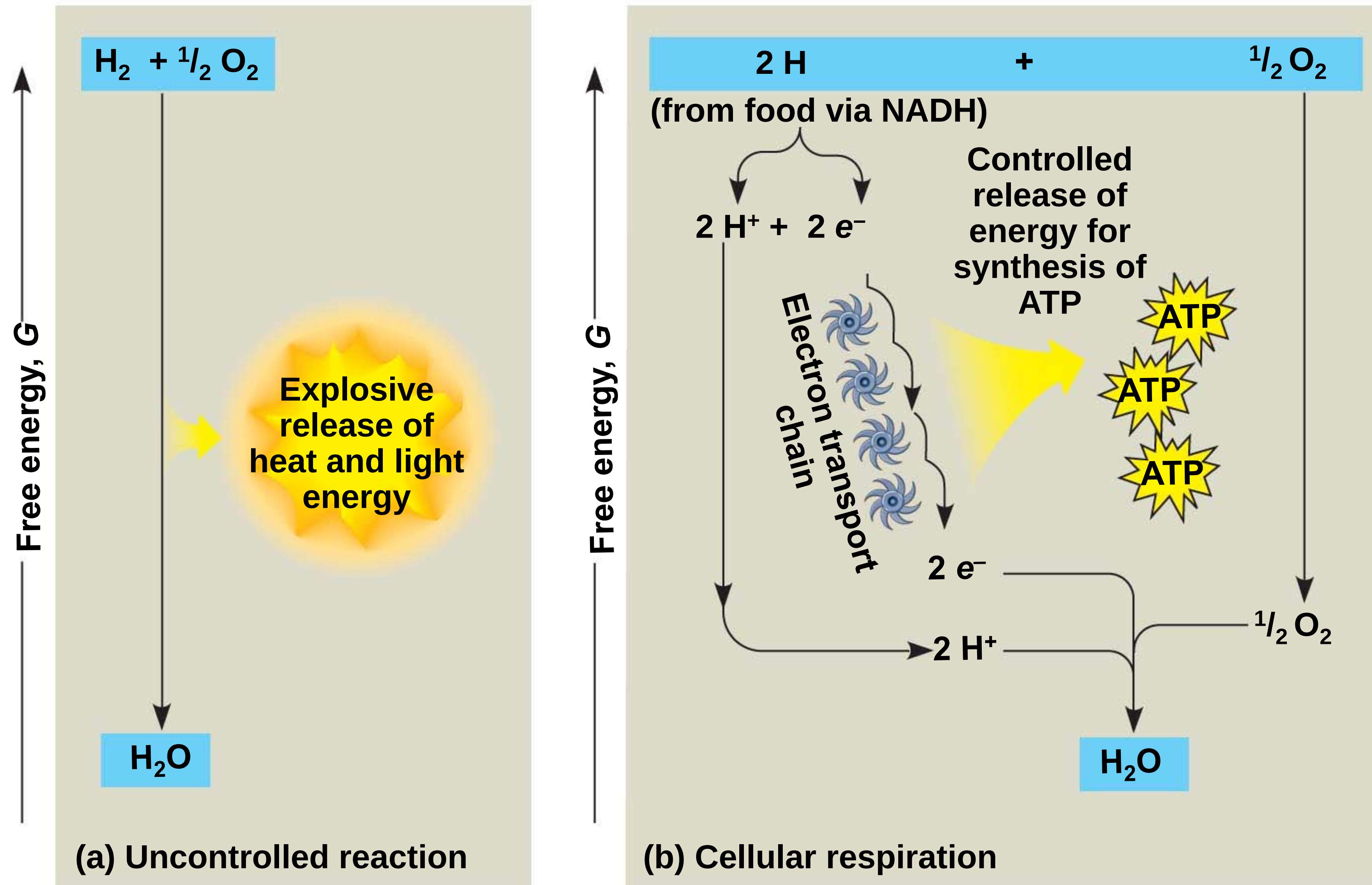
Fig. 9-4



NAD+ as an electron shuttle

Fig. 9-5

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

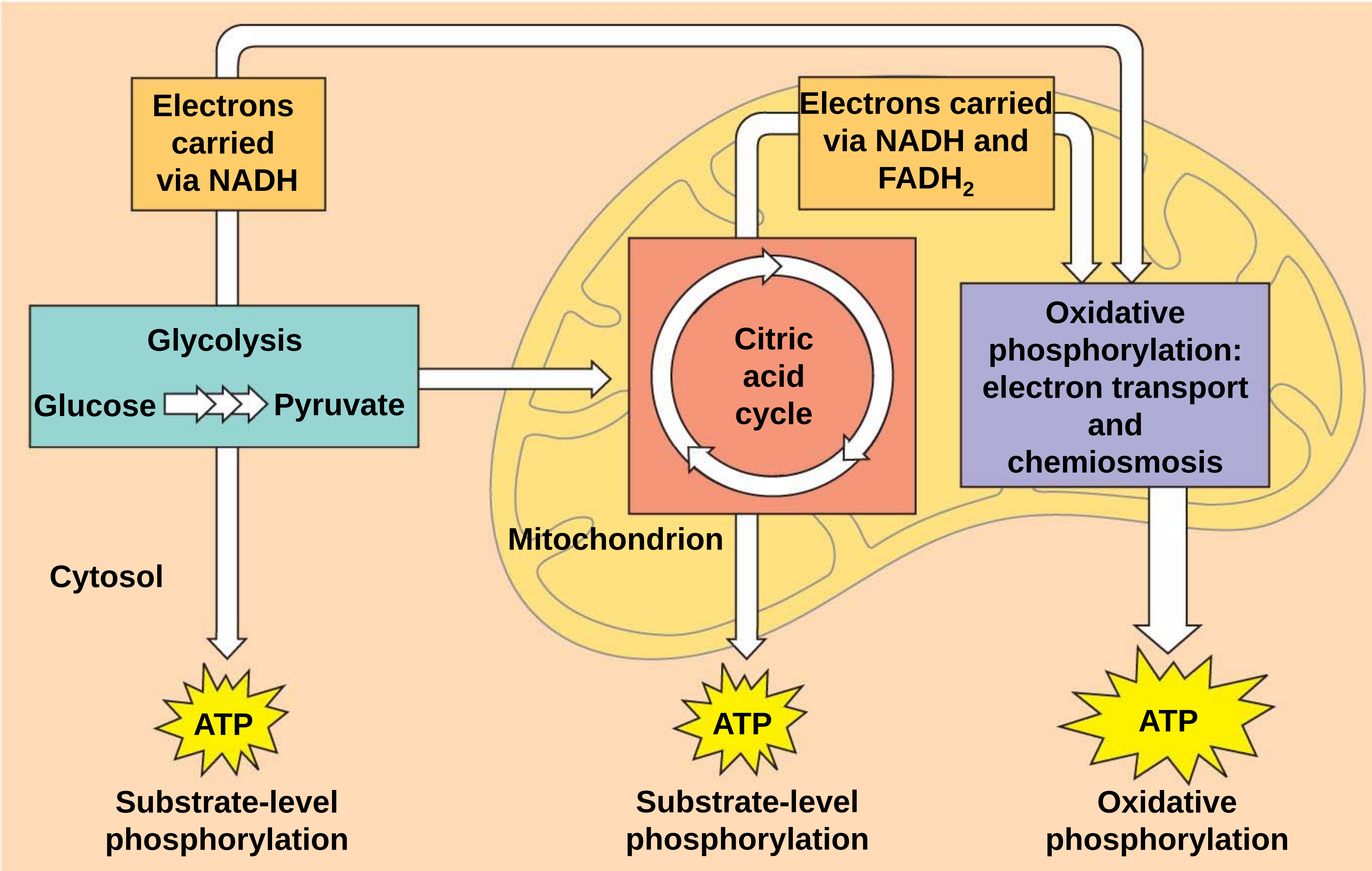


O_2 pulls electrons down the chain in an energy-yielding tumble

The Stages of Cellular Respiration: *A Preview*

- Cellular respiration 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)

Fig. 9-6-3



PLAY

BioFlix: Cellular Respiration

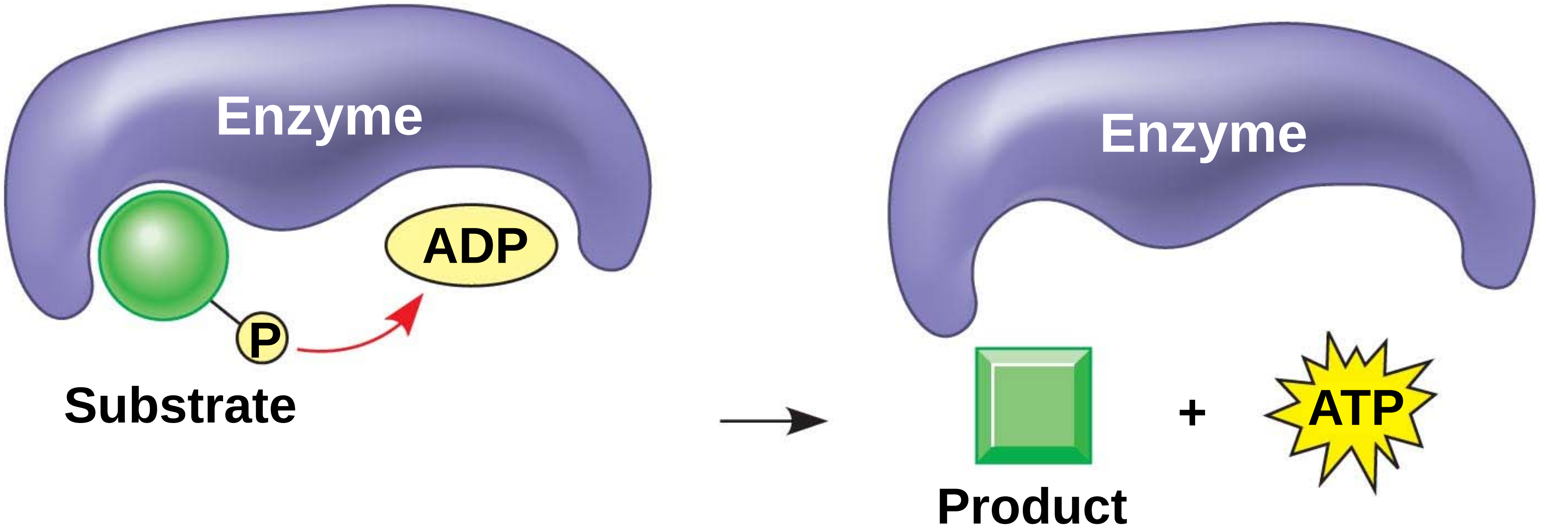
- The process that generates most of the ATP is called oxidative phosphorylation because it is powered by redox reactions

- 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**

Fig. 9-7

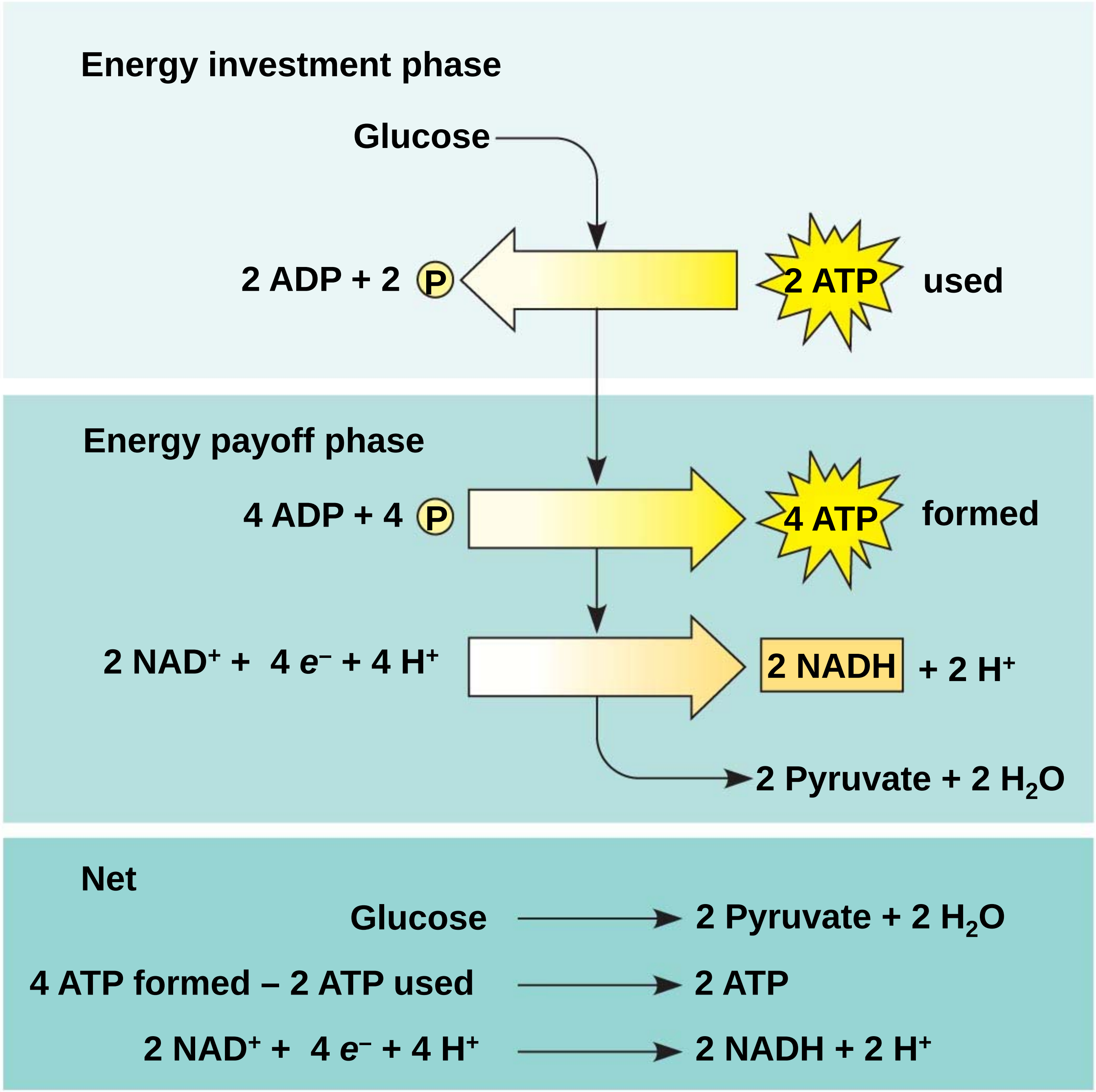
Substrate-level phosphorylation



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

Fig. 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 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$^+$

Fig. 9-9-1

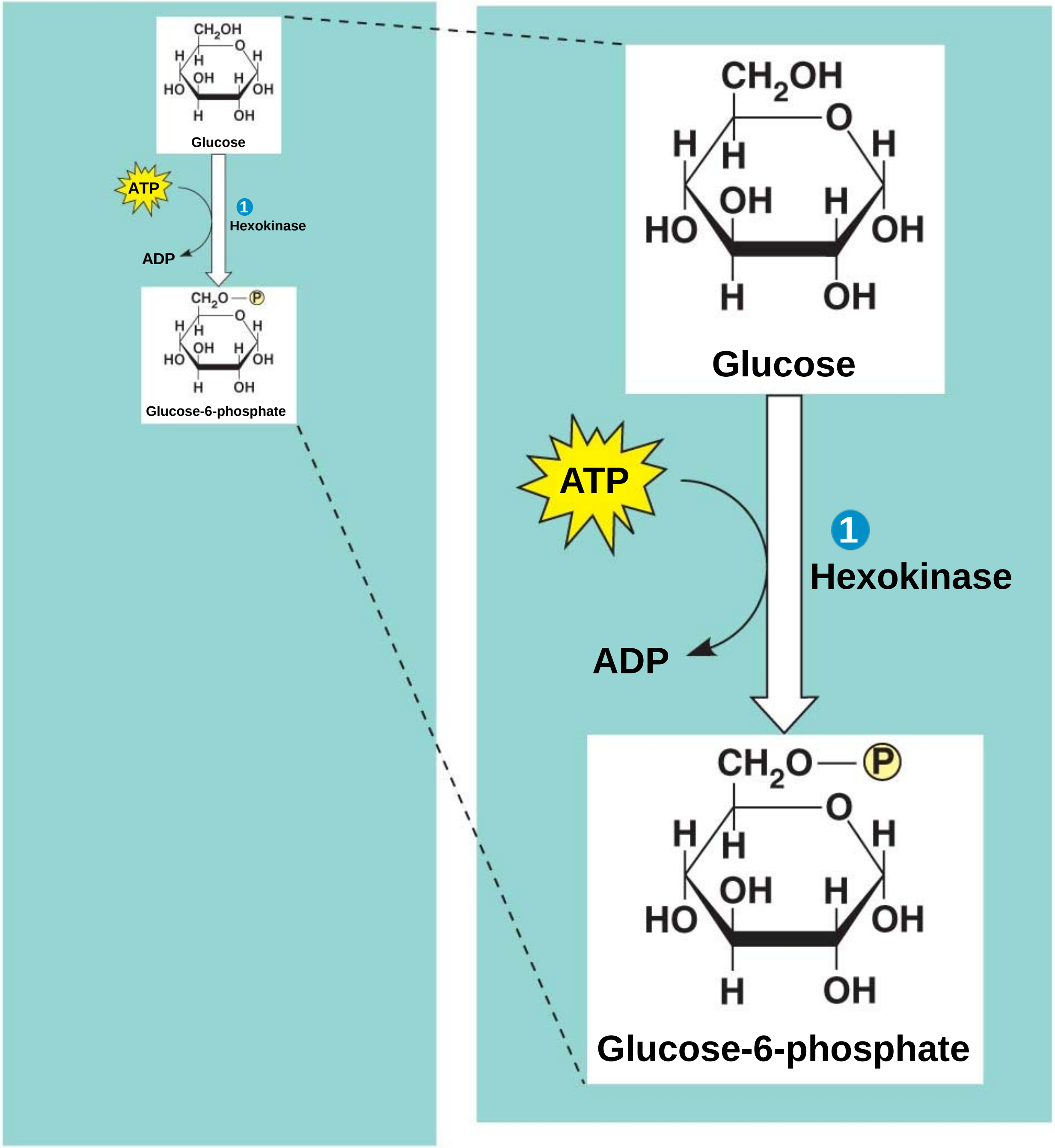
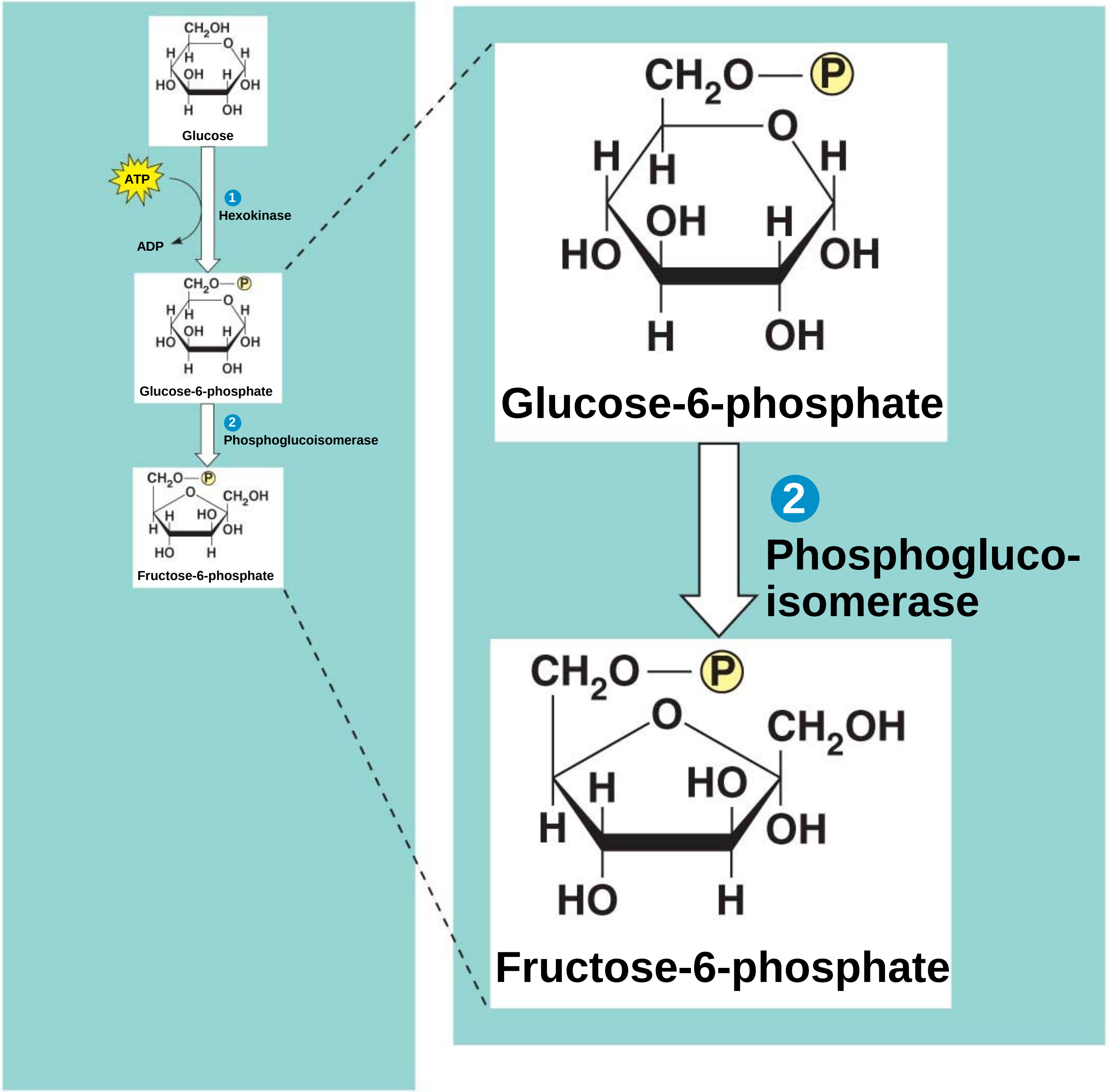
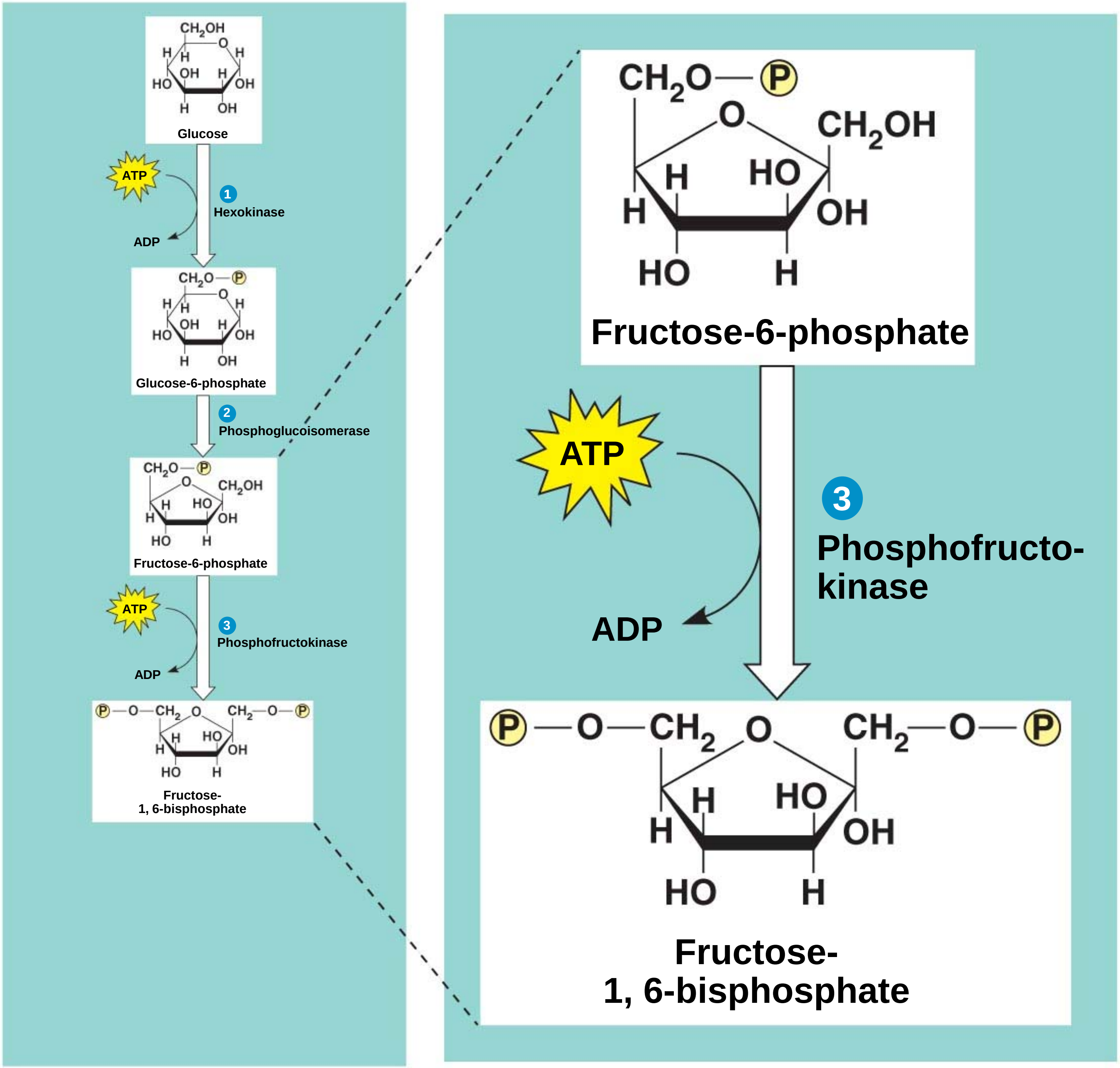


Fig. 9-9-2



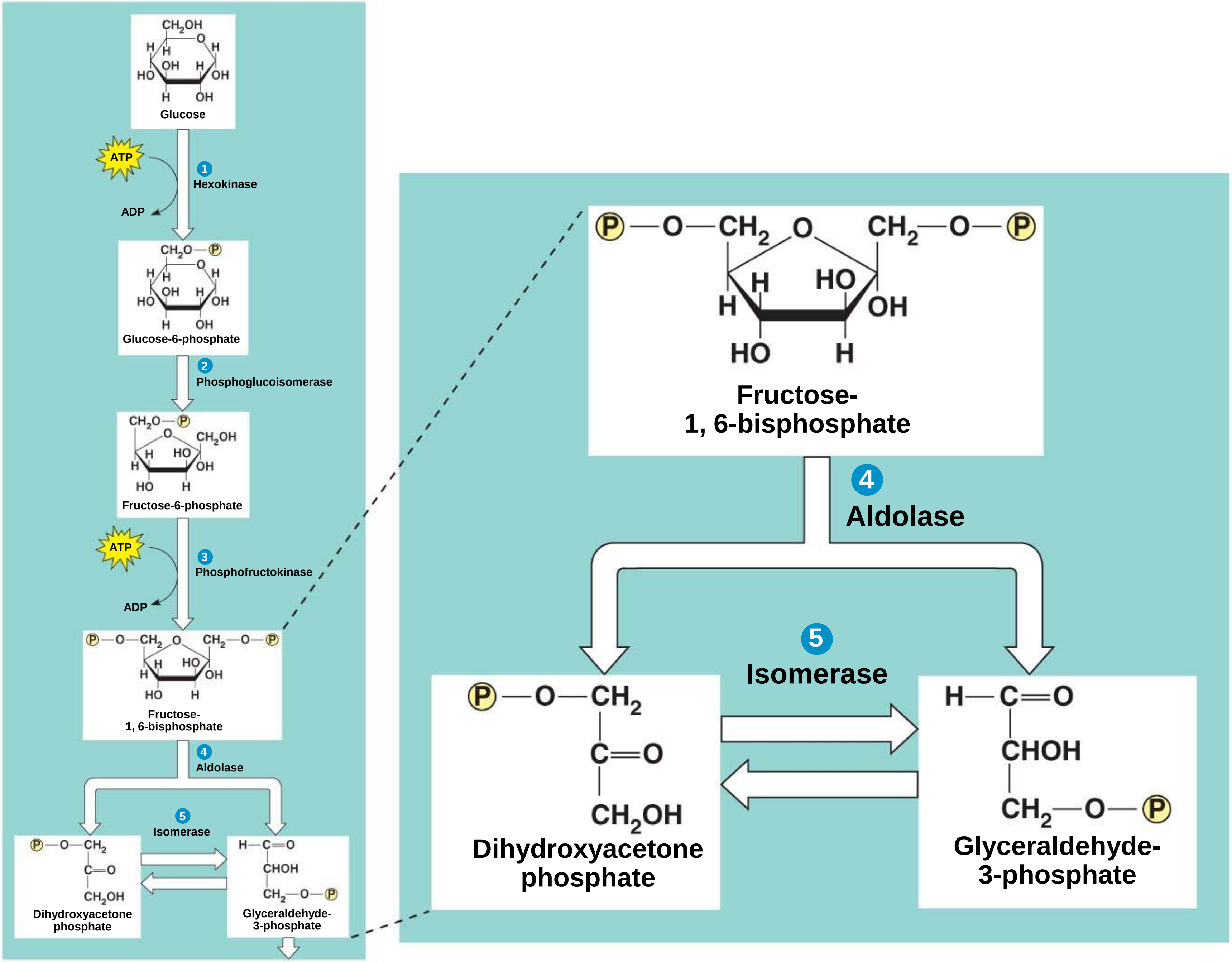
CH2OH
Glucose
ATP
ADP
1
Hexokinase
CH2O—P
Glucose-6-phosphate
2
Phosphoglucoisomerase
Fructose-6-phosphate
Glucose-6-phosphate
2
Phosphogluco-
isomerase
Fructose-6-phosphate

Fig. 9-9-3



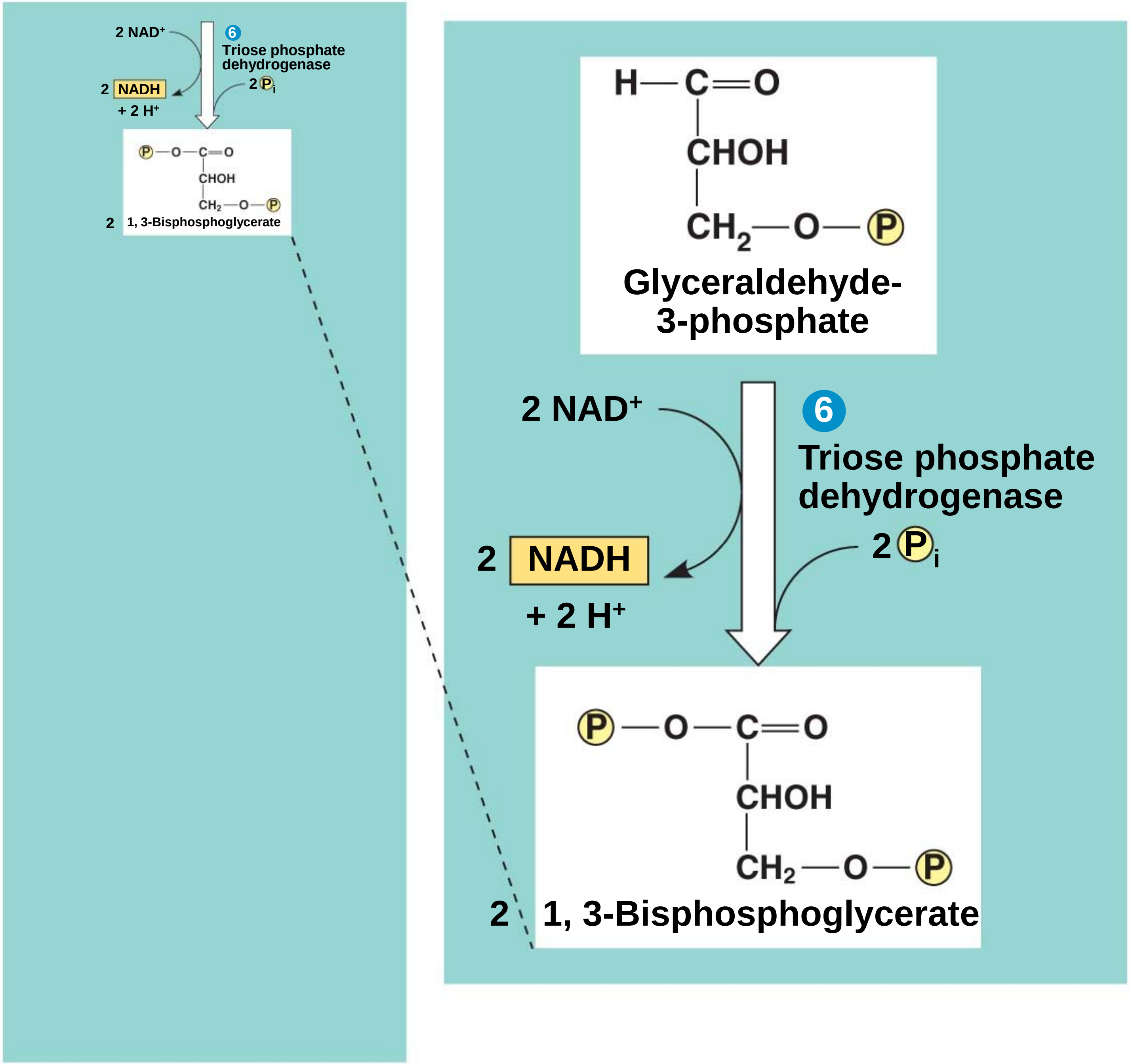
Glucose
ATP
1
Hexokinase
ADP
Glucose-6-phosphate
2
Phosphoglucoisomerase
Fructose-6-phosphate
ATP
3
Phosphofructokinase
ADP
Fructose-
1, 6-bisphosphate
Fructose-6-phosphate
ATP
3
Phosphofructo-
kinase
ADP
Fructose-
1, 6-bisphosphate

Fig. 9-9-4



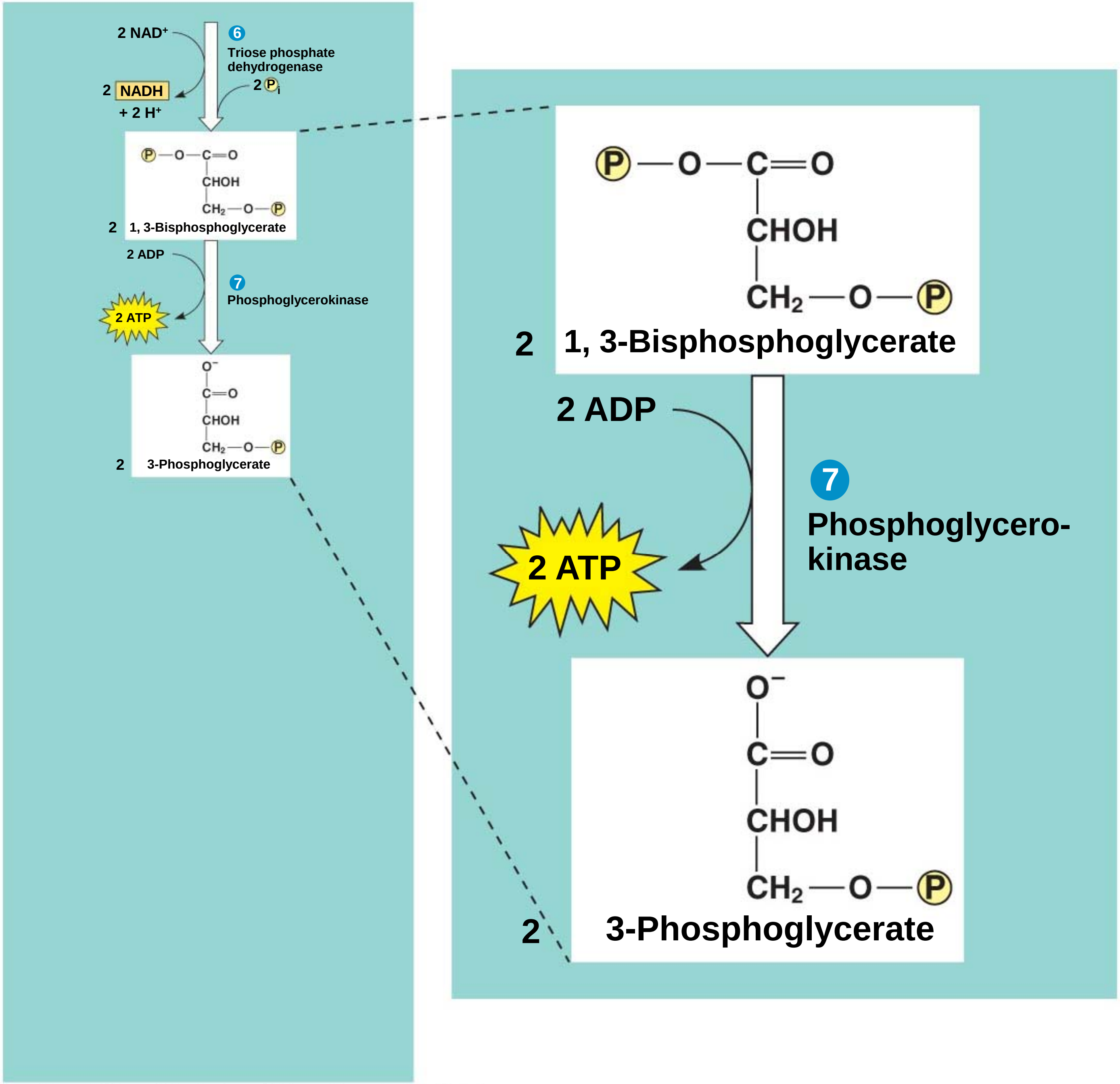
Glucose
ATP
1
Hexokinase
ADP
Glucose-6-phosphate
2
Phosphoglucoisomerase
Fructose-6-phosphate
ATP
3
Phosphofructokinase
ADP
Fructose-
1, 6-bisphosphate
4
Aldolase
5
Isomerase
Dihydroxyacetone
phosphate
Glyceraldehyde-
3-phosphate
Fructose-
1, 6-bisphosphate
4
Aldolase
5
Isomerase
Dihydroxyacetone
phosphate
Glyceraldehyde-
3-phosphate

Fig. 9-9-5



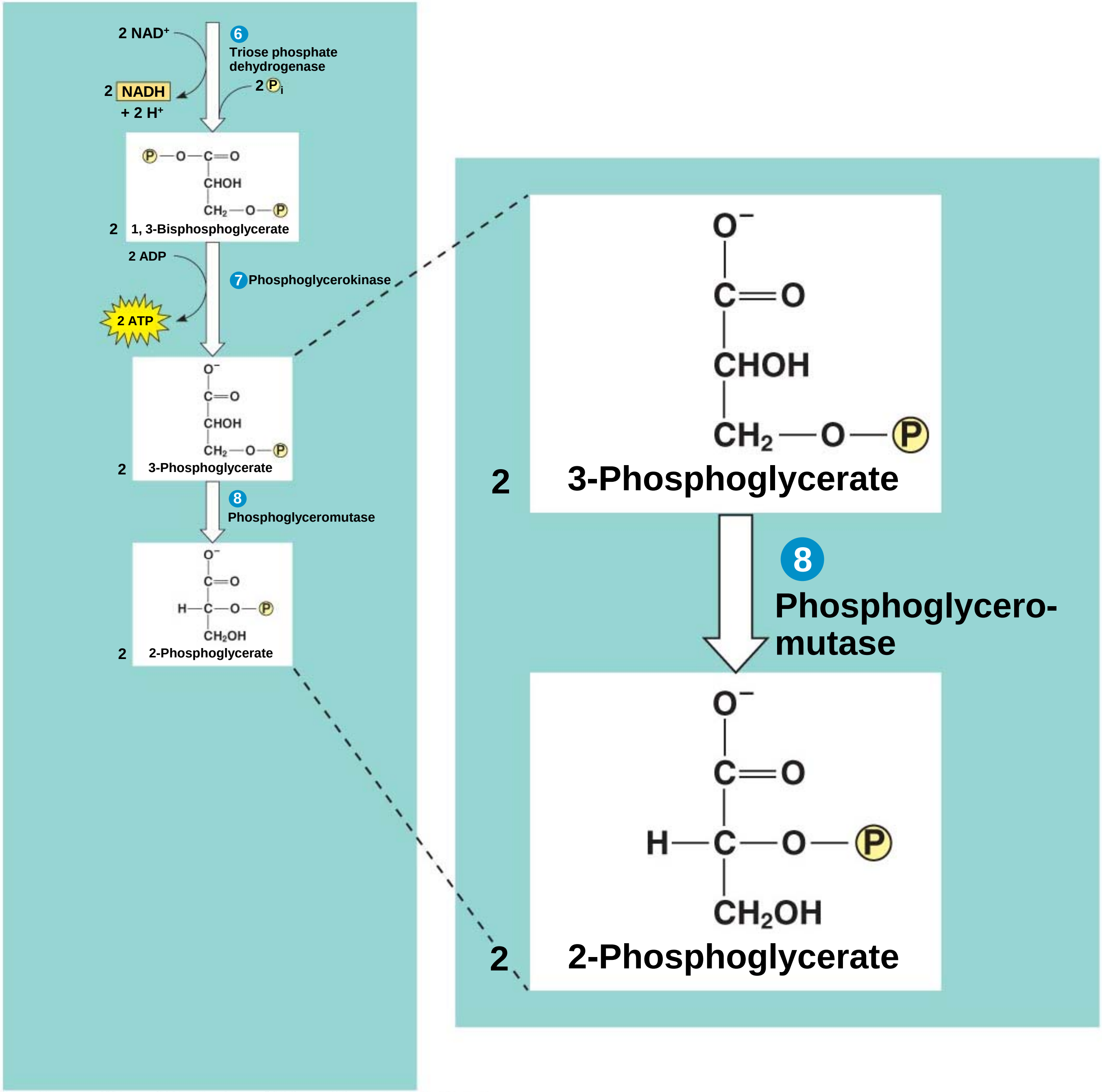
2 NAD+
6
Triose phosphate dehydrogenase
2 NADH
+ 2 H+
2 Pi
P—O—C=O
CHOH
CH2—O—P
2 1, 3-Bisphosphoglycerate
H—C=O
CHOH
CH2—O—P
Glyceraldehyde-3-phosphate
2 NAD+
6
Triose phosphate dehydrogenase
2 NADH
+ 2 H+
2 Pi
P—O—C=O
CHOH
CH2—O—P
2 1, 3-Bisphosphoglycerate

Fig. 9-9-6



2 NAD+
6
Triose phosphate dehydrogenase
2 P i
2 NADH
+ 2 H+
P—O—C═O
CHOH
CH2—O—P
2 1, 3-Bisphosphoglycerate
2 ADP
7
Phosphoglycerokinase
2 ATP
O−
C═O
CHOH
CH2—O—P
2 3-Phosphoglycerate
P—O—C═O
CHOH
CH2—O—P
2 1, 3-Bisphosphoglycerate
2 ADP
7
Phosphoglycero-kinase
2 ATP
O−
C═O
CHOH
CH2—O—P
2 3-Phosphoglycerate

Fig. 9-9-7



2 NAD+
6
Triose phosphate dehydrogenase
2 P i
2 NADH
+ 2 H+
P — O — C = O
CHOH
CH2 — O — P
2 1, 3-Bisphosphoglycerate
2 ADP
7 Phosphoglycerokinase
2 ATP
O−
C = O
CHOH
CH2 — O — P
2 3-Phosphoglycerate
8
Phosphoglyceromutase
O−
C = O
H — C — O — P
CH2OH
2 2-Phosphoglycerate
O−
C = O
CHOH
CH2 — O — P
2 3-Phosphoglycerate
8
Phosphoglycero-
mutase
O−
C = O
H — C — O — P
CH2OH
2 2-Phosphoglycerate

Fig. 9-9-8

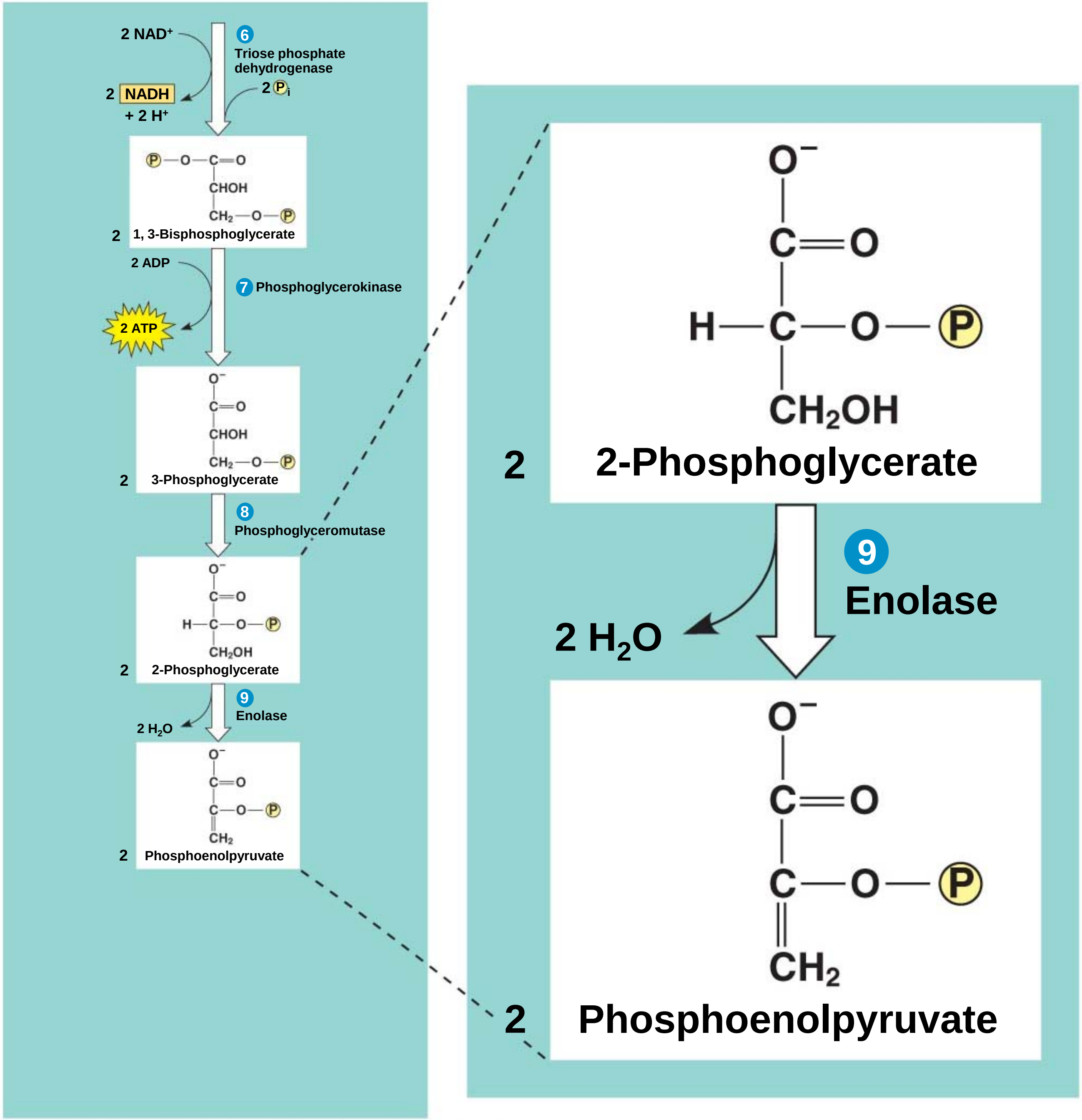
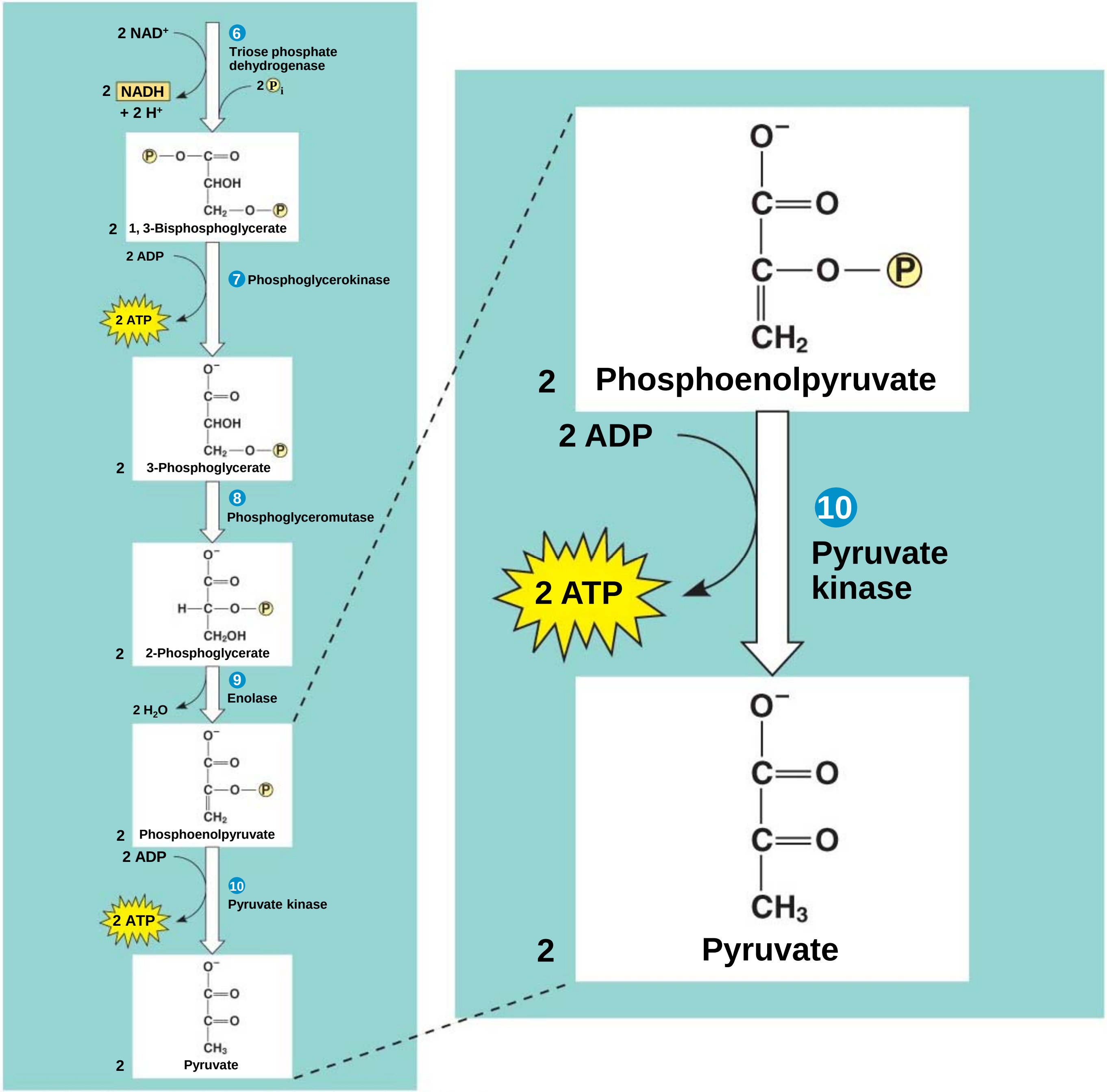
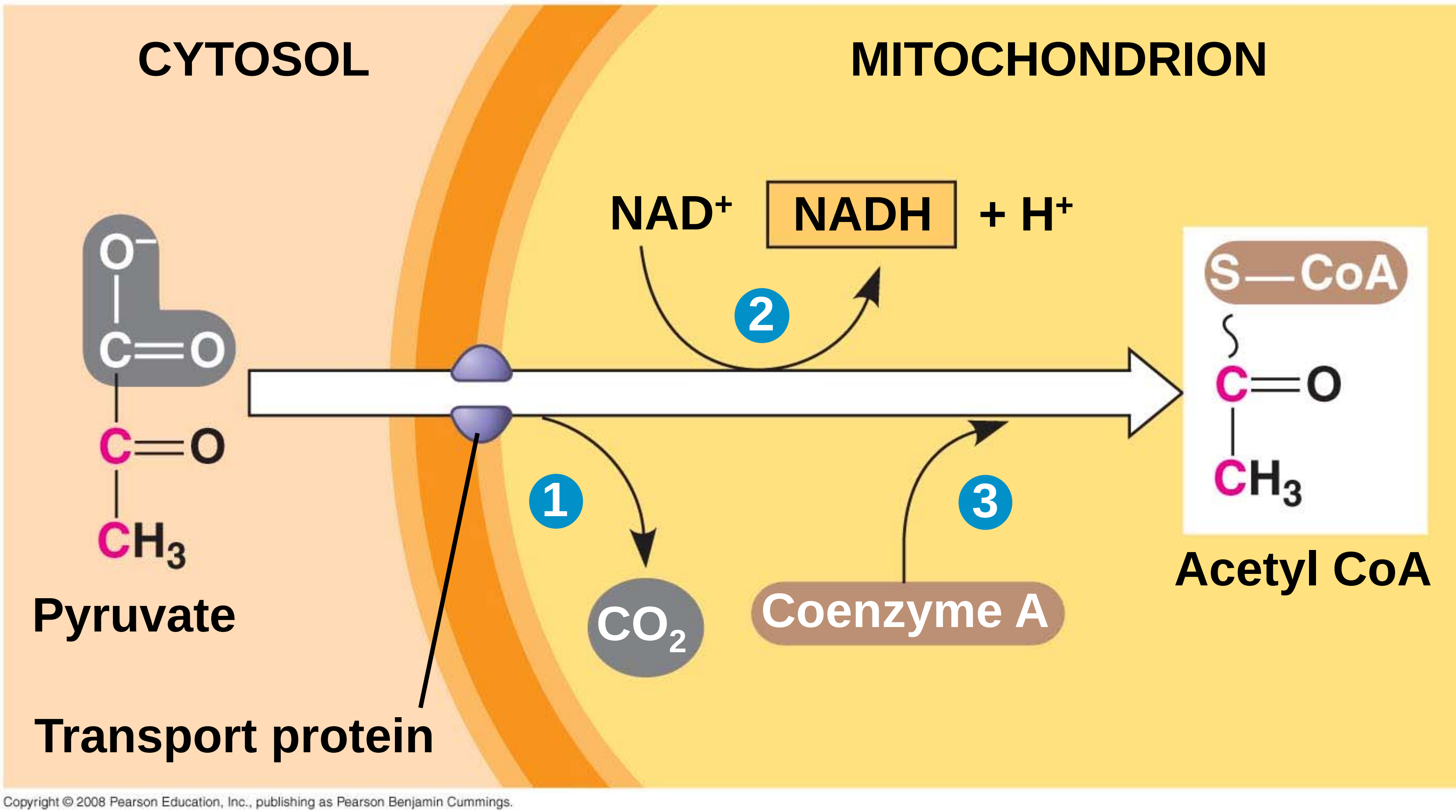

2 NAD+
6 Triose phosphate dehydrogenase
2 NADH + 2 H+
2 Pi
2 1, 3-Bisphosphoglycerate
2 ADP
2 ATP
7 Phosphoglycerokinase
2 3-Phosphoglycerate
8 Phosphoglyceromutase
2 2-Phosphoglycerate
9 Enolase
2 H2O
2 Phosphoenolpyruvate
2 2-Phosphoglycerate
9 Enolase
2 H2O
2 Phosphoenolpyruvate

Fig. 9-9-9


2 NAD+
6 Triose phosphate dehydrogenase
2 NADH
+ 2 H+
2 Pi
2 1, 3-Bisphosphoglycerate
2 ADP
7 Phosphoglycerokinase
2 ATP
2 3-Phosphoglycerate
8 Phosphoglyceromutase
2 2-Phosphoglycerate
9 Enolase
2 H2O
2 Phosphoenolpyruvate
2 ADP
10 Pyruvate kinase
2 ATP
2 Pyruvate
2 Phosphoenolpyruvate
2 ADP
10 Pyruvate kinase
2 ATP
2 Pyruvate

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

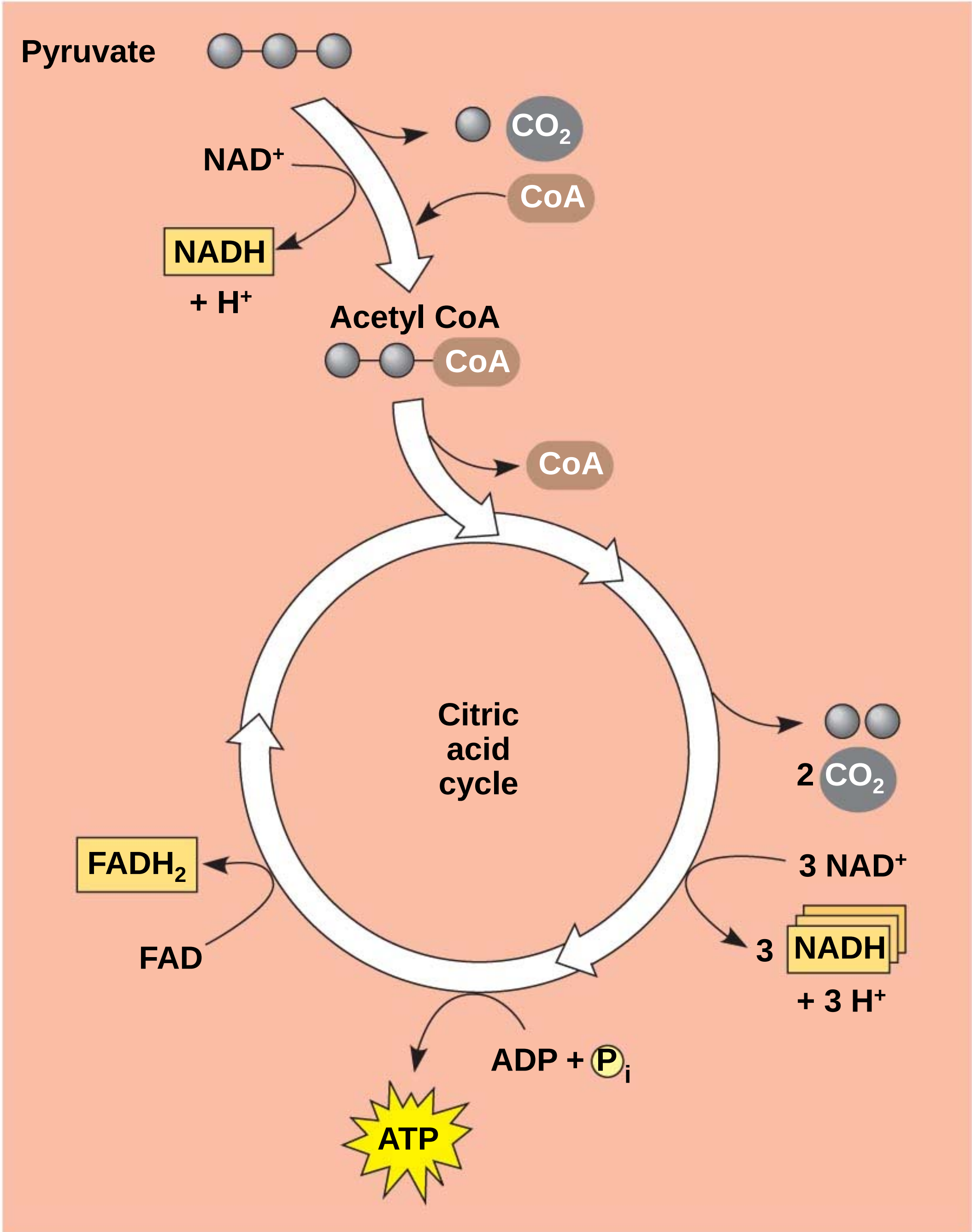
Before the citric acid cycle can begin, pyruvate must be converted to **acetyl CoA**, which links the cycle to glycolysis



- The citric acid cycle, also called the Krebs cycle, takes place within the mitochondrial matrix

- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn

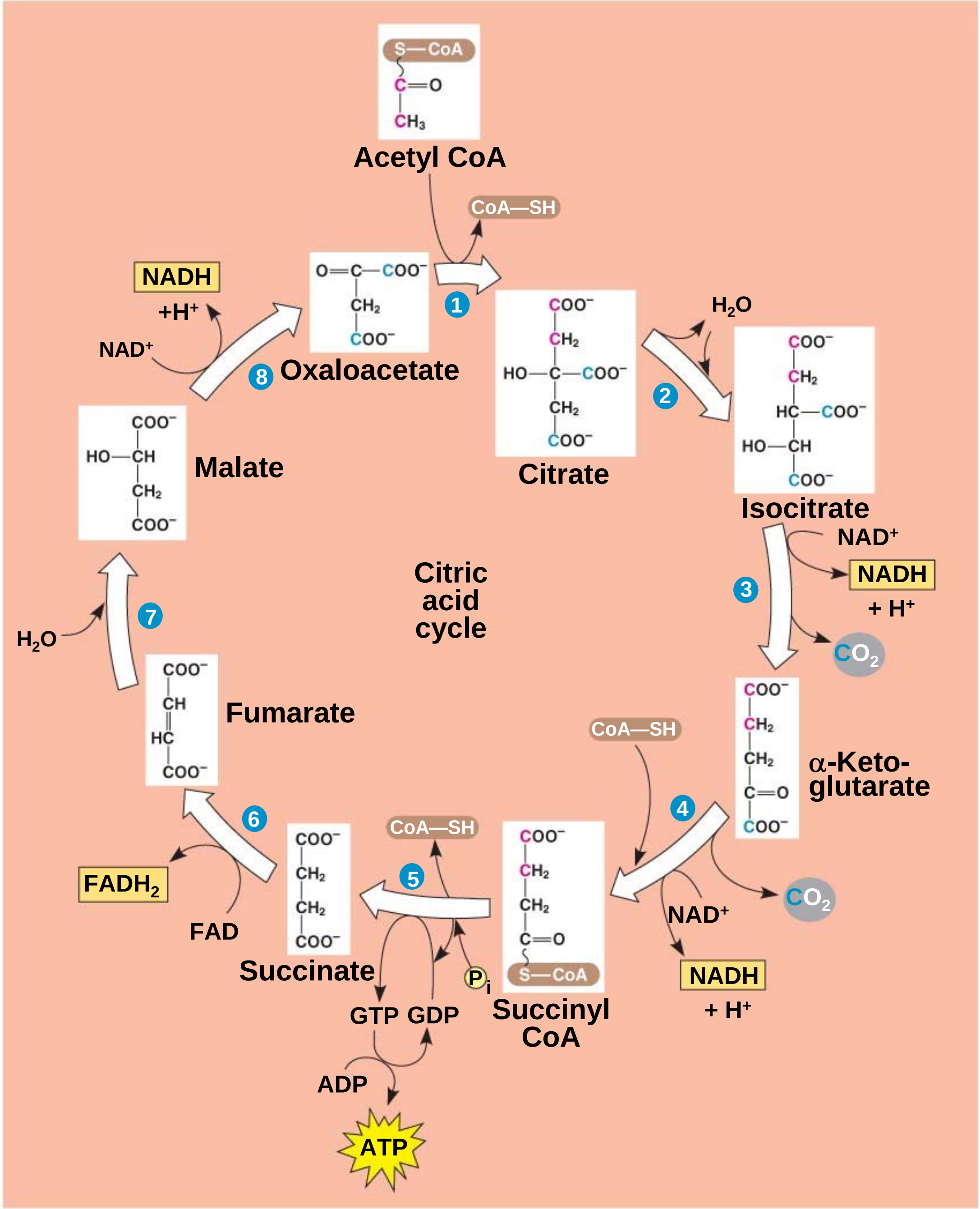
Fig. 9-11



Pyruvate
CO_2
NAD^+
CoA
NADH
$+ H^+$
Acetyl CoA
CoA
CoA
Citric acid cycle
2 CO_2
3 NAD^+
FADH$_2$
3 NADH
FAD
$+ 3 H^+$
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

Fig. 9-12-8



S—CoA
C=O
CH3
Acetyl CoA
CoA—SH
1
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
8
NADH
+H+
NAD+
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
2
H2O
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
3
NAD+
NADH
+ H+
CO2
COO⁻
CH2
CH2
C=O
COO⁻
α-Keto-glutarate
4
CoA—SH
NAD+
NADH
+ H+
CO2
COO⁻
CH2
CH2
C=O
S—CoA
Succinyl CoA
5
CoA—SH
Pi
GTP GDP
ADP
ATP
COO⁻
CH2
CH2
COO⁻
Succinate
6
FADH2
FAD
COO⁻
CH
HC
COO⁻
Fumarate
7
H2O
COO⁻
HO—CH
CH2
COO⁻
Malate
Citric acid cycle

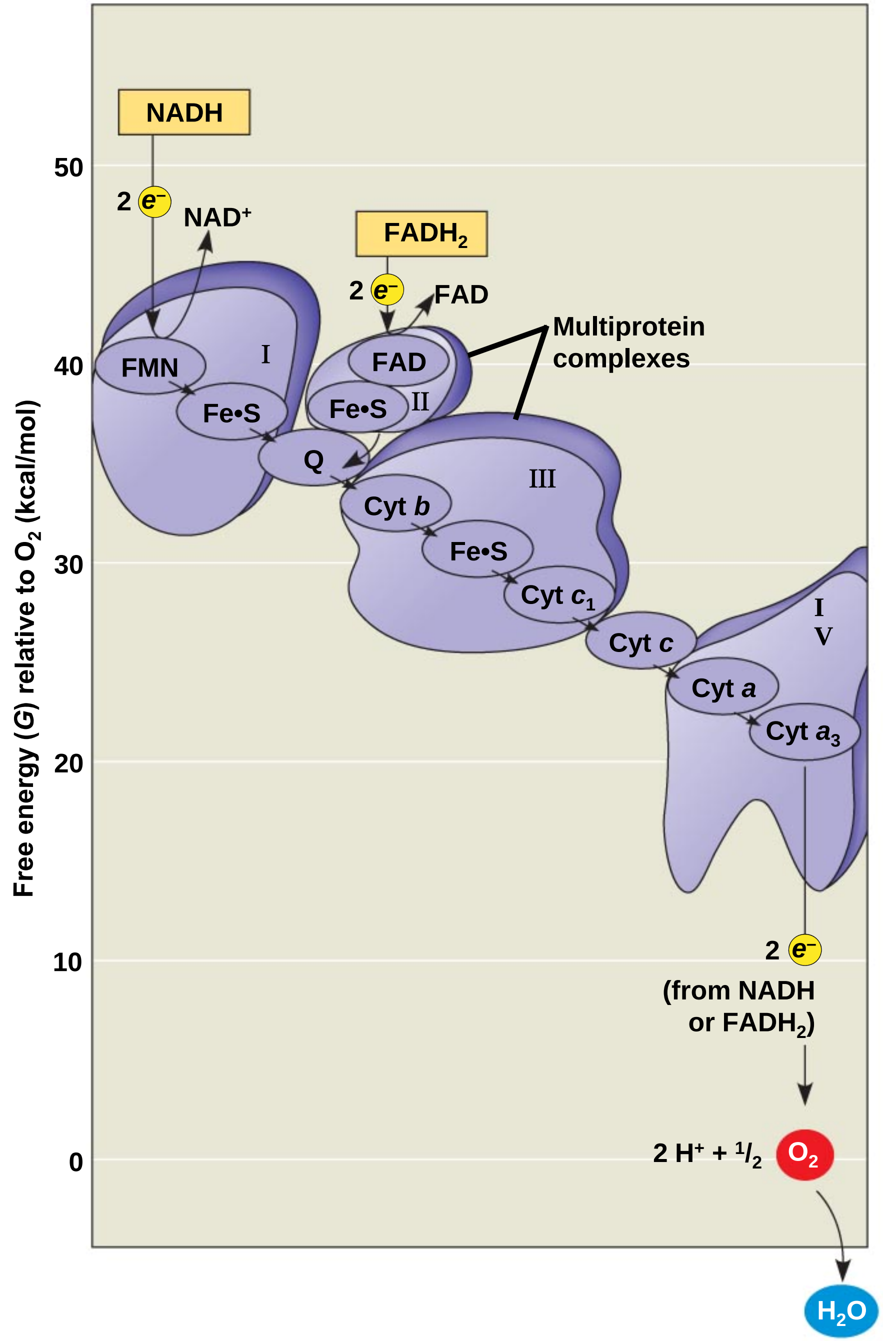
Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- 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
- 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

Fig. 9-13

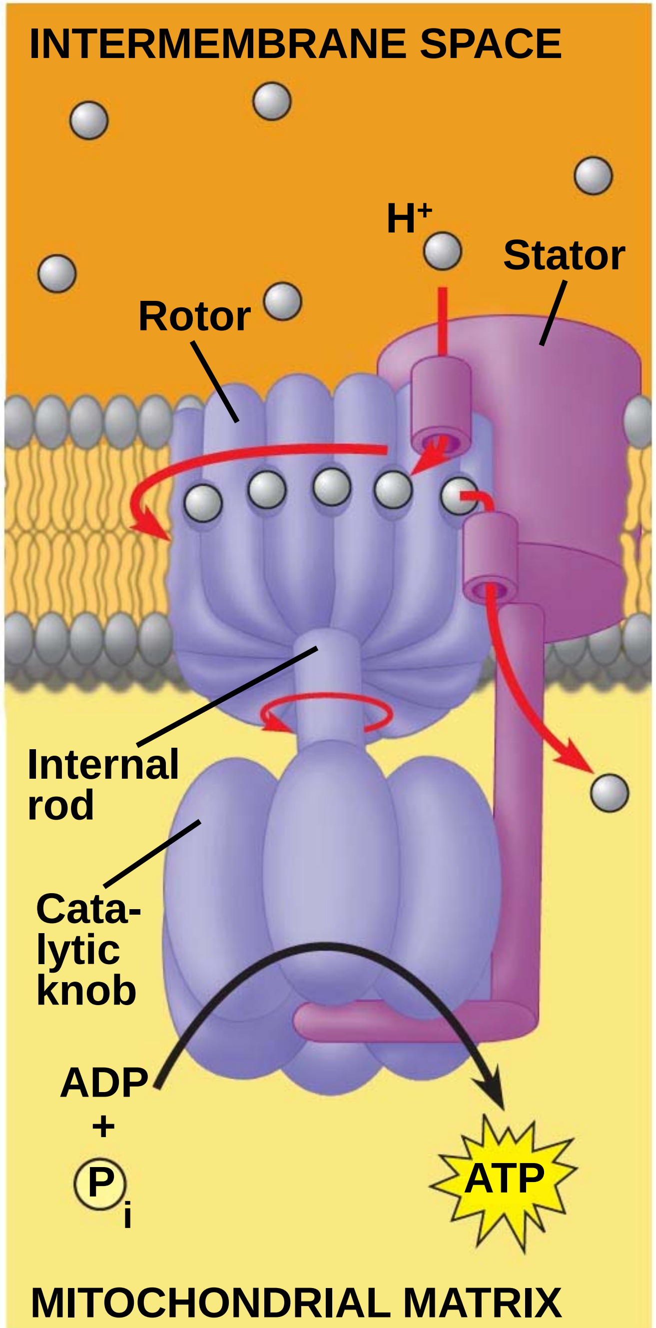

NADH
50
2 e⁻
NAD⁺
FADH₂
2 e⁻
FAD
Multiprotein complexes
40
FMN
I
FAD
Fe•S
II
Fe•S
Q
III
Cyt b
30
Fe•S
Cyt c₁
I V
Cyt c
Cyt a
Cyt a₃
20
10
2 e⁻
(from NADH or FADH₂)
0
2 H⁺ + ½ O₂
H₂O
Free energy (G) relative to O₂ (kcal/mol)

- 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
- The chain's function is to break 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

Fig. 9-14

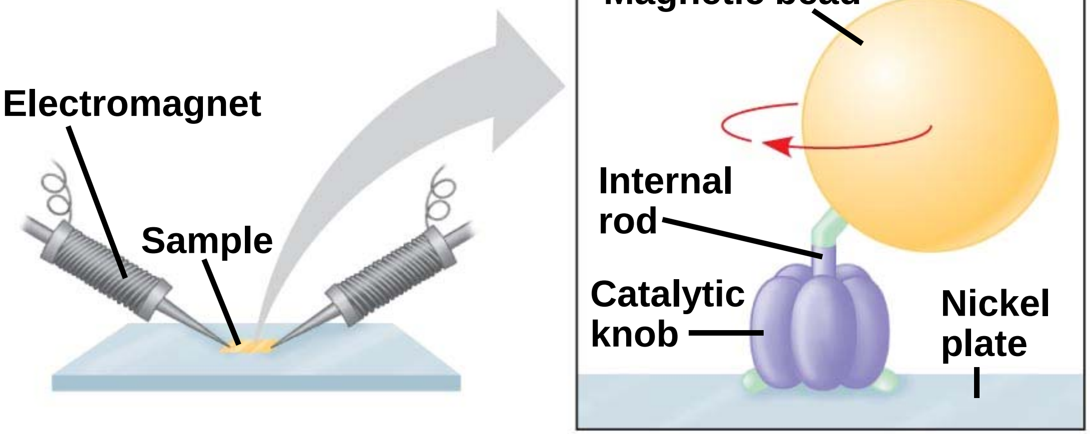


ATP synthase, a molecular mill

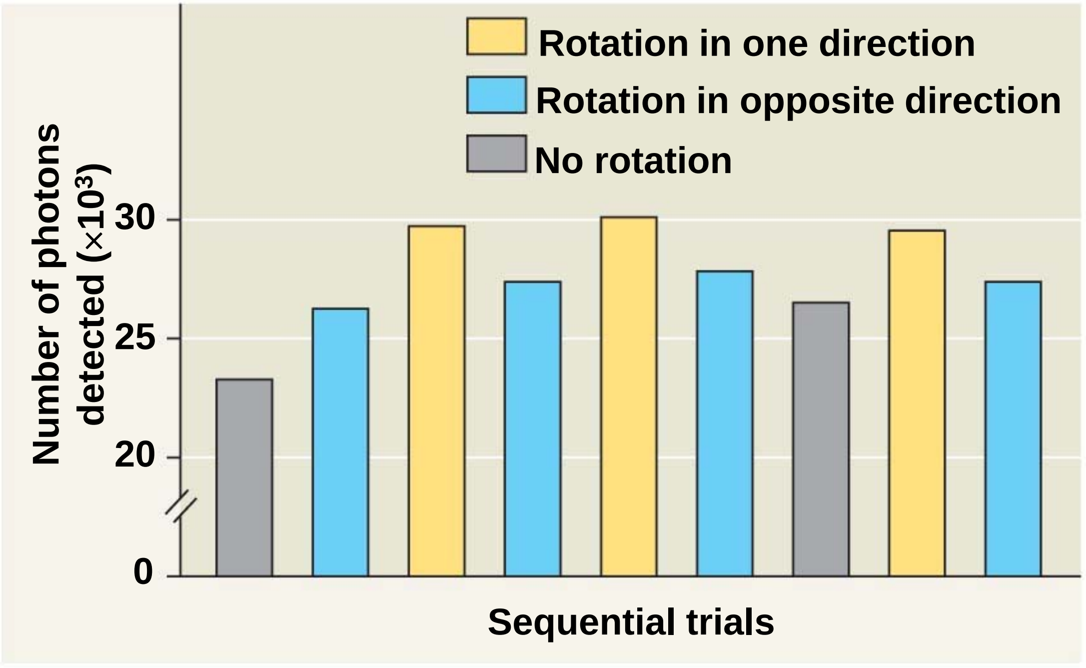
Fig. 9-15

The rotation of the internal rod in ATP synthase is responsible for ATP synthesis

EXPERIMENT



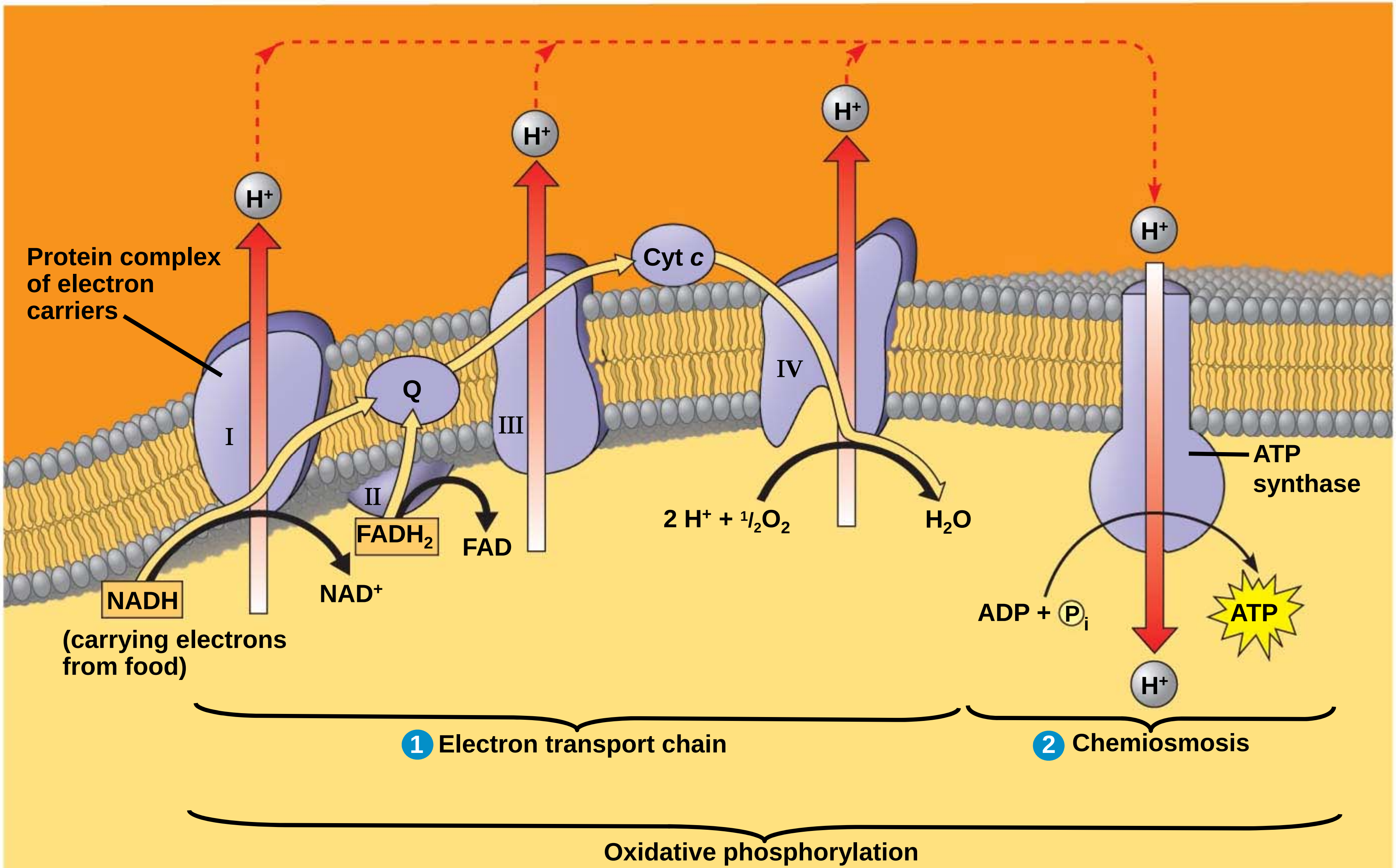
RESULTS



- 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

Fig. 9-16

Chemiosmosis couples the electron transport chain to ATP synthesis



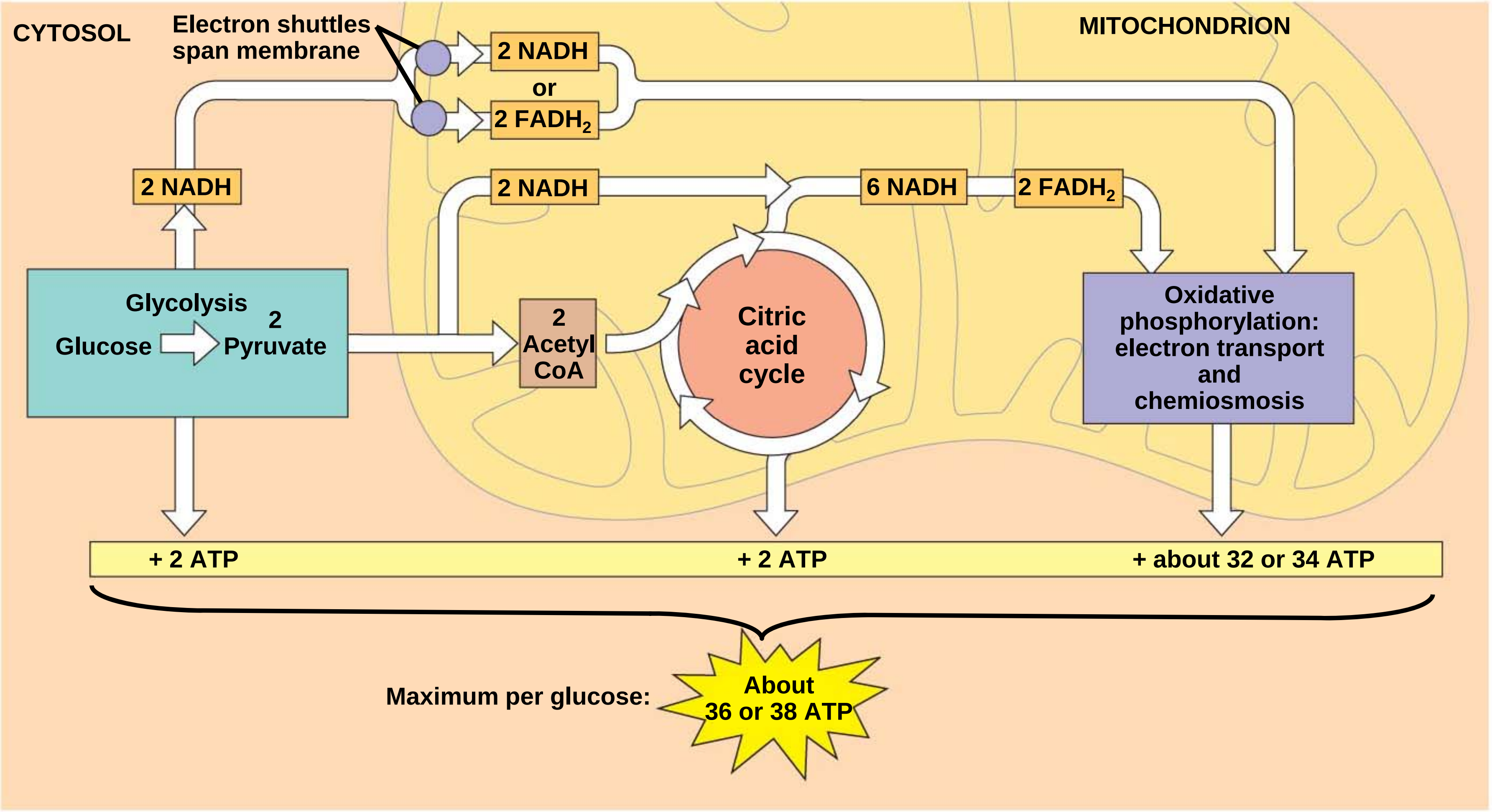
An Accounting of ATP Production by Cellular Respiration

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

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

- About 40% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making about 38 ATP

Fig. 9-17


CYTOSOL
Electron shuttles span membrane
MITOCHONDRION
2 NADH
or
2 $FADH_2$
2 NADH
2 NADH
6 NADH
2 $FADH_2$
Glycolysis
Glucose
2 Pyruvate
2 Acetyl CoA
Citric acid cycle
Oxidative phosphorylation: electron transport and chemiosmosis
+ 2 ATP
+ 2 ATP
+ about 32 or 34 ATP
Maximum per glucose:
About 36 or 38 ATP

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

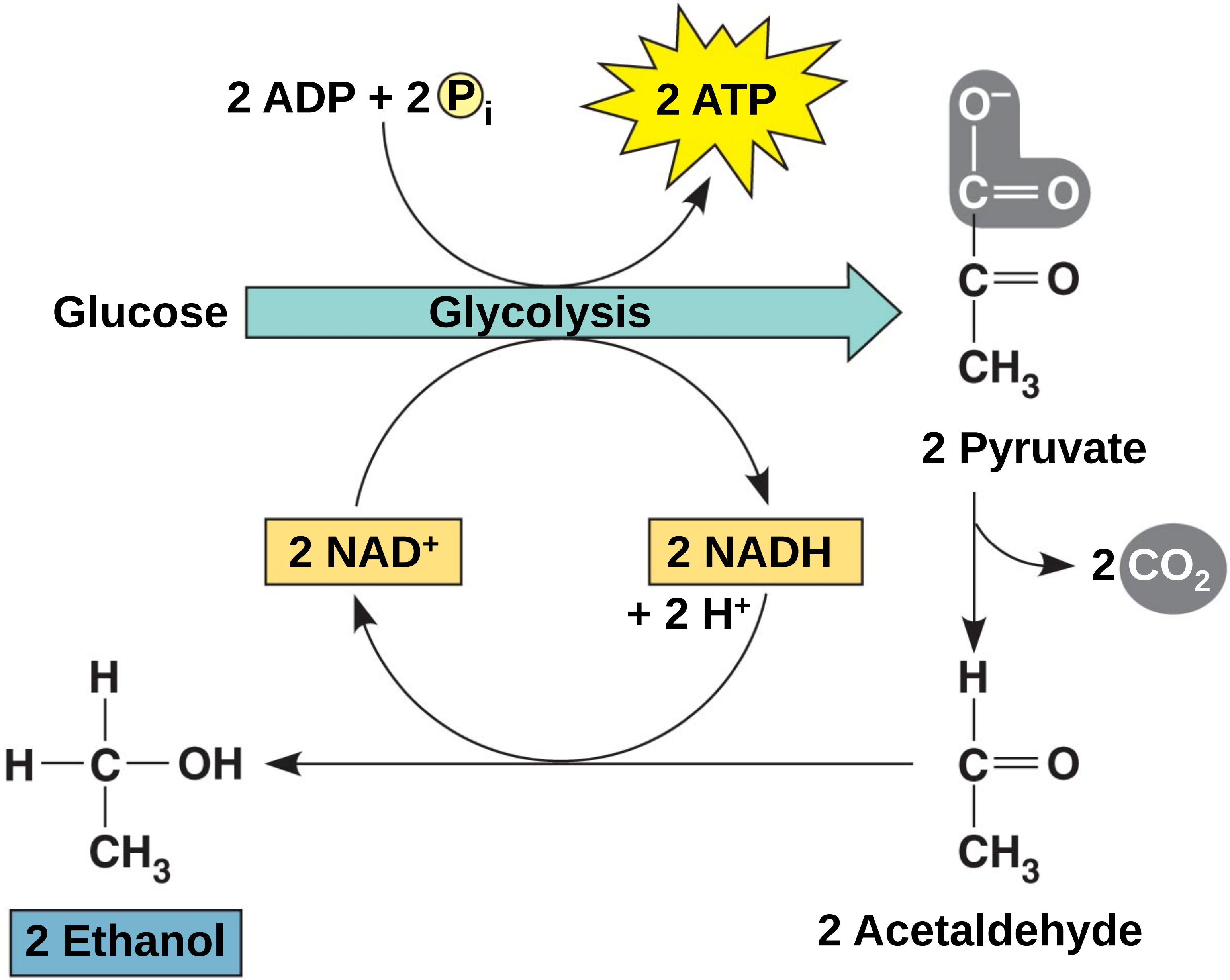
- Most cellular respiration requires O_2 to produce ATP
- Glycolysis can produce ATP with or without O_2 (in aerobic or anaerobic conditions)
- In the absence of O_2, glycolysis couples with fermentation or anaerobic respiration to produce ATP

- Anaerobic respiration uses an electron transport chain with an electron acceptor other than O_2, for example sulfate
- Fermentation uses 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

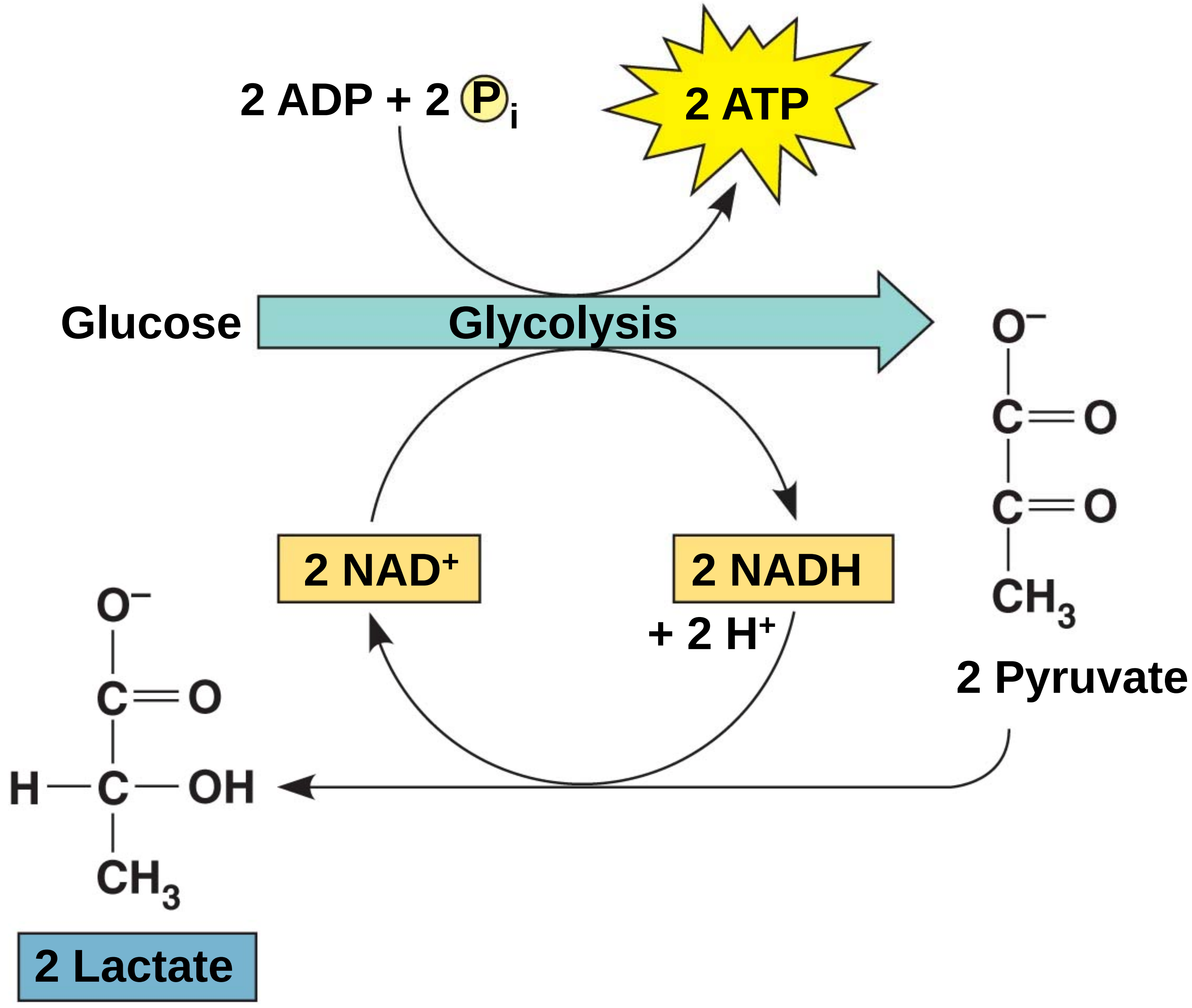
- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps, with the first releasing CO_2
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking



(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

Fig. 9-18b



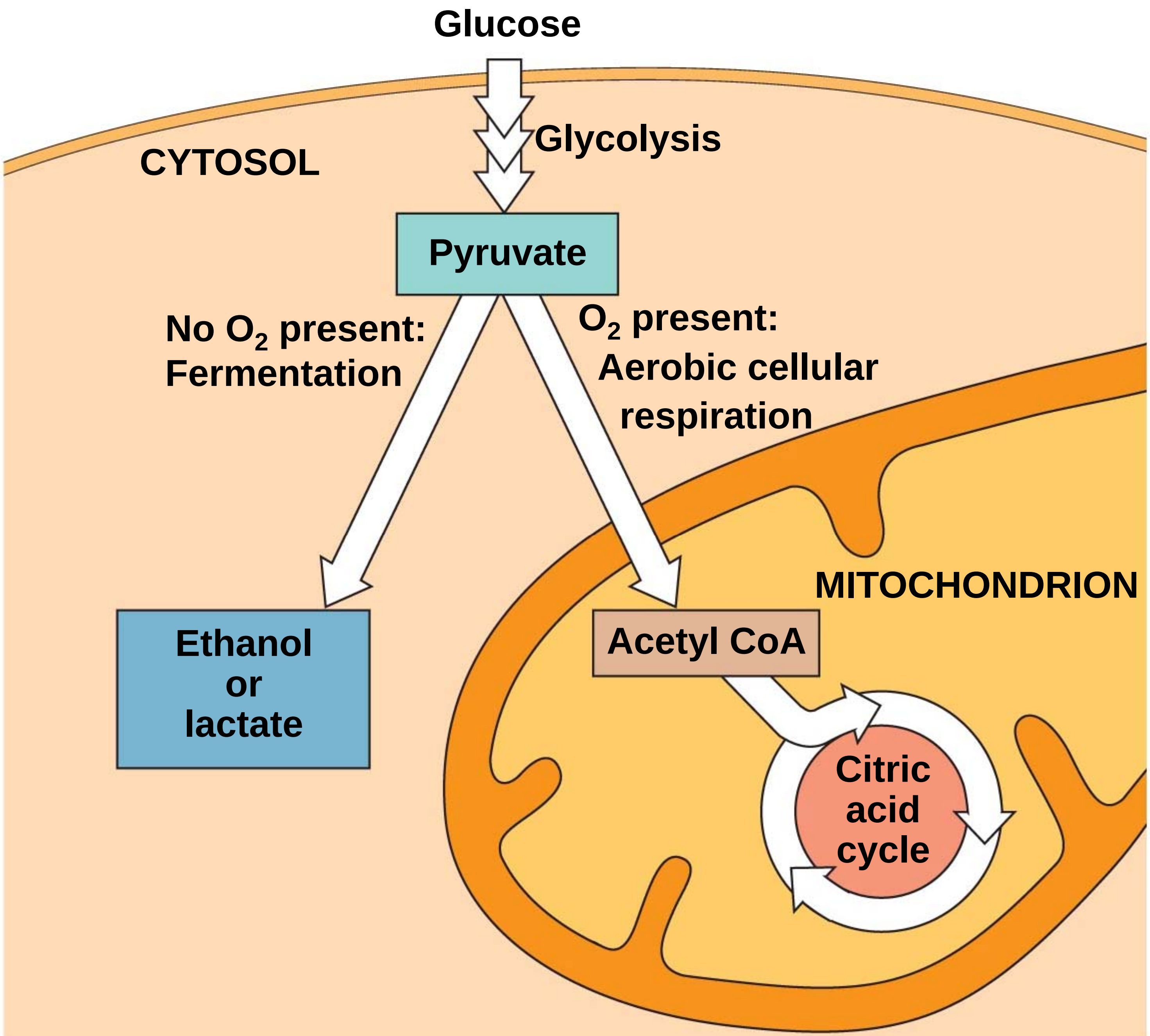
(b) Lactic acid fermentation

Fermentation and Aerobic Respiration Compared

- Both processes use glycolysis to oxidize glucose and other organic fuels to pyruvate
- 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 38 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

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

The Evolutionary Significance of Glycolysis

- Glycolysis occurs in nearly all organisms
- Glycolysis probably evolved in ancient prokaryotes before there was oxygen in the atmosphere

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

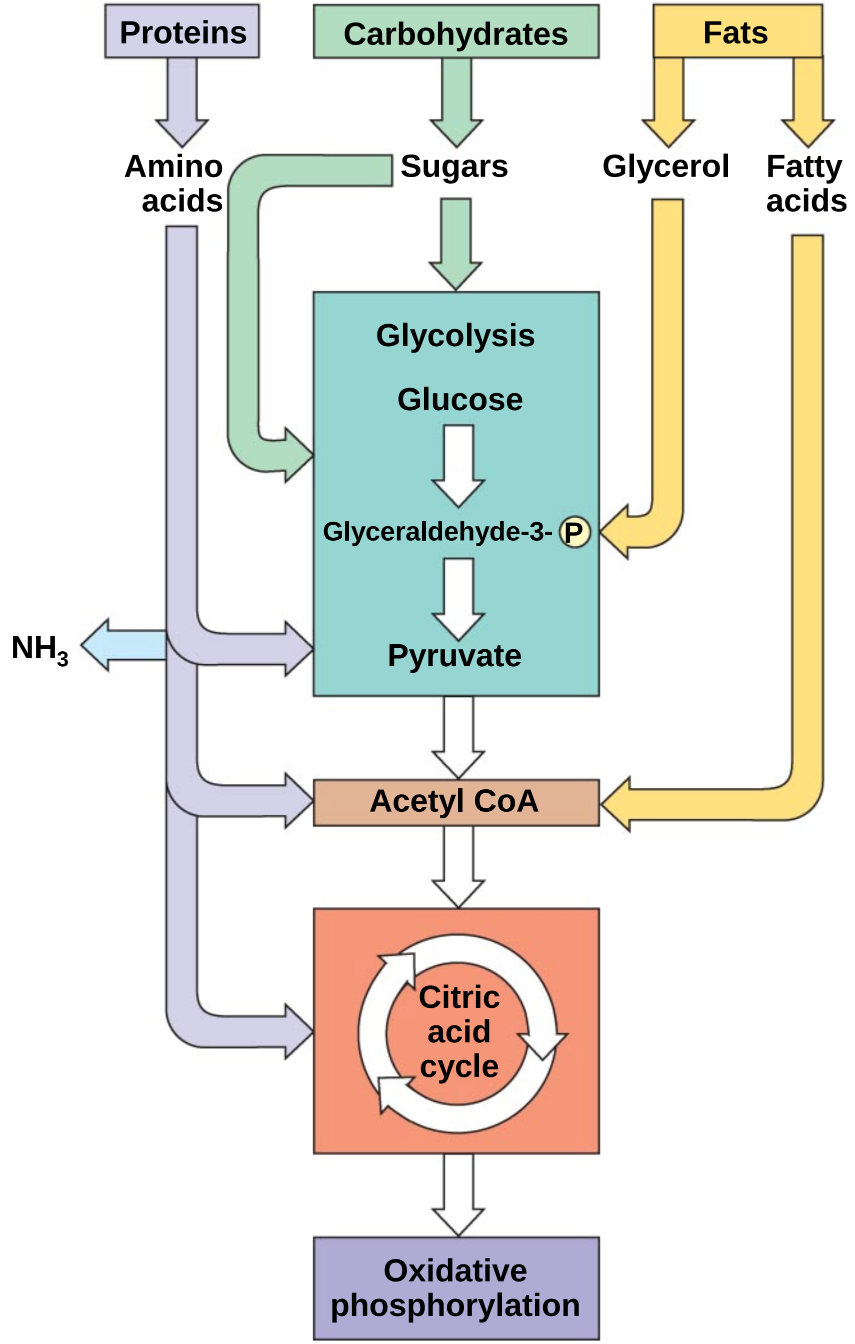
- Gycolysis and the citric acid cycle are major intersections to various catabolic and anabolic pathways

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

Fig. 9-20


Proteins
Carbohydrates
Fats
Amino acids
Sugars
Glycerol
Fatty acids
Glycolysis
Glucose
Glyceraldehyde-3- P
NH$_3$
Pyruvate
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

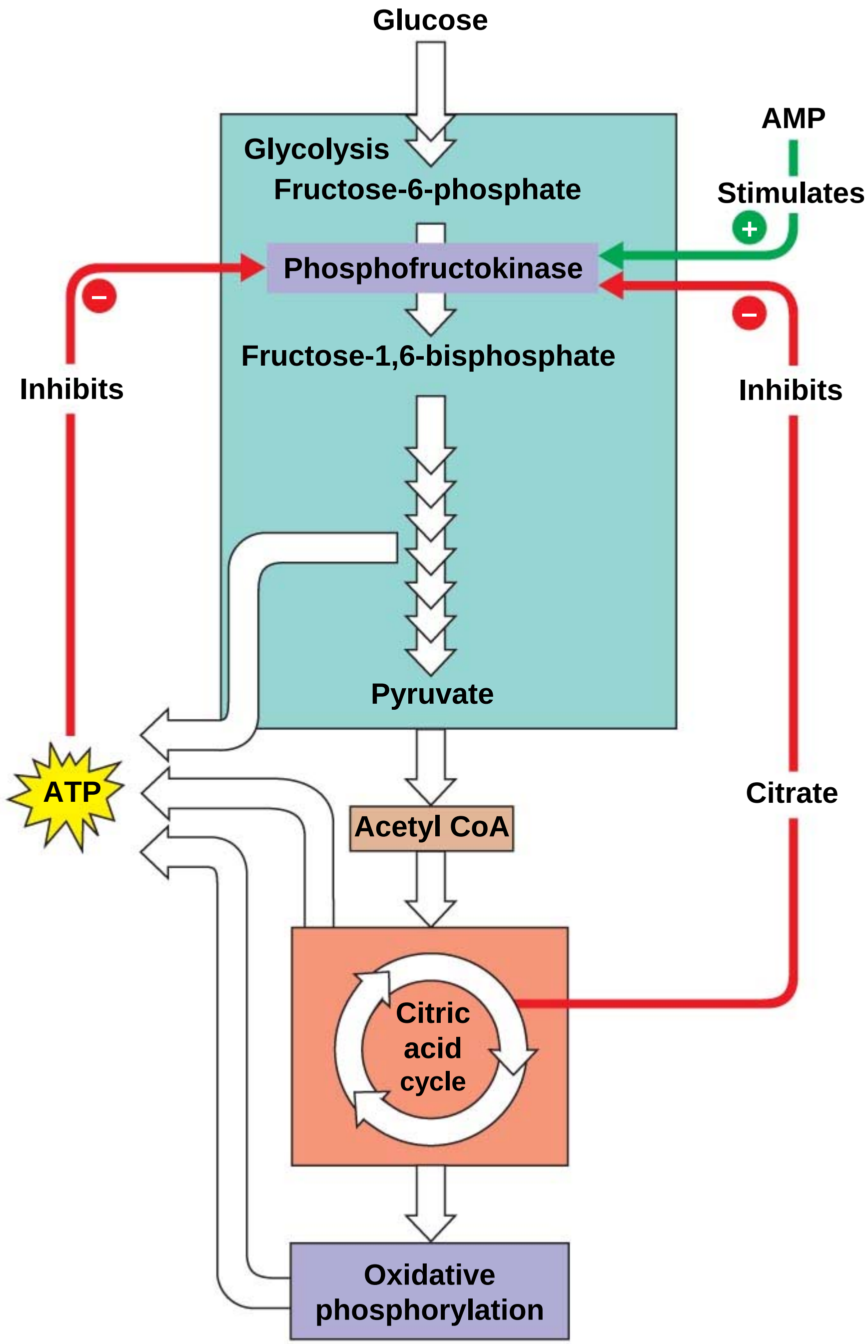
Biosynthesis (Anabolic Pathways)

- 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

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

Fig. 9-21


Glucose
Glycolysis
Fructose-6-phosphate
AMP
Stimulates
+
Phosphofructokinase
–
–
Fructose-1,6-bisphosphate
Inhibits
Inhibits
Pyruvate
ATP
Citrate
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

You should now be able to:

1. Explain in general terms how redox reactions are involved in energy exchanges
2. Name the three stages of cellular respiration; for each, state the region of the eukaryotic cell where it occurs and the products that result
3. In general terms, explain the role of the electron transport chain in cellular respiration

4. Explain where and how the respiratory electron transport chain creates a proton gradient
5. Distinguish between fermentation and anaerobic respiration
6. Distinguish between obligate and facultative anaerobes