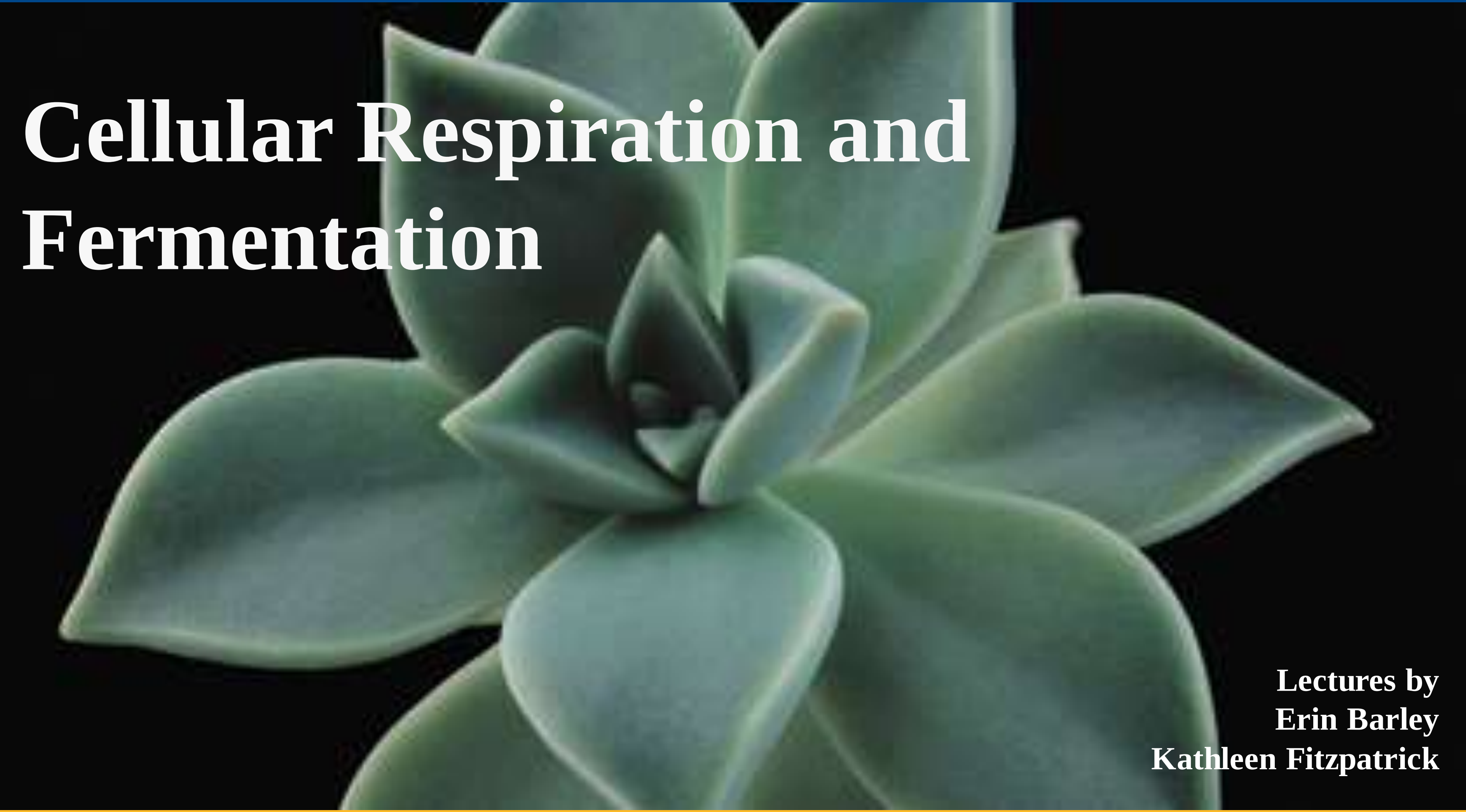
LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 9



Cellular Respiration and Fermentation

Lectures by
Erin Barley
Kathleen Fitzpatrick

Introduction

Energy is the capacity to cause change

Energy types

1-kinetic energy (الطاقة الحركية)

Such as heat energy (thermal energy)

2- potential energy(طاقة الوضع)

The energy that is caused by the location or the structure of the molocule

---

Chemical energy

Any energy that is realesd by a chemical reaction it is a type of PE

Metabolism

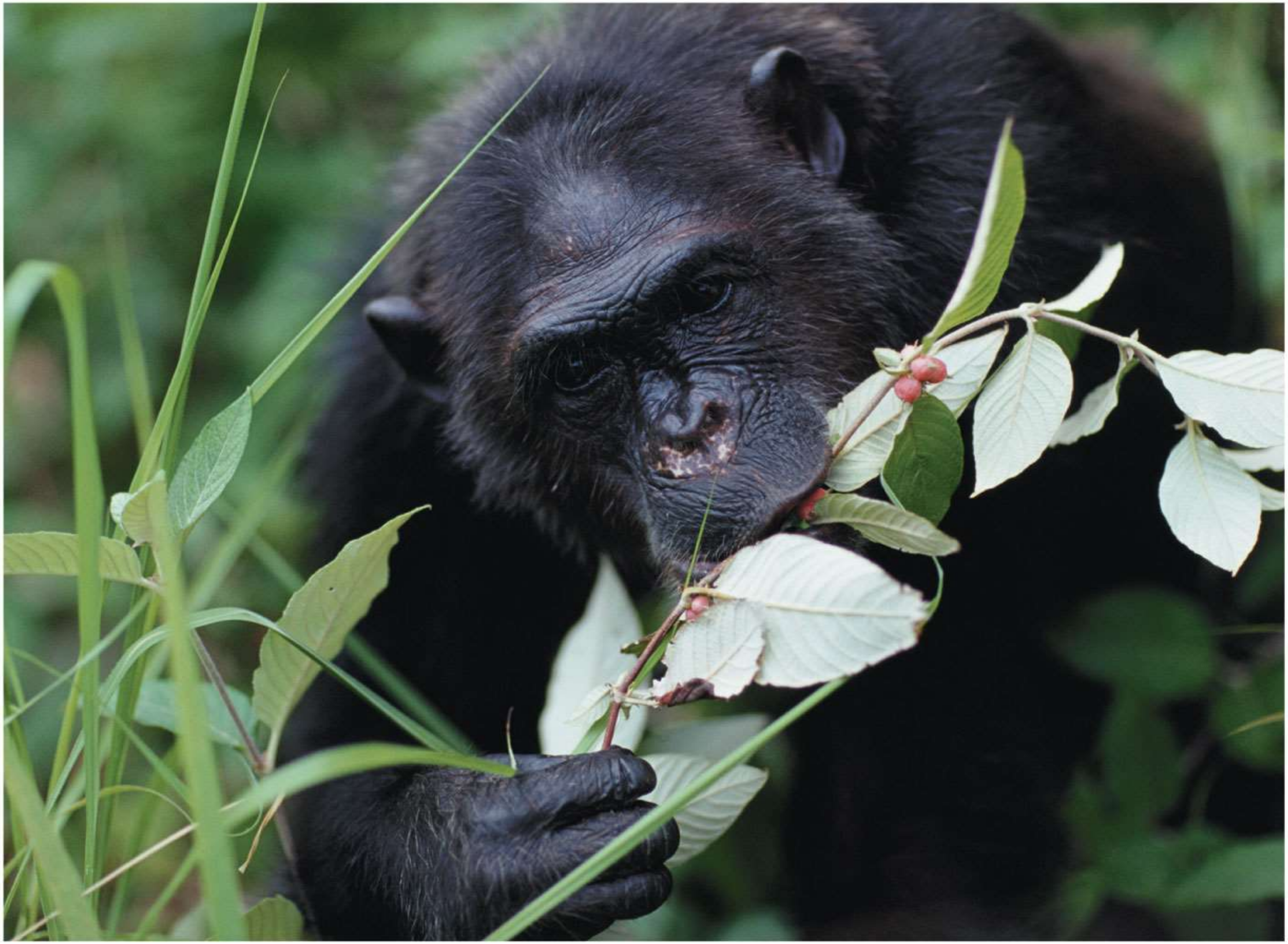
1-Anabolic reactions (البناء):needs energy (endergonic)

2-Catabolic reactions (الهدم):produce energy (exergonic)

Overview: Life Is Work

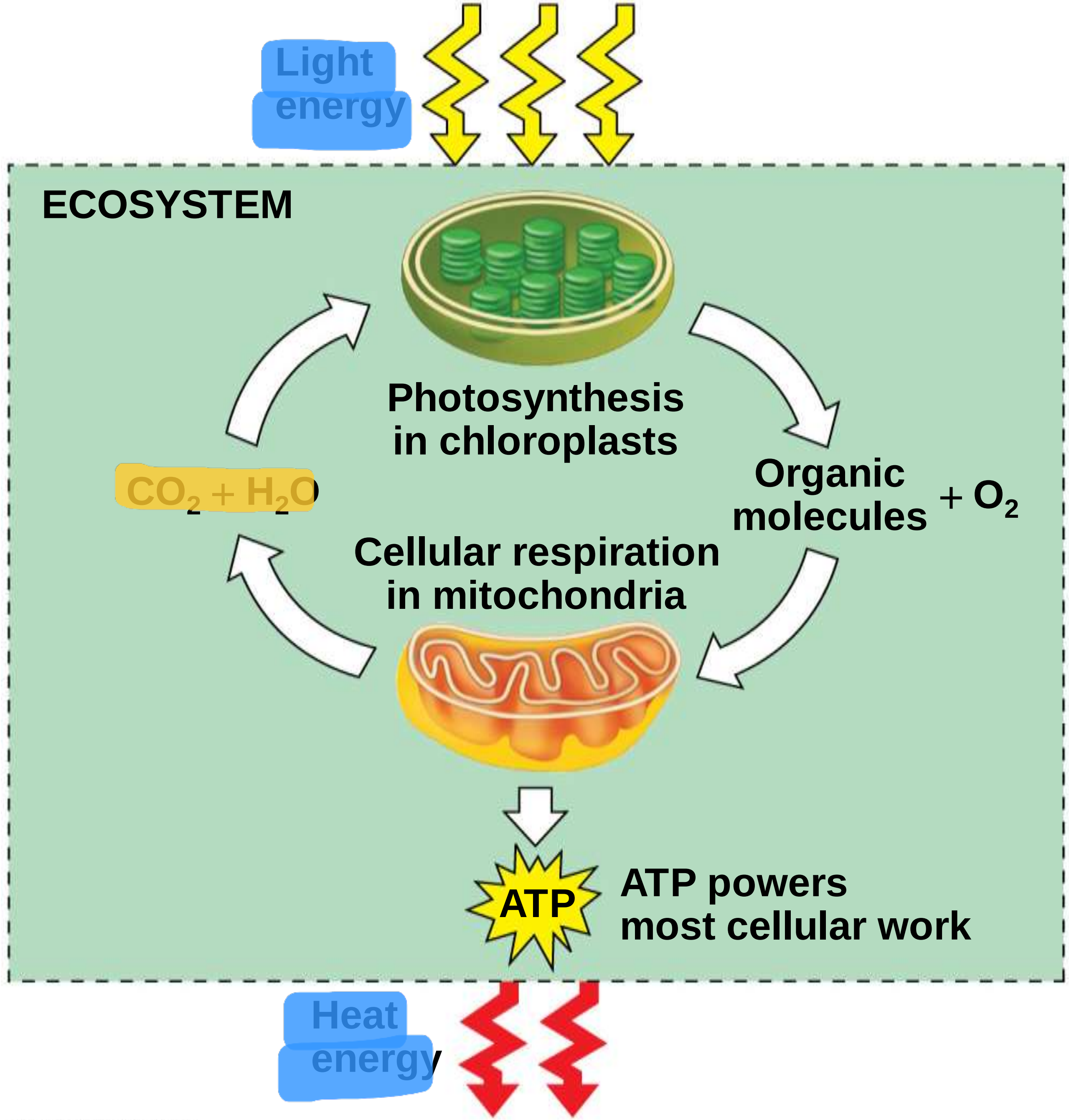
- Living cells require energy from outside sources
- Some animals, such as the chimpanzee, obtain energy by eating plants, and some animals feed on other organisms that eat plants

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
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

تأكسد / اختزال

- 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

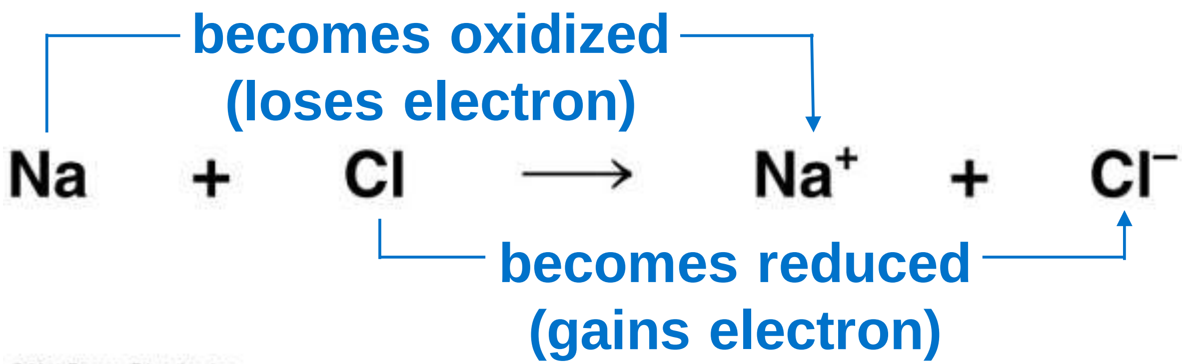
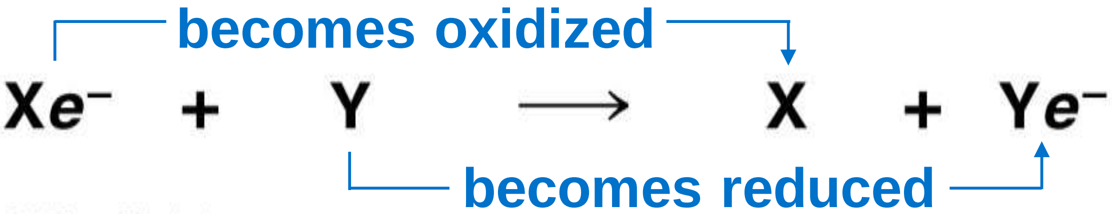


Figure 9.UN02



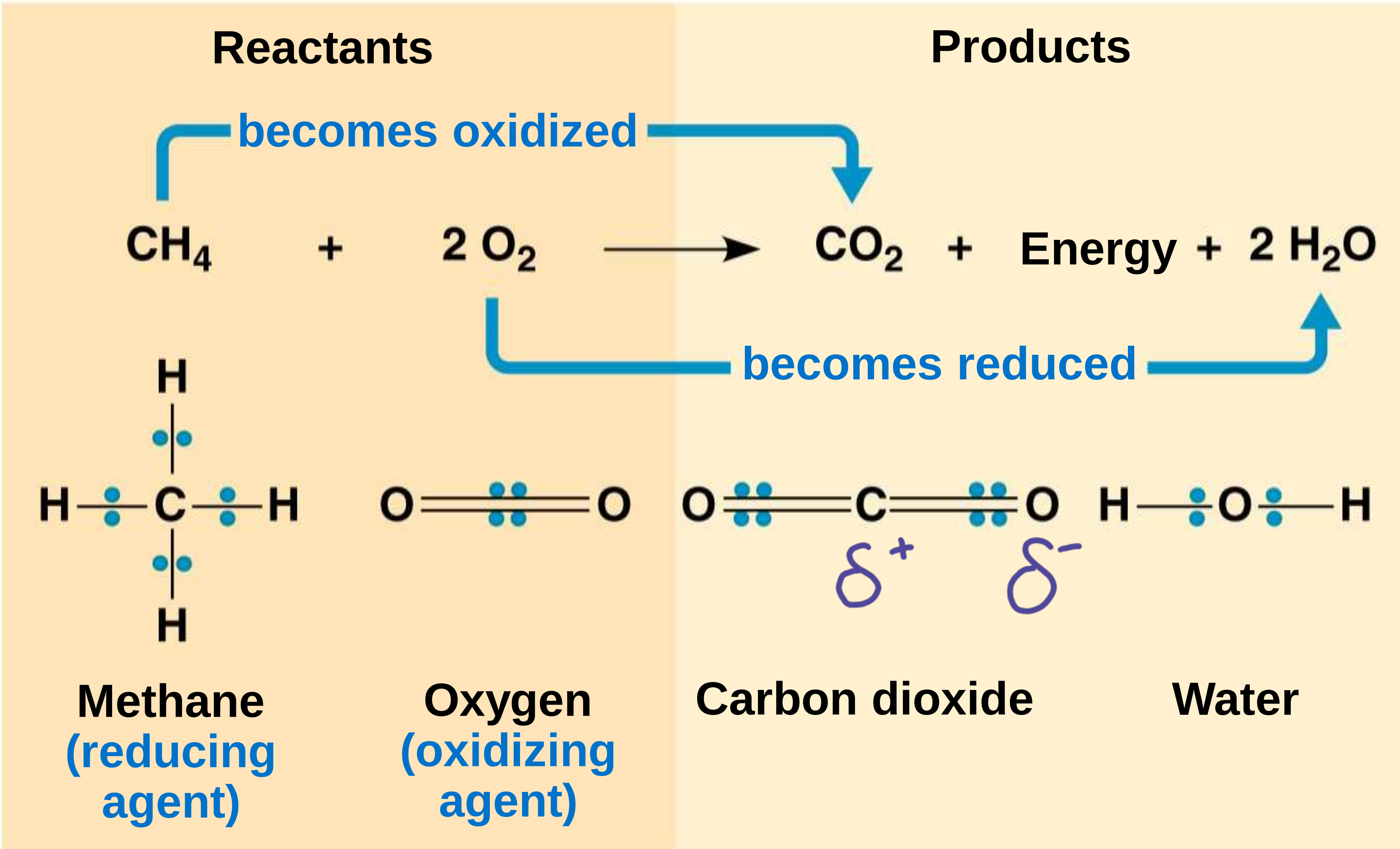
الي يتأكسد

- The electron donor is called the reducing agent

الي يختزل

- 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
H
H C H
H
O O
O C O
δ+ δ−
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

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
- As an electron acceptor, NAD⁺ functions as an oxidizing agent during cellular respiration

reduced to NADH

- Each NADH (the reduced form of NAD⁺) represents stored energy that is tapped to synthesize ATP

تستخدم

Figure 9.4

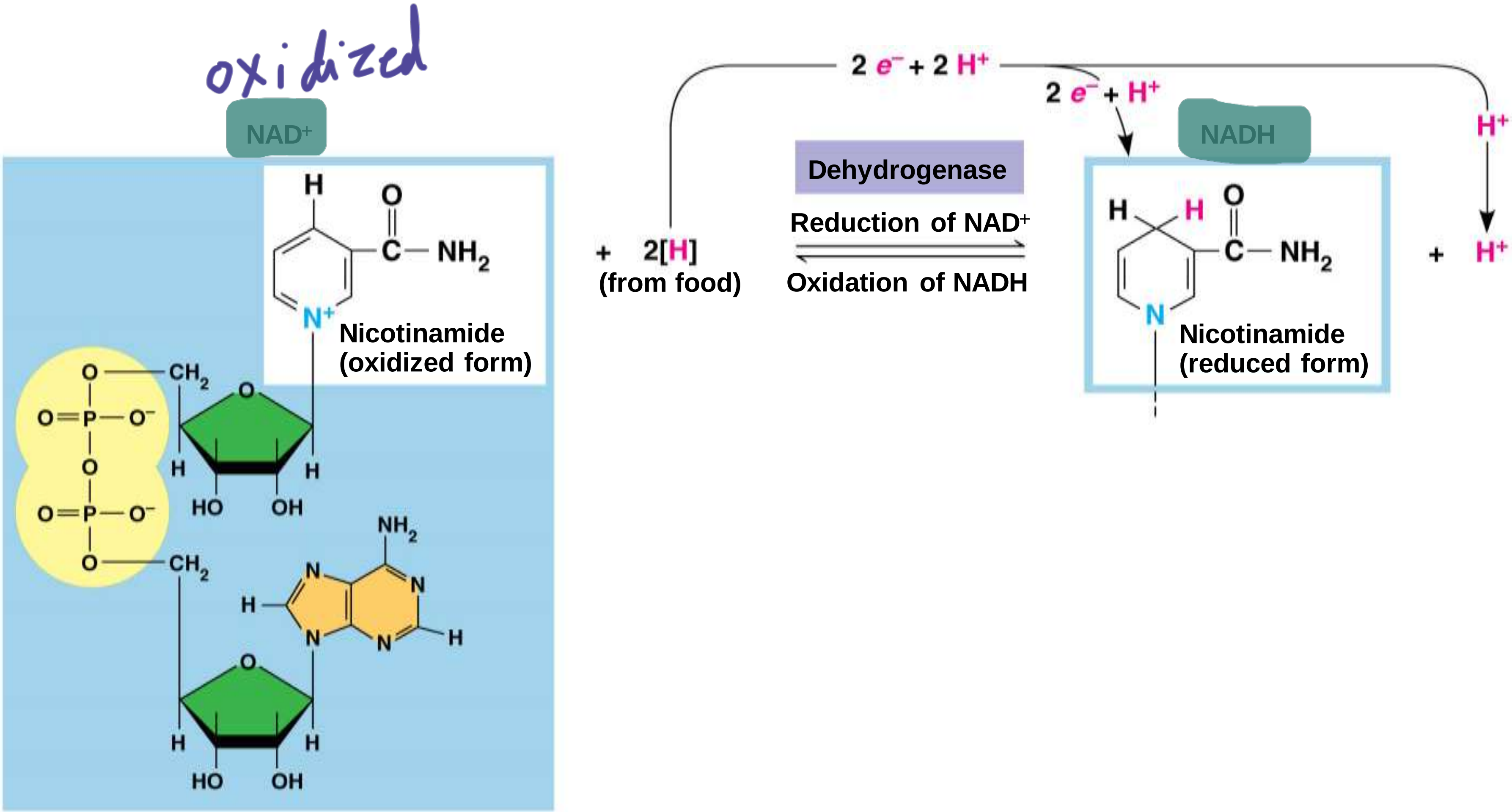
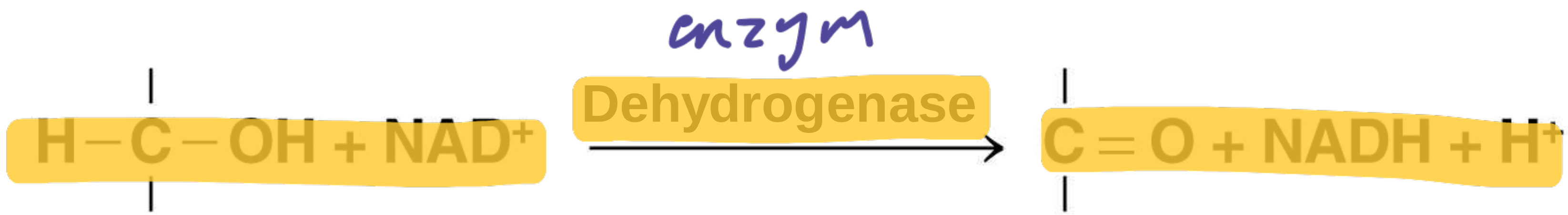
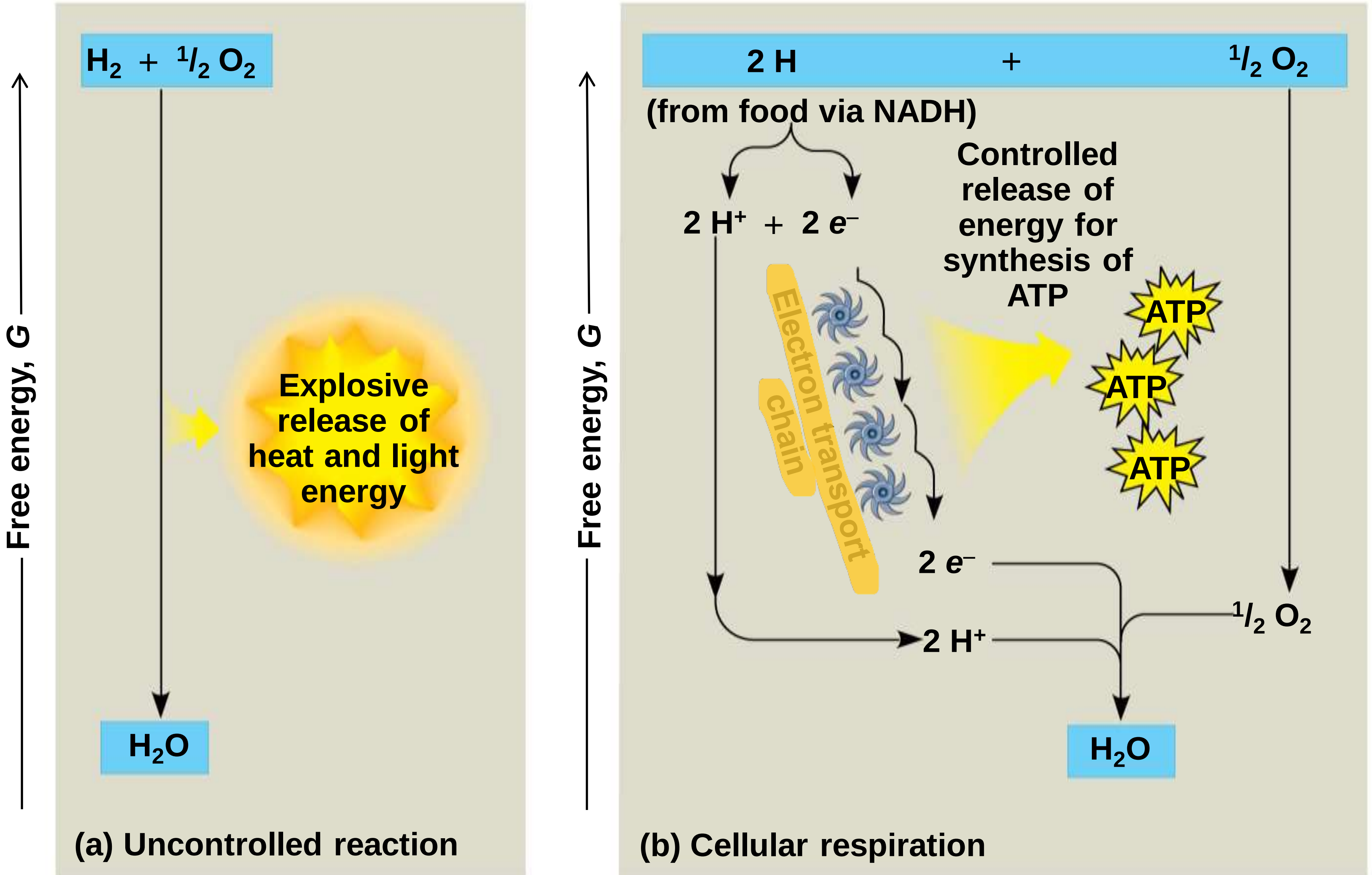

oxidized
NAD+
Nicotinamide (oxidized form)
+ 2[H] (from food)
2 e− + 2 H+
2 e− + H+
Dehydrogenase
Reduction of NAD+
Oxidation of NADH
NADH
Nicotinamide (reduced form)
+ H+
H+

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



H_2 + $^1/_2$ O_2
Free energy, G
Explosive release of heat and light energy
H_2O
(a) Uncontrolled reaction
2 H
+
$^1/_2$ O_2
(from food via NADH)
$2 H^+$ + $2 e^-$
Controlled release of energy for synthesis of ATP
ATP
ATP
ATP
Electron transport chain
$2 e^-$
$^1/_2$ O_2
$2 H^+$
H_2O
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)

6C

3C

krips cycle

90% of ATP

Figure 9.UN05

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

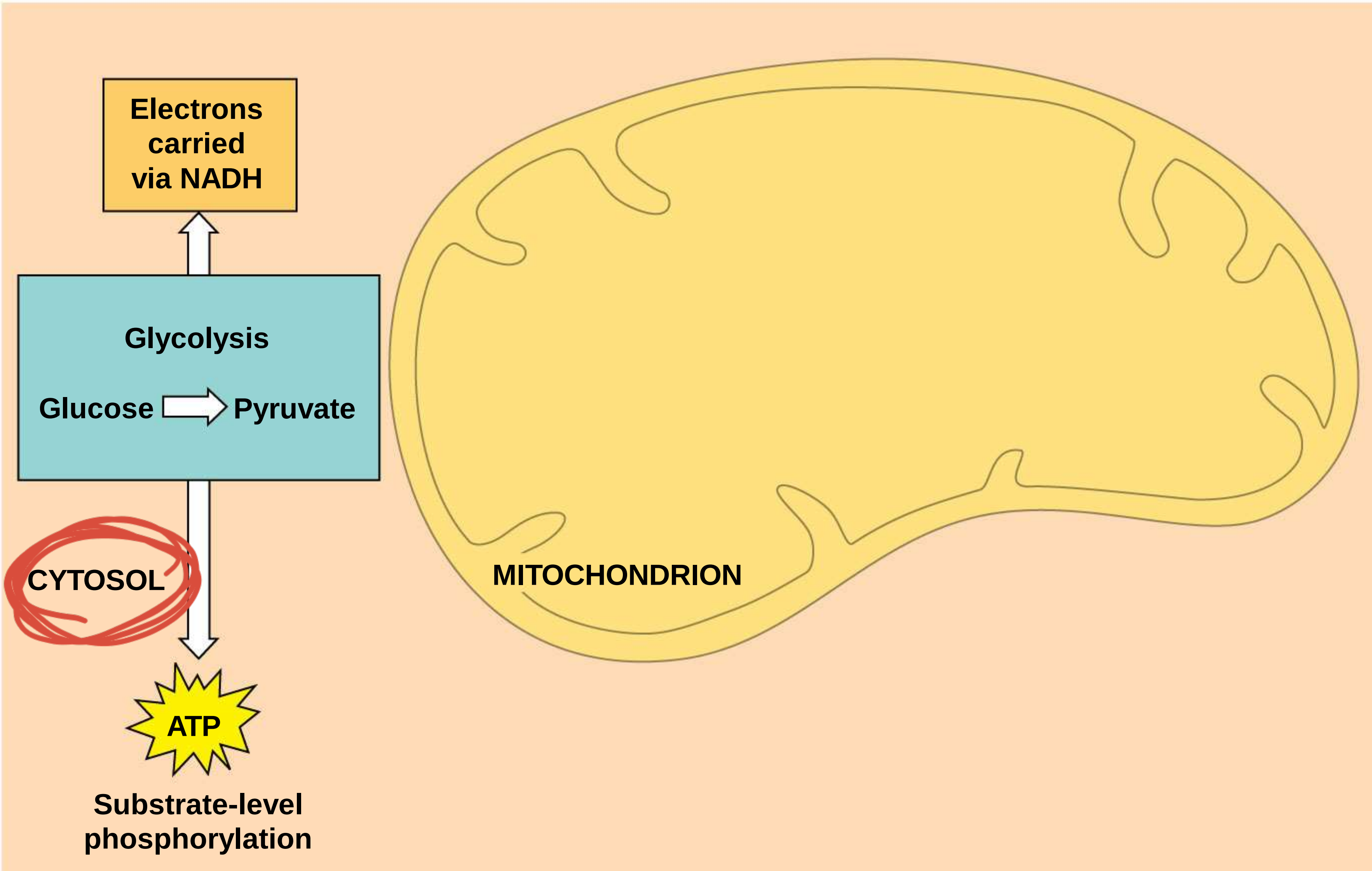
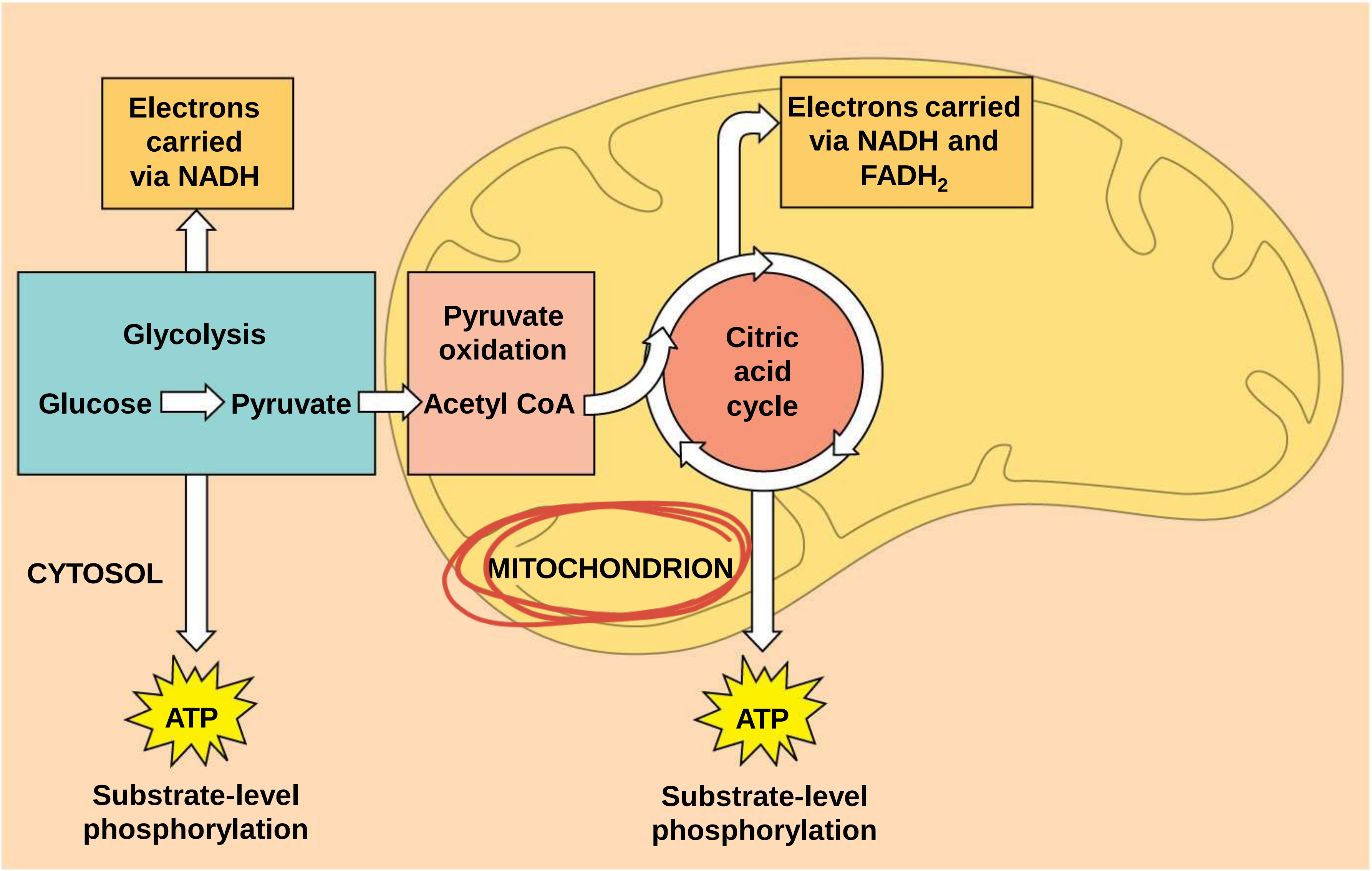
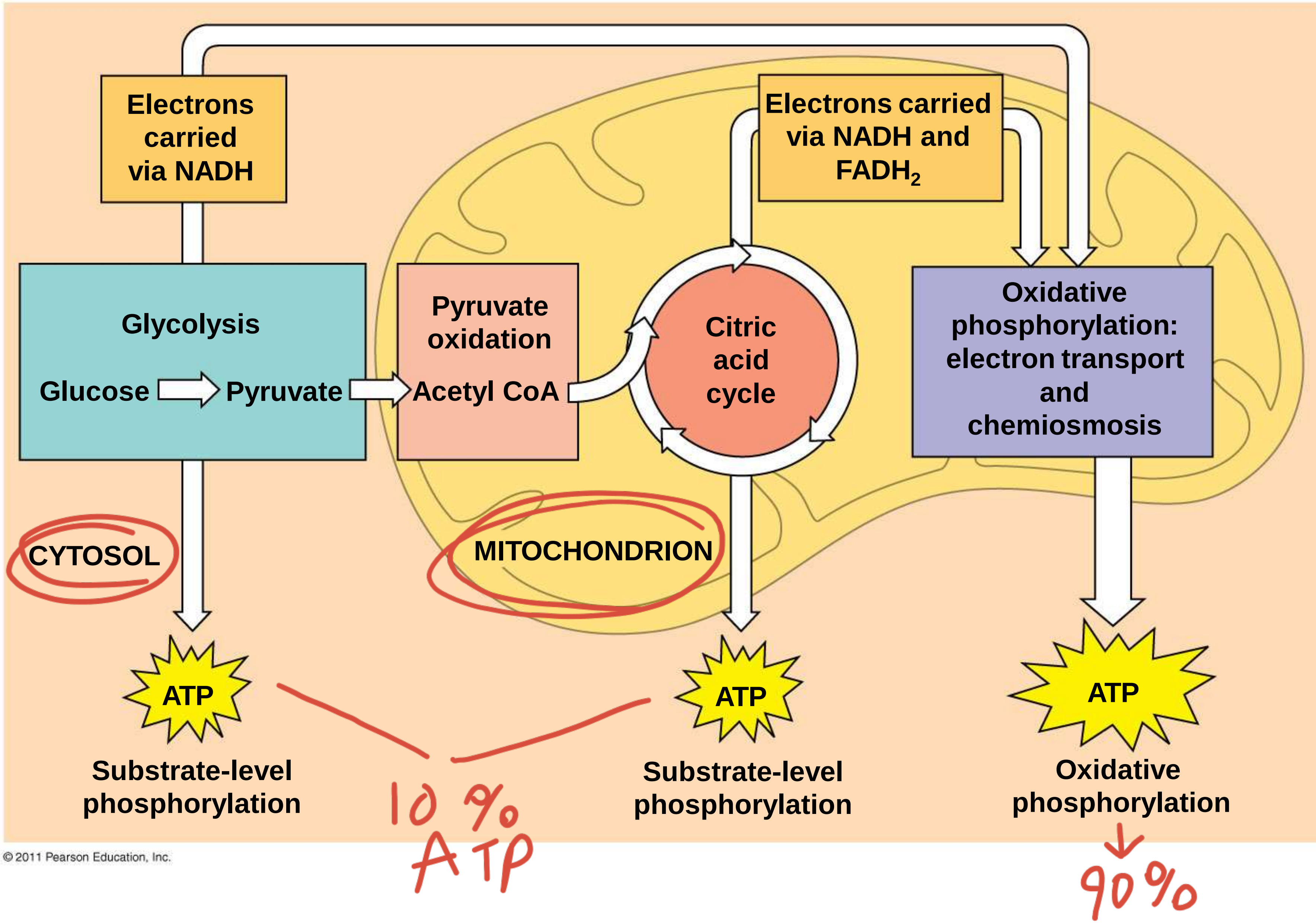

Electrons carried via NADH
Glycolysis
Glucose
Pyruvate
CYTOSOL
ATP
Substrate-level phosphorylation
MITOCHONDRION

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

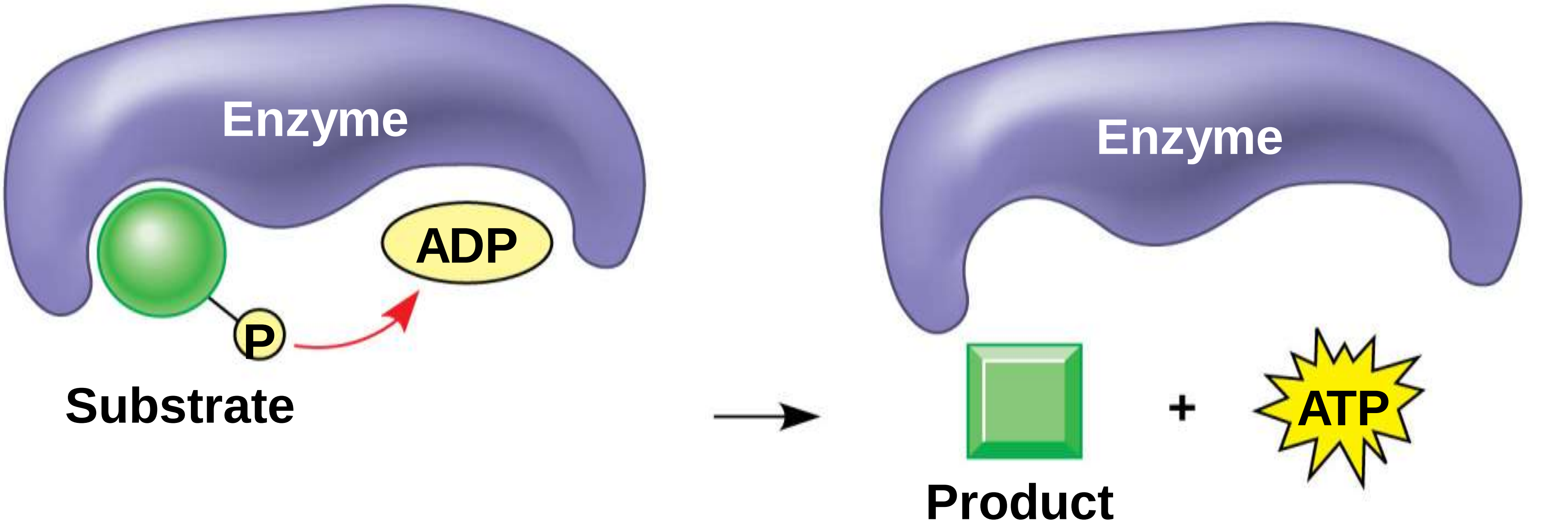
Figure 9.6-3


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
10 % ATP
90%

- 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**
- 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

Figure 9.8

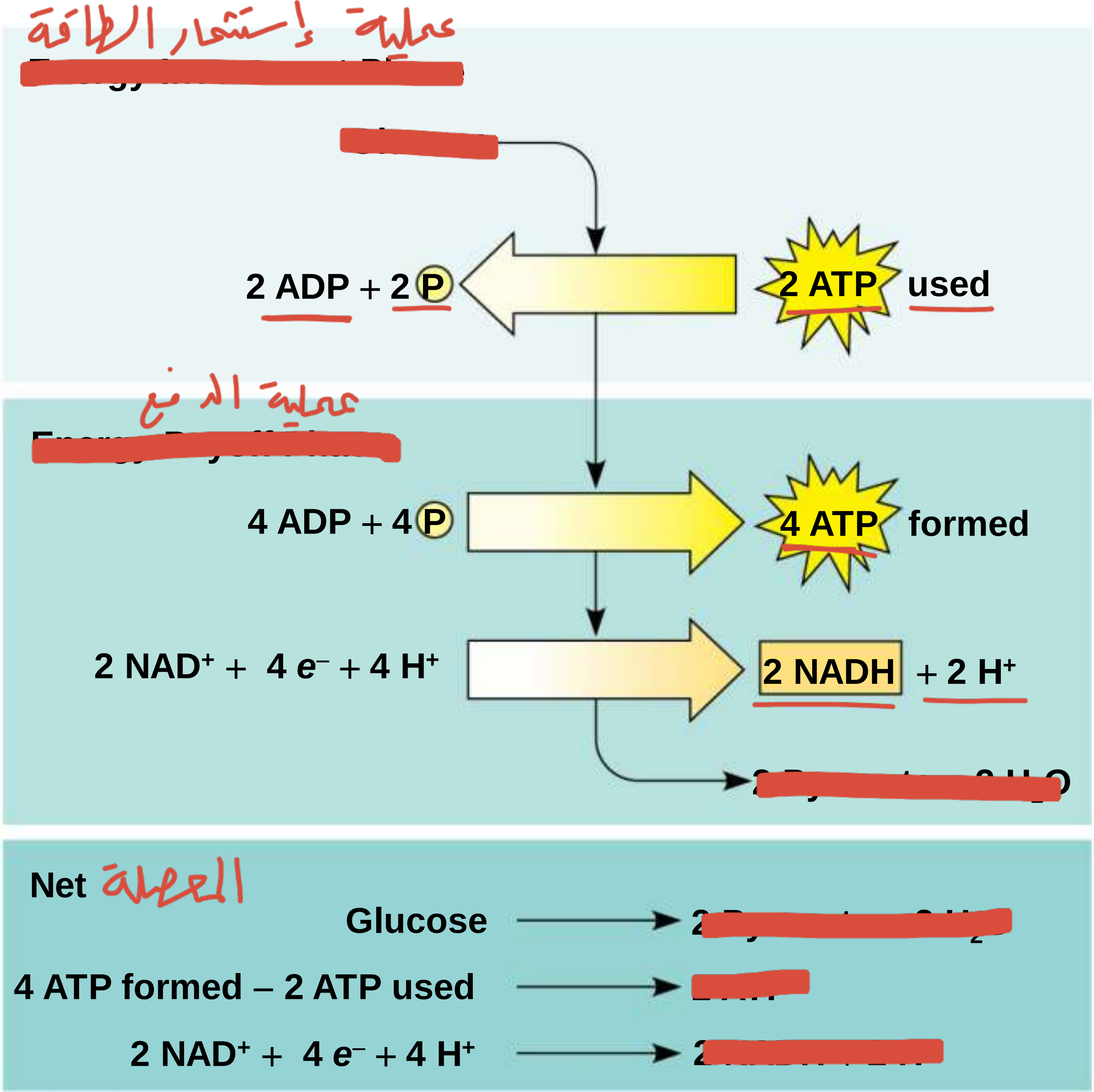

عملية إستثمار الطاقة
[redacted]
[redacted]
2 ADP + 2 P
2 ATP used
عملية الدفع
[redacted]
4 ADP + 4 P
4 ATP formed
2 NAD+ + 4 e− + 4 H+
2 NADH + 2 H+
[redacted]
Net المحصلة
Glucose
[redacted]
4 ATP formed – 2 ATP used
[redacted]
2 NAD+ + 4 e− + 4 H+
[redacted]

Figure 9.9a

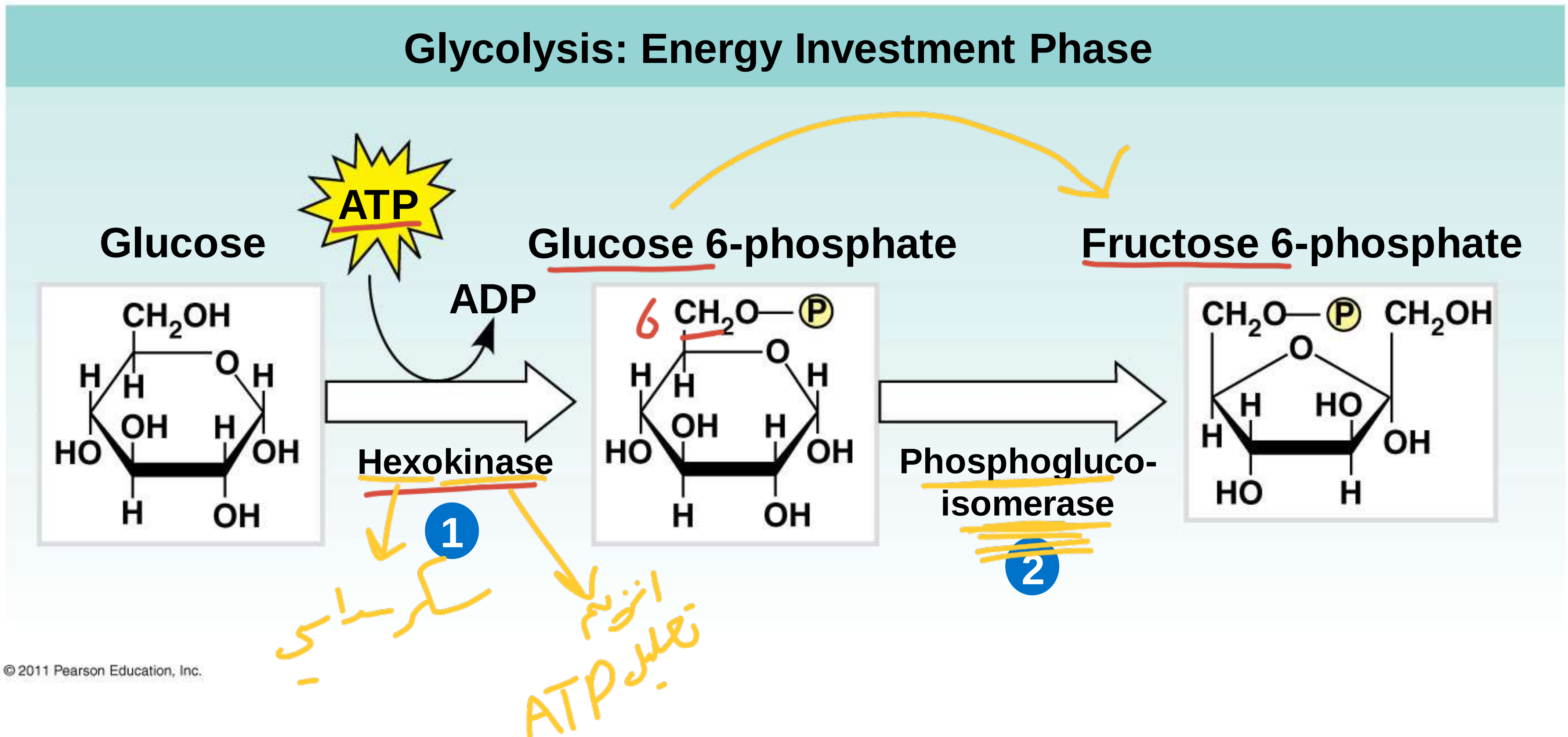

Glycolysis: Energy Investment Phase
Glucose
ATP
ADP
Glucose 6-phosphate
Fructose 6-phosphate
Hexokinase
1
Phosphogluco-
isomerase
2

Figure 9.9b

Glycolysis: Energy Investment Phase

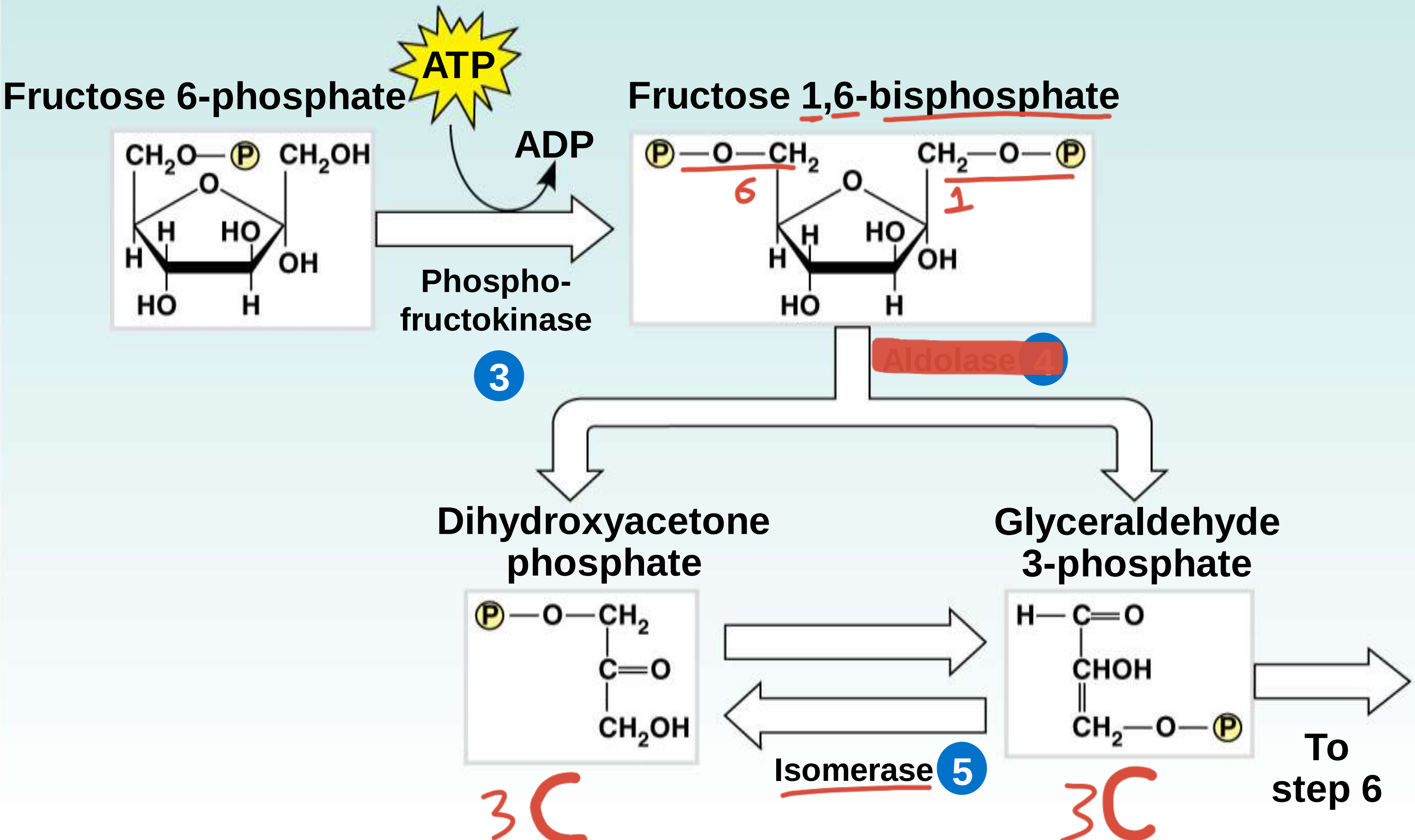


Figure 9.9c

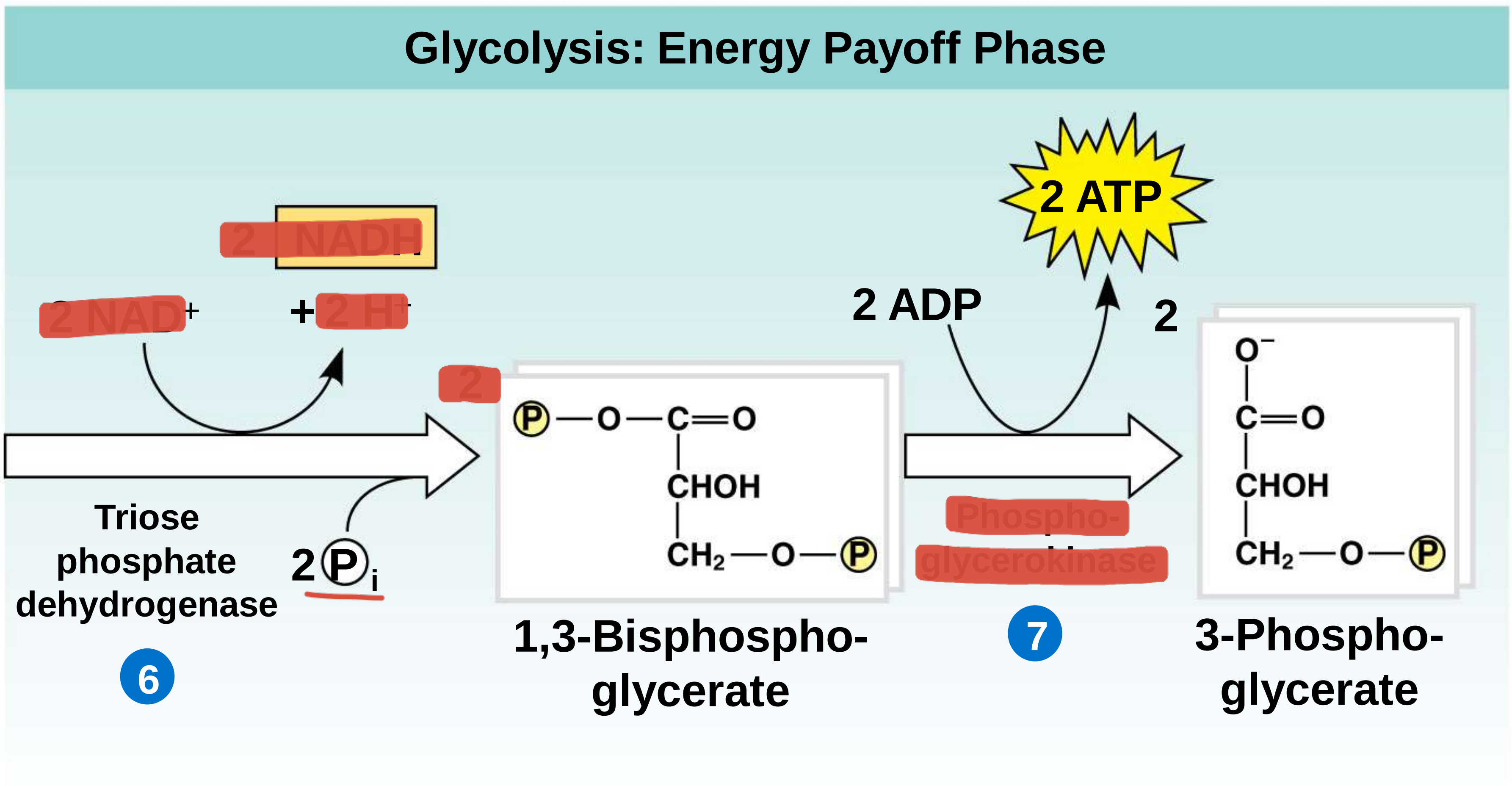
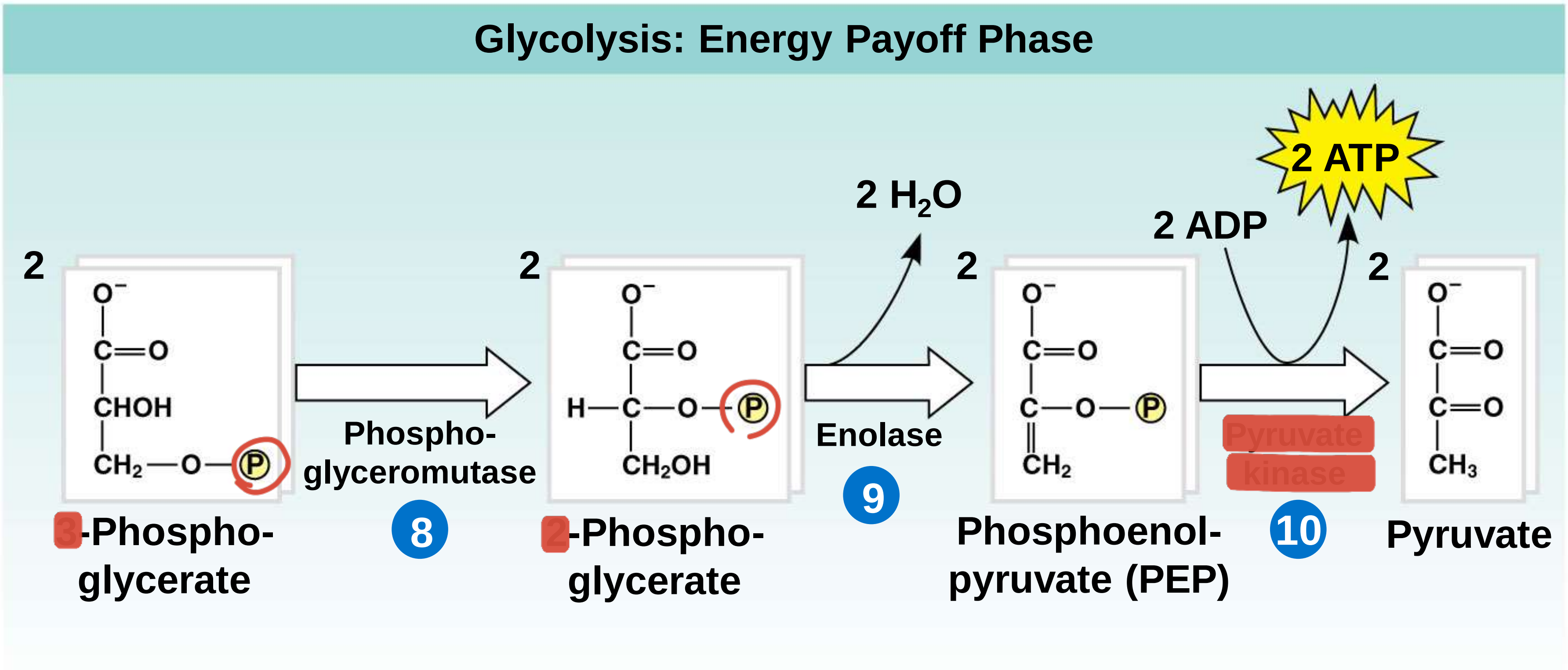

Glycolysis: Energy Payoff Phase
2 ATP
2 ADP
2
+
Triose
phosphate
dehydrogenase
2 Pi
6
CHOH
CH2—O—P
P—O—C=O
1,3-Bisphospho-
glycerate
7
O−
C=O
3-Phospho-
glycerate

Figure 9.9d



Glycolysis: Energy Payoff Phase
2
3-Phospho-
glycerate
Phospho-
glyceromutase
8
2
2-Phospho-
glycerate
2 H_2O
Enolase
9
2
Phosphoenol-
pyruvate (PEP)
2 ADP
2 ATP
Pyruvate
kinase
10
2
Pyruvate

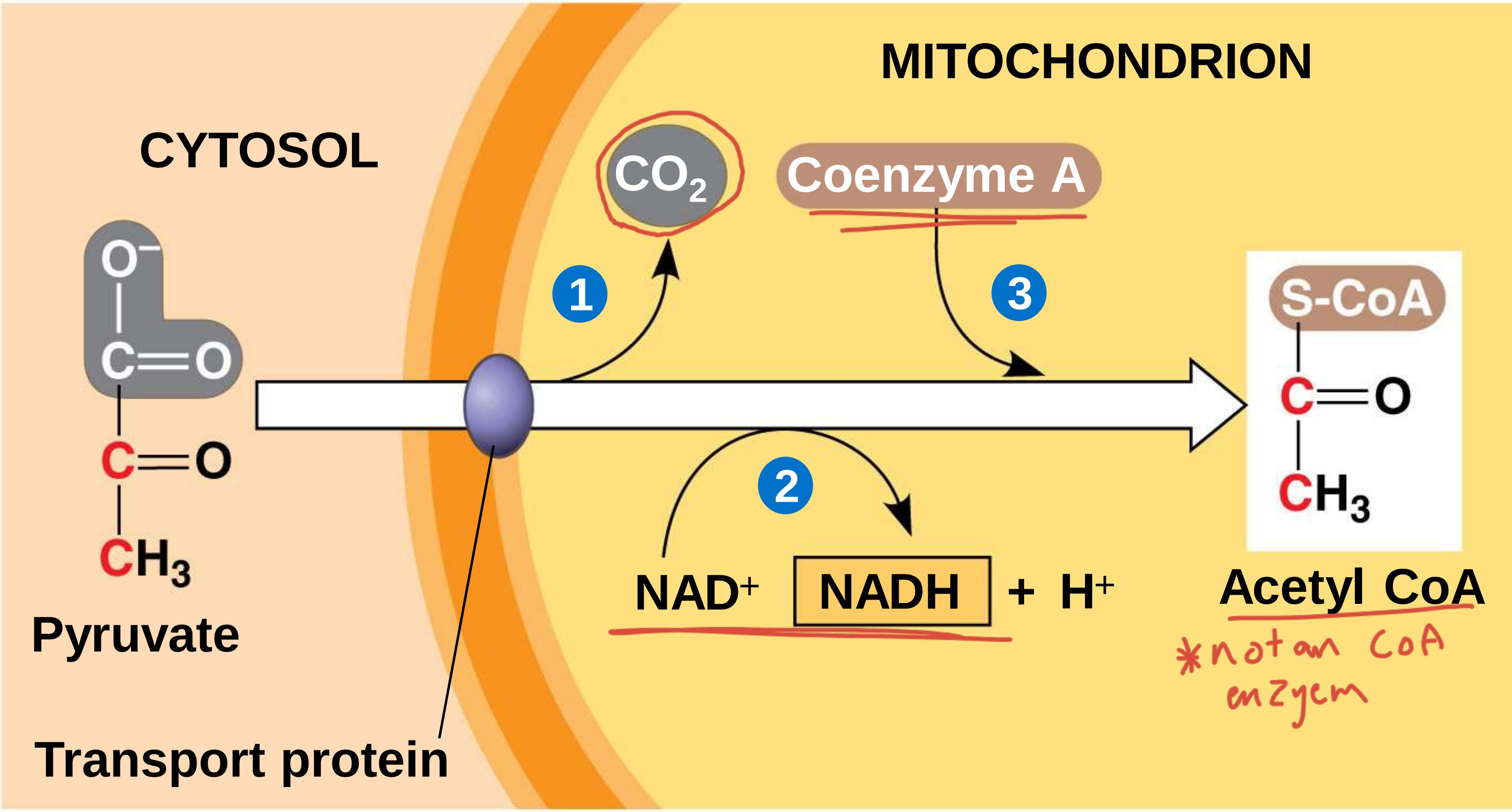
Concept 9.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

- 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



the NET for one Pyruvet
- Co_2 - Acetyl CoA
- NADH

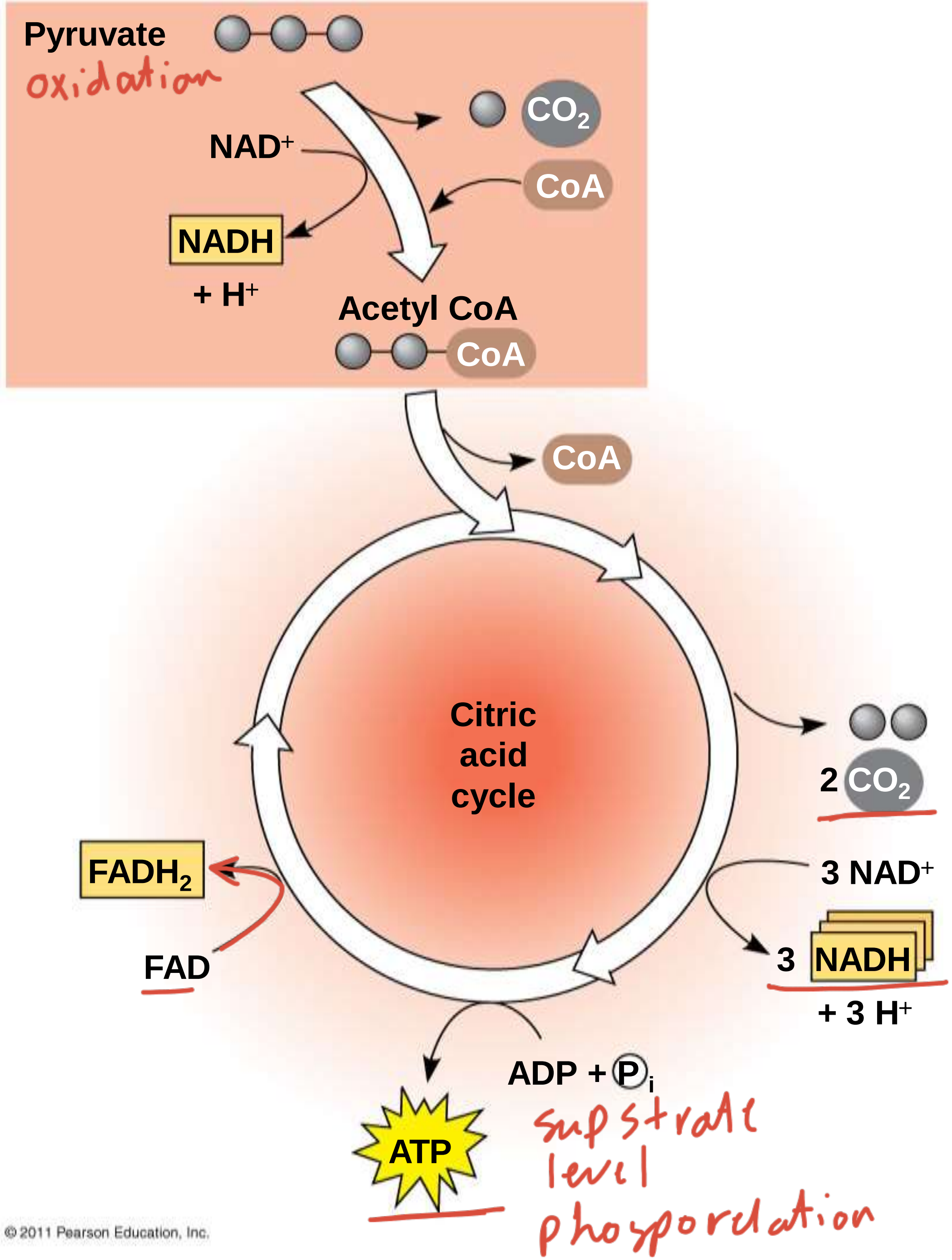
x2 → one Glucose

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 $2CO_2$

there is tow turns per Glucose

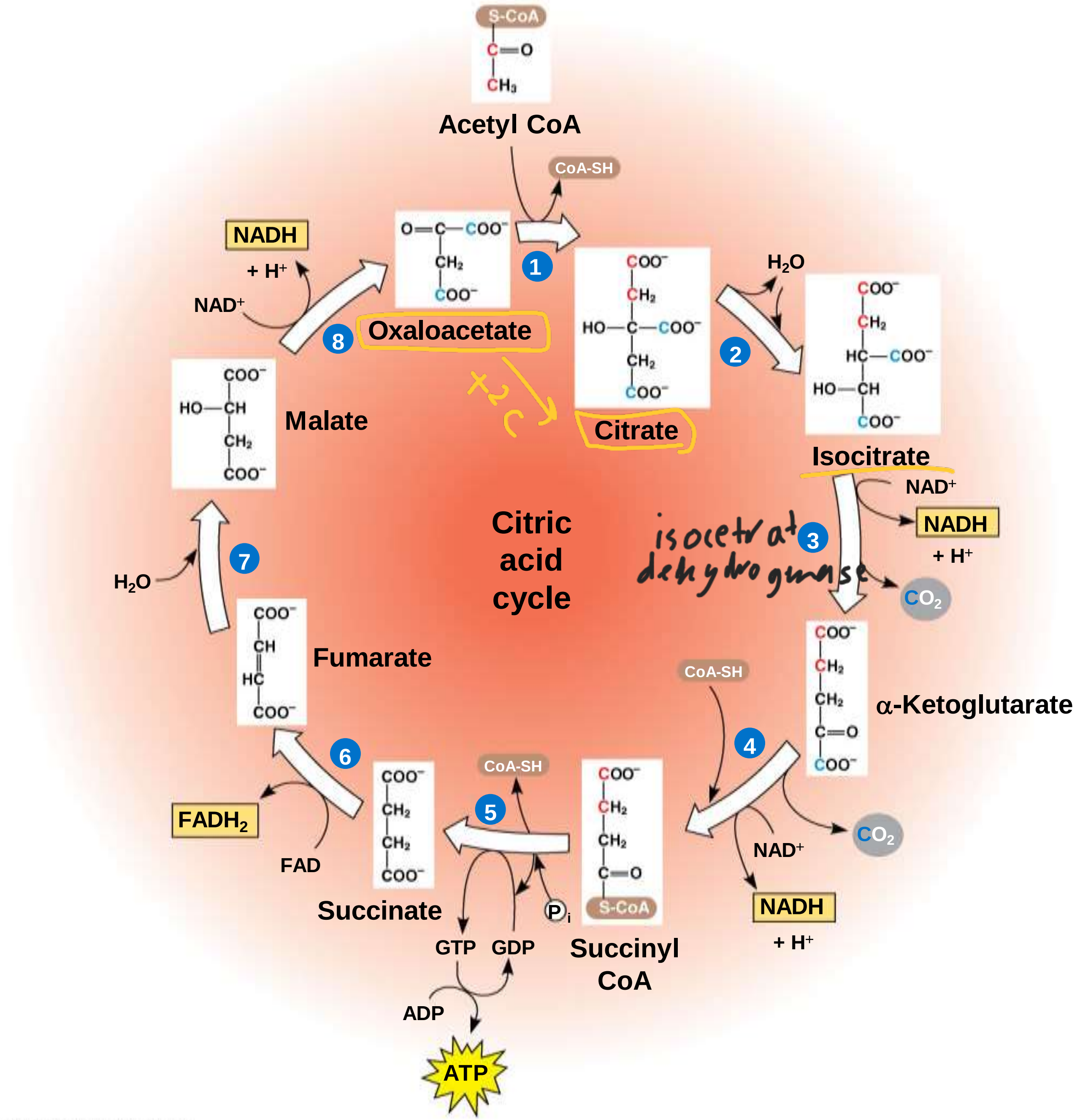
Figure 9.11



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

- 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 9.12-8



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

Figure 9.12a

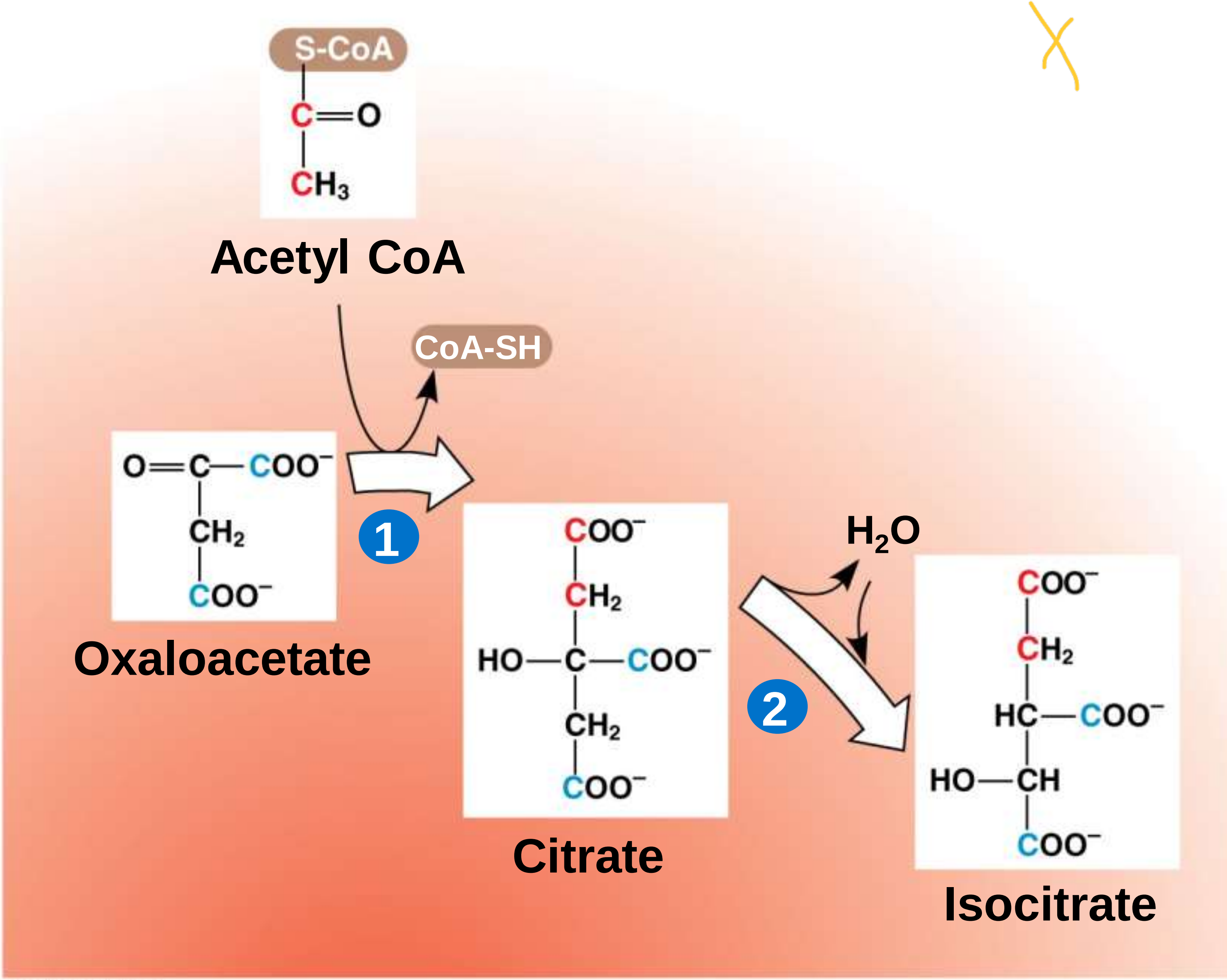
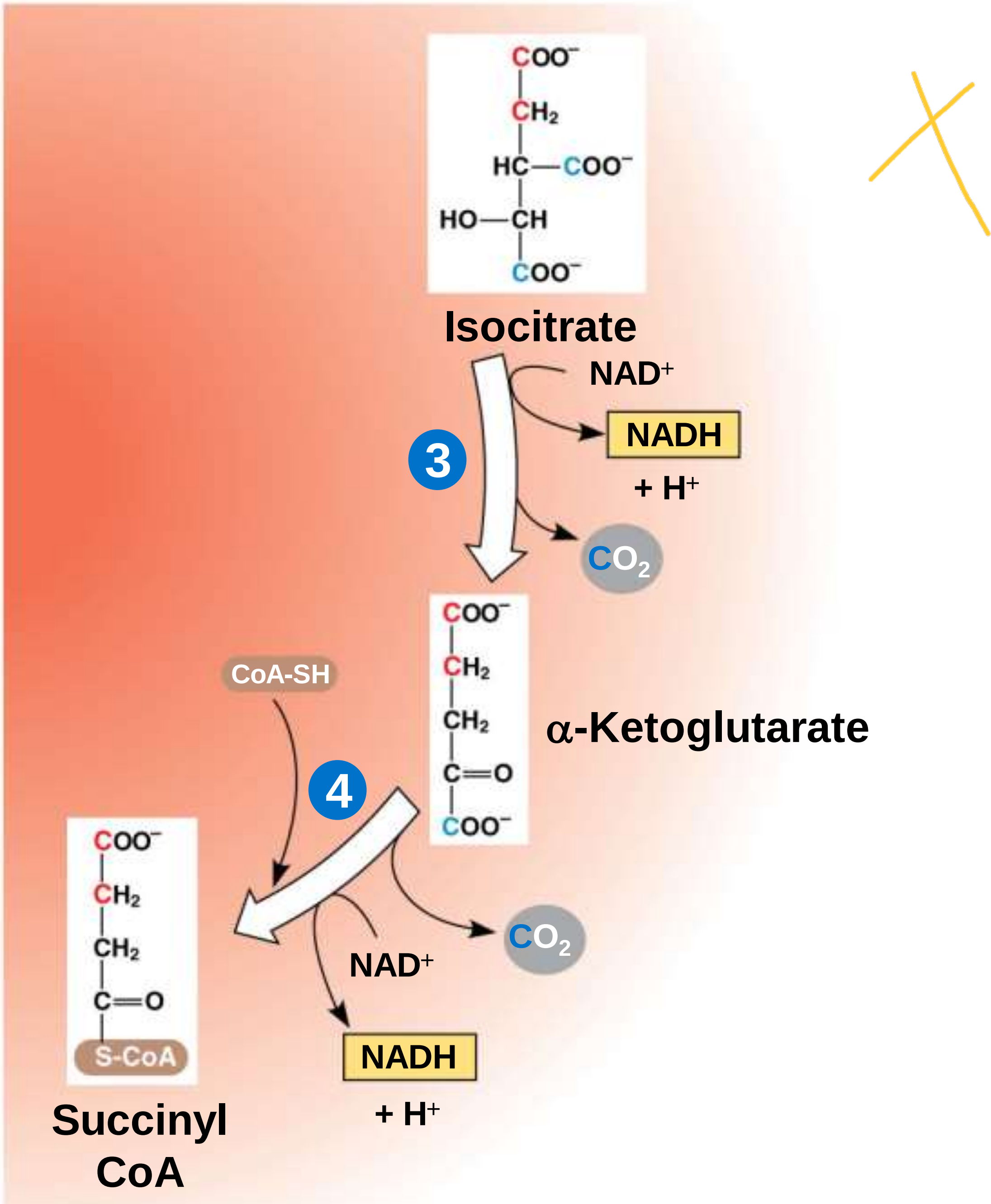
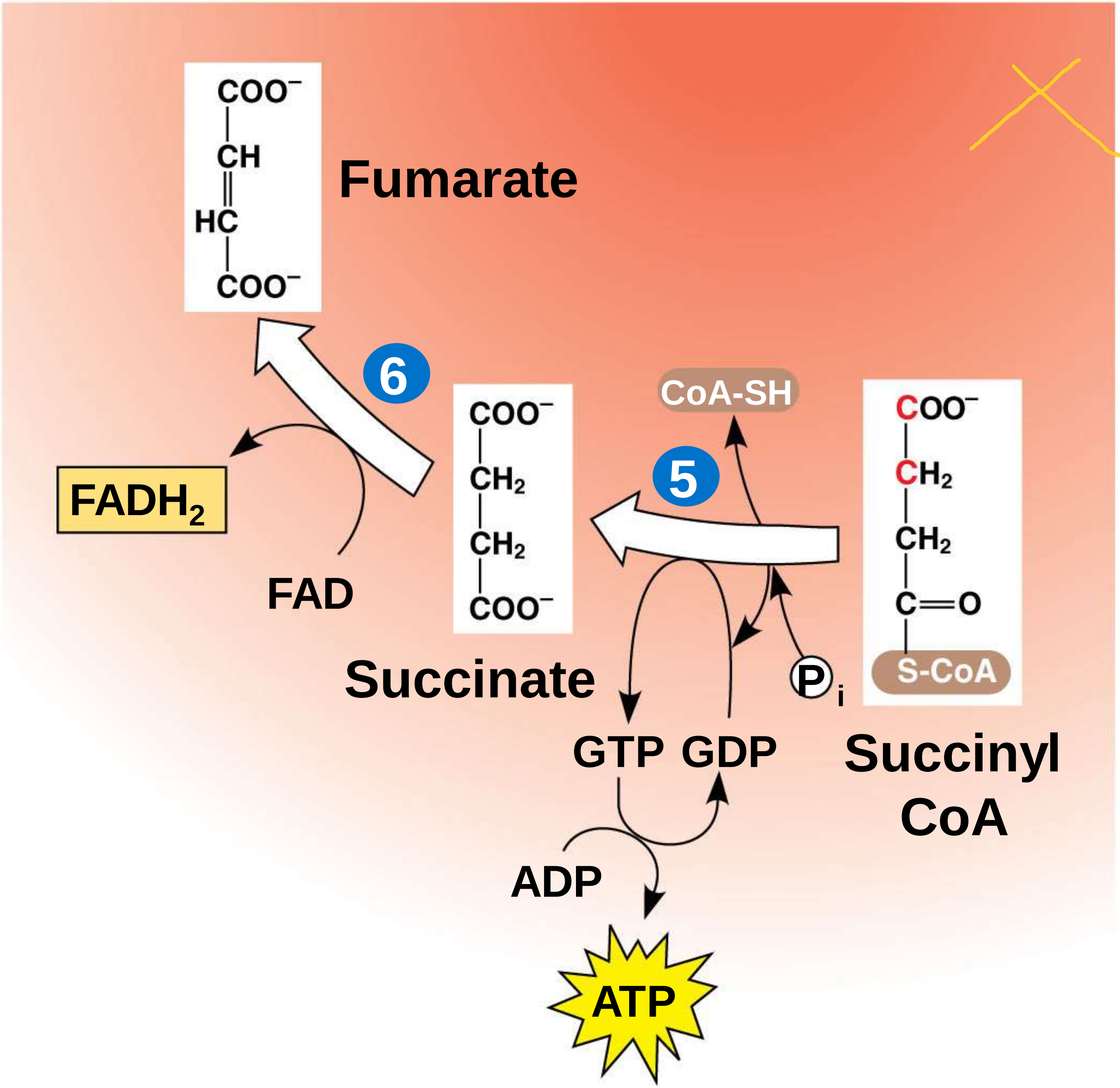

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate

Figure 9.12b



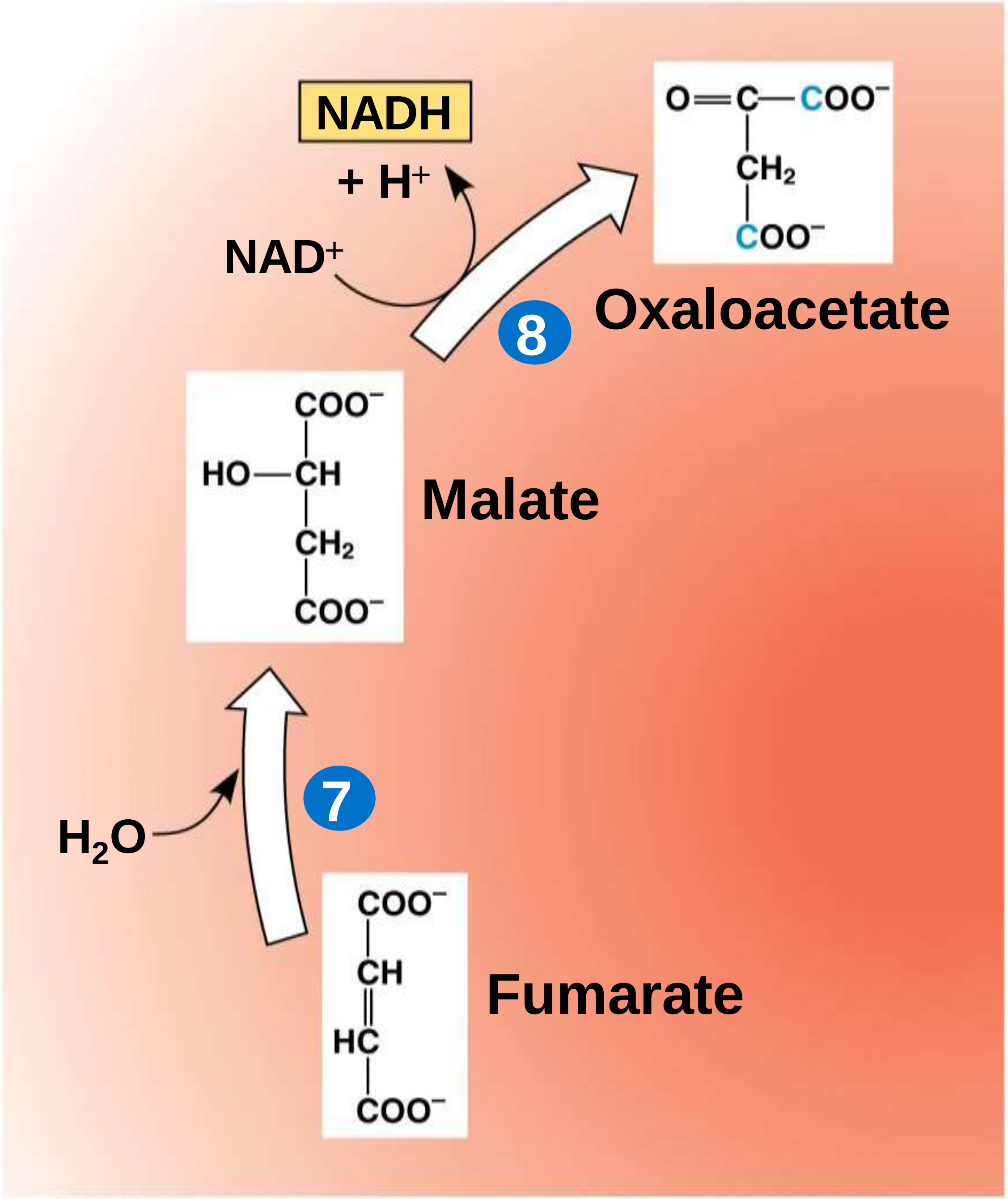
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
COO⁻
CH2
CH2
C=O
COO⁻
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
COO⁻
CH2
CH2
C=O
S-CoA
Succinyl CoA

Figure 9.12c



Fumarate
6
FADH2
FAD
Succinate
CoA-SH
5
GTP
GDP
ADP
ATP
Pi
Succinyl CoA
S-CoA

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

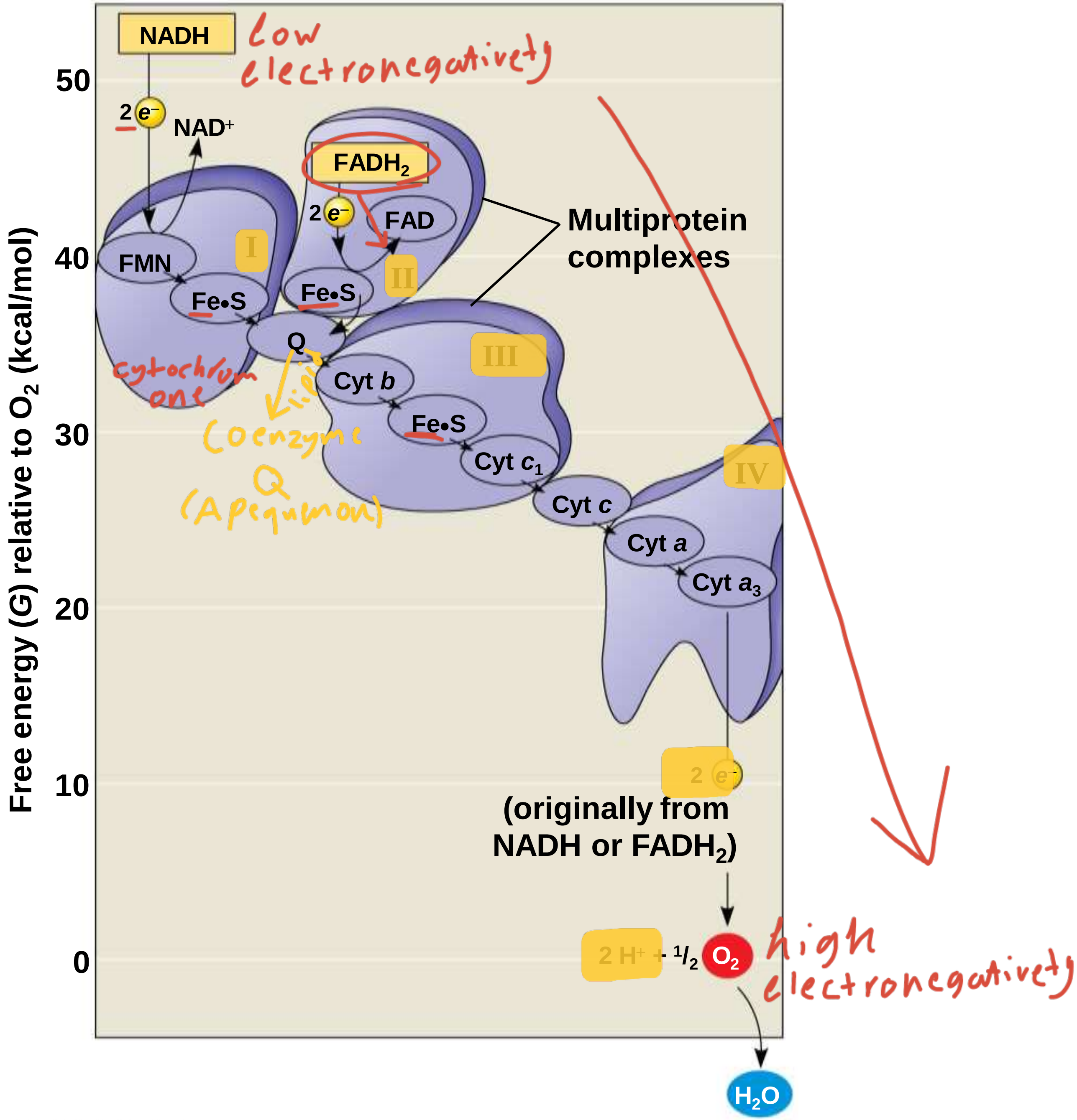
Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- Following glycolysis and the citric acid cycle, NADH and $FADH_2$ account for most of the energy extracted from food
  $\rightarrow$ $FADH_2$ & NADH
- 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
low electronegativity
50
2 e⁻
NAD+
FADH2
2 e⁻
FAD
Multiprotein complexes
40
FMN
I
Fe•S
Fe•S
II
Q
III
cytochrom one
Cyt b
30
Fe•S
Coenzyme Q (Apequmon)
Cyt c1
IV
Cyt c
Cyt a
Cyt a3
20
Free energy (G) relative to O2 (kcal/mol)
10
2 e⁻
(originally from NADH or FADH2)
0
2 H+ + 1/2 O2
high electronegativity
H2O

- 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

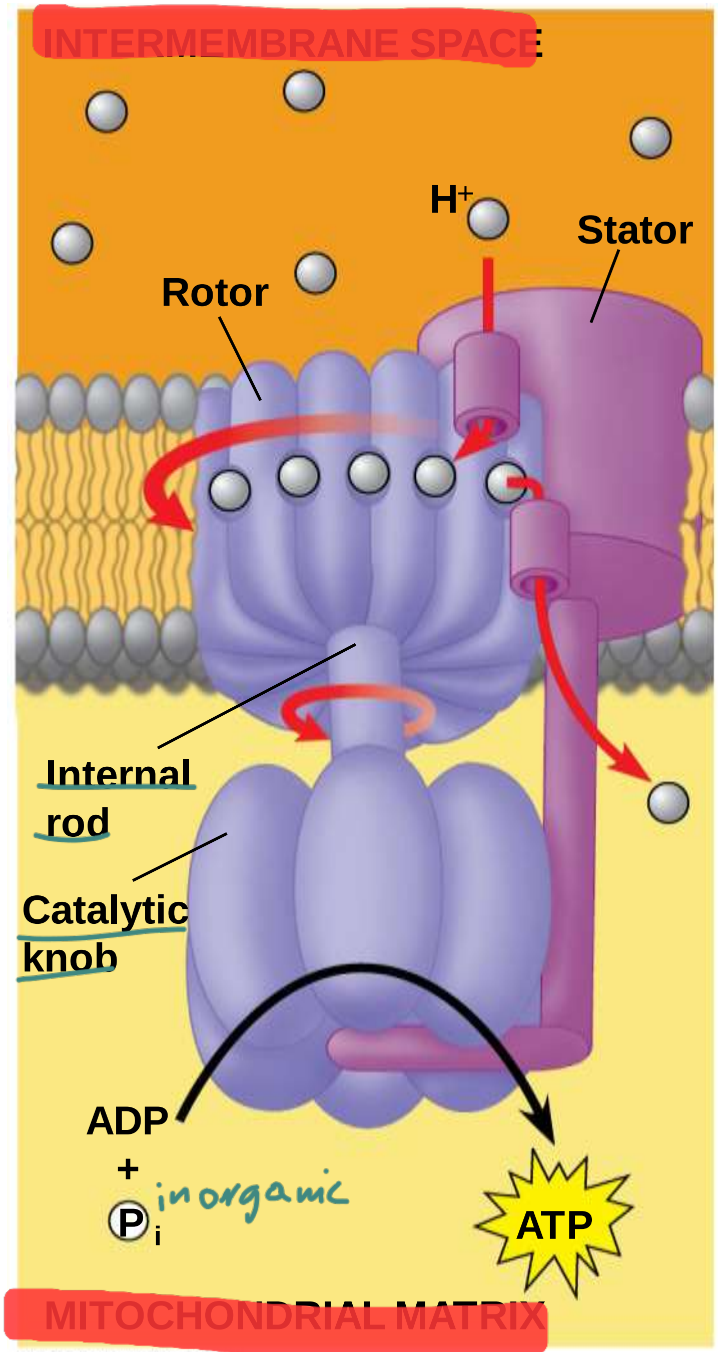
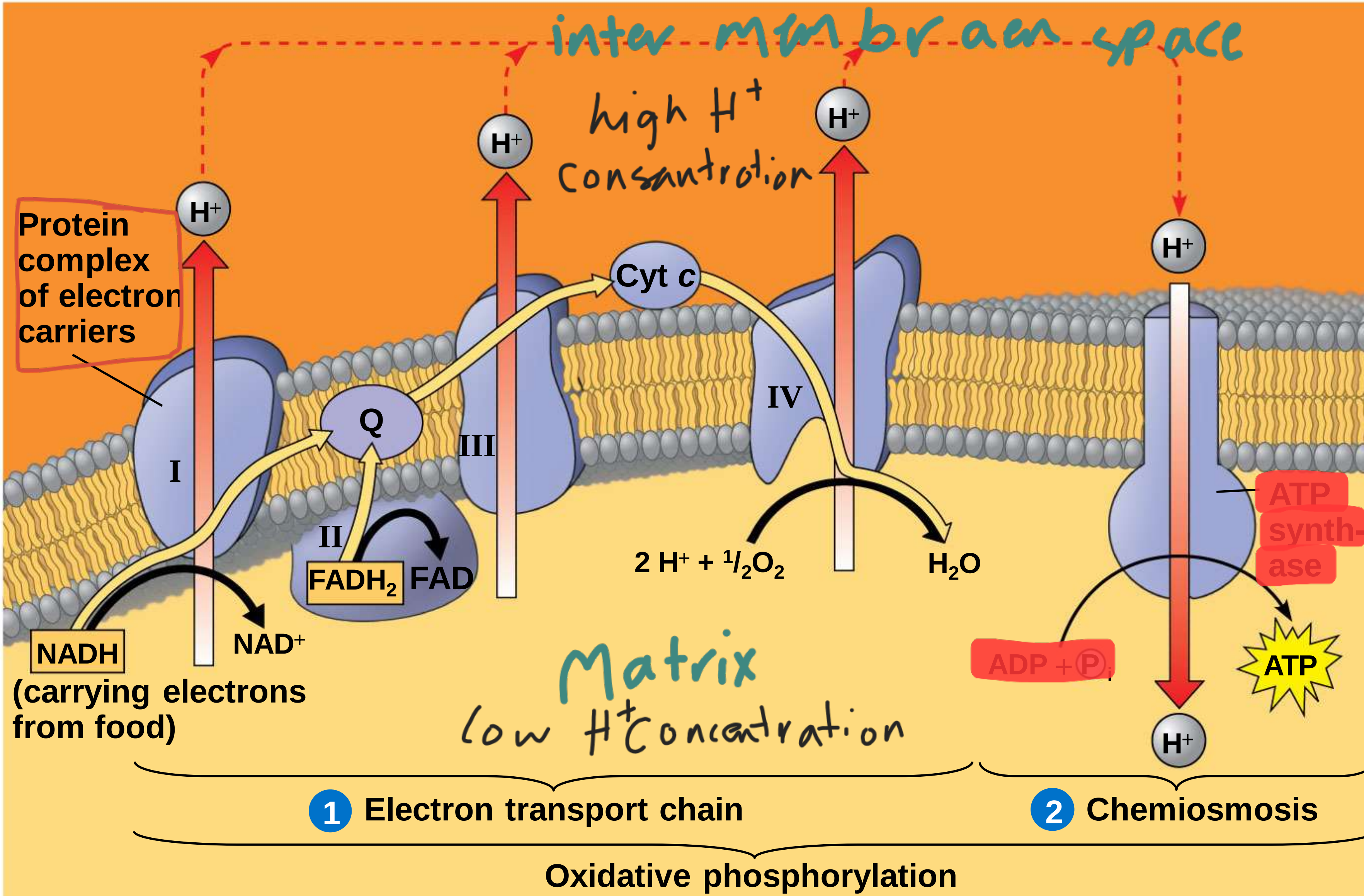

INTERMEMBRANE SPACE
H+
Stator
Rotor
Internal rod
Catalytic knob
ADP
+
Pi
inorganic
ATP
MITOCHONDRIAL MATRIX

Figure 9.15


inter mmbraen space
high H+ consantrotion
H+
Protein complex of electron carriers
I
II
III
IV
Q
Cyt c
NADH
(carrying electrons from food)
NAD+
FADH2
FAD
2 H+ + 1/2 O2
H2O
ATP synthase
ADP + P i
ATP
Matrix
low H+ concentration
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

fancy name

An Accounting of ATP Production by Cellular Respiration

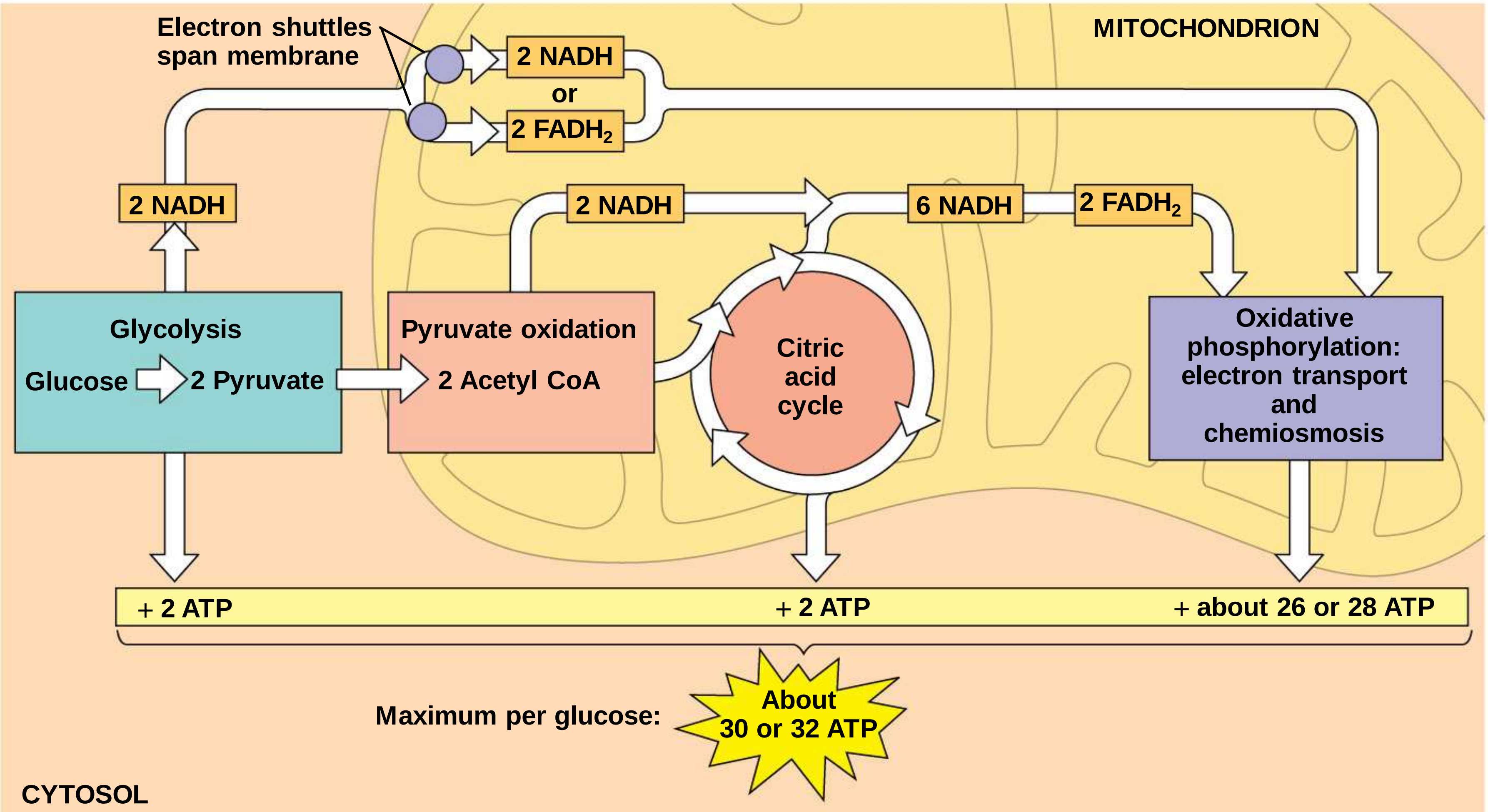
NADH → 2.5 ATP + 0.5 heat
FADH → 1.5 ATP + 0.5 heat

- During cellular respiration, most energy flows in this sequence: (90%)

  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
2 NADH
or
2 FADH2
MITOCHONDRION
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 S_2
- Fermentation uses substrate-level phosphorylation instead of an electron transport chain to generate ATP

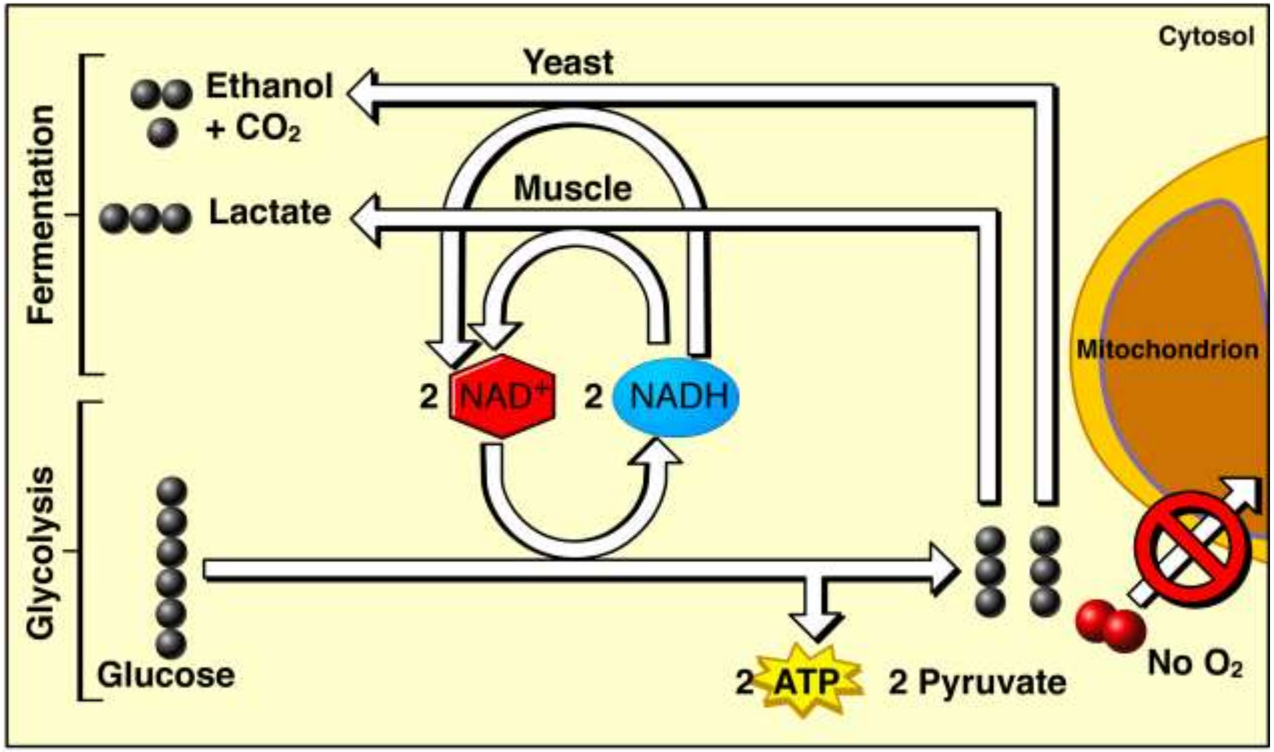
Types of Fermentation

- 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

الخميرة

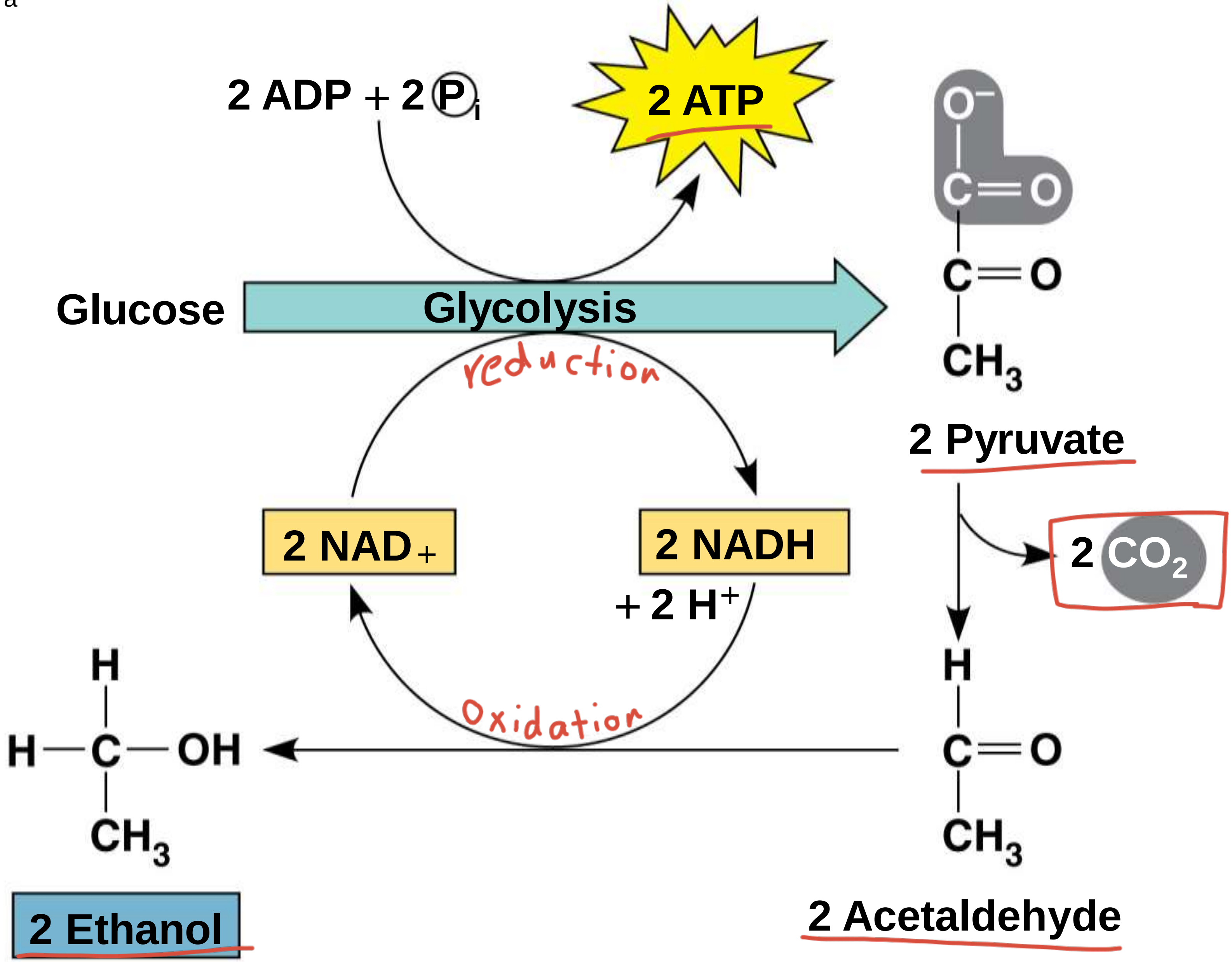
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking



Animation: Fermentation Overview

Right-click slide / select “Play”

Figure 9.17a

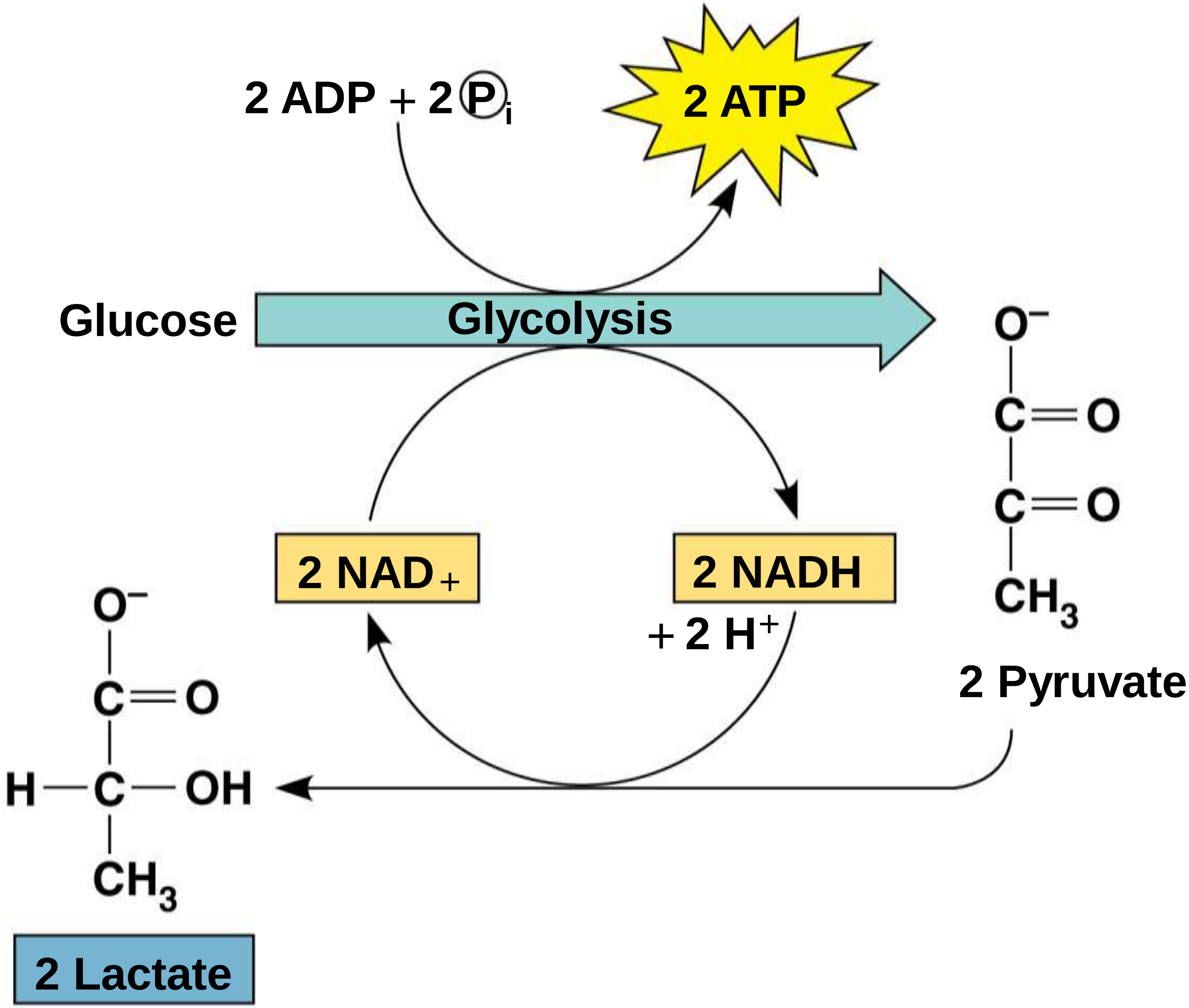


(a) Alcohol fermentation

- 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

قليل

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

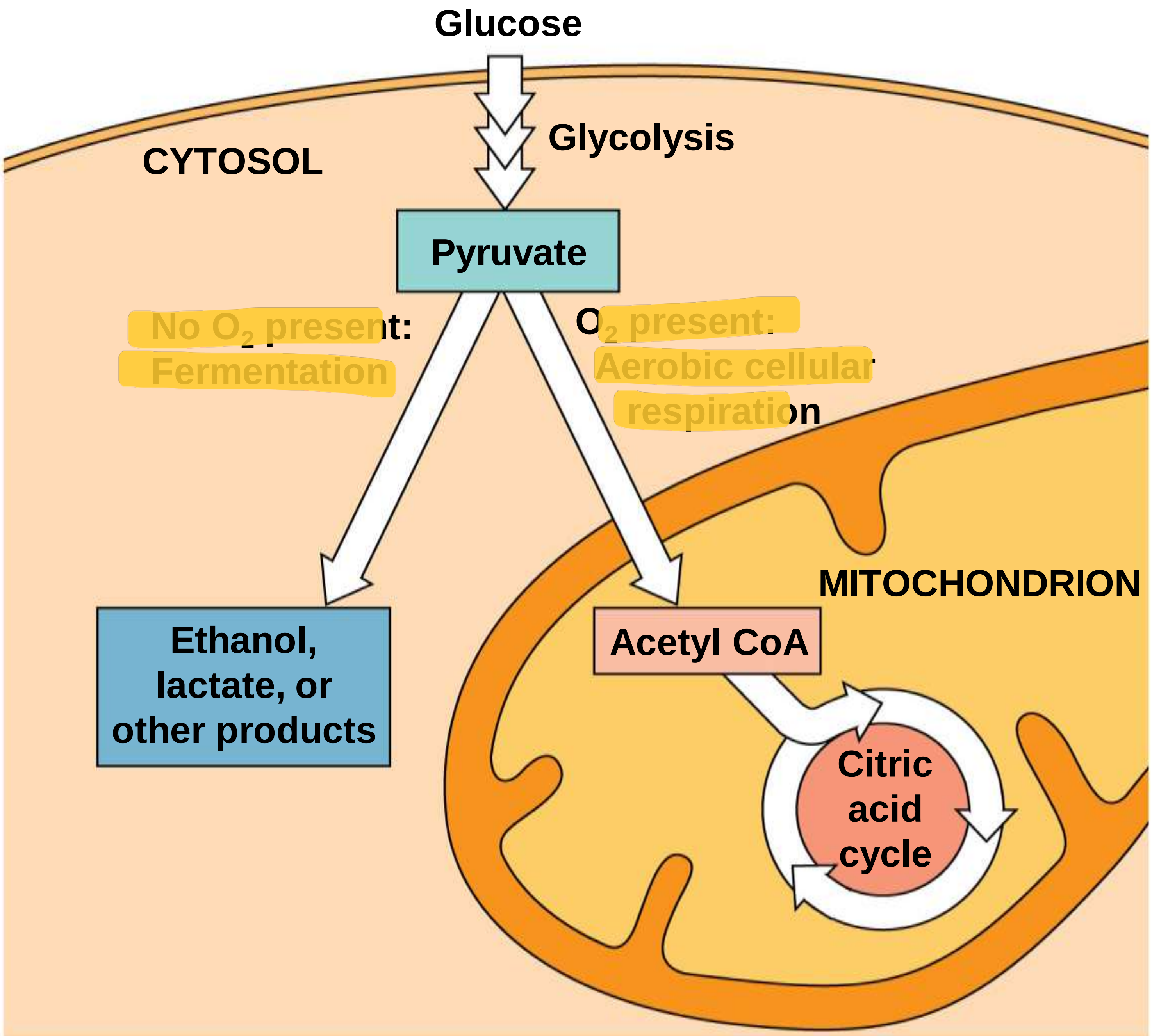
Obligate aerobes

ما بقدر تعيش إذا في O_2

- 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

مفترق طرق

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

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

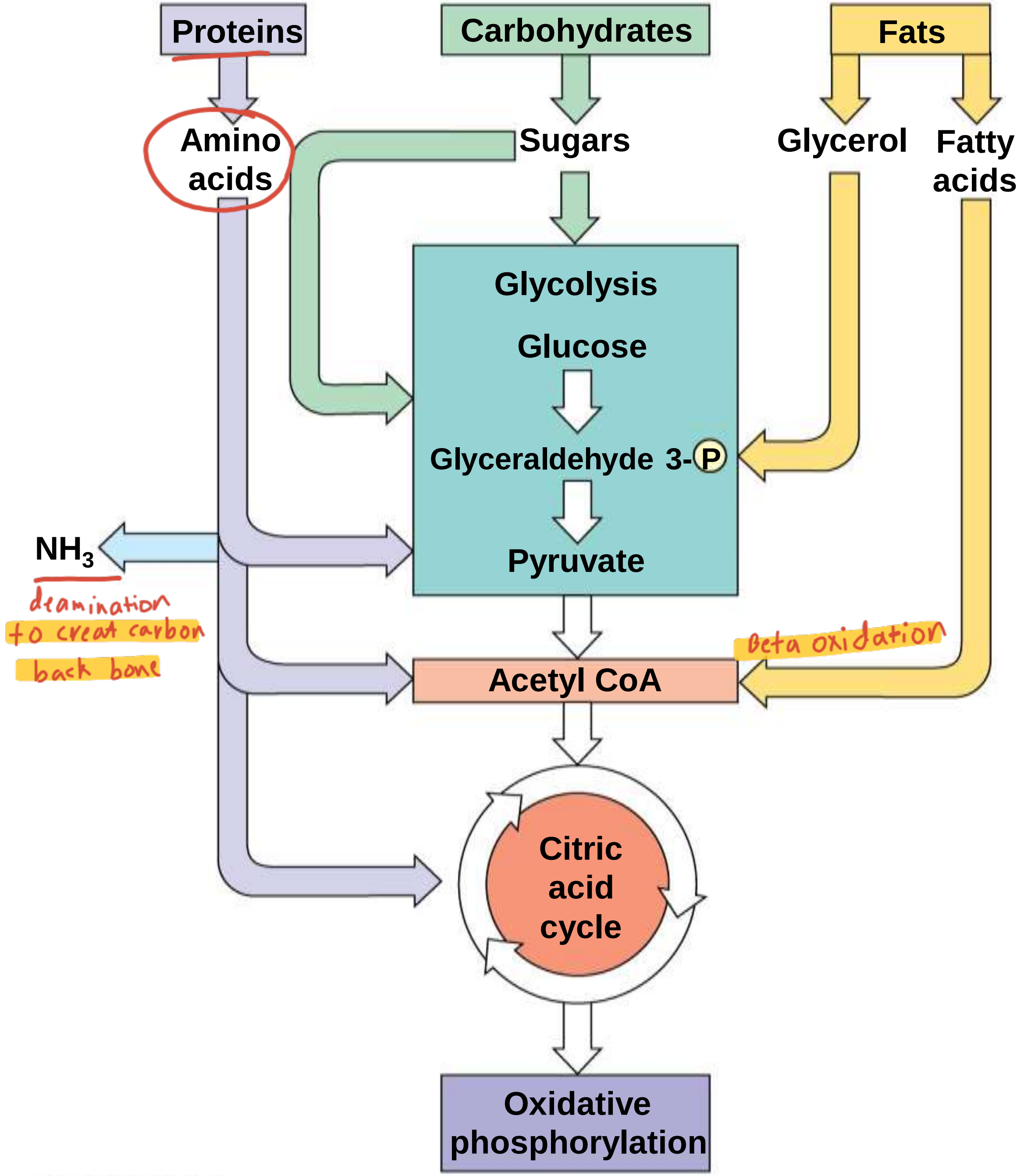
The Versatility of Catabolism

- 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

- 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

→ produce NADH directly

Figure 9.19


Proteins
Carbohydrates
Fats
Amino acids
Sugars
Glycerol
Fatty acids
Glycolysis
Glucose
Glyceraldehyde 3-P
NH3
Pyruvate
deamination
to creat carbon
back bone
beta oxidation
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

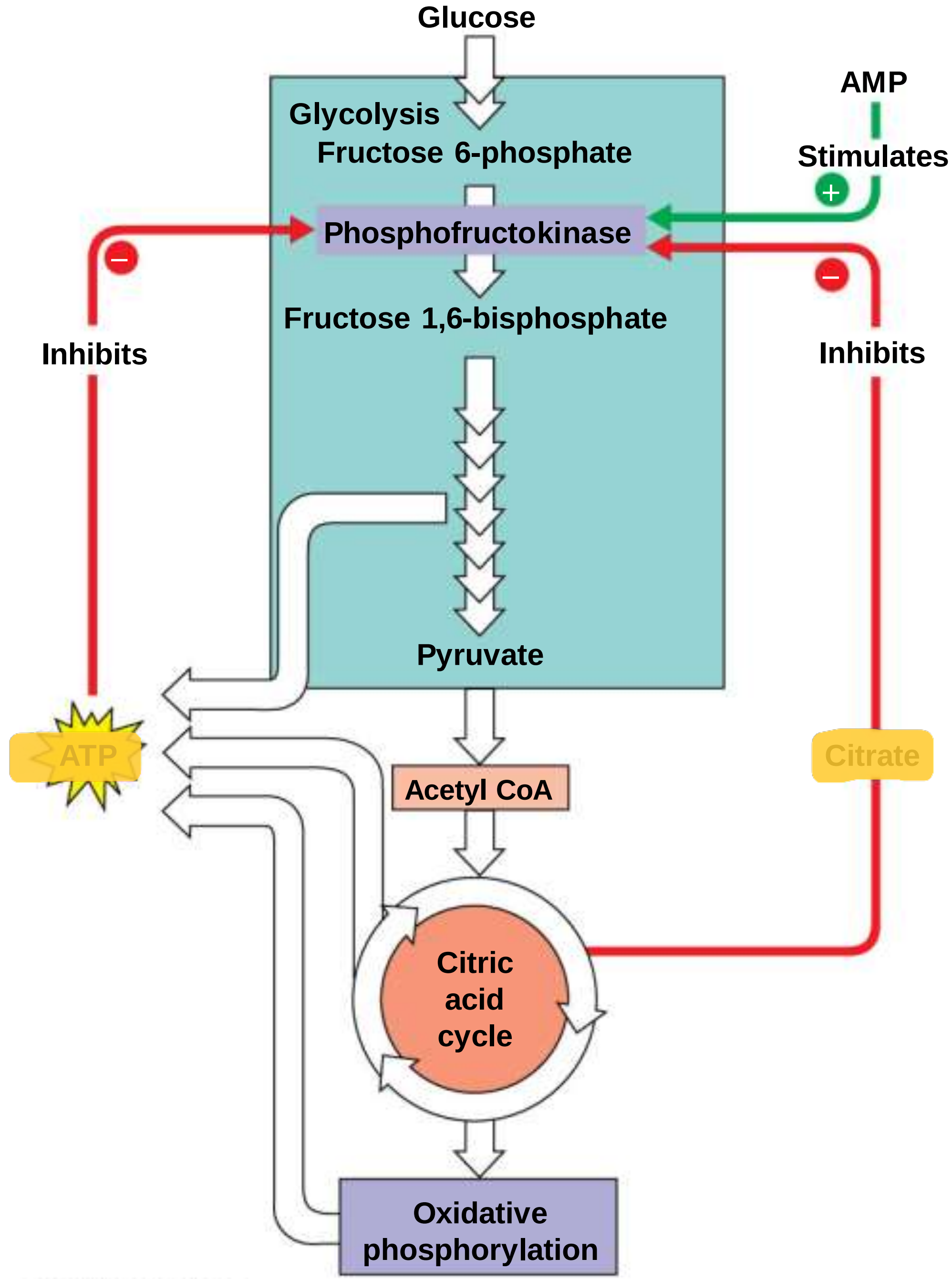
Regulation of Cellular Respiration via Feedback Mechanisms

تثبيط

- 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

stimulation
تنشيط

Figure 9.20



inhipiters of glycolysis
- ATP
- Citrate

simulater of Glycolysis
- AMP

Figure 9.UN06

Figure 9.UN07

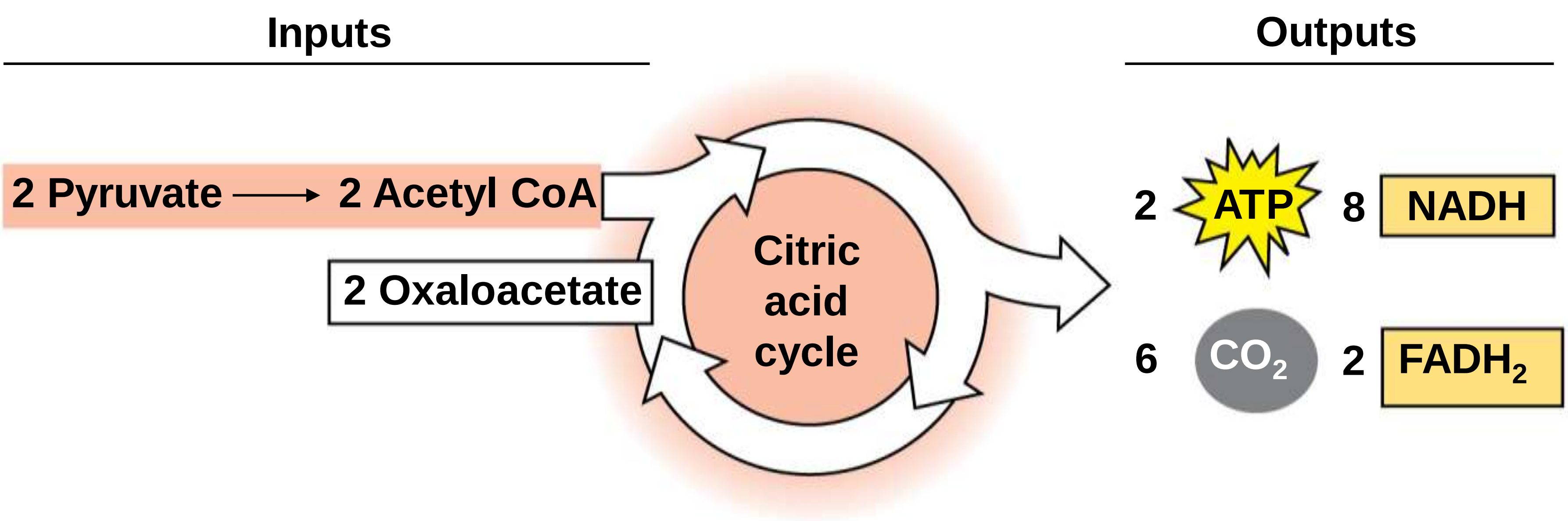


Figure 9.UN08

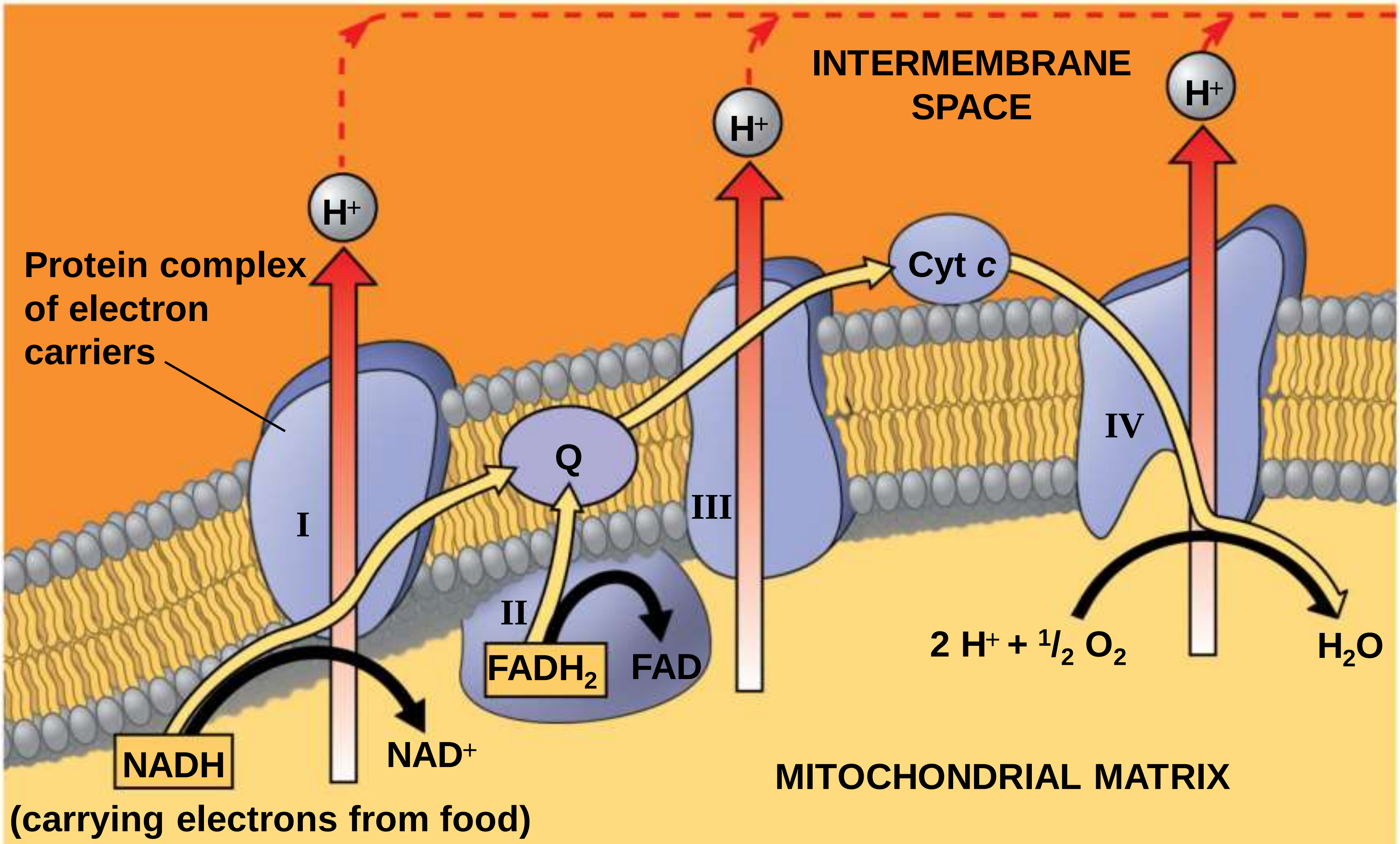


Figure 9.UN09

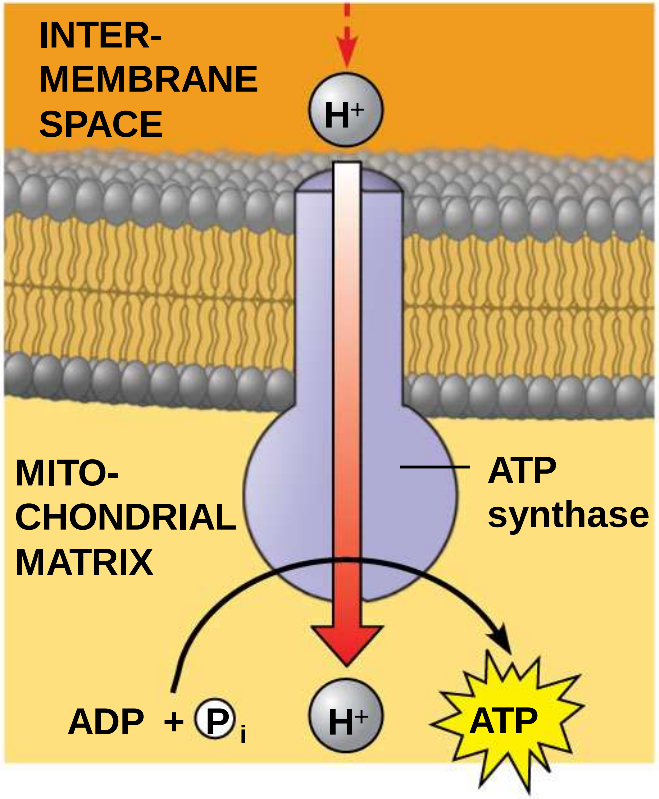


Figure 9.UN10

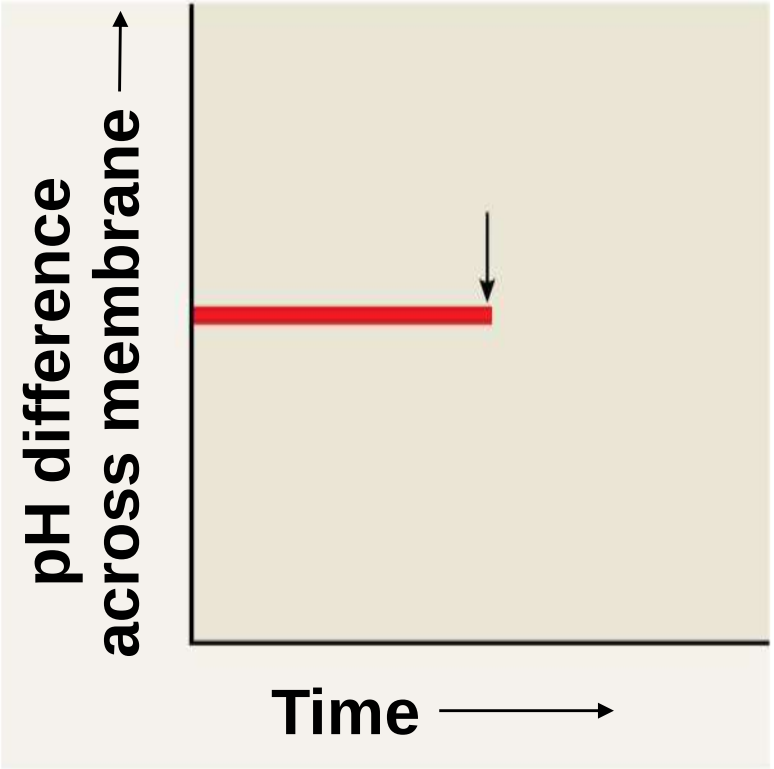


Figure 9.UN11