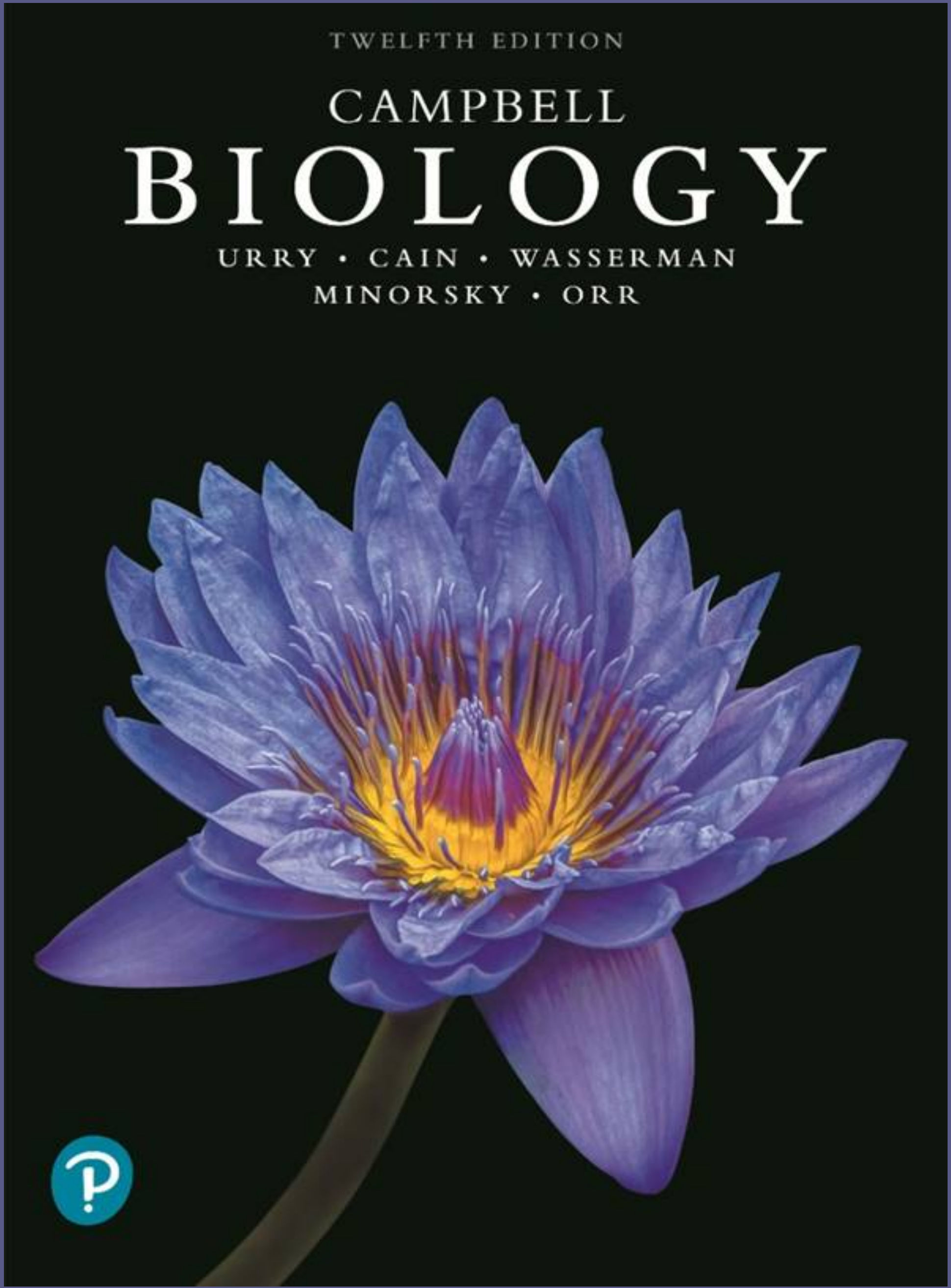


Chapter 9

Cellular Respiration and Fermentation

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

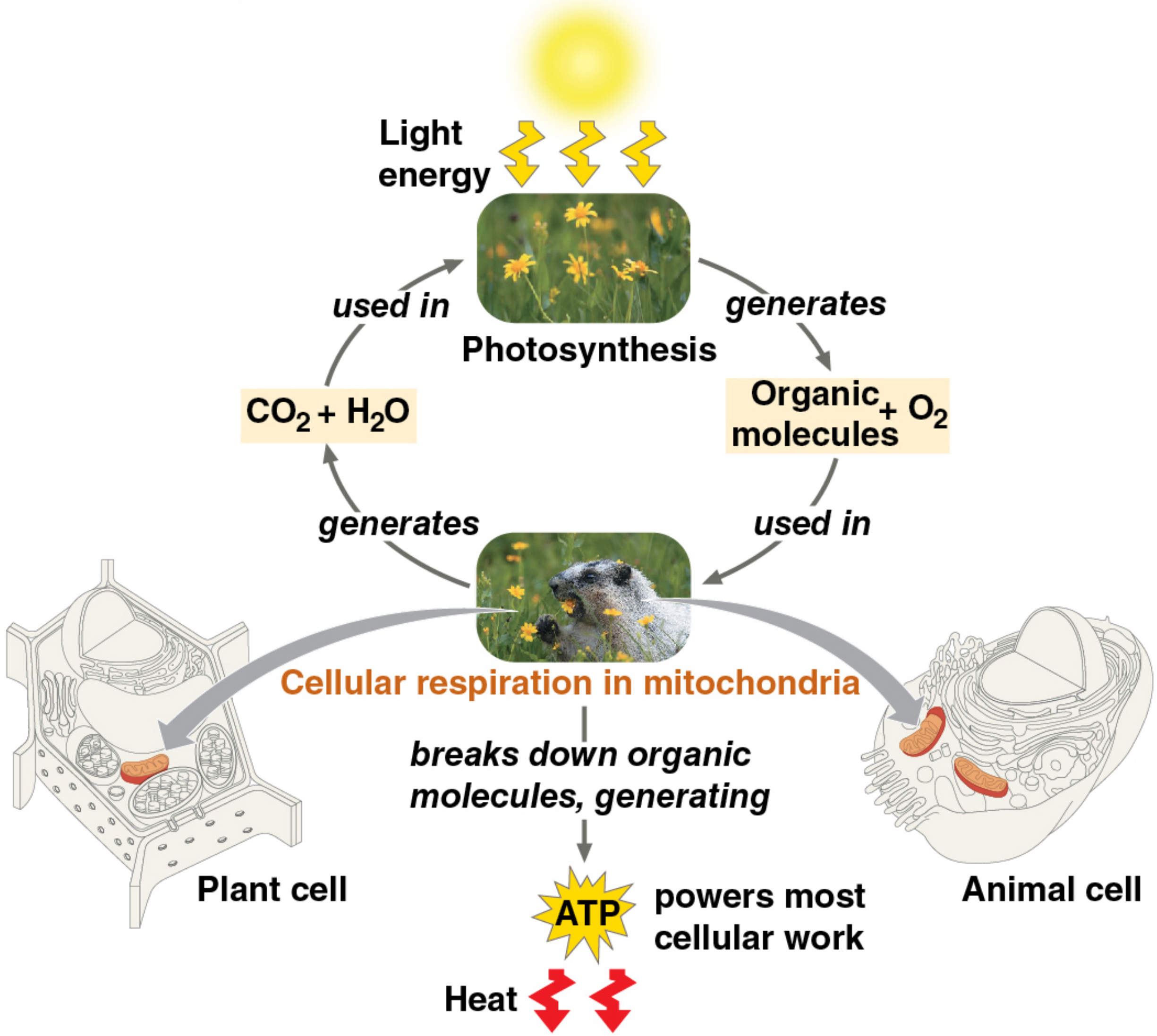
Figure 9.1a

How is the chemical energy stored in food used to generate ATP, the molecule that drives most cellular work?

- Plant and animal cells break down organic molecules by cellular respiration in the mitochondria
- The chemical energy in food is transformed into chemical energy in ATP
- Some energy is released to the environment as heat

Figure 9.1b

How is the chemical energy stored in food used to generate ATP, the molecule that drives most cellular work?



CONCEPT 9.1: Catabolic pathways yield energy by oxidizing organic fuels

- Energy enters ecosystems as light and exits as heat
- The chemical elements essential to life are recycled
  - Photosynthesis uses CO_2 and H_2O to make organic molecules and O_2
  - Cellular respiration uses O_2 and organic molecules to make ATP; CO_2 and H_2O are produced as waste

Animation: Energy Flow and Chemical Recycling

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

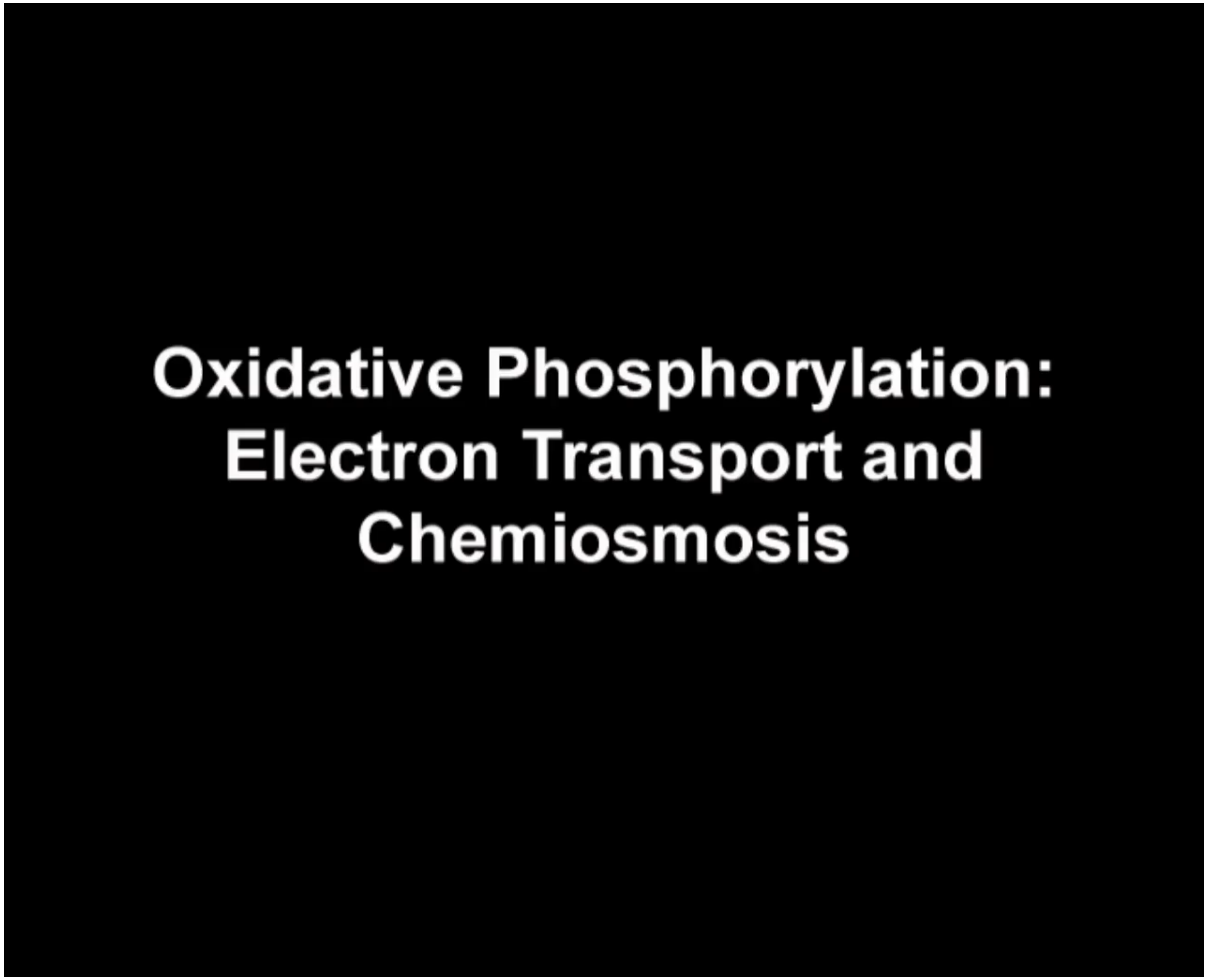
Catabolic Pathways and Production of ATP

- The breakdown of organic molecules is exergonic
- **Fermentation** is a partial degradation of sugars that occurs without oxygen
- **Aerobic respiration** consumes organic molecules and oxygen and yields ATP
- Anaerobic respiration is similar to aerobic respiration but consumes compounds other than oxygen

- **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

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (ATP + heat)}$$

BioFlix® Animation: Introduction to Cellular Respiration



- Catabolic pathways do not directly power work in the cell; they are linked to work by ATP
- Cells must constantly regenerate their supply of ATP from ADP and phosphate

Redox Reactions: Oxidation and Reduction

- The transfer of electrons during chemical reactions releases energy stored in organic molecules
- This 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 redox reactions, the loss of electrons from a substance is called **oxidation**
- The addition of electrons to a substance is called **reduction** (the amount of positive charge is reduced)

Figure 9.UN01

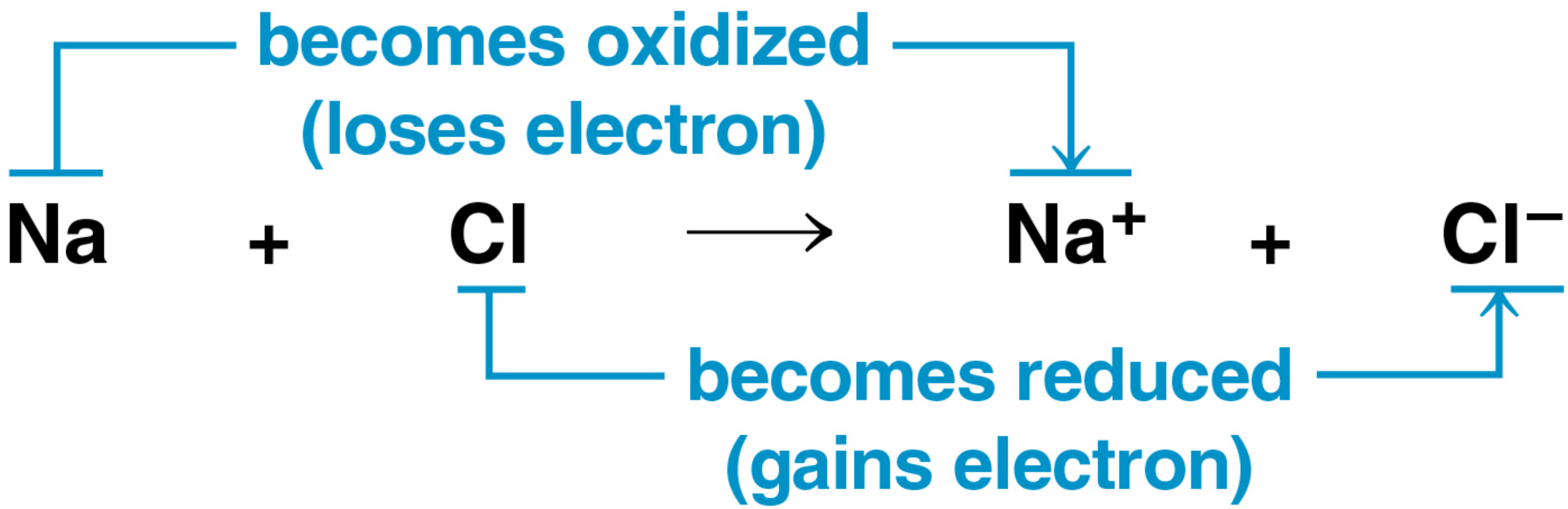
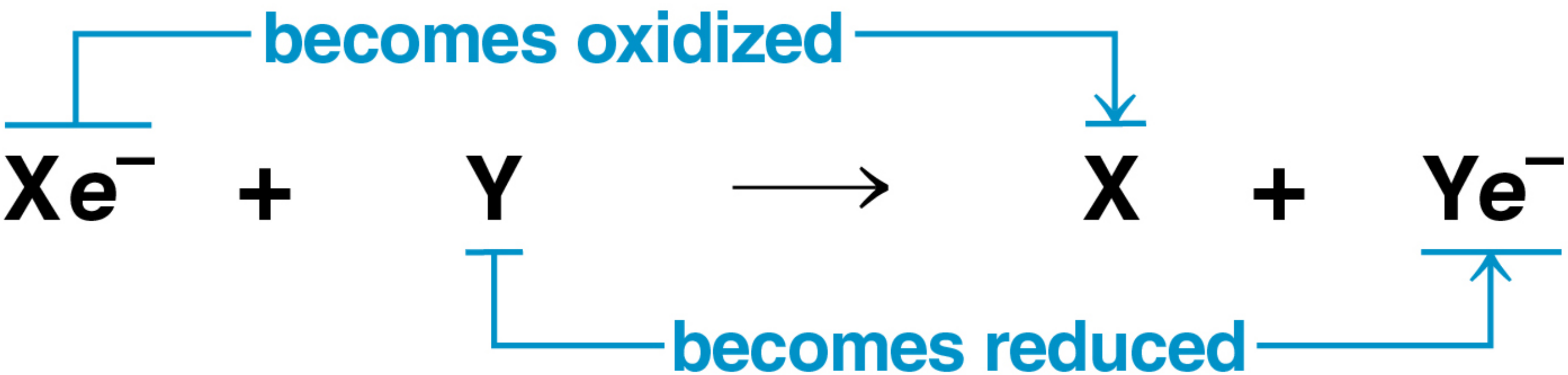


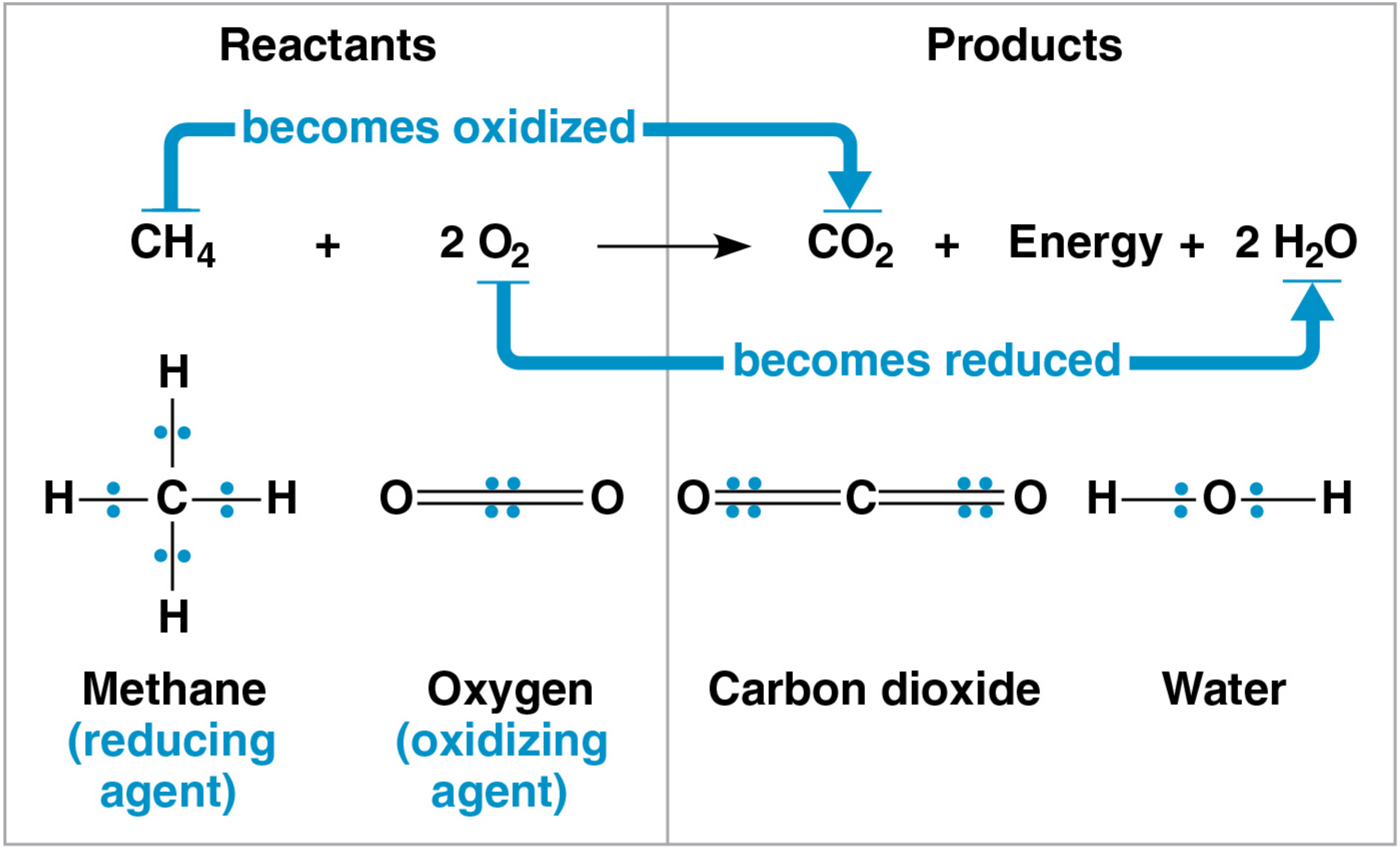
Figure 9.UN02



- Oxidation and reduction always go hand in hand
- The electron donor is called the **reducing agent**, it reduces the electron acceptor
- The electron acceptor is called the **oxidizing agent**, it oxidizes the electron donor

- Instead of fully transferring electrons, some redox reactions change electron sharing in covalent bonds
- Oxygen (O) atoms are very electronegative; they attract electrons and do not share them equally
- The partial “gain” of electrons by O atoms and the partial “loss” of electrons by their bonding partners constitutes a redox reaction
  - For example, electrons are not completely transferred in the redox reaction between methane and O_2

Figure 9.2


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

Animation: Redox Reactions

Complete Electron Transfer

A reduction-oxidation (redox) reaction always involves two events: one substance loses electrons and is said to be oxidized, while another substance gains electrons and is said to be reduced.

Sodium chloride, or table salt, offers an example of atoms that have undergone oxidation and reduction to become *ions*. When sodium and chlorine react to form sodium chloride, one electron is completely transferred from the sodium atom to the chlorine atom. The result is a sodium *cation* and a chloride *anion*.

- An electron loses potential energy when it shifts from a less electronegative atom toward a more electronegative one
- Redox reactions that move electrons closer to electronegative O atoms release energy

Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, fuel molecules (such as glucose) are oxidized, and O_2 is reduced
- Organic molecules with an abundance of hydrogen are excellent sources of high-energy electrons
- Cellular respiration is a redox process; energy is released as hydrogen and electrons are transferred to O atoms

Figure 9.UN03

becomes oxidized

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

becomes reduced

- The oxidation of glucose transfers electrons from a higher energy state (in glucose) to a lower energy state with O atoms
- This releases energy that is be used to synthesize ATP

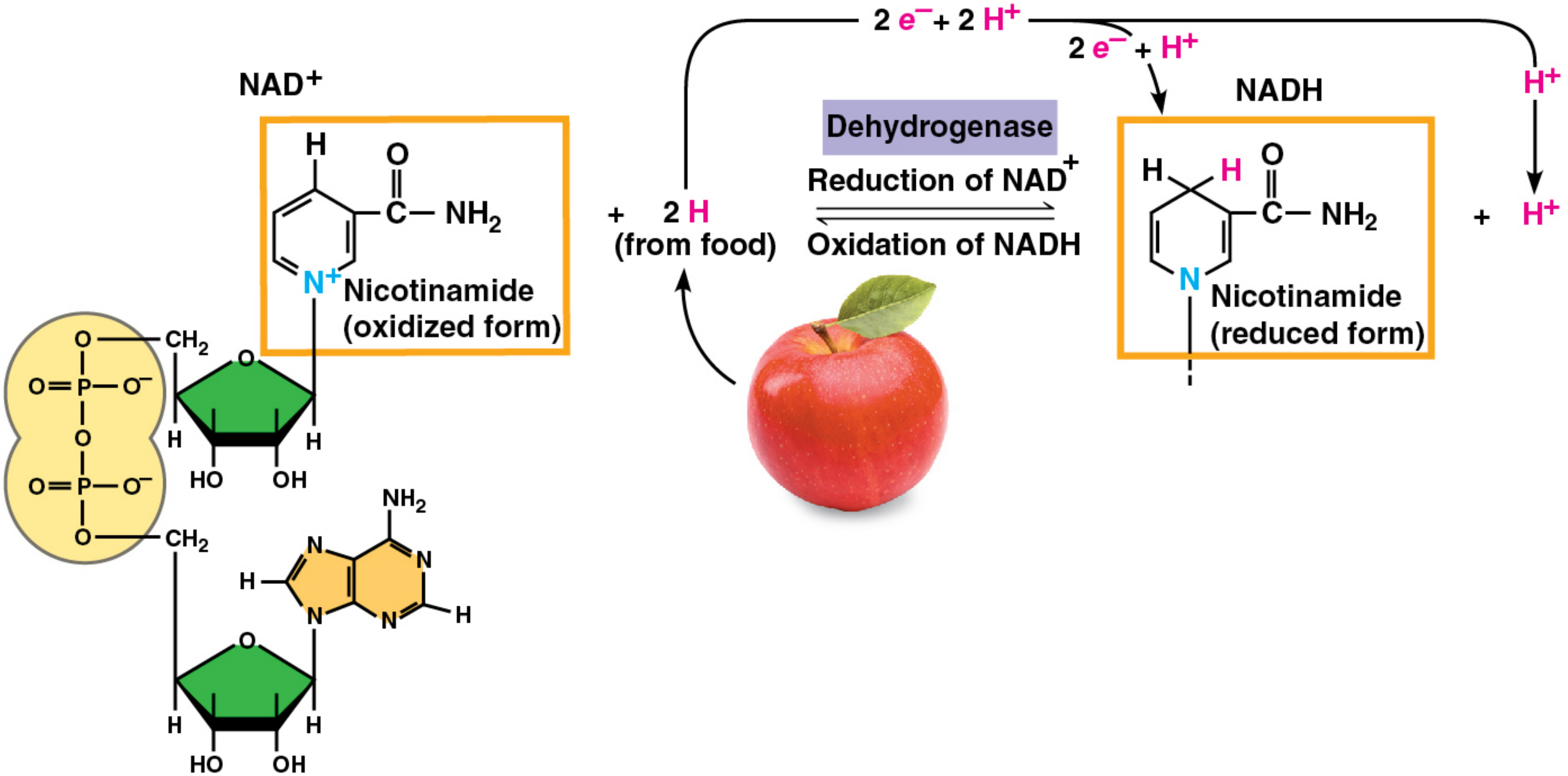
Stepwise Energy Harvest via NAD^+ and the Electron Transport Chain

- In cellular respiration, glucose and other organic molecules are oxidized in a series of steps
- Each electron travels with a proton—thus, as a hydrogen atom
- Hydrogen atoms are usually first passed to electron carriers, rather than directly to O_2

- Nicotinamide adenine dinucleotide, **NAD^+**, is a coenzyme that functions as an electron carrier
- 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

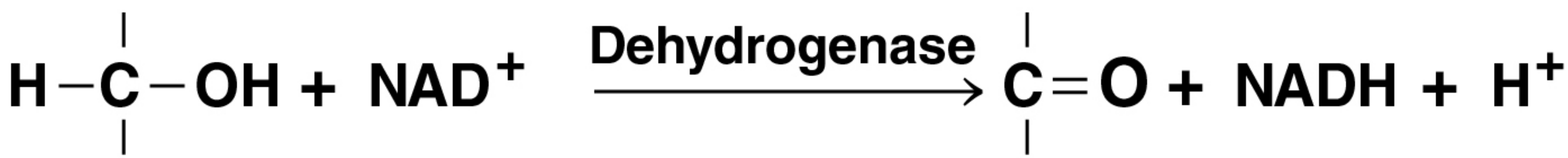
- Enzymes called dehydrogenases remove a pair of hydrogen atoms (2 electrons and 2 protons) from the substrate
- The 2 electrons and 1 proton is transferred to NAD^+ forming NADH
- The other proton is released as a hydrogen ion (H^+) into the surrounding solution

Figure 9.3



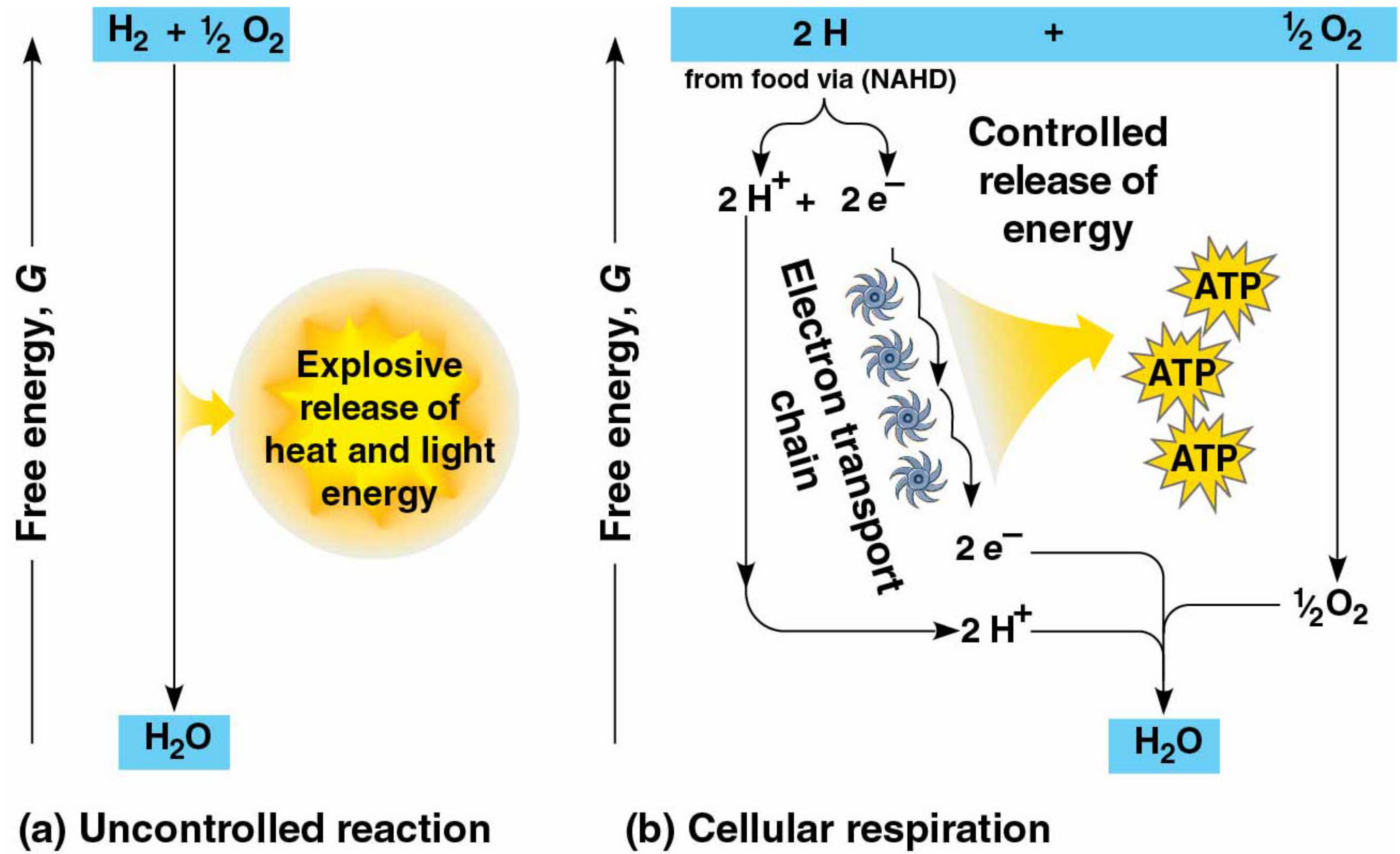
NAD+
H
O
C— NH2
N+
Nicotinamide
(oxidized form)
O
CH2
O=P—O−
O
O=P—O−
O
CH2
O
H
H
HO
OH
NH2
N
N
H
N
N
H
O
H
H
HO
OH
+ 2 H
(from food)
2 e− + 2 H+
2 e− + H+
Dehydrogenase
Reduction of NAD+
Oxidation of NADH
NADH
H
H
O
C— NH2
N
Nicotinamide
(reduced form)
H+
+ H+

Figure 9.UN04



- If NADH transferred electrons directly to oxygen, energy would be released in one explosive reaction
- Instead, cellular respiration uses an electron transport chain to break the fall of electrons to O_2 into several energy-releasing steps
- An **electron transport chain** consists of a series of molecules built into the inner membrane of the mitochondria (or plasma membrane of prokaryotes)

Figure 9.4



H_2 + ½ O_2
Free energy, G
Explosive release of heat and light energy
H_2O
(a) Uncontrolled reaction
2 H + ½ O_2
from food via (NAHD)
$2 H^+$ + $2 e^-$
Controlled release of energy
Electron transport chain
ATP
ATP
ATP
$2 e^-$
½O_2
$2 H^+$
H_2O
Free energy, G
(b) Cellular respiration

- NADH passes electrons to the electron transport chain where they are transferred in a series of redox reactions, each releasing a small amount of energy
- O_2, the final electron acceptor, captures the electrons and the hydrogen nuclei (H^+), forming H_2O
- The energy yielded is used to regenerate ATP

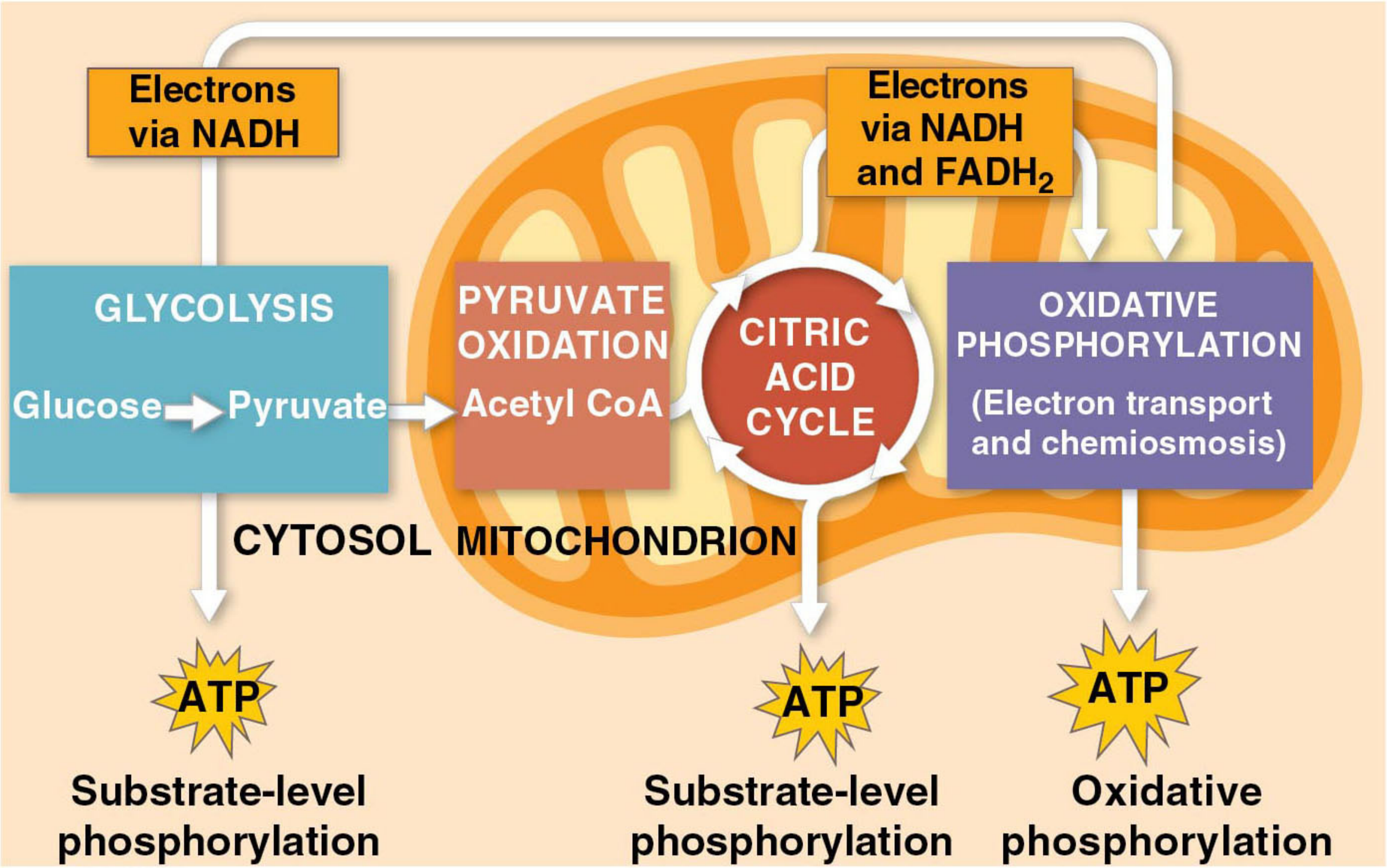
The Stages of Cellular Respiration: *A Preview*

- Harvesting energy from glucose by cellular respiration has three stages
  1. **Glycolysis** breaks down glucose into two molecules of pyruvate
  2. Pyruvate oxidation and the **citric acid cycle** complete the breakdown of glucose to CO_2
  3. During **oxidative phosphorylation** the electron transfer chain and chemiosmosis facilitate synthesis of most of the cell’s ATP

Figure 9.UN05

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

Figure 9.5

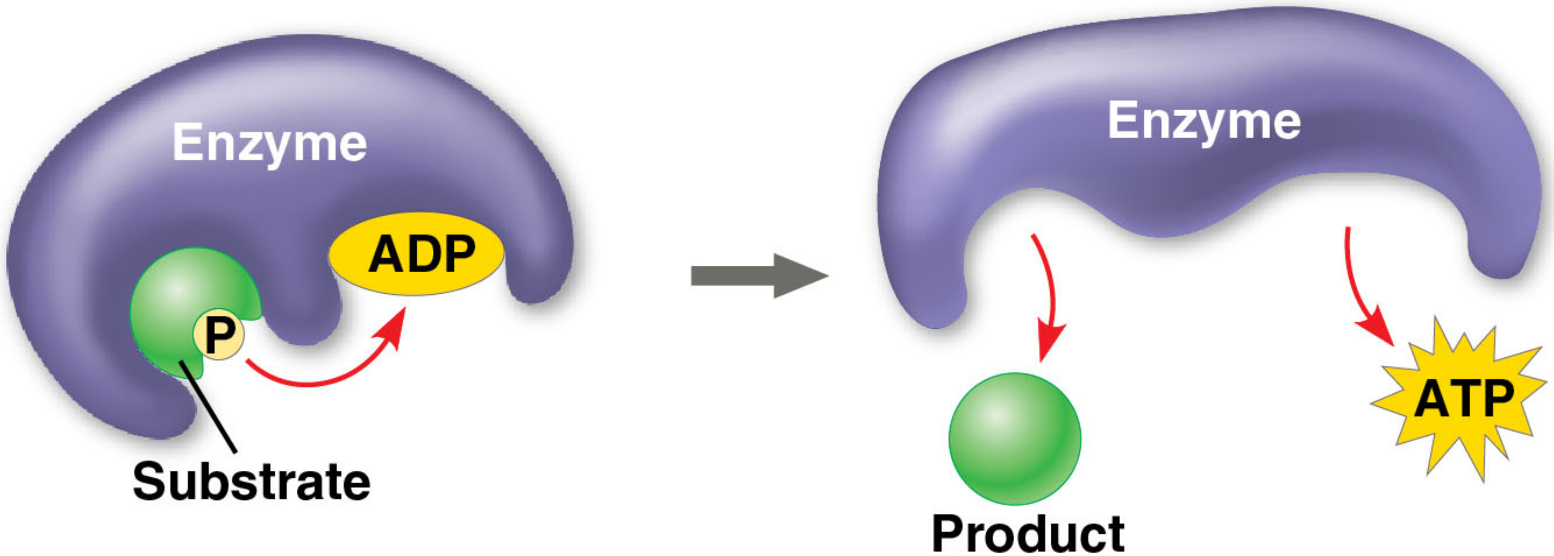


Electrons via NADH
Electrons via NADH and FADH$_2$
GLYCOLYSIS
Glucose
Pyruvate
PYRUVATE OXIDATION
Acetyl CoA
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION
(Electron transport and chemiosmosis)
CYTOSOL
MITOCHONDRION
ATP
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation

Animation: Overview of Cellular Respiration

- The process that generates almost 90% of the ATP is called **oxidative phosphorylation** because it is powered by redox reactions
- Some ATP is also formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation**
- Substrate-level phosphorylation occurs when an enzyme transfers a phosphate group directly from a substrate to ADP

Figure 9.6



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

- For each molecule of glucose degraded to CO_2 and H_2O by cellular respiration, up to 32 molecules of ATP are produced

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

- Glycolysis occurs in the cytoplasm and has two major phases
  - In the energy investment phase, 2 ATP are used to split glucose into 2 three-carbon sugar molecules
  - In the energy payoff phase, 4 ATP are synthesized, 2 NAD^+ are reduced to NADH, the small sugars are oxidized to form 2 pyruvate and 2 H_2O
  - A net of 2 ATP are produced by substrate-level phosphorylation during glycolysis

Figure 9.UN06

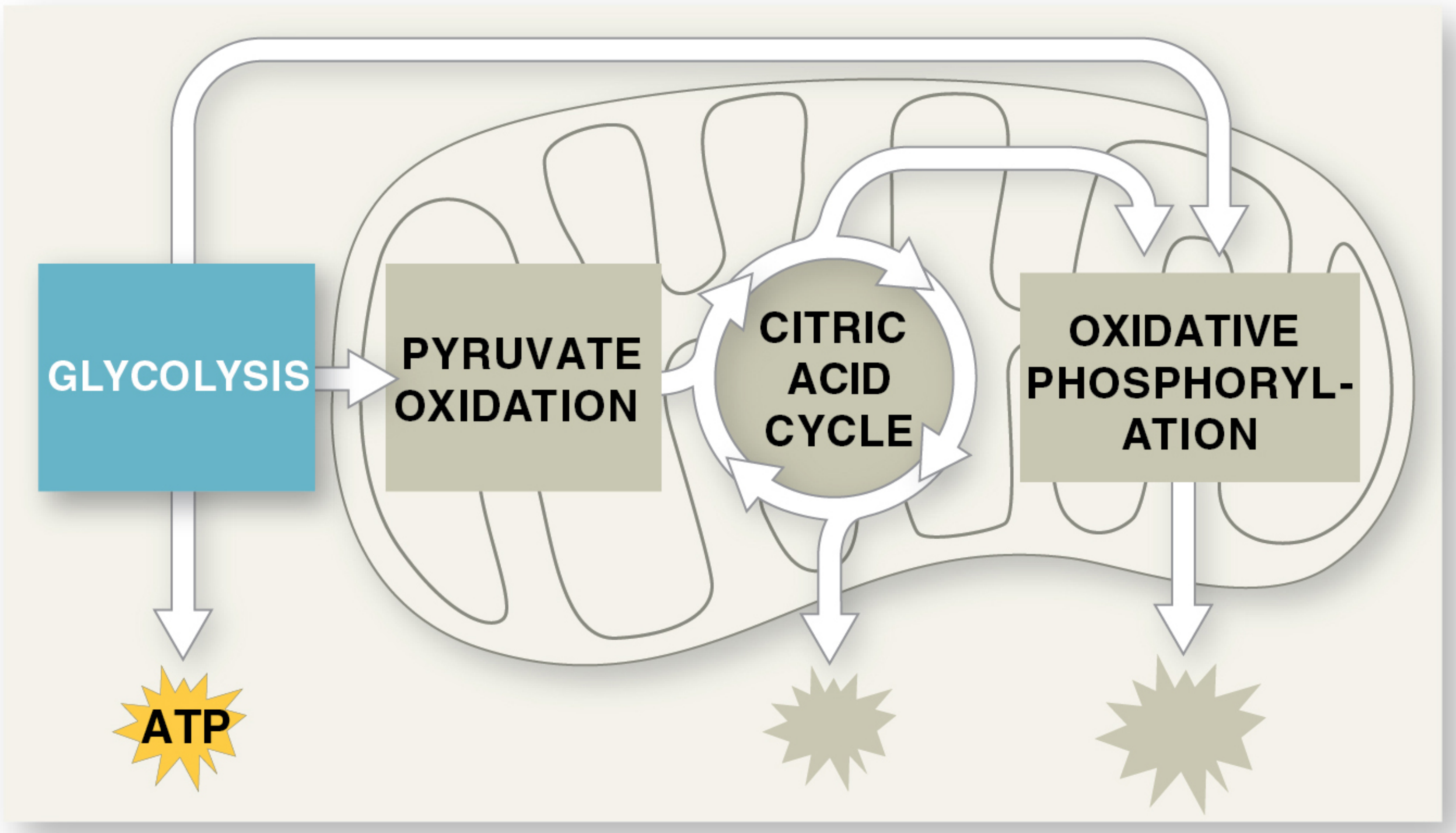
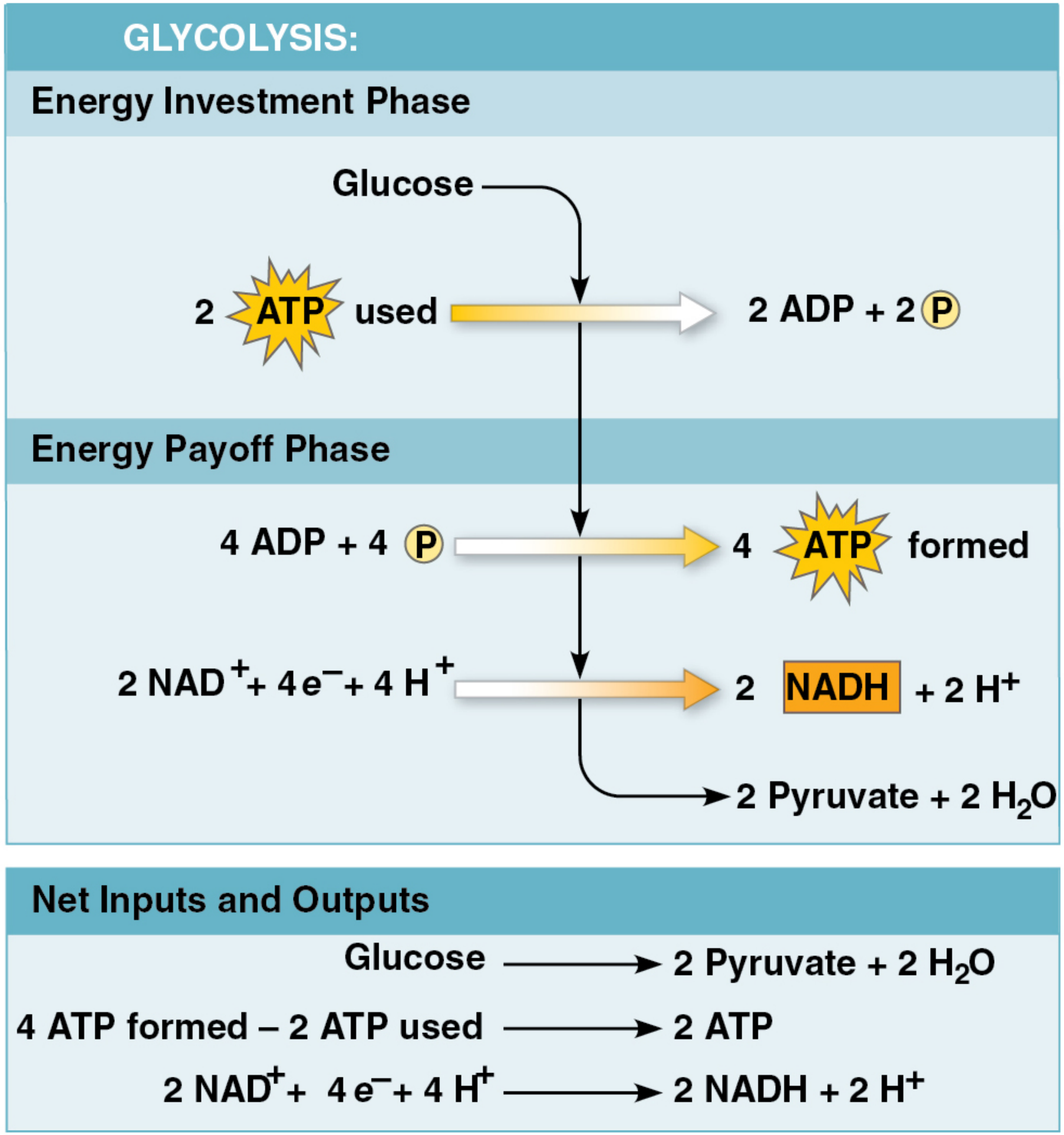
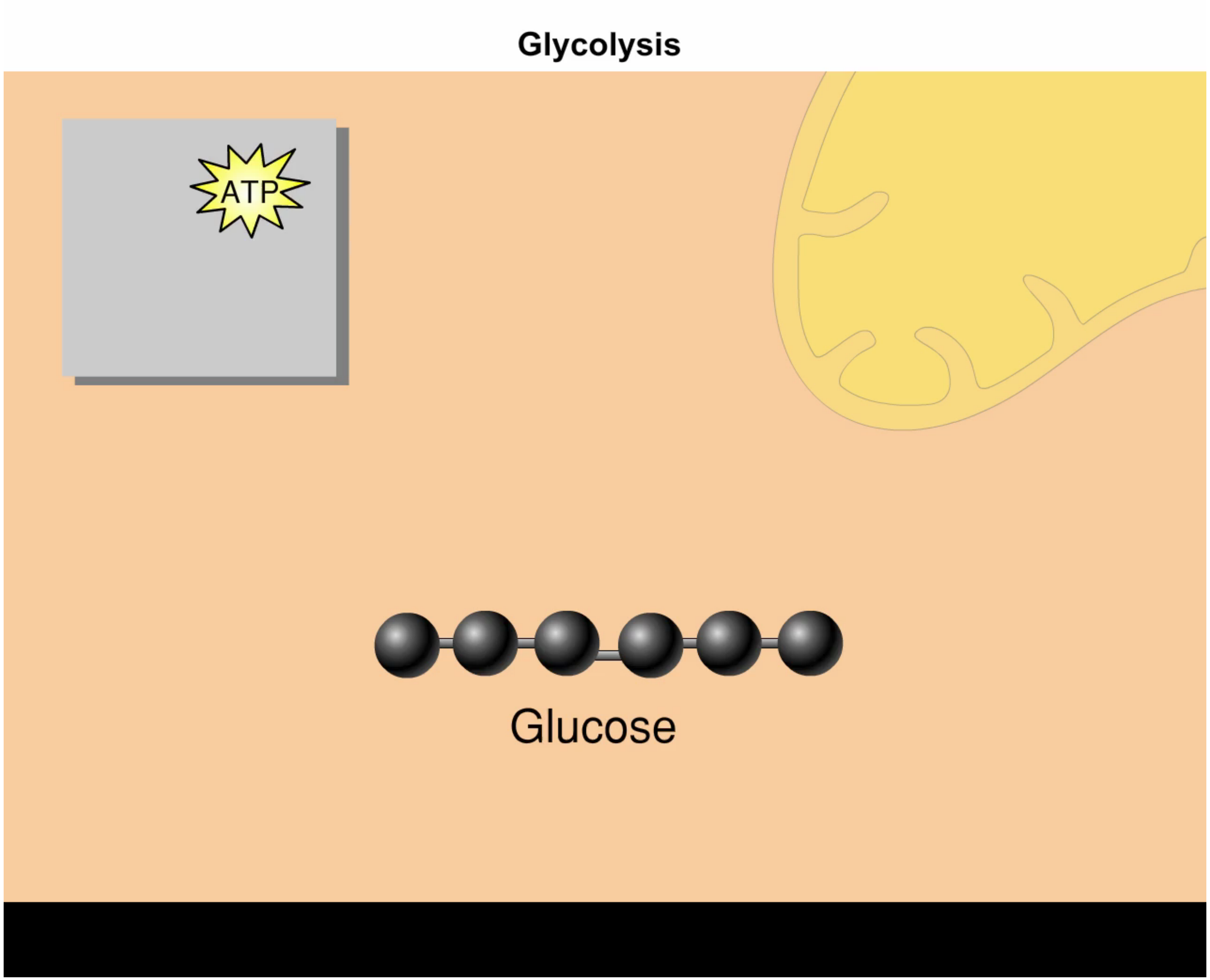


Figure 9.7

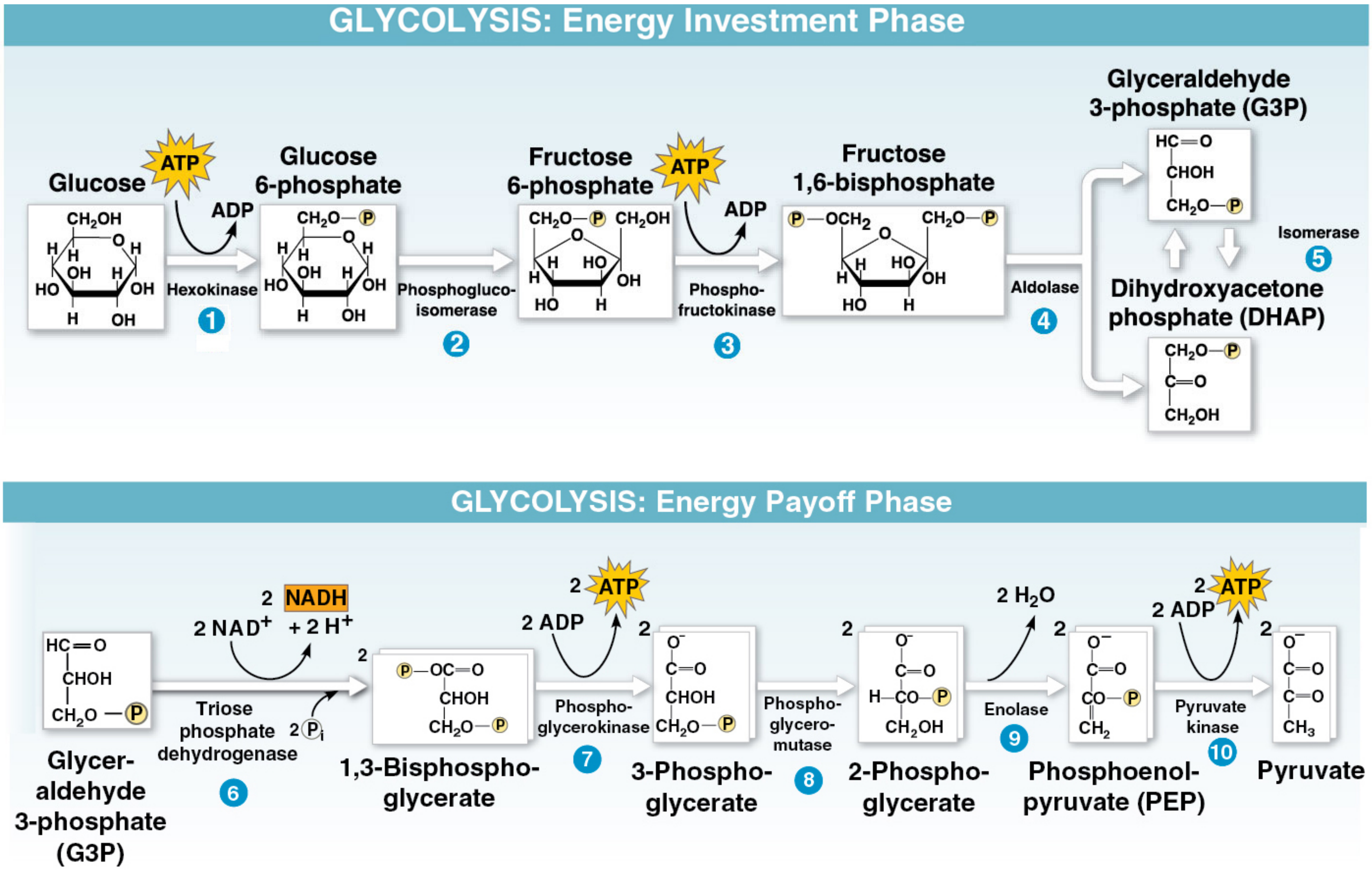

GLYCOLYSIS:
Energy Investment Phase
Glucose
2 ATP used
2 ADP + 2 P
Energy Payoff Phase
4 ADP + 4 P
4 ATP formed
2 NAD$^+$ + 4 e$^-$ + 4 H$^+$
2 NADH + 2 H$^+$
2 Pyruvate + 2 H_2O
Net Inputs and Outputs
Glucose → 2 Pyruvate + 2 H_2O
4 ATP formed – 2 ATP used → 2 ATP
2 NAD$^+$ + 4 e$^-$ + 4 H$^+$ → 2 NADH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

Animation: Glycolysis

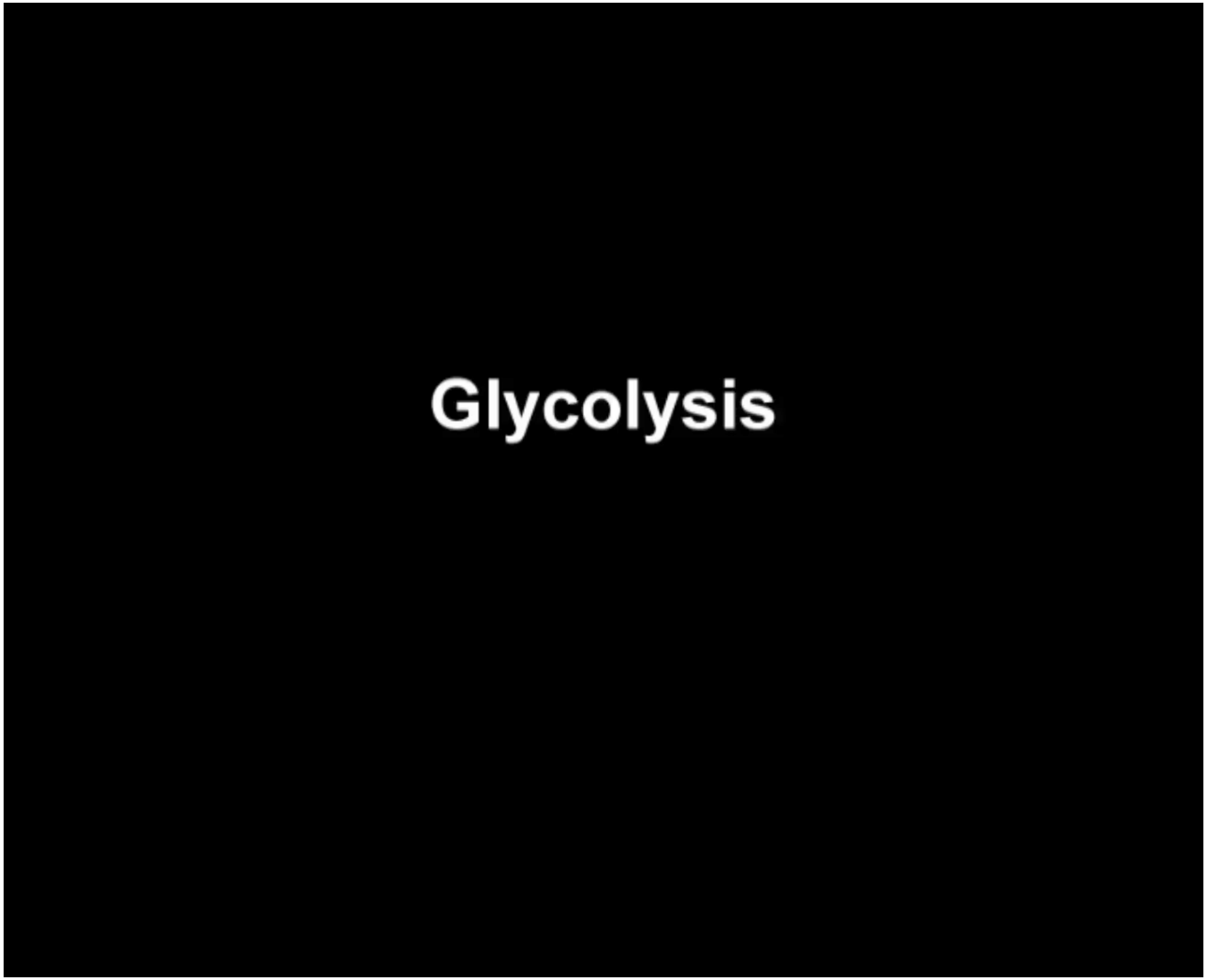


- All of the carbon originally present in glucose is accounted for in the two molecules of pyruvate
- Glycolysis does not release any CO_2, and occurs whether or not O_2 is present

Figure 9.8


GLYCOLYSIS: Energy Investment Phase
Glucose
ATP
ADP
Hexokinase
1
Glucose 6-phosphate
Phosphoglucoisomerase
2
Fructose 6-phosphate
ATP
ADP
Phosphofructokinase
3
Fructose 1,6-bisphosphate
Aldolase
4
Glyceraldehyde 3-phosphate (G3P)
Isomerase
5
Dihydroxyacetone phosphate (DHAP)
GLYCOLYSIS: Energy Payoff Phase
Glyceraldehyde 3-phosphate (G3P)
2 NAD+
2 NADH
+ 2 H+
Triose phosphate dehydrogenase
2 Pi
6
1,3-Bisphosphoglycerate
2 ADP
2 ATP
Phosphoglycerokinase
7
3-Phosphoglycerate
Phosphoglyceromutase
8
2-Phosphoglycerate
2 H2O
Enolase
9
Phosphoenolpyruvate (PEP)
2 ADP
2 ATP
Pyruvate kinase
10
Pyruvate

BioFlix® Animation: Glycolysis



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

- Most of the energy in glucose remains stored in the pyruvate molecules produced by glycolysis
- In eukaryotic cells, if O_2 is present, pyruvate enters a mitochondrion to complete glucose oxidation
- This occurs in the cytosol for aerobic prokaryotes

Oxidation of Pyruvate to Acetyl CoA

- Pyruvate is converted to acetyl coenzyme A (**acetyl CoA**) before entering the citric acid cycle
- Pyruvate dehydrogenase catalyzes three reactions
  1. Oxidation of pyruvate's carboxyl group, releasing the first CO_2 of cellular respiration
  2. Reduction of NAD^+ to NADH
  3. Combination of the remaining two-carbon fragment with coenzyme A to form acetyl CoA

Figure 9.UN07

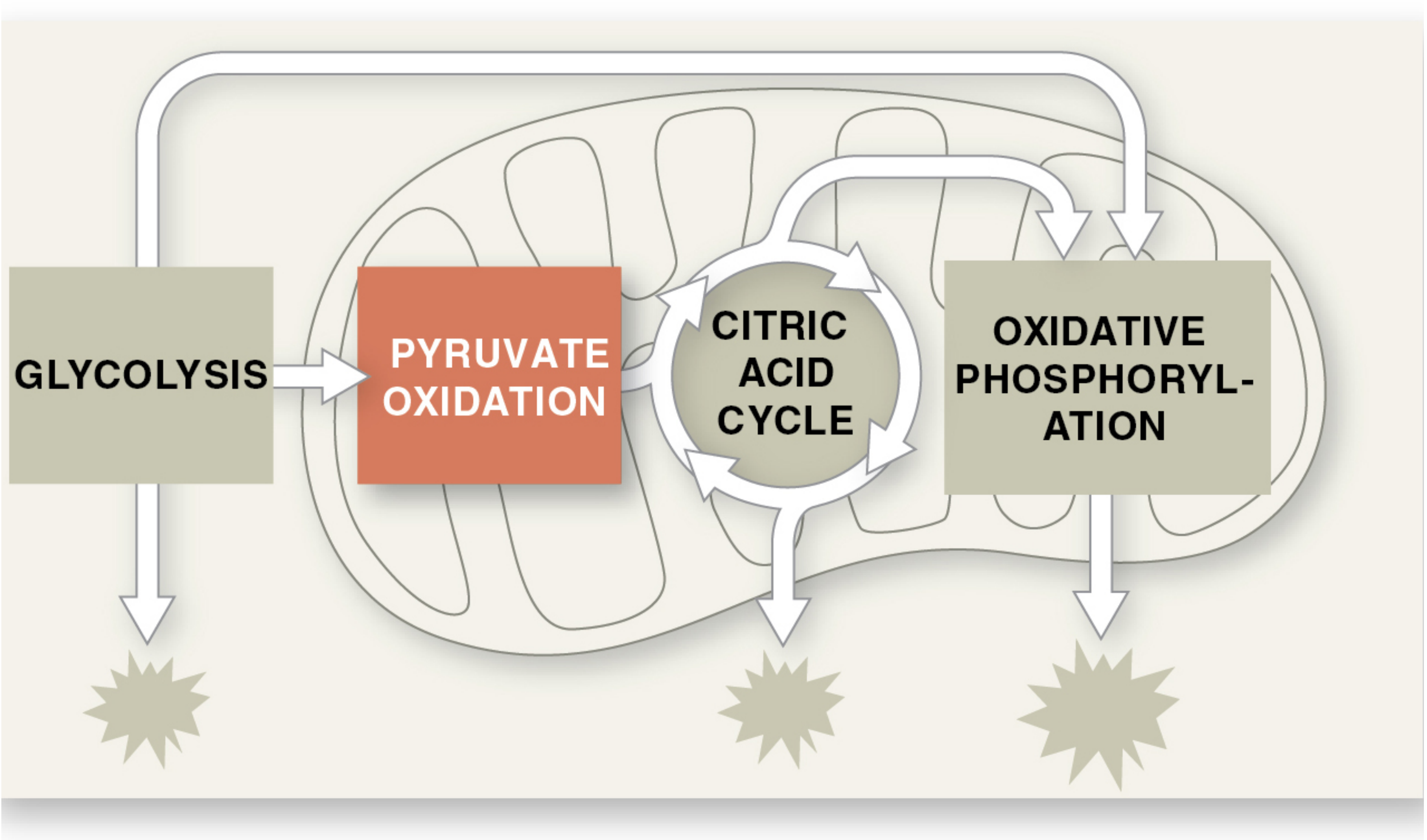
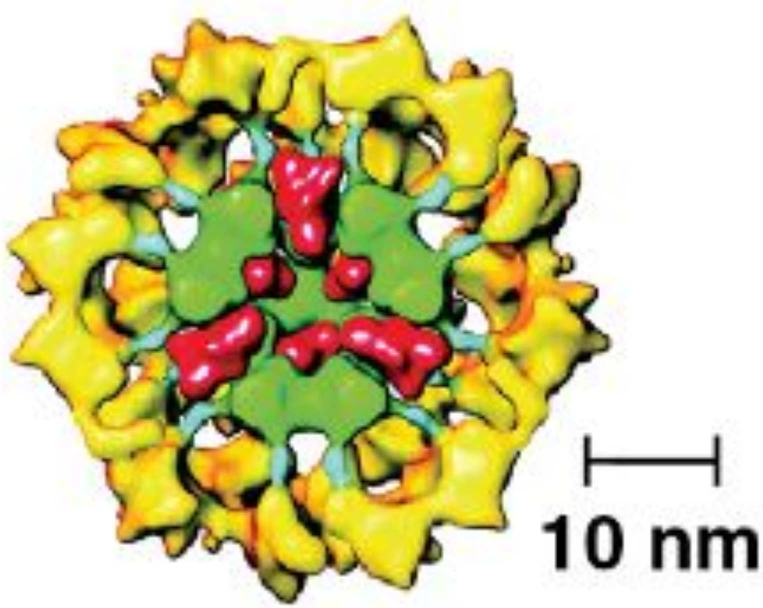
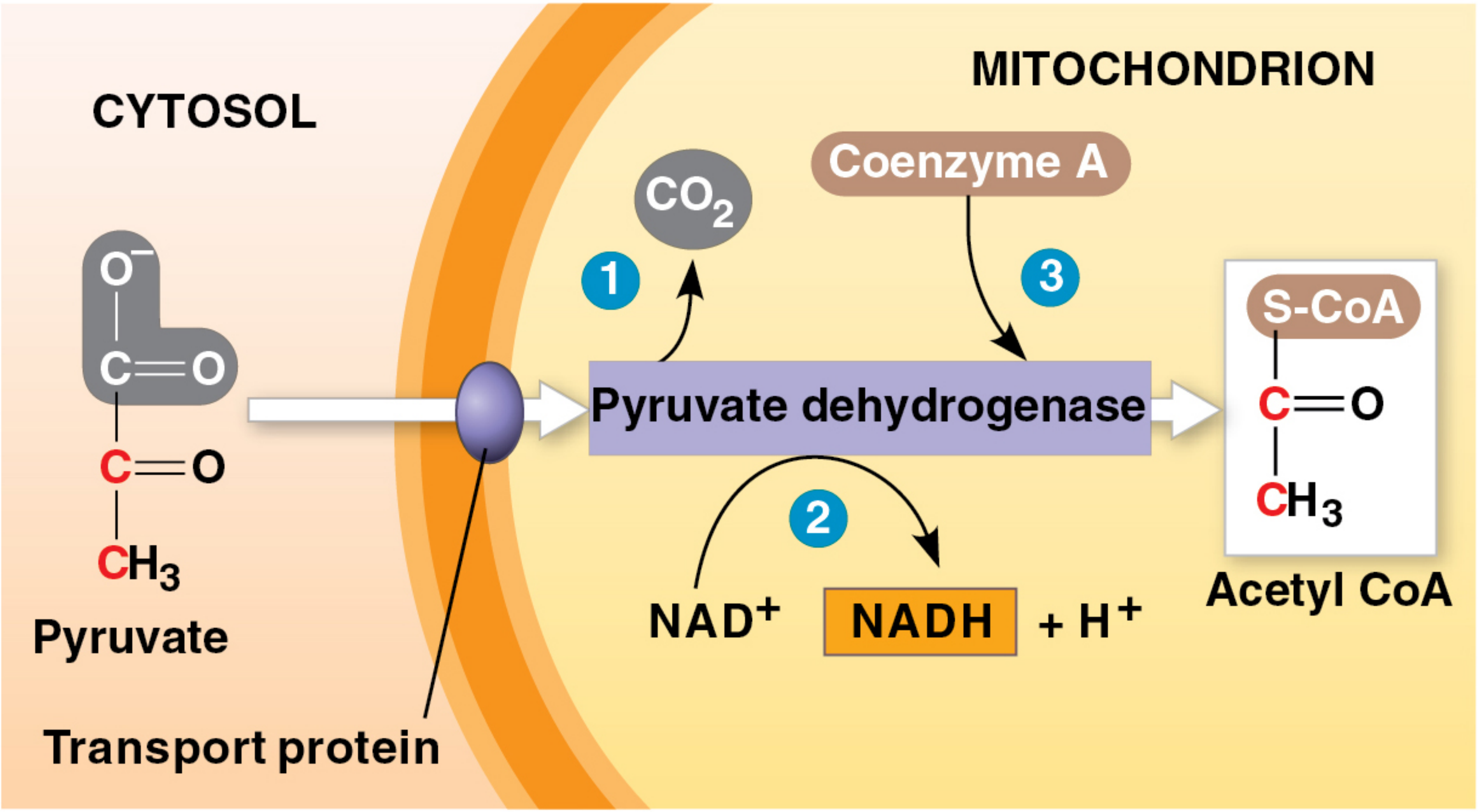


Figure 9.UN08



Pyruvate dehydrogenase

Figure 9.9



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

BioFlix Animation: Acetyl CoA

The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn
- Another 2 CO_2 are produced as a waste product
- Because 2 pyruvate are produced per glucose, the cycle runs twice per glucose molecule consumed

Figure 9.UN09

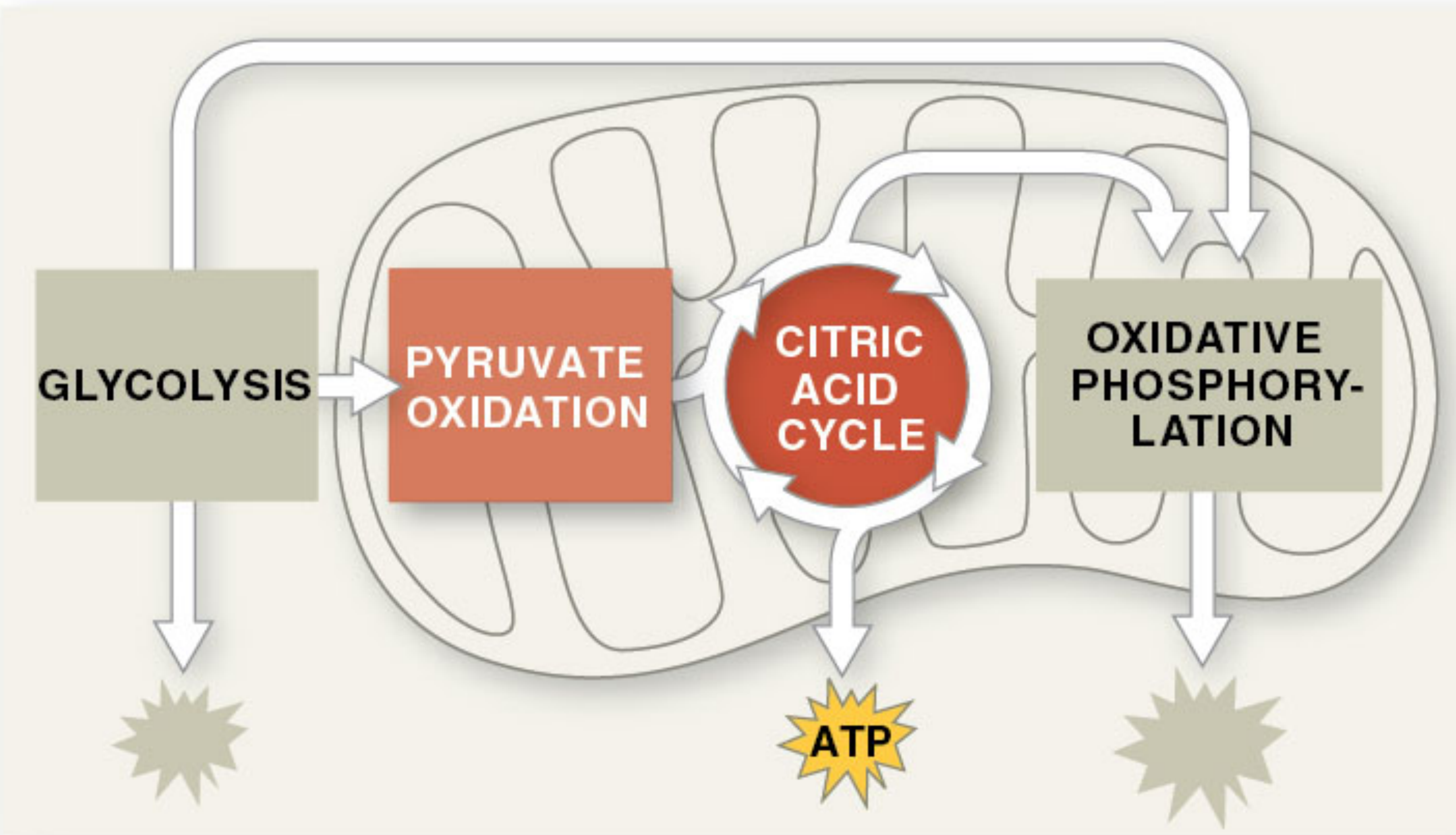
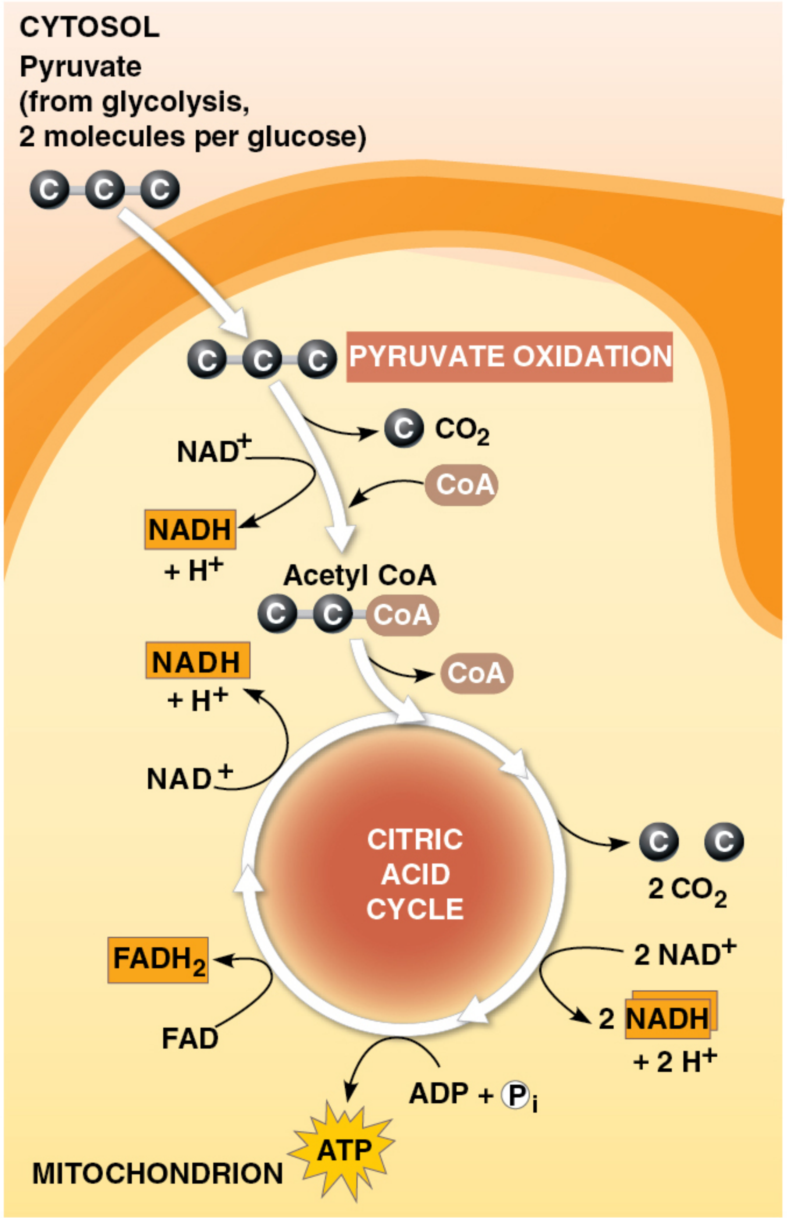
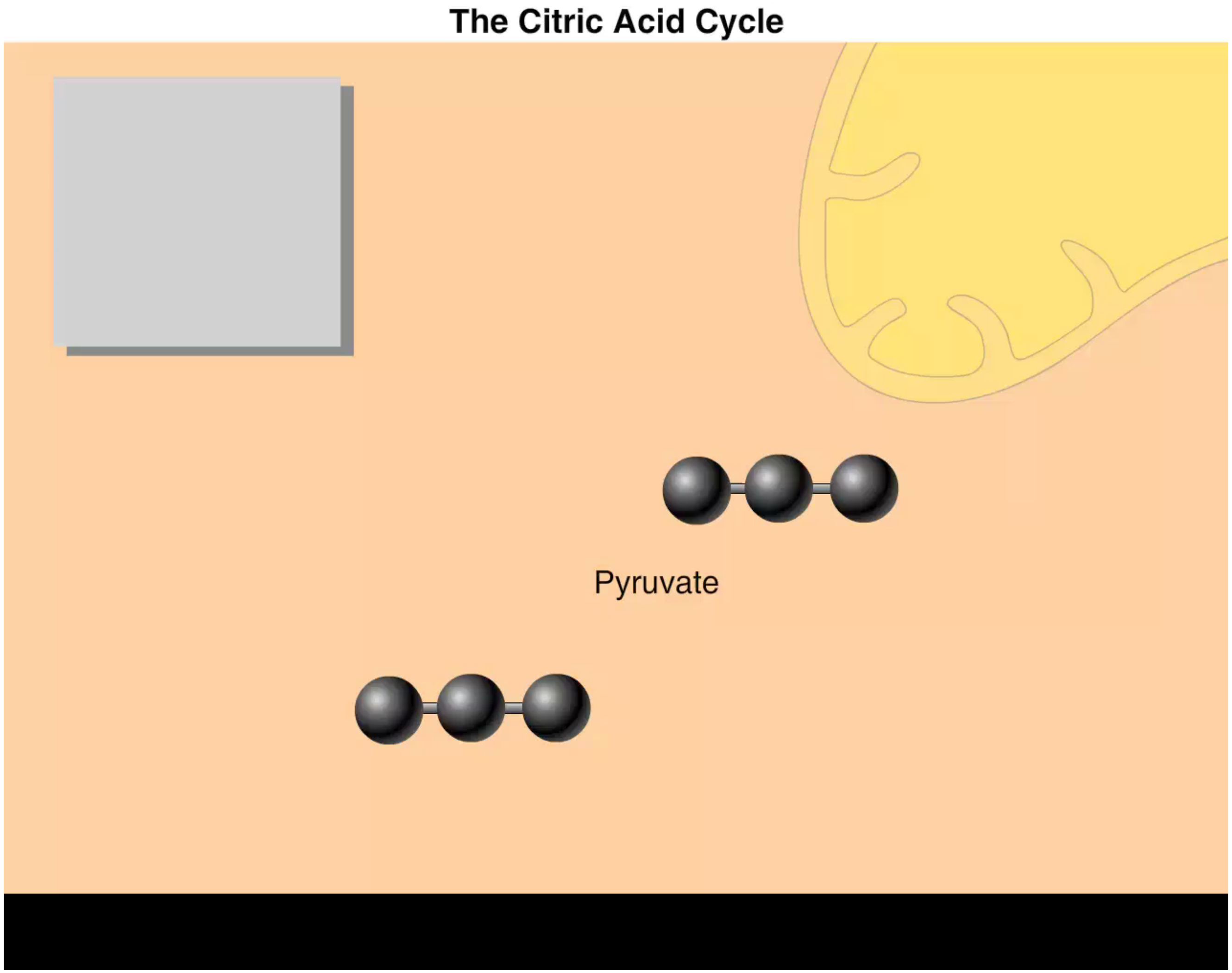


Figure 9.10



CYTOSOL
Pyruvate
(from glycolysis,
2 molecules per glucose)
C C C
C C C
PYRUVATE OXIDATION
C CO_2
CoA
NAD^+
NADH
$+ H^+$
Acetyl CoA
C C CoA
NADH
$+ H^+$
CoA
NAD^+
CITRIC
ACID
CYCLE
C C
$2\ CO_2$
$2\ NAD^+$
2 NADH
$+ 2\ H^+$
$FADH_2$
FAD
ADP + P_i
ATP
MITOCHONDRION

Animation: The Citric Acid Cycle



- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- First 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 carry electrons to the electron transport chain

Figure 9.UN10

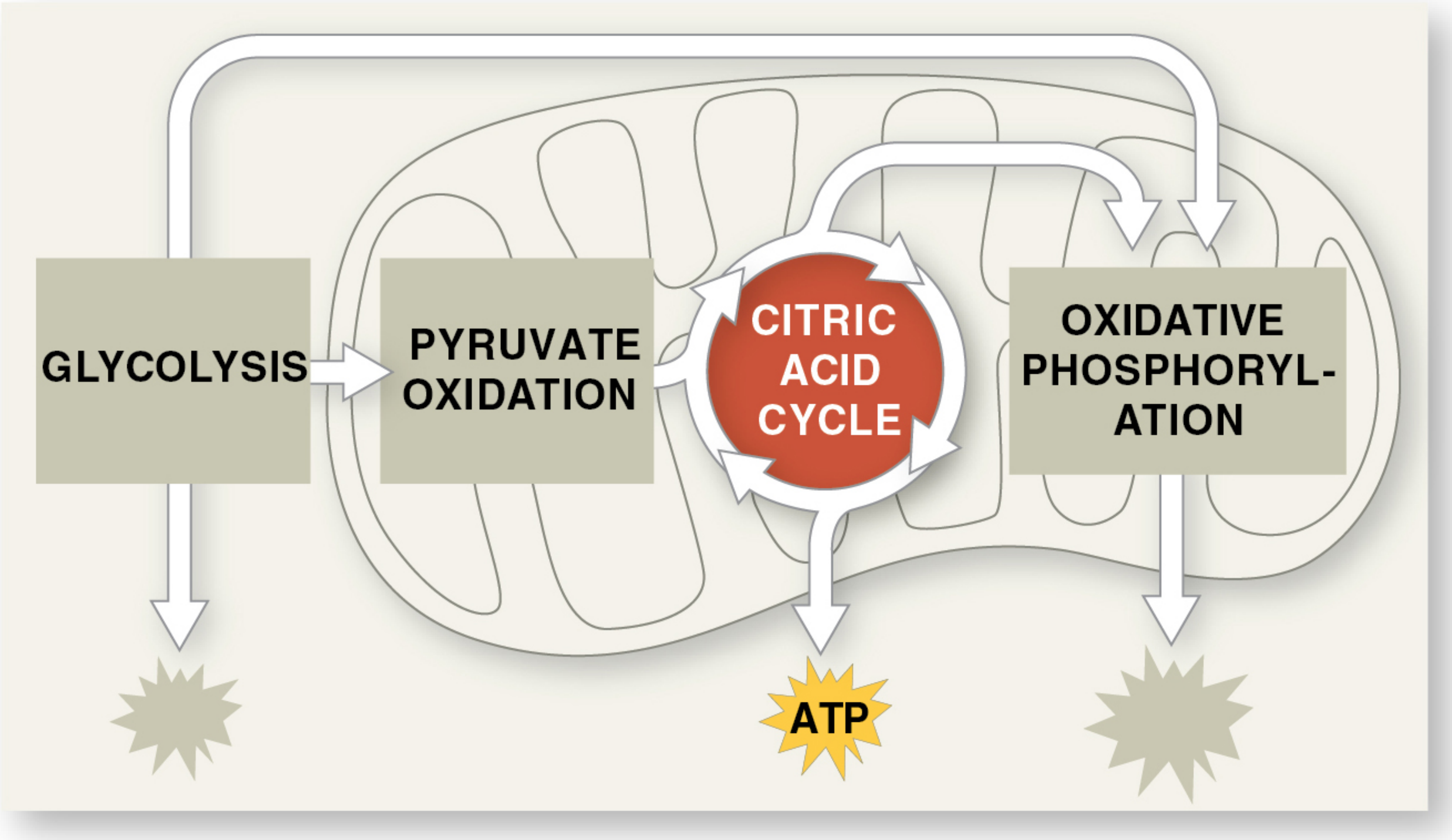
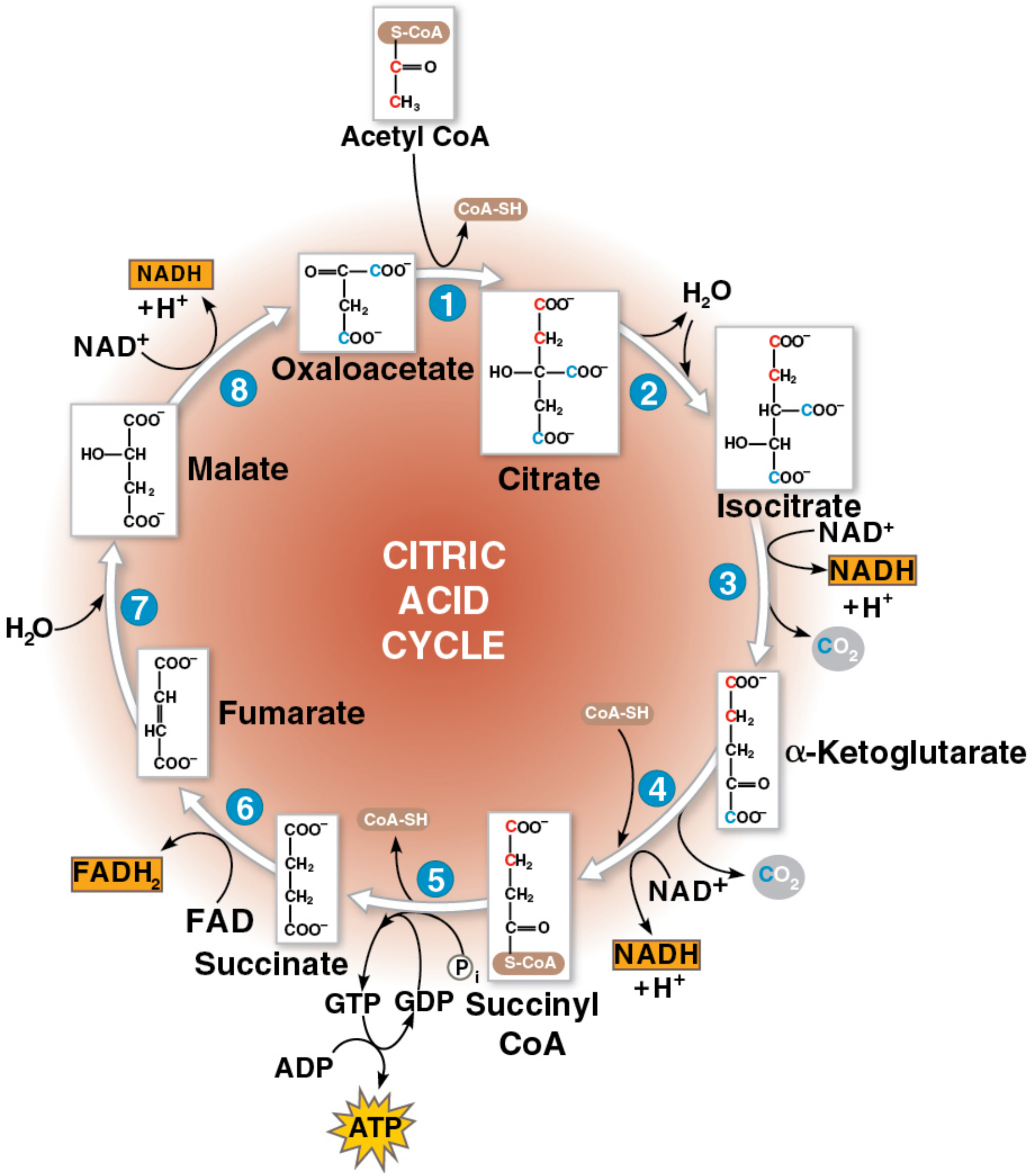


Figure 9.11



S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
NADH
+H+
NAD+
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
8
COO−
HO—CH
CH2
COO−
Malate
CITRIC
ACID
CYCLE
NAD+
NADH
+H+
3
CO2
H2O
7
COO−
CH
HC
COO−
Fumarate
CoA-SH
COO−
CH2
CH2
C=O
COO−
α-Ketoglutarate
4
6
CoA-SH
FADH2
COO−
CH2
CH2
COO−
5
COO−
CH2
CH2
C=O
S-CoA
CO2
NAD+
FAD
Succinate
Pi
NADH
+H+
GTP
GDP
Succinyl
CoA
ADP
ATP

BioFlix® Animation: The Citric Acid Cycle

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

- Molecules of NADH and $FADH_2$ produced during glycolysis and the citric acid cycle account for most of the energy extracted from glucose
- NADH and $FADH_2$ donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation

The Pathway of Electron Transport

- Molecules of the electron transport chain are embedded in the inner mitochondrial membrane in eukaryotic cells
- The membrane is folded into cristae to increase surface area for electron transport chains
- In prokaryotes, the electron transport chain is embedded in the plasma membrane

- Most of the molecules in the electron transport chain are proteins, which exist in multiprotein complexes
- NADH and $FADH_2$ donate electrons to different electron acceptors early in the chain
- Electrons are passed through a number of carrier molecules including several **cytochromes** (proteins with heme groups containing an iron atom)
- Electron carriers alternate between reduced and oxidized states as they accept and donate electrons

- Electrons drop in free energy as they are transferred down the chain, finally passing to O_2 to form H_2O
- The electron transport chain breaks the large free-energy drop from glucose to O_2 into smaller steps, releasing energy in manageable amounts
- No ATP is produced directly by the chain

Figure 9.UN11

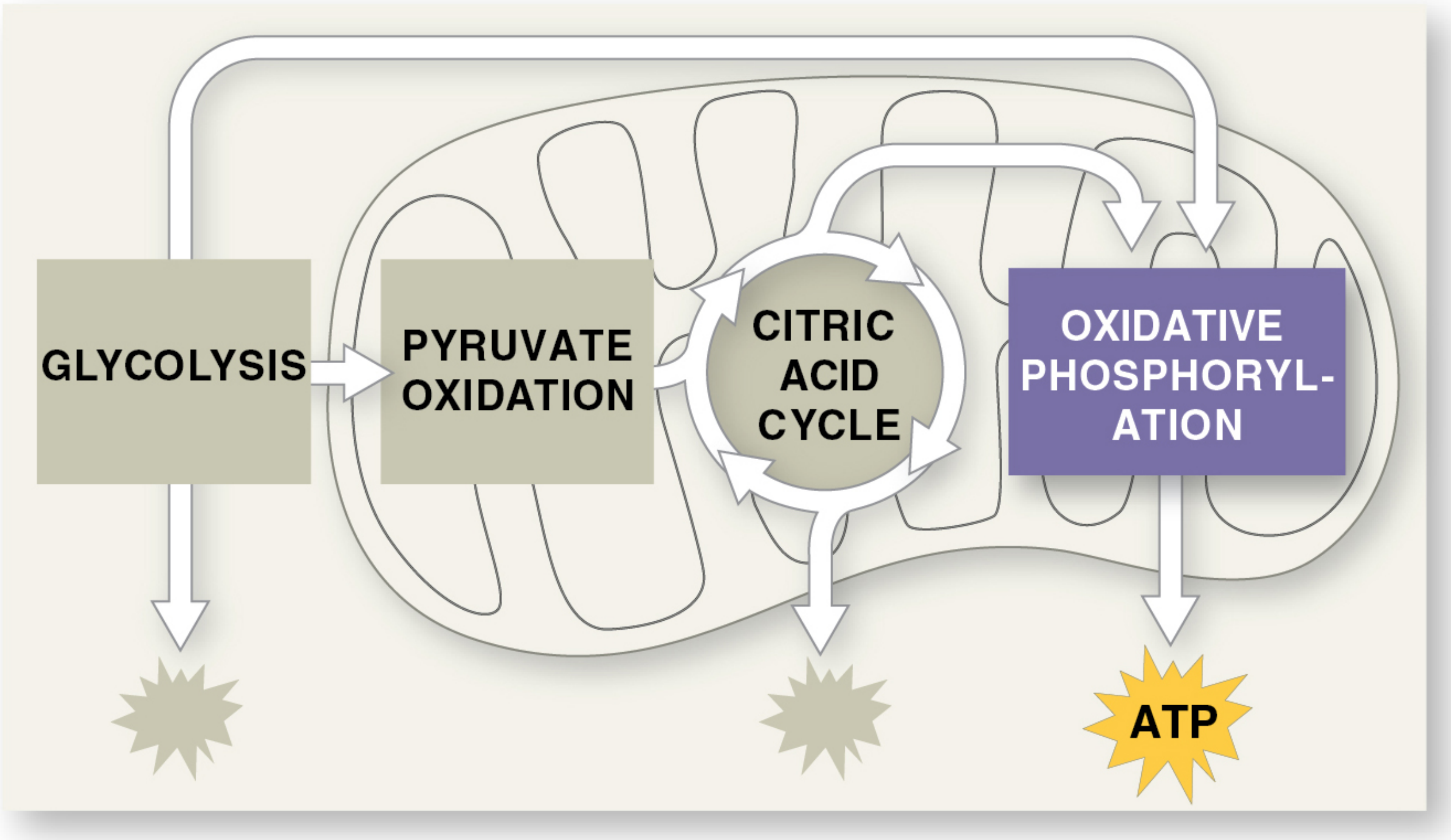
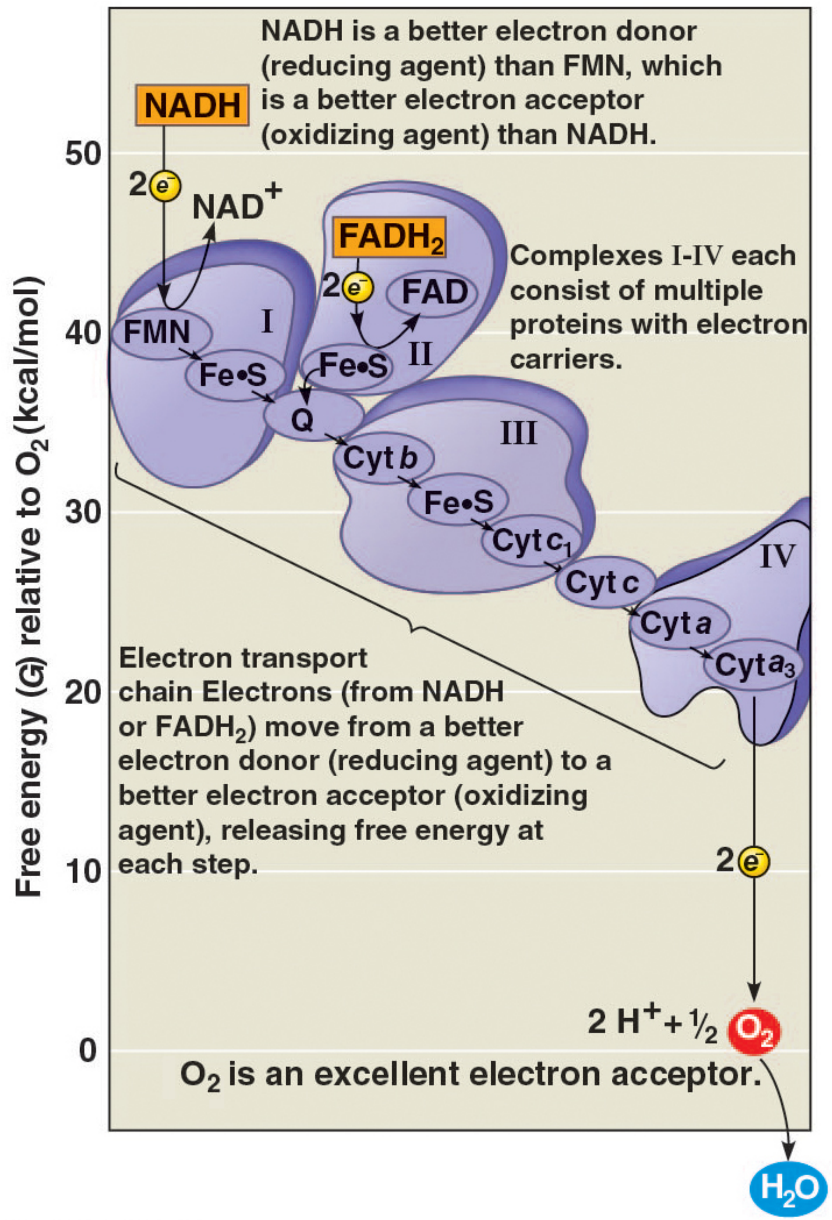


Figure 9.12



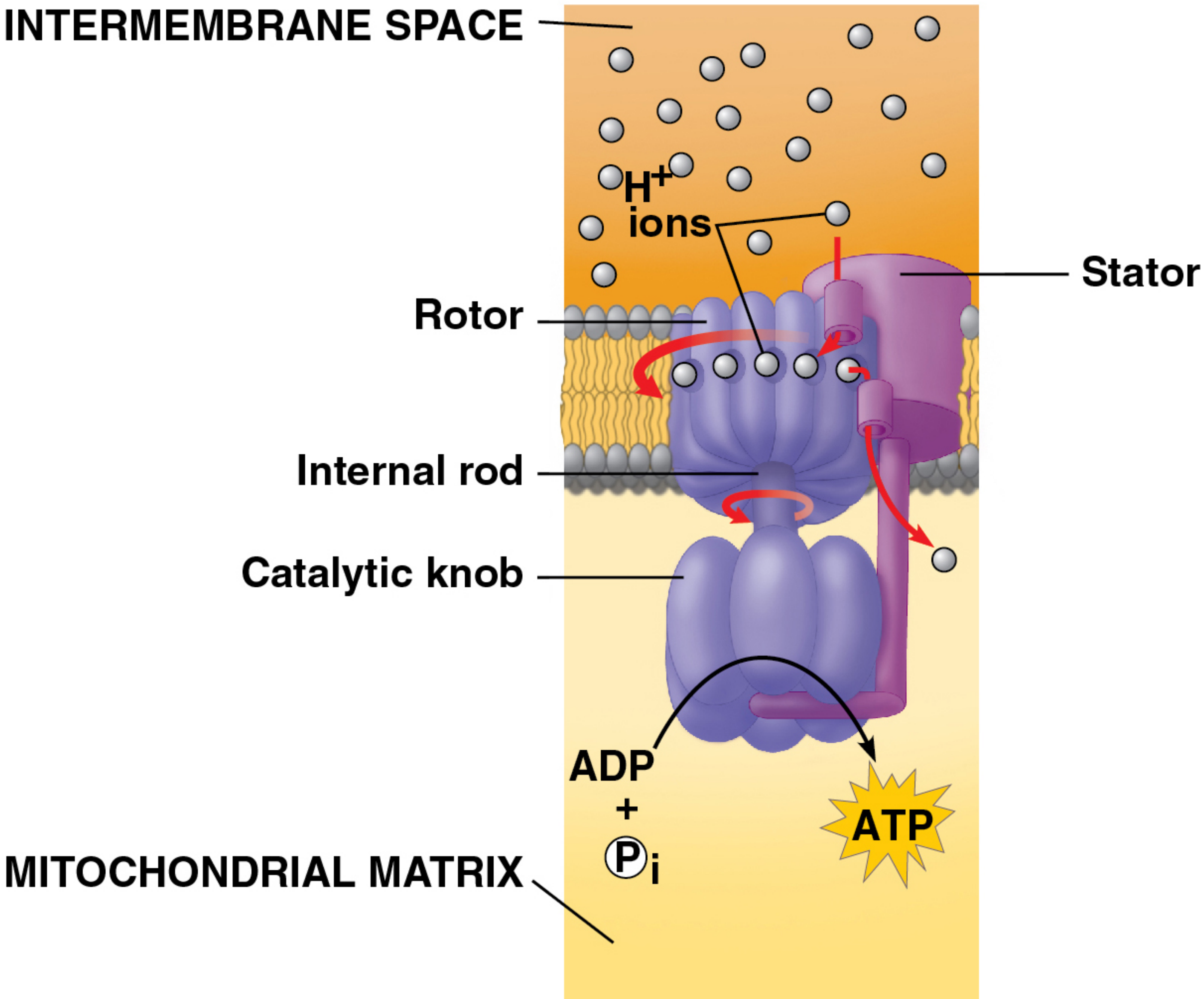
NADH is a better electron donor (reducing agent) than FMN, which is a better electron acceptor (oxidizing agent) than NADH.
NADH
50
40
30
20
10
0
Free energy (G) relative to O_2 (kcal/mol)
$2e^-$
NAD^+
$FADH_2$
$2e^-$
FAD
FMN
I
Fe•S
Fe•S
II
Q
III
Cyt *b*
Fe•S
Cyt c_1
Cyt *c*
IV
Cyt *a*
Cyt a_3
Complexes I-IV each consist of multiple proteins with electron carriers.
Electron transport chain Electrons (from NADH or $FADH_2$) move from a better electron donor (reducing agent) to a better electron acceptor (oxidizing agent), releasing free energy at each step.
$2e^-$
$2 H^+ + \frac{1}{2} O_2$
O_2 is an excellent electron acceptor.
H_2O

Chemiosmosis: The Energy-Coupling Mechanism

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

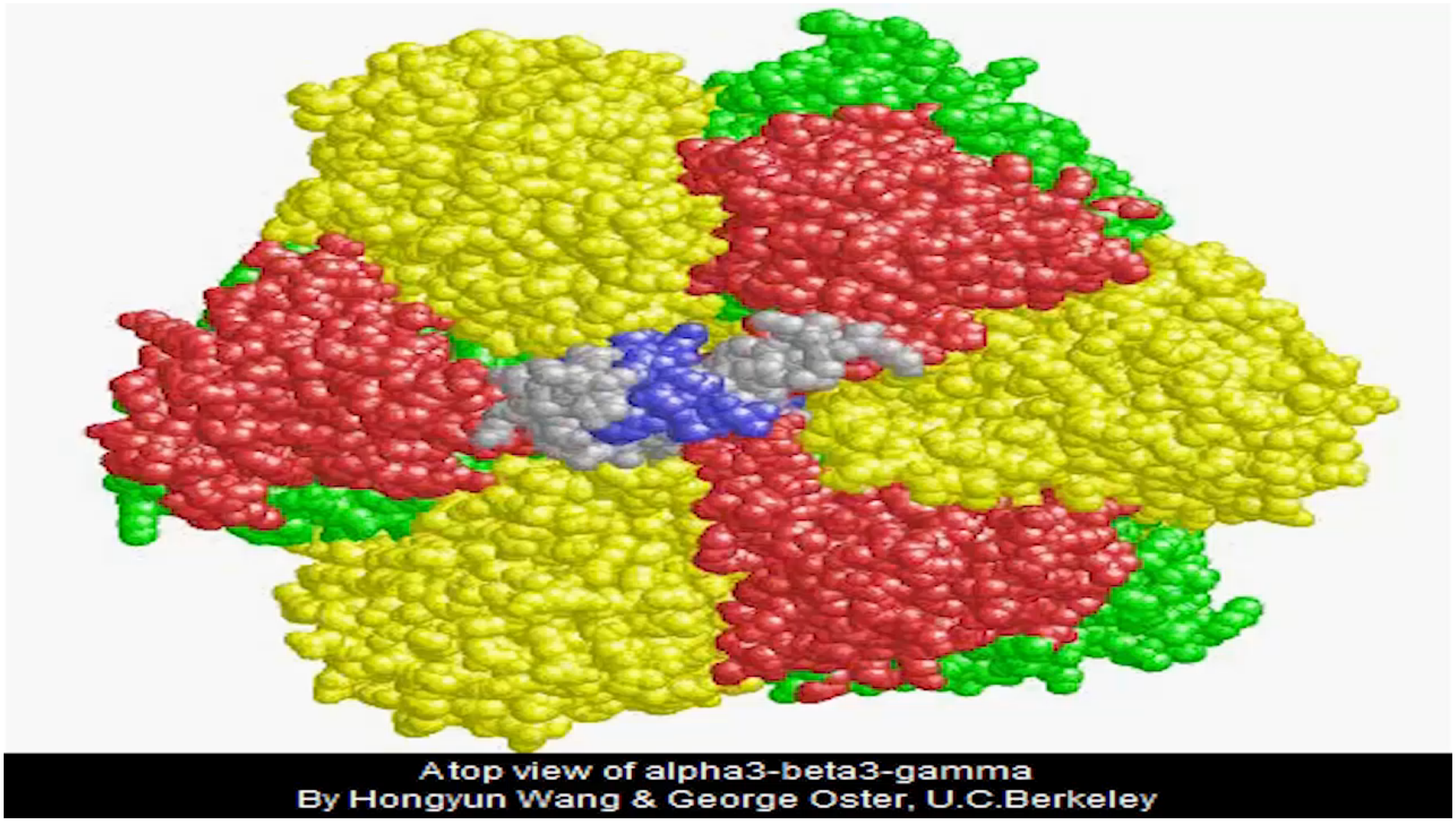
- H^+ moves into binding sites on the rotor of ATP synthase, causing it to spin in a way that catalyzes phosphorylation of ADP to ATP
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive cellular work

Figure 9.13

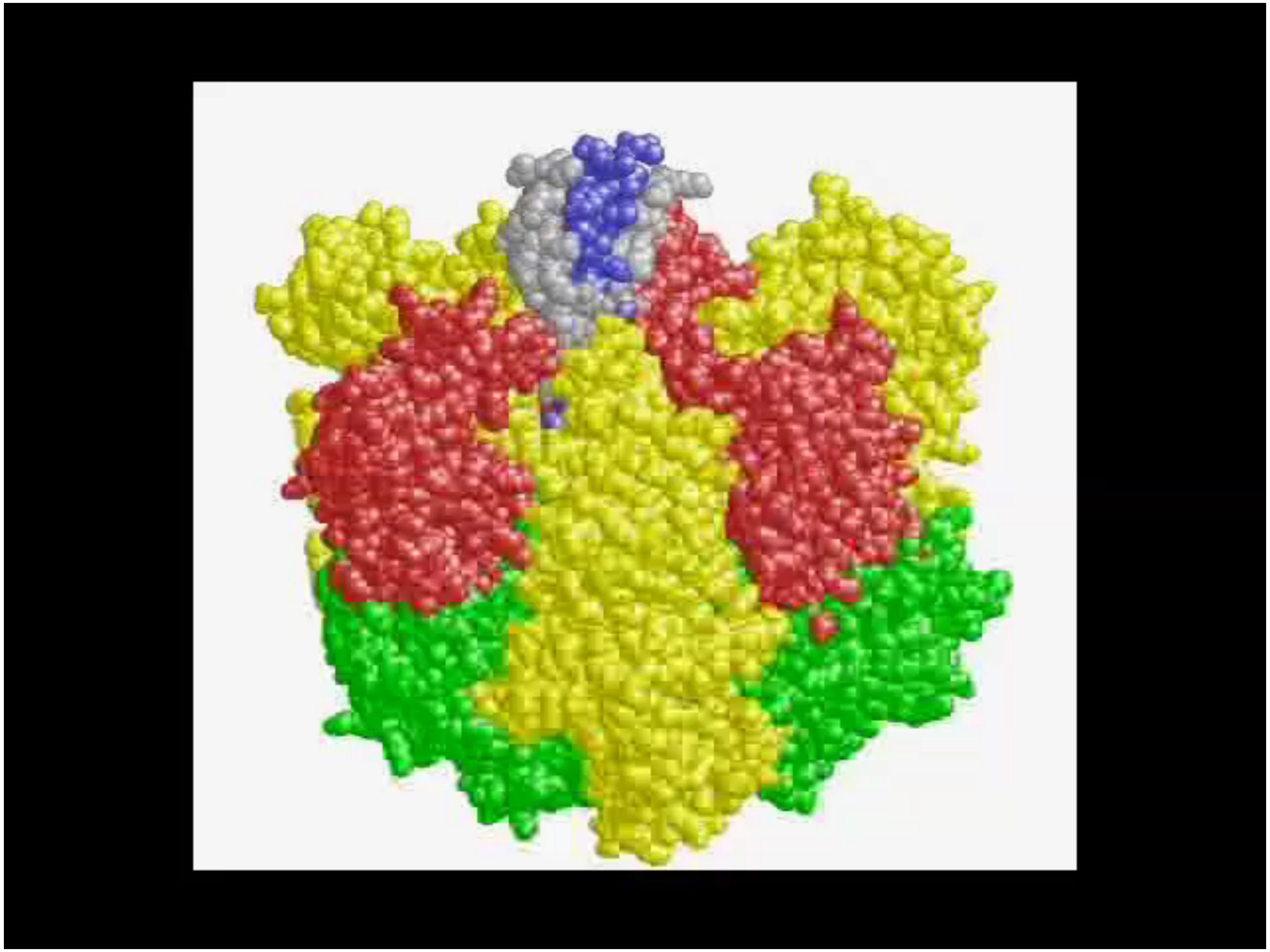


INTERMEMBRANE SPACE
H+ ions
Stator
Rotor
Internal rod
Catalytic knob
ADP
+
Ⓟi
ATP
MITOCHONDRIAL MATRIX

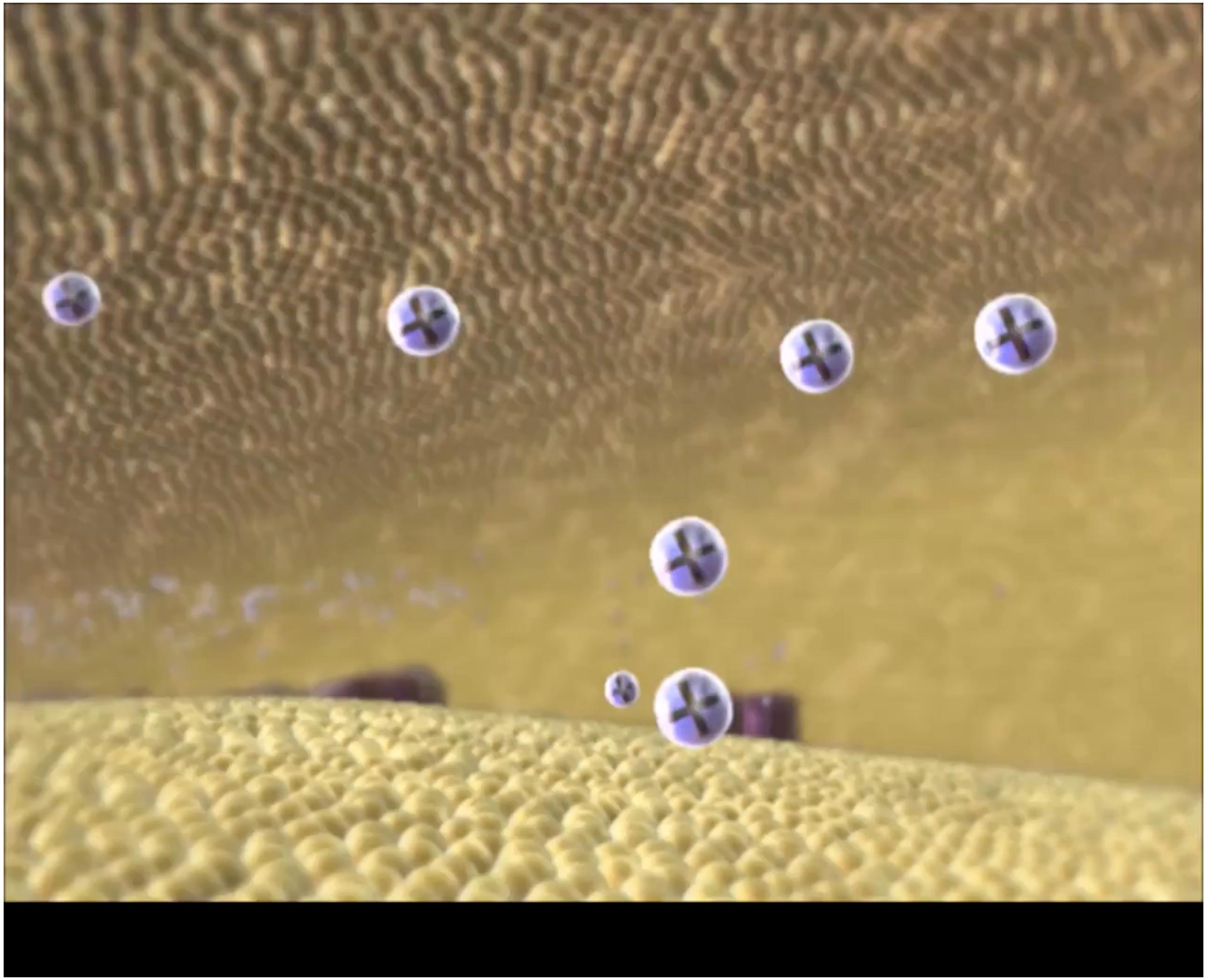
Video: ATP Synthase 3-D Structure, Top View



Video: ATP Synthase 3-D Structure, Side View



BioFlix Animation: ATP Synthase



- Certain electron carriers in the electron transport chain accept and release H^+ along with the electrons
- Maintaining the H^+ gradient couples redox reactions of the electron transport chain to ATP synthesis
- The H^+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

Figure 9.UN12

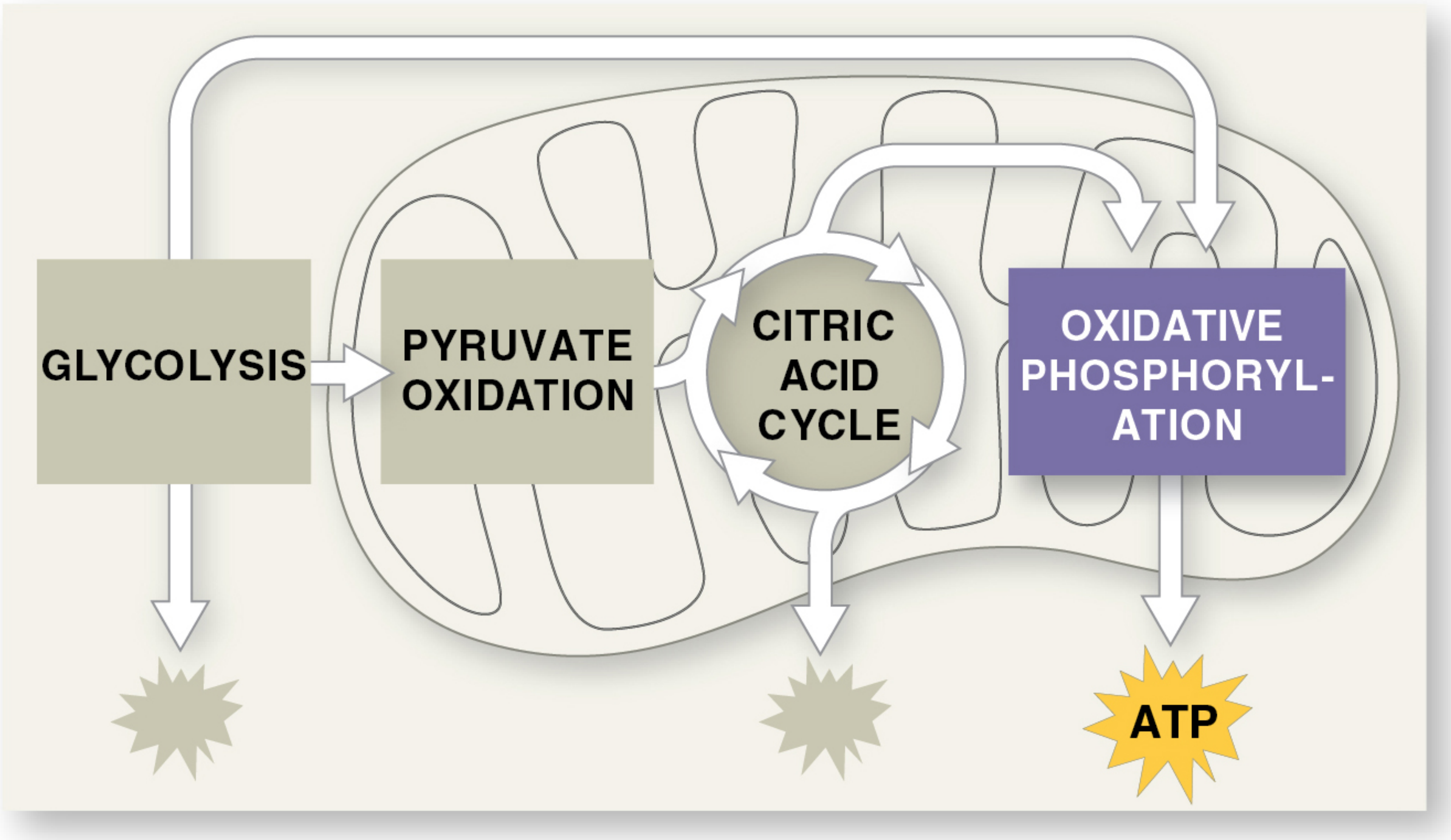
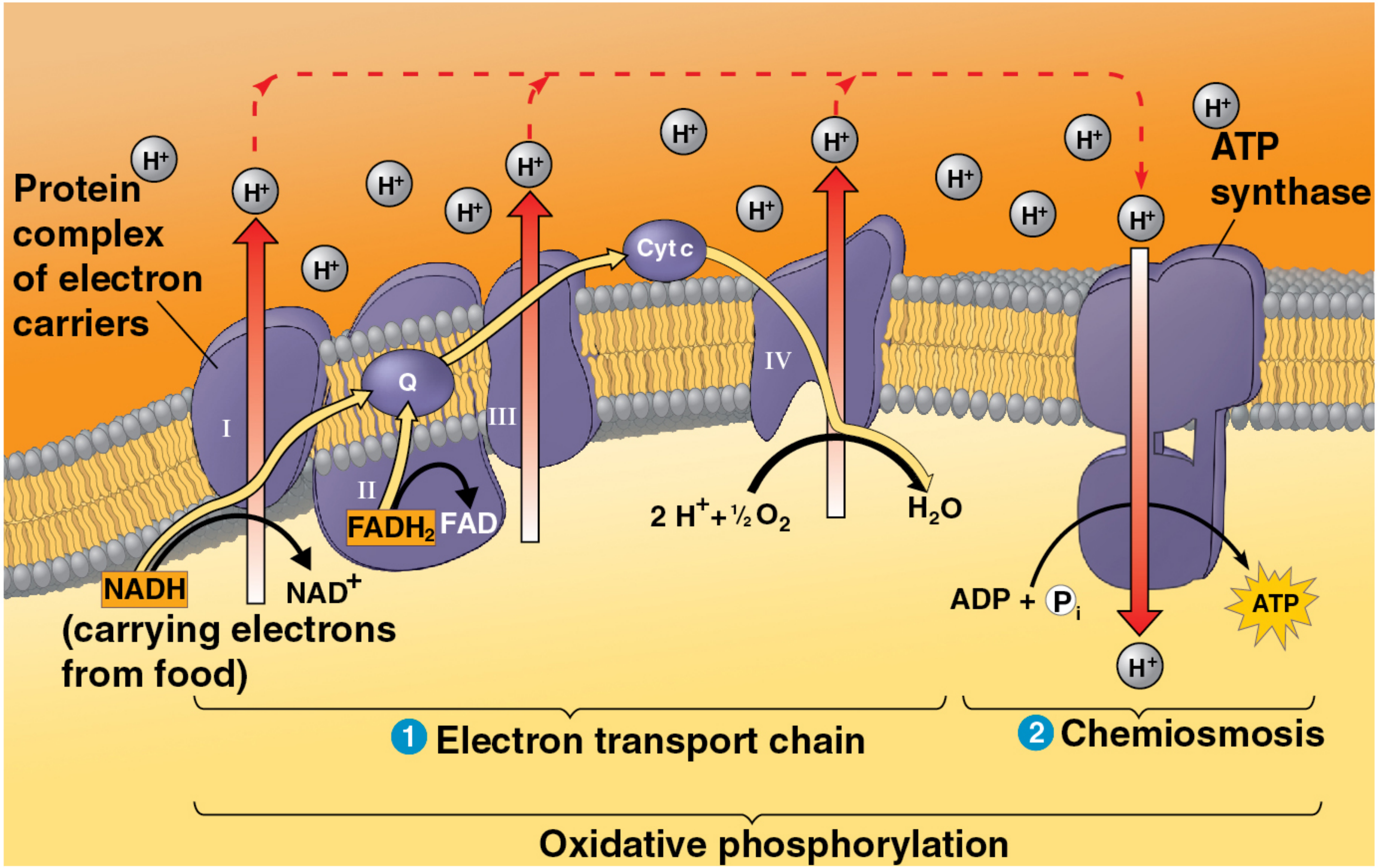


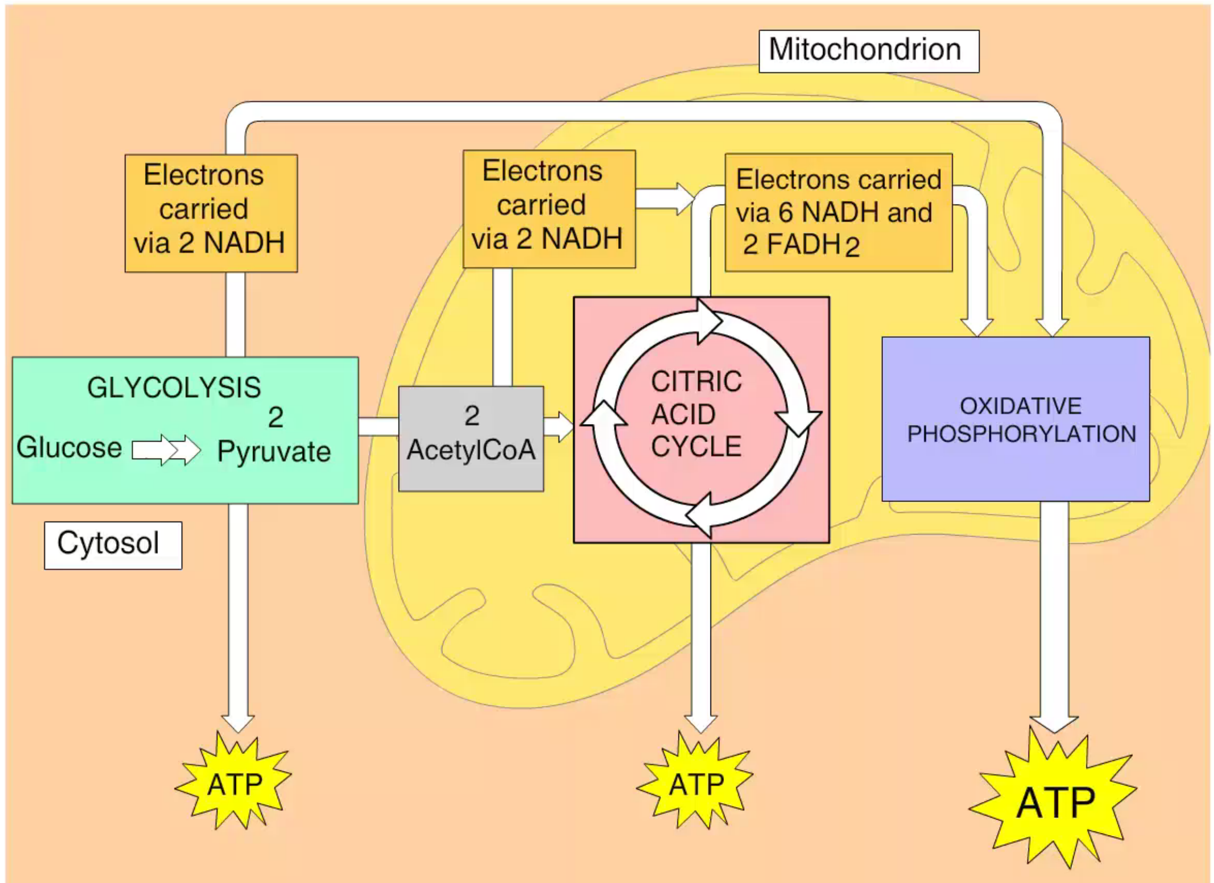
Figure 9.14



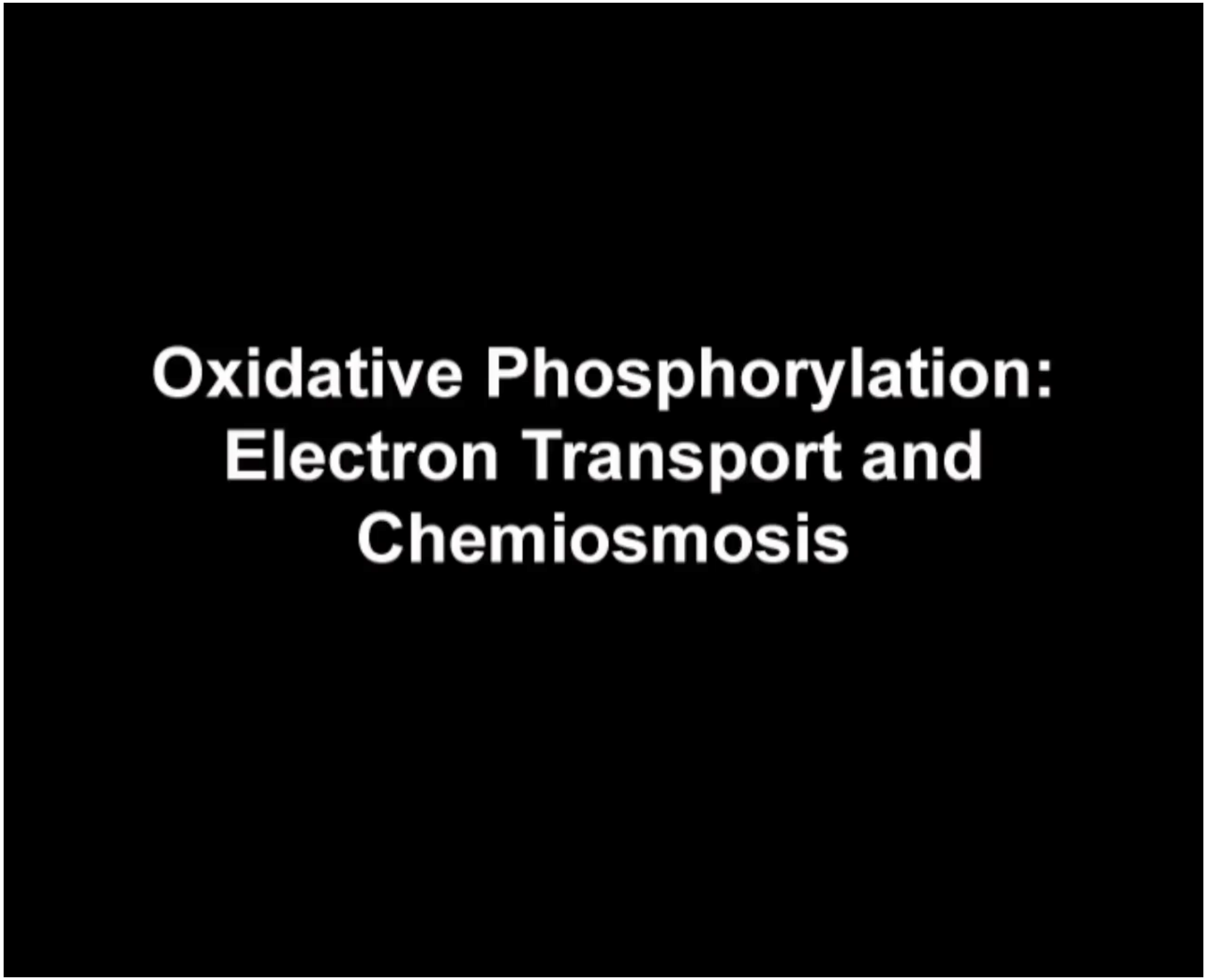
Protein complex of electron carriers
H+
I
II
III
IV
Q
Cyt c
ATP synthase
NADH
NAD+
(carrying electrons from food)
FADH2
FAD
2 H+ + ½ O2
H2O
ADP + P i
ATP
1 Electron transport chain
2 Chemiosmosis
Oxidative phosphorylation

Animation: Electron Transport

Electron Transport



BioFlix® Animation: Electron Transport



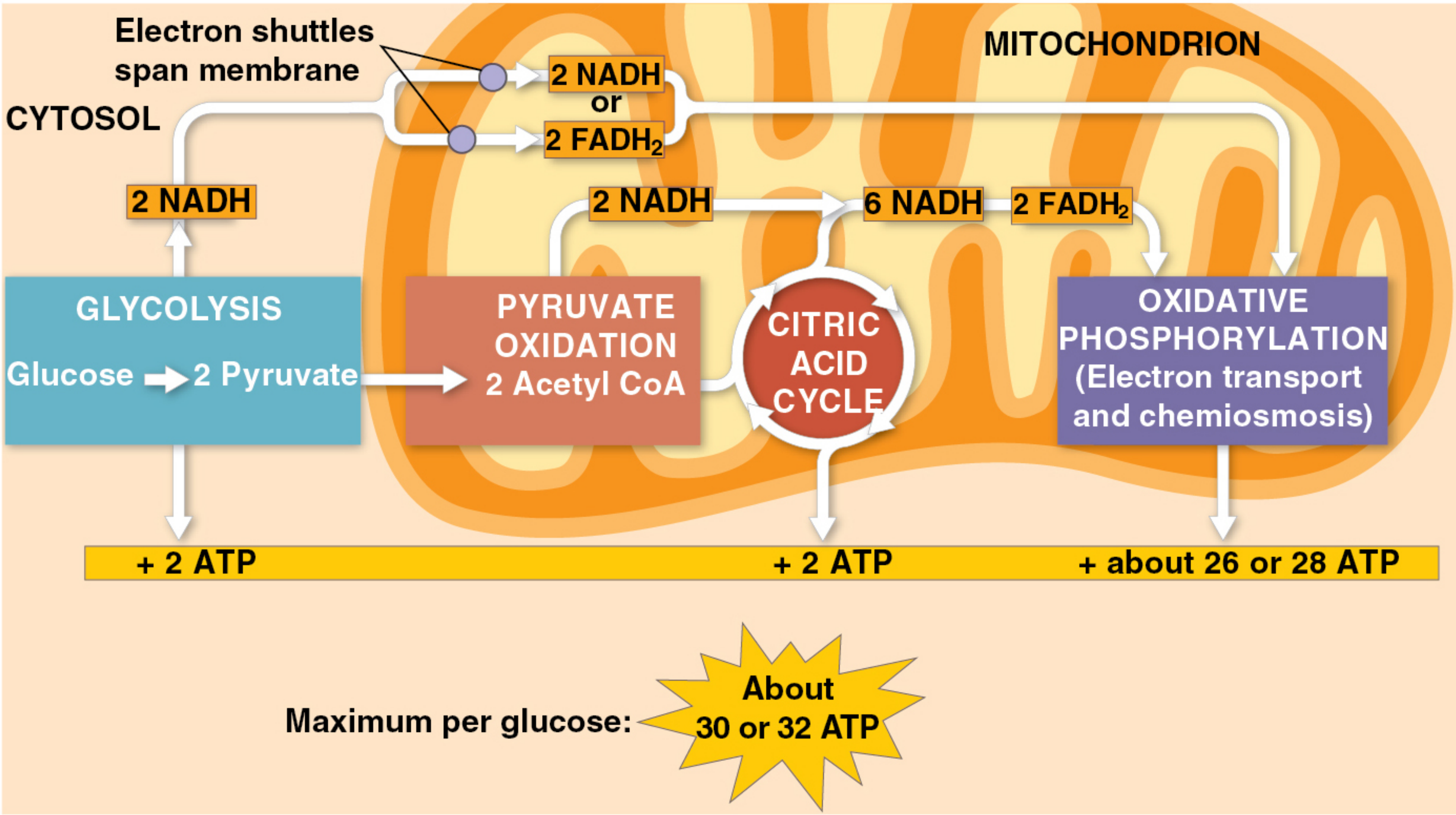
An Accounting of ATP Production by Cellular Respiration

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

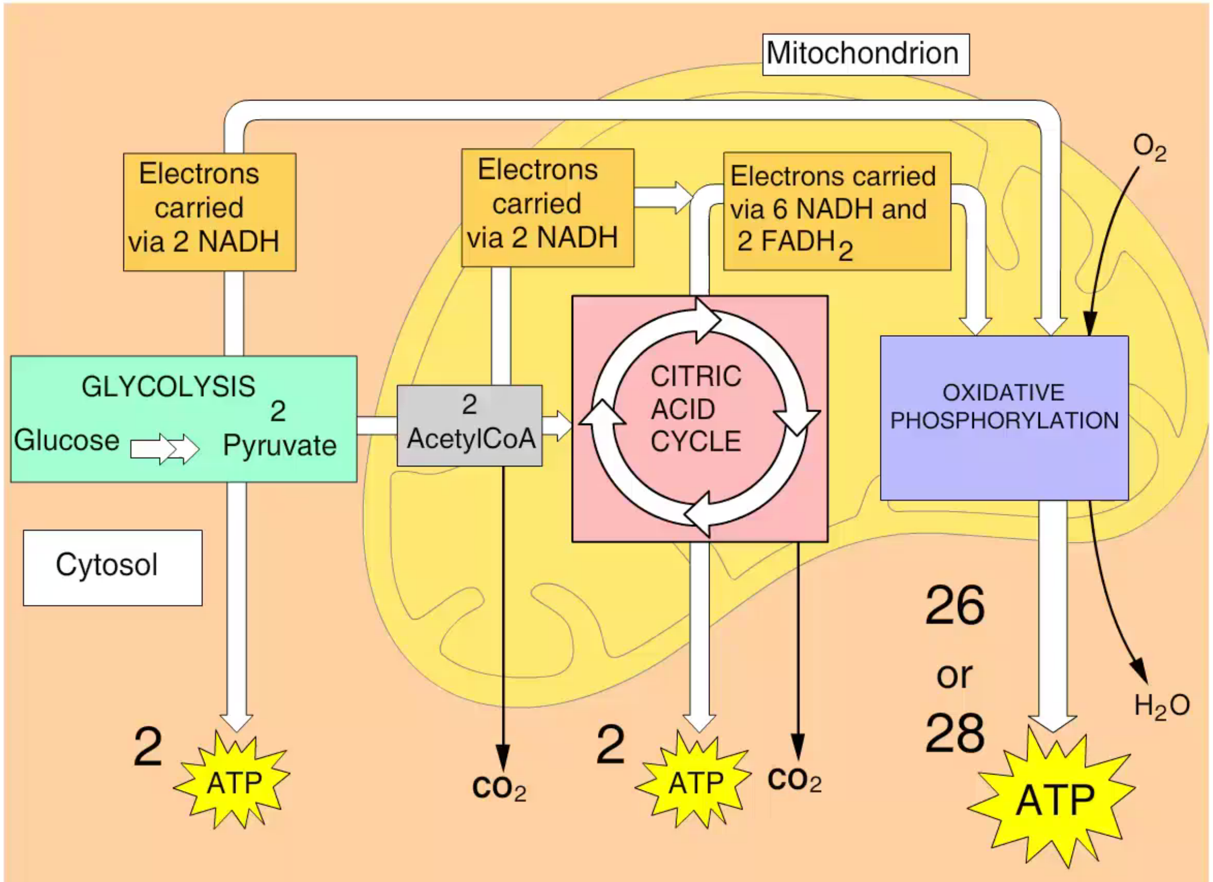
glucose → NADH → electron transport chain → proton-motive force → ATP

- About 34% of the energy in a glucose molecule is transferred to ATP, making about 32 ATP
- The rest of the energy is lost as heat

Figure 9.15

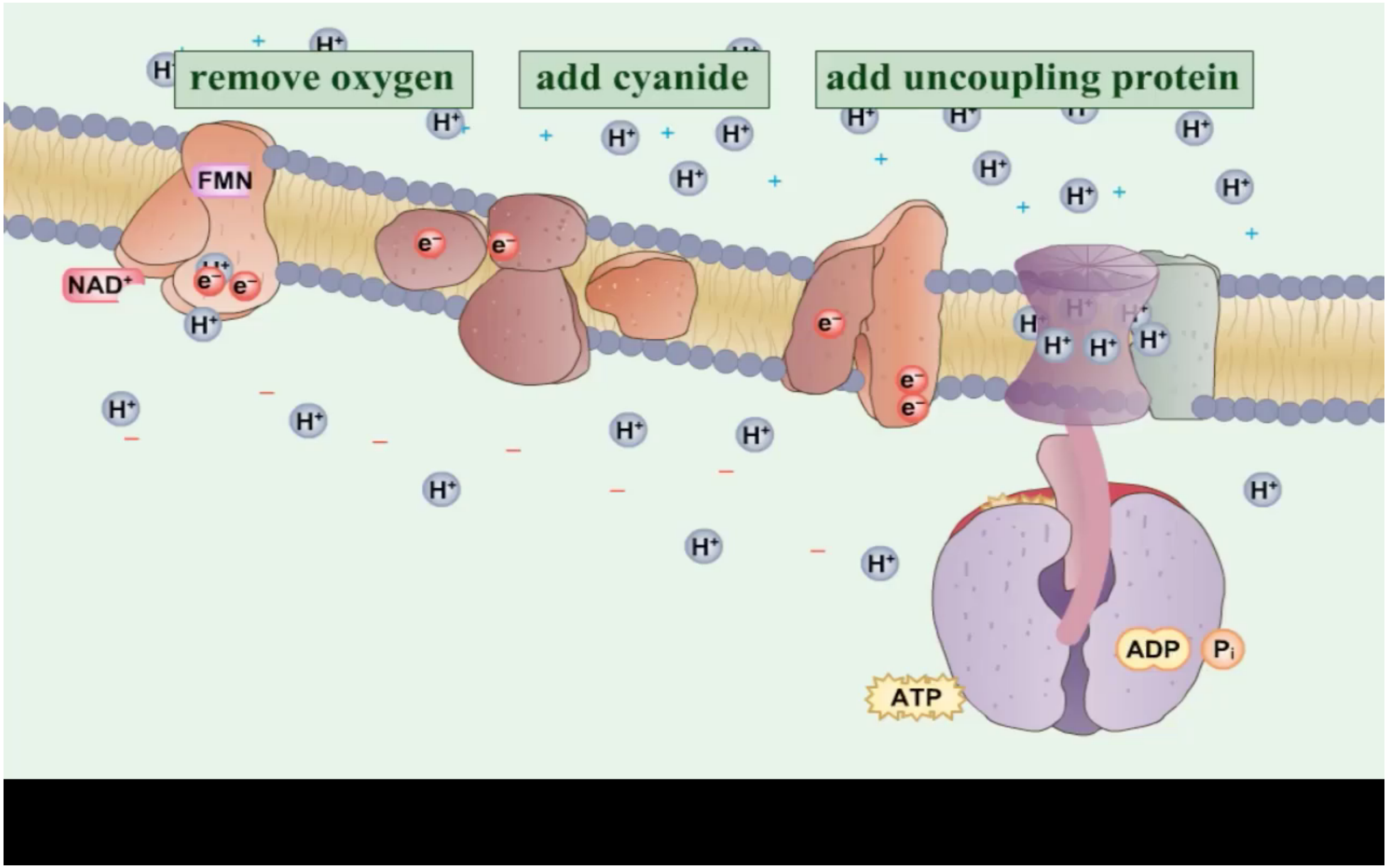

Electron shuttles
span membrane
MITOCHONDRION
CYTOSOL
2 NADH
or
2 FADH2
2 NADH
2 NADH
6 NADH
2 FADH2
GLYCOLYSIS
Glucose
2 Pyruvate
PYRUVATE
OXIDATION
2 Acetyl CoA
CITRIC
ACID
CYCLE
OXIDATIVE
PHOSPHORYLATION
(Electron transport
and chemiosmosis)
+ 2 ATP
+ 2 ATP
+ about 26 or 28 ATP
Maximum per glucose: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

Animation: ATP Yield from Cellular Respiration

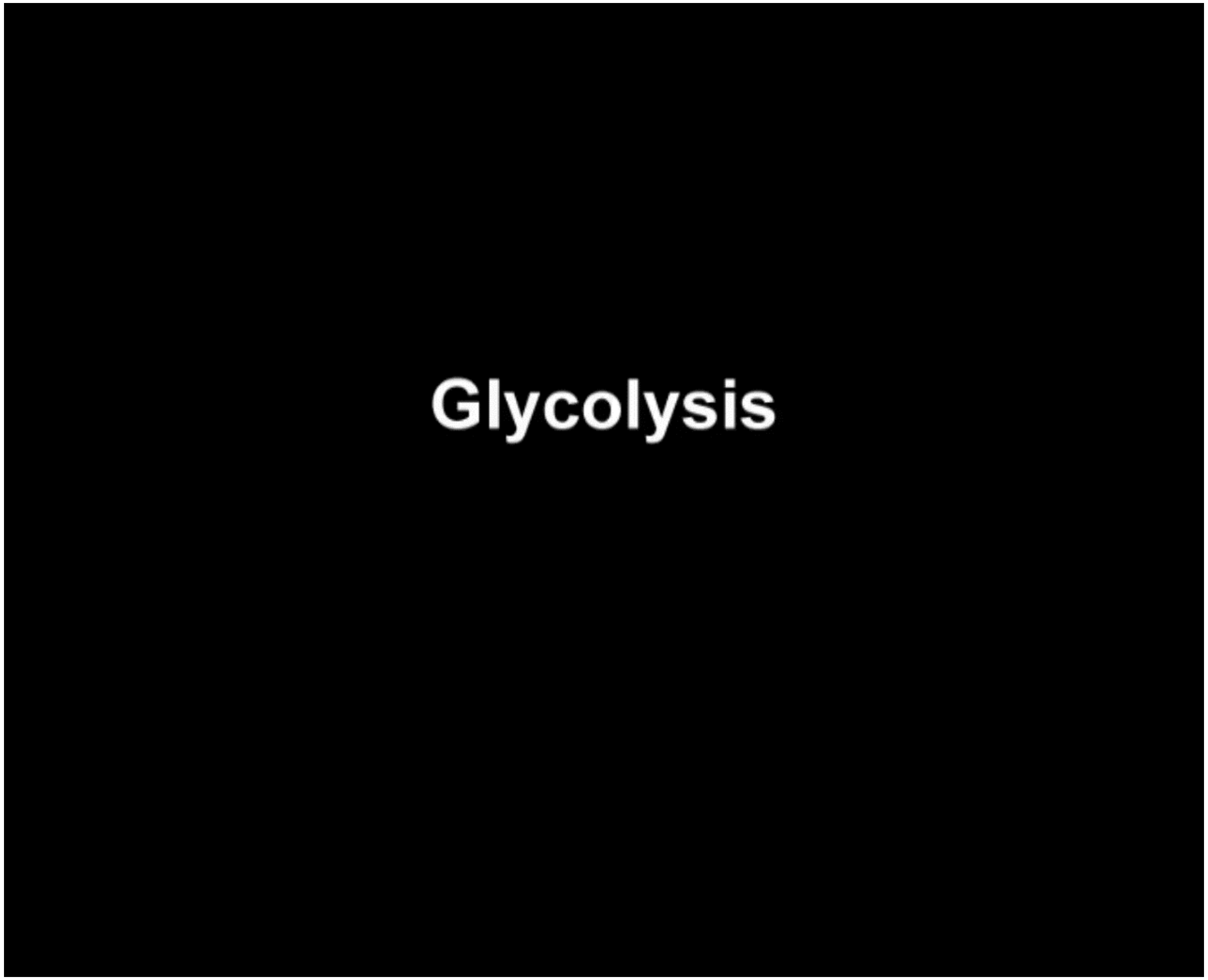


- There are three reasons why the exact number of ATP produced is not known
  1. Photophosphorylation and the redox reactions are not directly coupled; the ratio of NADH to ATP molecules is not a whole number
  2. ATP yield varies depending on whether electrons are passed to NAD^+ or FAD
  3. The proton-motive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

Animation: Electron Transport Chain: Factors Affecting ATP Yield



BioFlix® Animation: Cellular Respiration



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

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

- Anaerobic respiration uses an electron transport chain with a final electron acceptor other than oxygen
  - For example, some organisms use a sulfate ion (SO_4^{2-}) as a final electron acceptor
  - In this case, H_2S (hydrogen sulfide) is made as a by-product instead of H_2O

- Glycolysis oxidizes glucose to pyruvate without the involvement of O_2 or an electron transport chain
- NAD^+ is the oxidizing agent used in glycolysis
- Glycolysis produces 2 ATP (net) by substrate-level phosphorylation whether O_2 is present or not

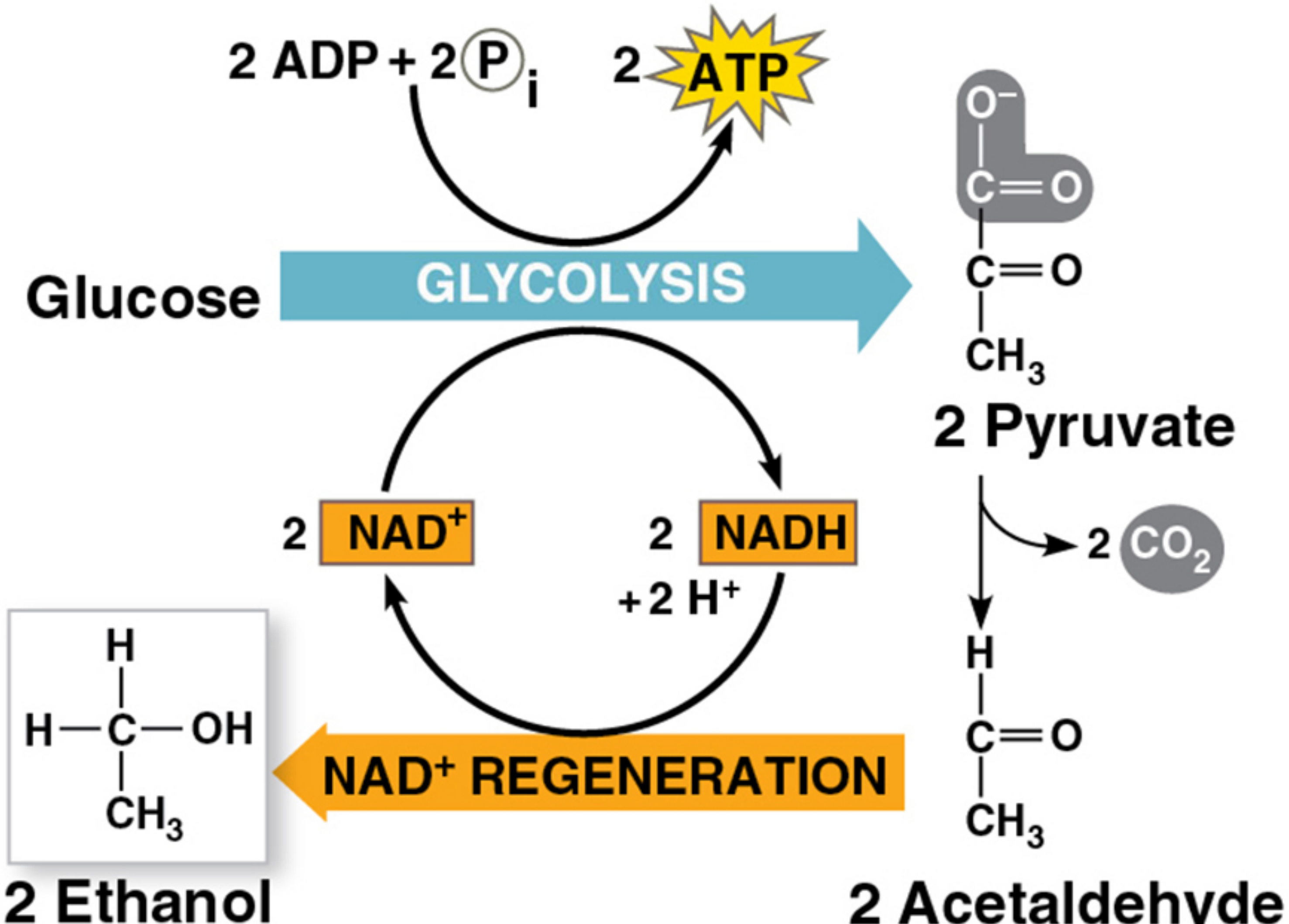
- Under aerobic conditions, NAD^+ is regenerated from NADH by transferring electrons to the electron transport chain
- Fermentation must use alternate mechanisms to regenerate NAD^+

Types of Fermentation

- Fermentation is an extension of glycolysis that oxidizes NADH by transferring electrons to pyruvate or its derivatives
- Two common types are alcohol fermentation and lactic acid fermentation

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

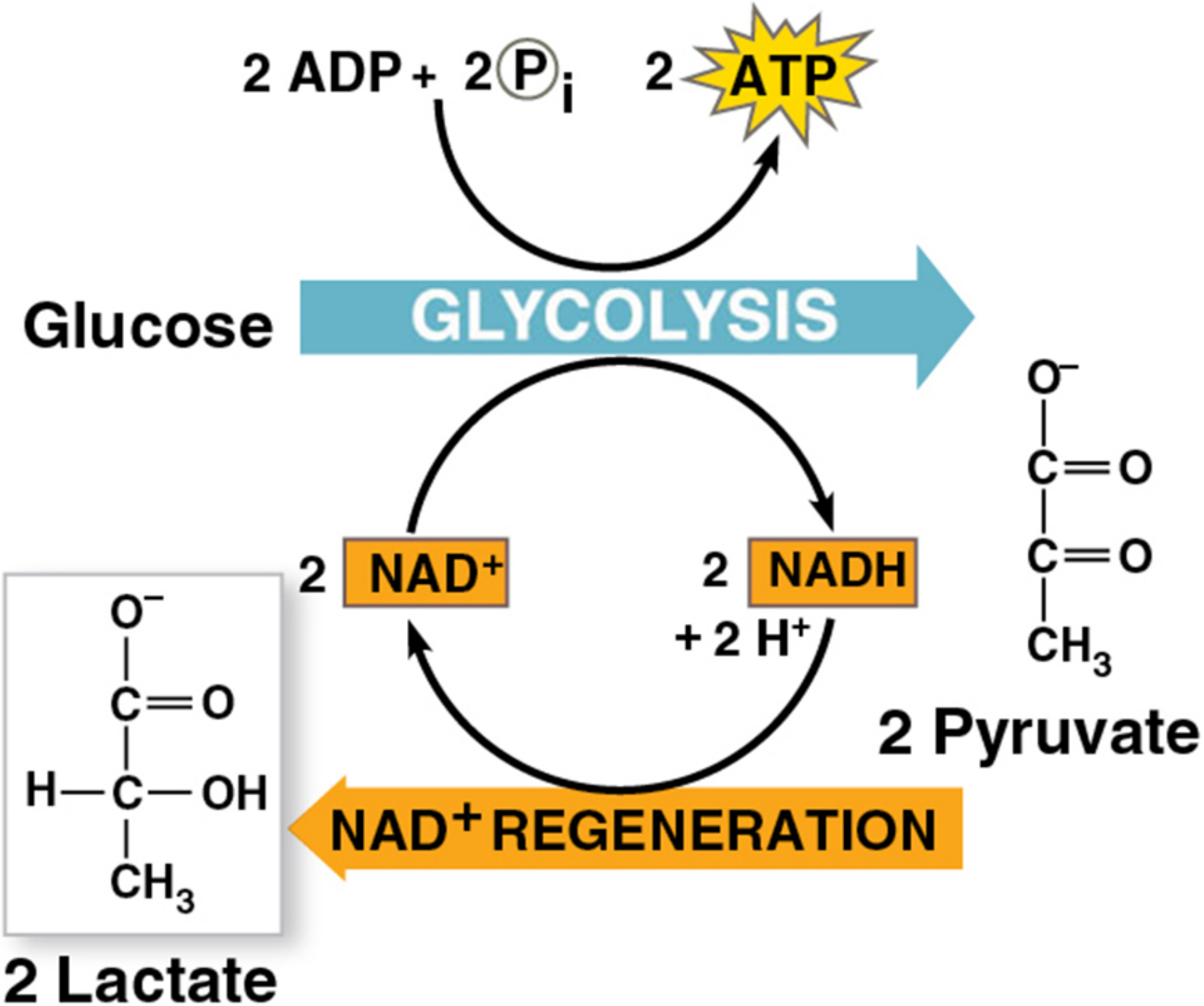
Figure 9.16a



(a) Alcohol fermentation

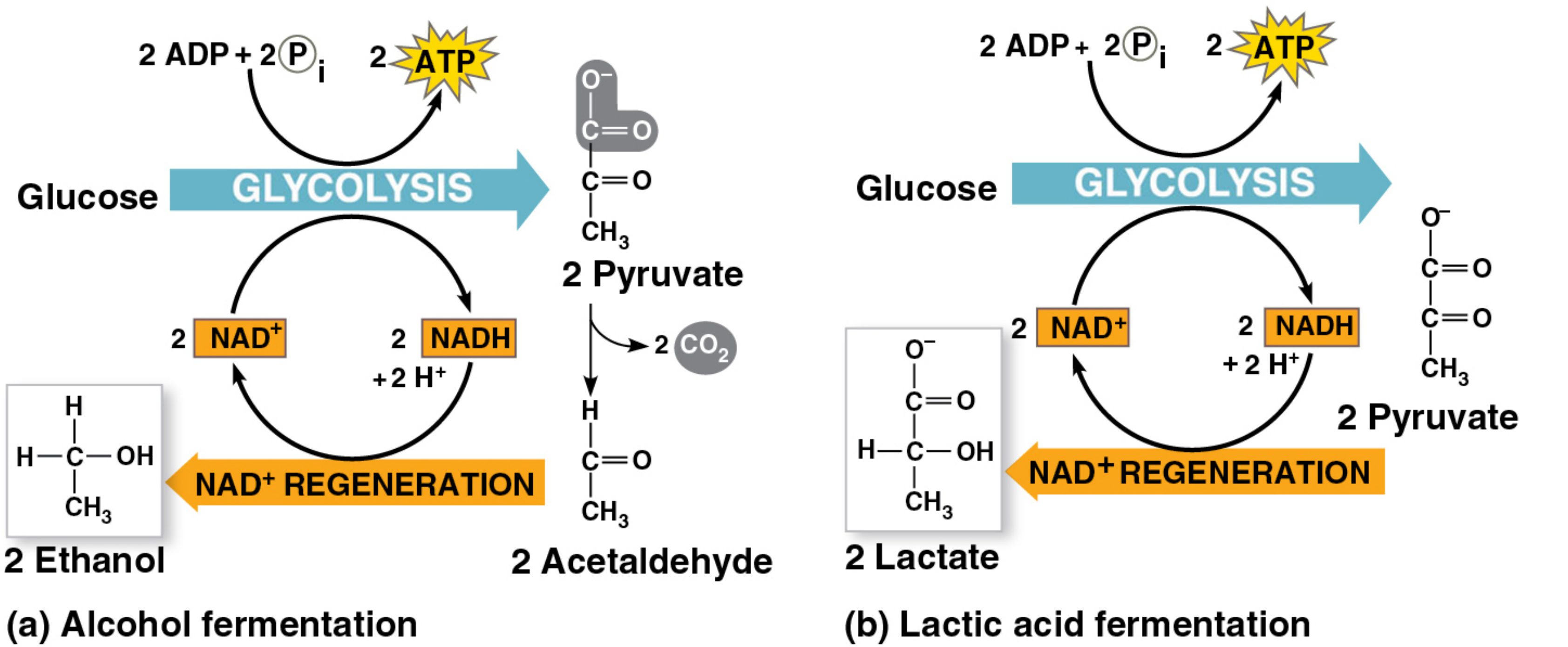
- In **lactic acid fermentation**, pyruvate is reduced directly by NADH to form lactate and NAD^+
- There is no release of CO_2 in lactic acid fermentation
- Lactic acid fermentation by fungi and bacteria is used to make cheese and yogurt

Figure 9.16b



(b) Lactic acid fermentation

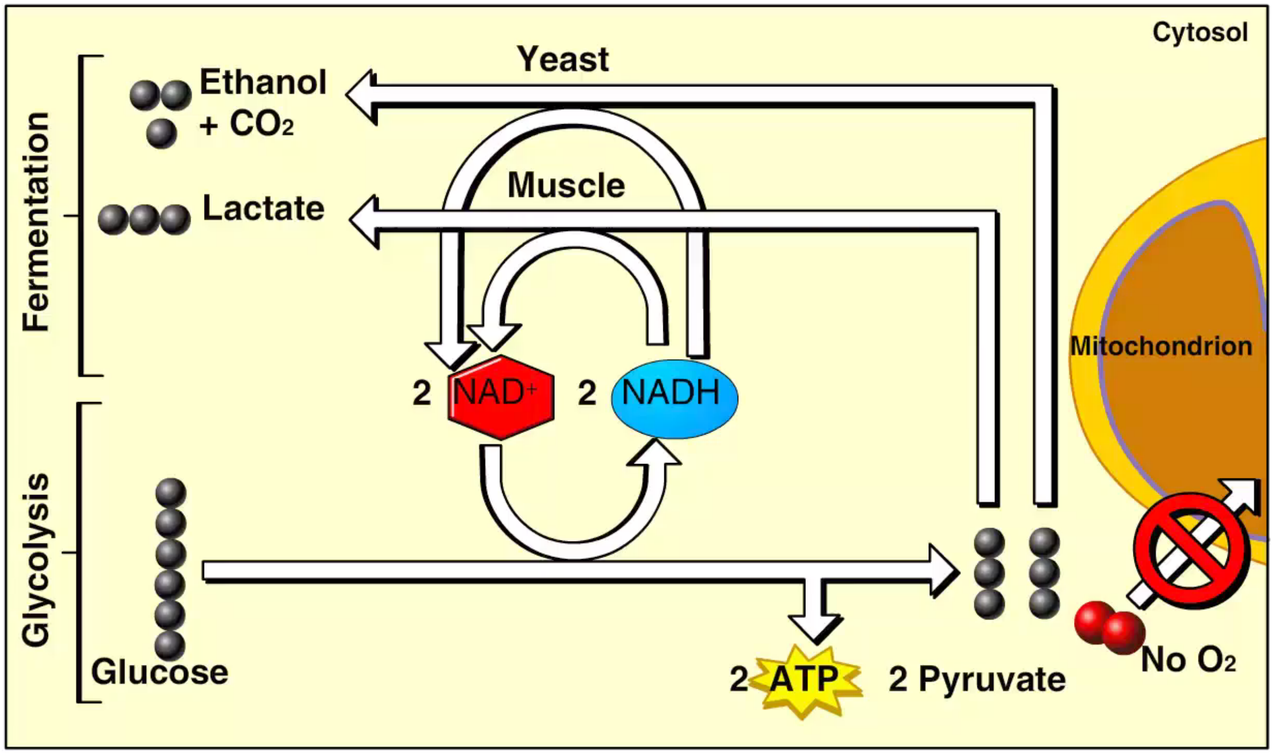
Figure 9.16



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

Animation: Fermentation

Fermentation



[redacted]

- A complex series of fermentation and aerobic respiration carried out by yeasts and bacteria on cacao beans is responsible for chocolate production

Figure 9.UN13

- Though previously thought that human muscle cells produced lactate only when O_2 was in short supply, recent research indicates a more complicated story
  - One type of skeletal muscle (red) oxidizes glucose completely to CO_2; the other (white) produces lactate even under aerobic conditions
  - The term fermentation is no longer used because lactate production is not anaerobic

Comparing Fermentation with Anaerobic and Aerobic Respiration

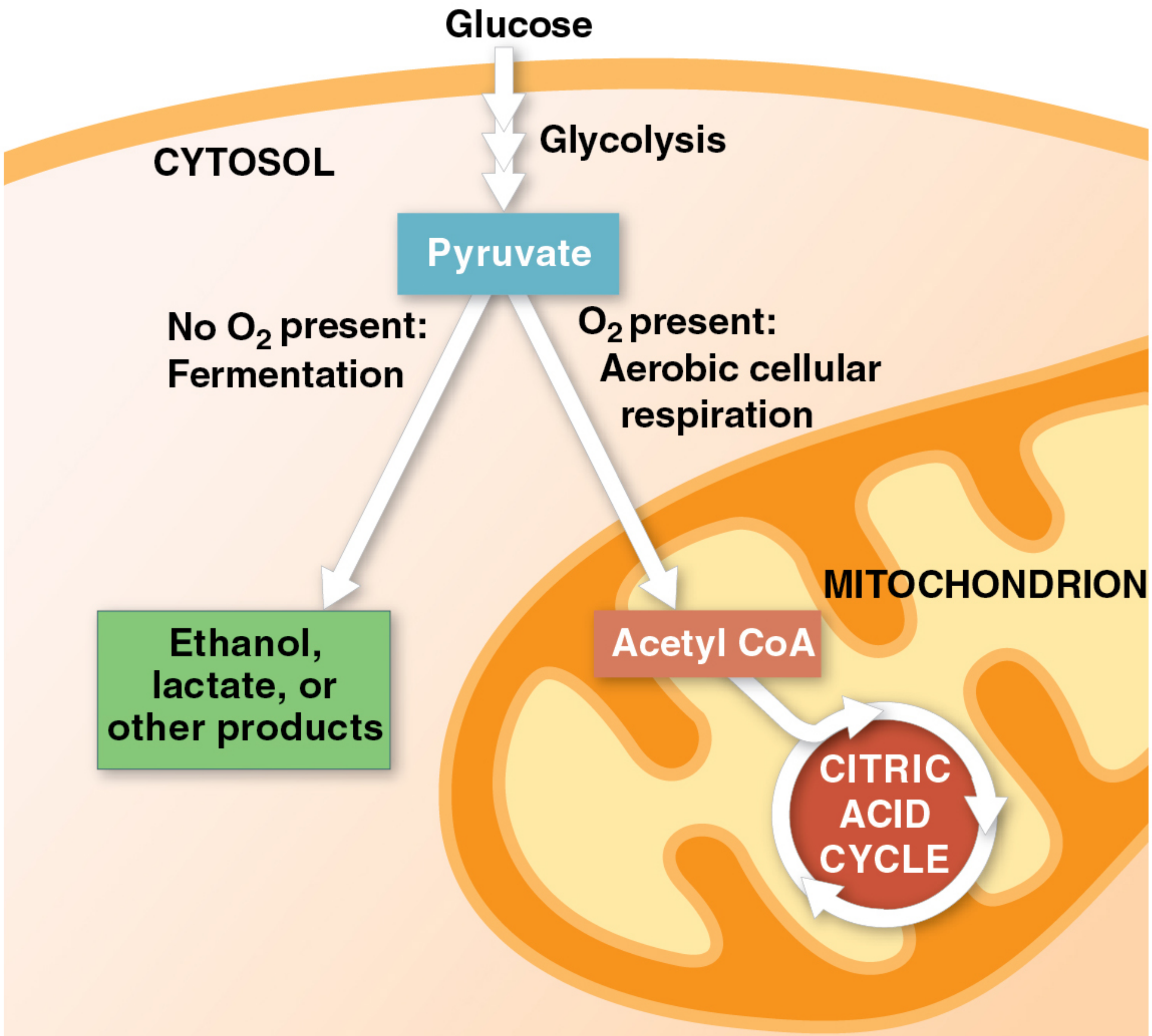
- Fermentation and anaerobic and aerobic respiration have some similarities
  - All use glycolysis (net ATP = 2) to oxidize glucose and harvest the chemical energy of food
  - In all three, NAD^+ is the oxidizing agent that accepts electrons during glycolysis

- One major difference is the mechanisms used to oxidize NADH to NAD^+:
  - In fermentation, an organic molecule (pyruvate or acetaldehyde) acts as a final electron acceptor
  - In cellular respiration, electrons are transferred to the electron transport chain

- Another difference is the amount of ATP produced per glucose molecule
  - Fermentation produces 2 ATP by substrate-level phosphorylation
  - Cellular respiration harvests much more ATP by oxidative phosphorylation—up to 32 ATP in aerobic respiration

- **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
- For facultative anaerobes, pyruvate is a fork in the metabolic road leading to alternative catabolic routes

Figure 9.17



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

- Early prokaryotes likely used glycolysis to produce ATP before oxygen accumulated in the atmosphere
- Used in both cellular respiration and fermentation, it is the most widespread metabolic pathway on Earth
- Glycolysis is a metabolic heirloom from early cells that continues to function in fermentation and cellular respiration

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

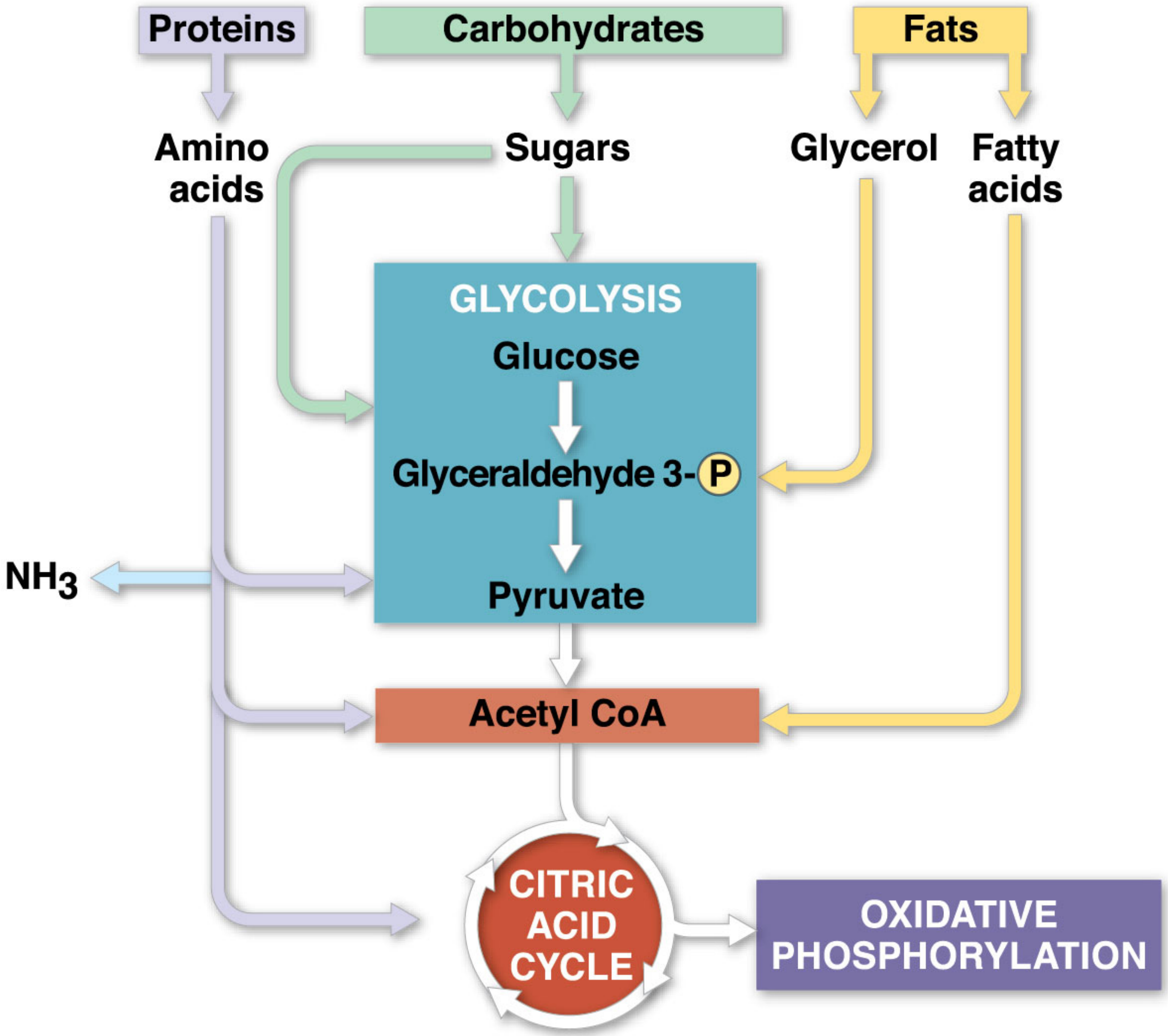
The Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
- Glycolysis can use many carbohydrates, including starch, glycogen, and several disaccharides

- Proteins used for fuel must be digested to amino acids and their amino groups must be removed in a process called *deamination*
- Nitrogenous waste is excreted as ammonia (NH_3), urea, or other products

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

Figure 9.18


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)

- Organisms use small molecules from food to build macromolecules, such as proteins from amino acids
- These small molecules may come directly from food, from glycolysis, or from the citric acid cycle

Regulation of Cellular Respiration via Feedback Mechanisms

- Feedback inhibition is the most common mechanism for metabolic control because it prevents wasteful production
- If ATP concentration drops, respiration speeds up; if there is plenty of ATP, respiration slows down
- Catabolism is controlled by regulating the activity of enzymes at strategic points in the pathway

Figure 9.19

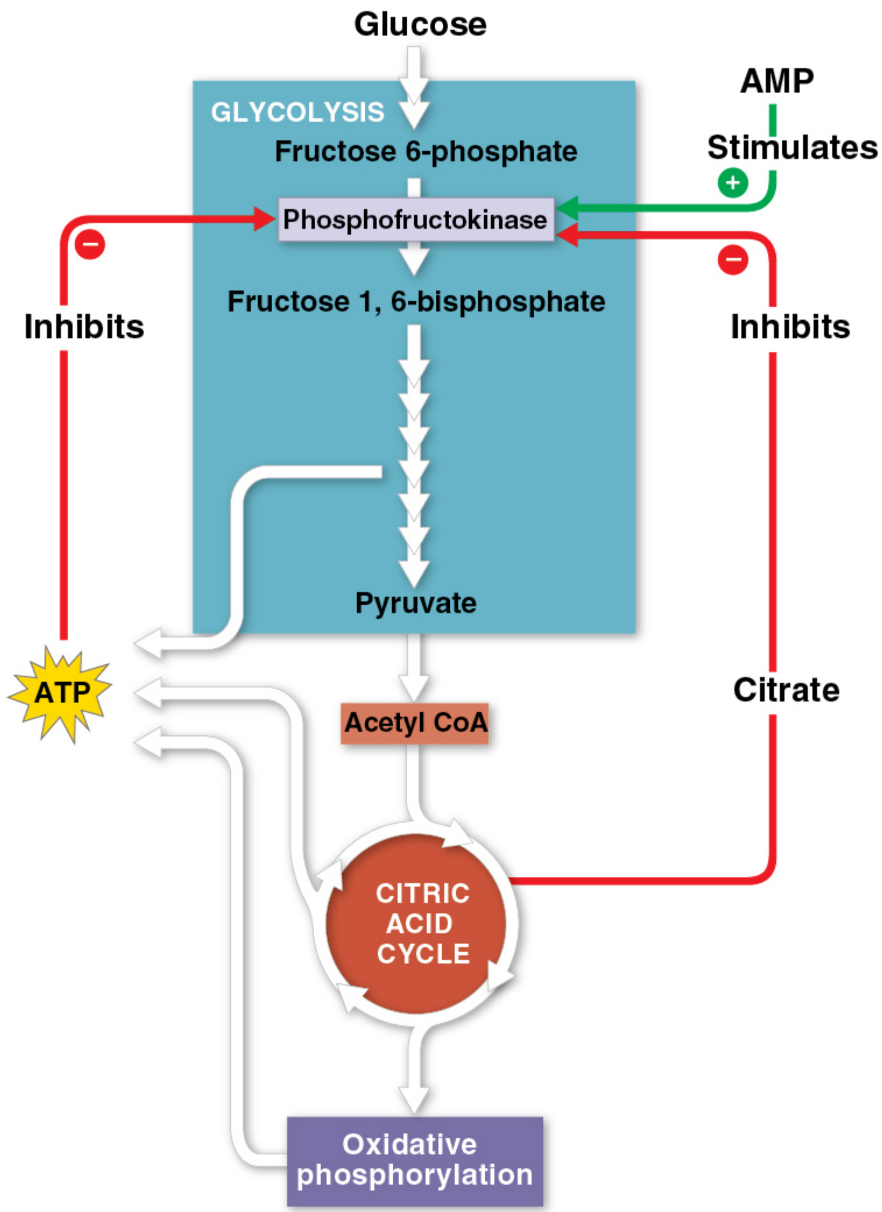

Glucose
AMP
GLYCOLYSIS
Stimulates
Fructose 6-phosphate
Phosphofructokinase
Fructose 1, 6-bisphosphate
Inhibits
Inhibits
Pyruvate
ATP
Citrate
Acetyl CoA
CITRIC
ACID
CYCLE
Oxidative
phosphorylation

Figure 9.UN14a

Data from the Experiment

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

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

Figure 9.UN14b

Figure 9.UN15

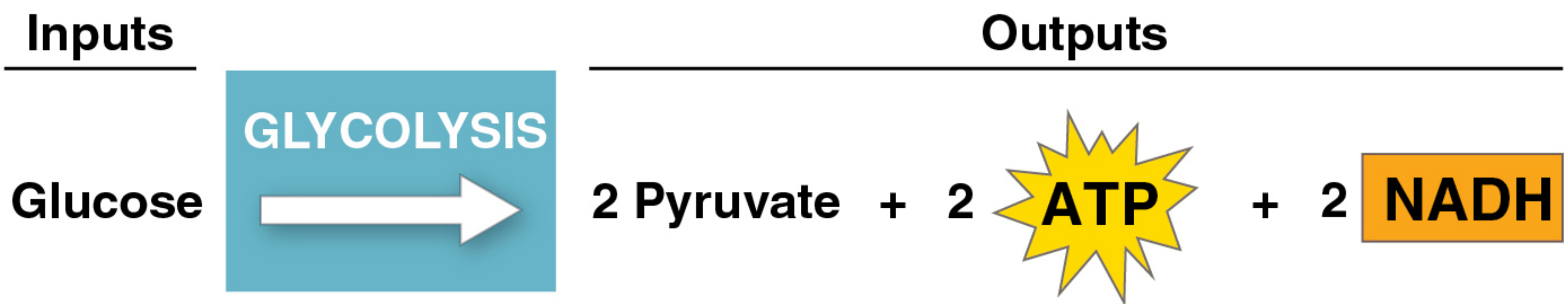


Figure 9.UN16

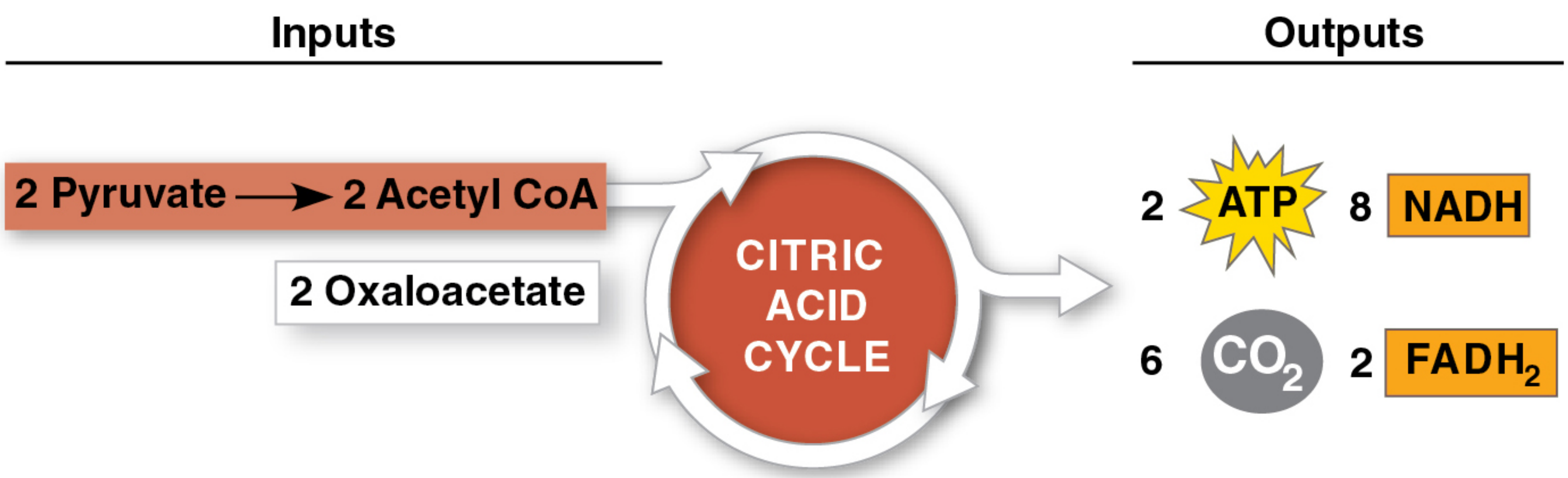


Figure 9.UN17

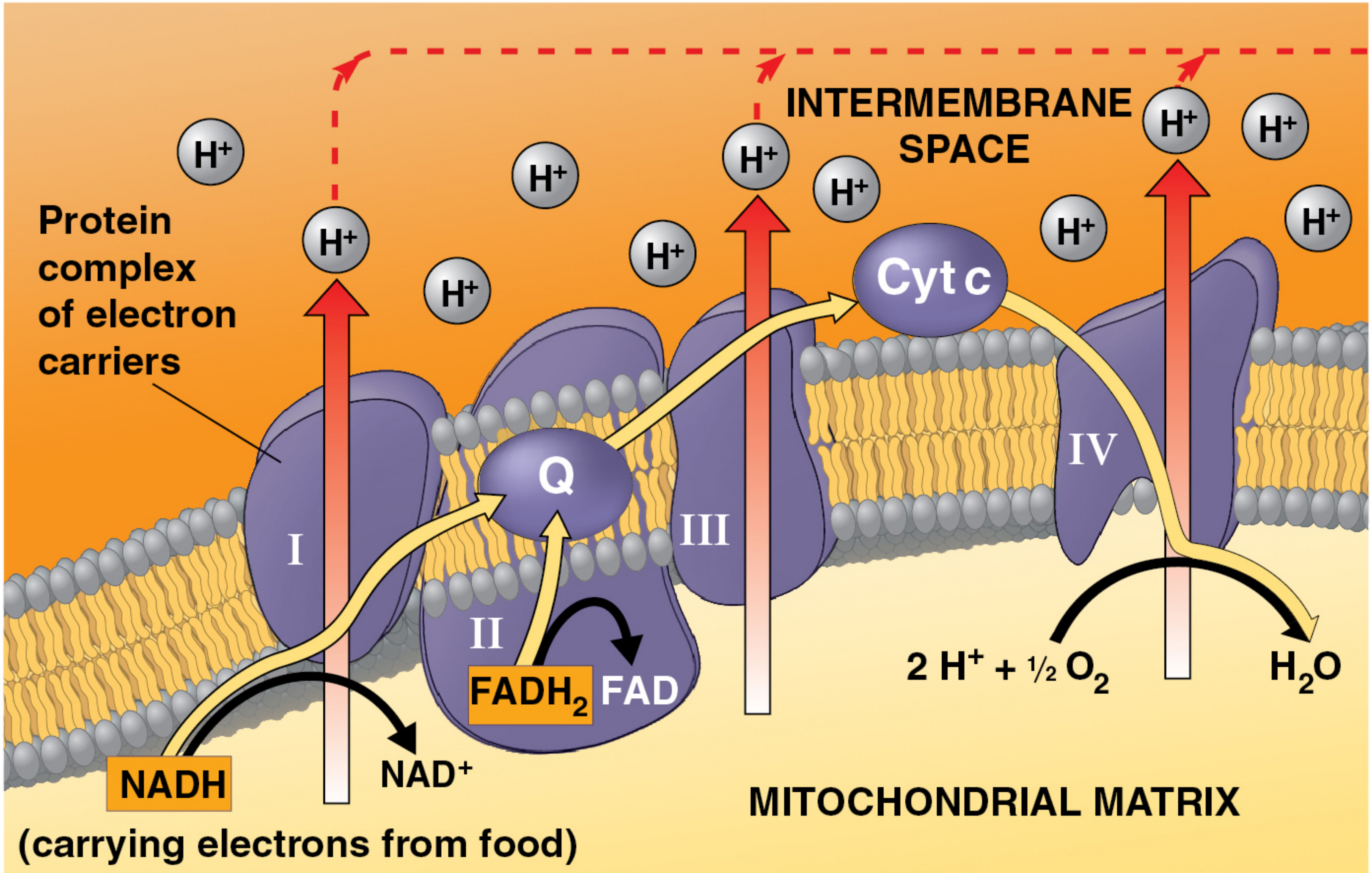


Figure 9.UN18

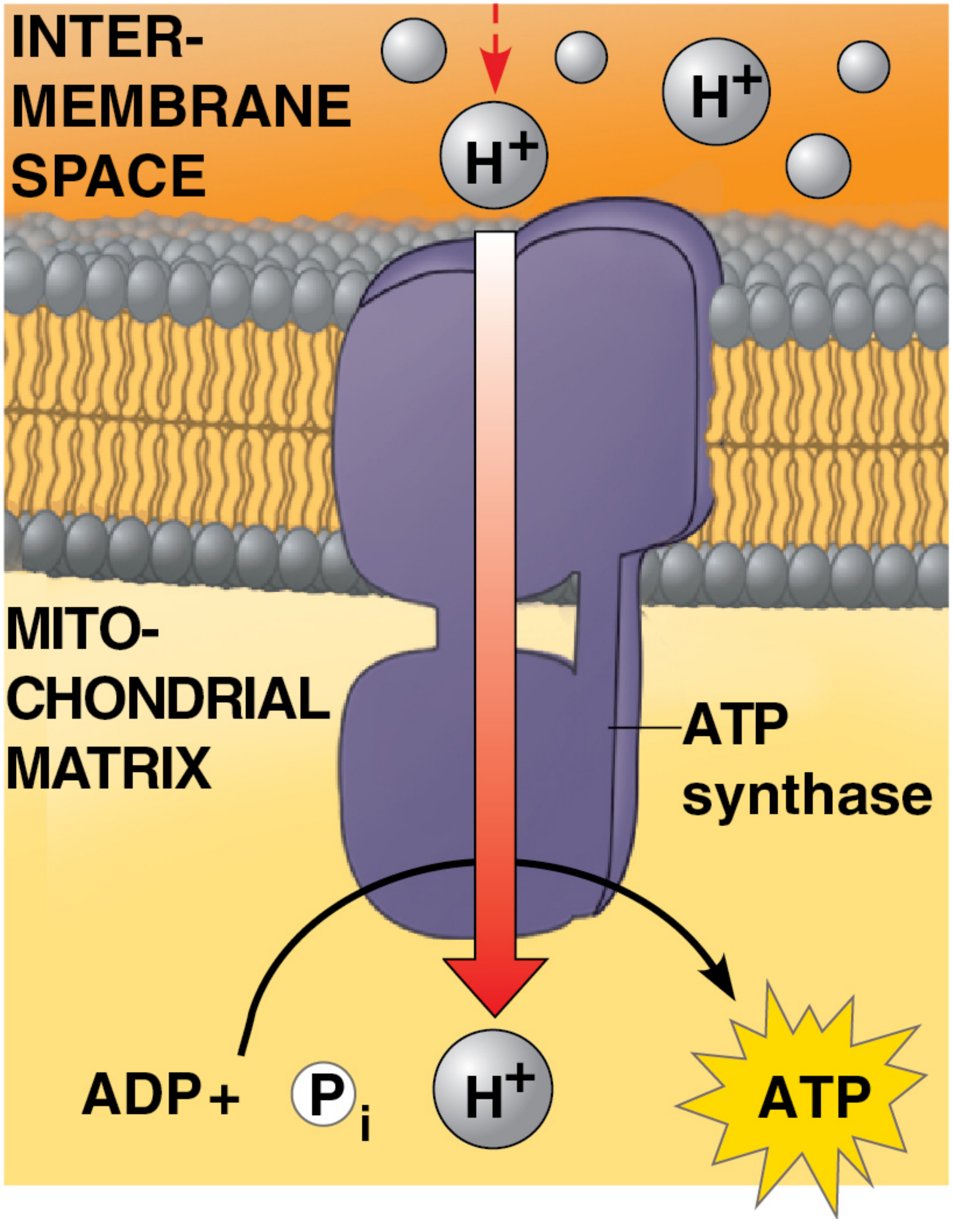


Figure 9.UN19

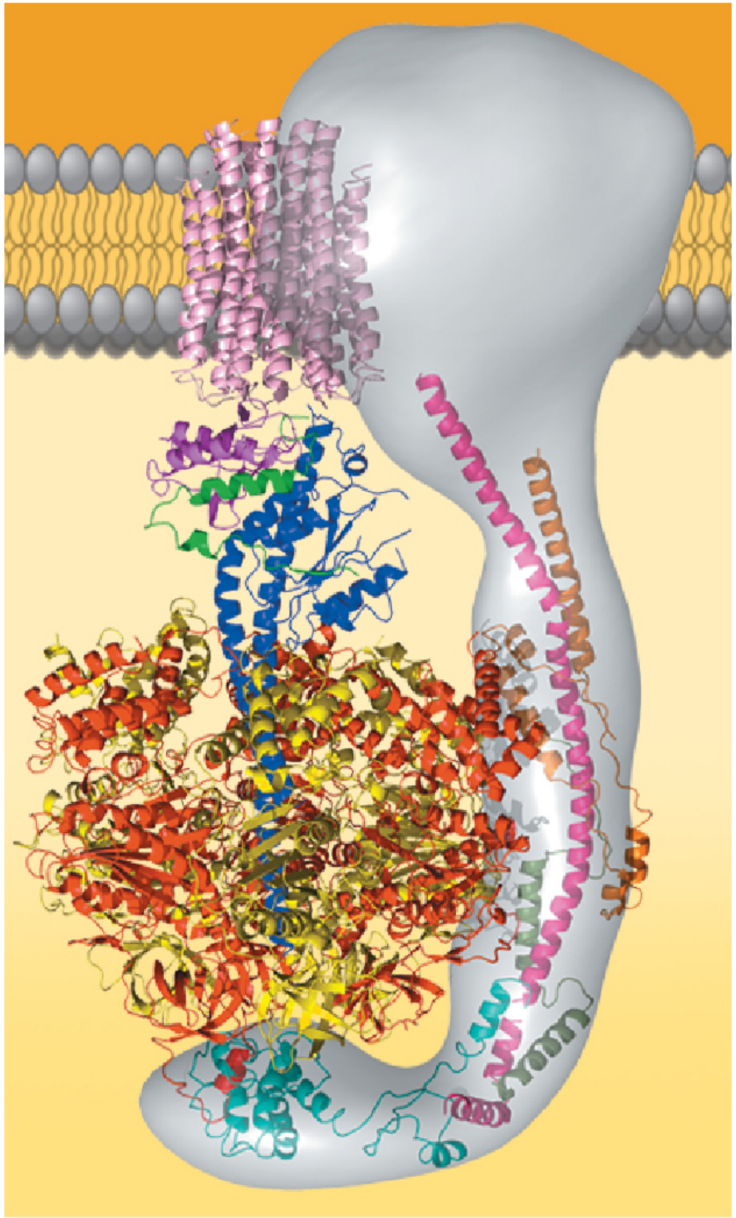


Figure 9.UN20

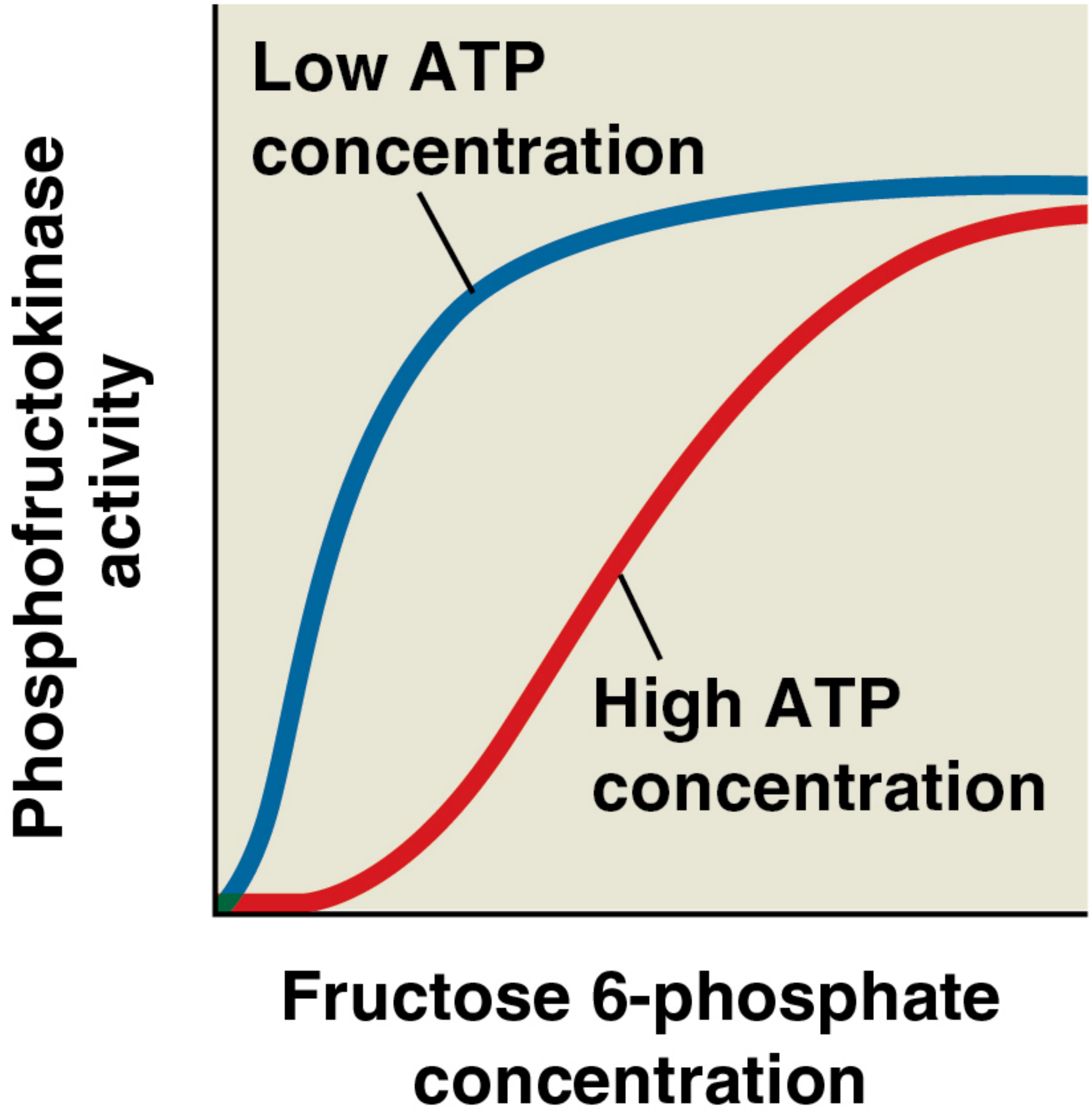


Figure 9.UN21

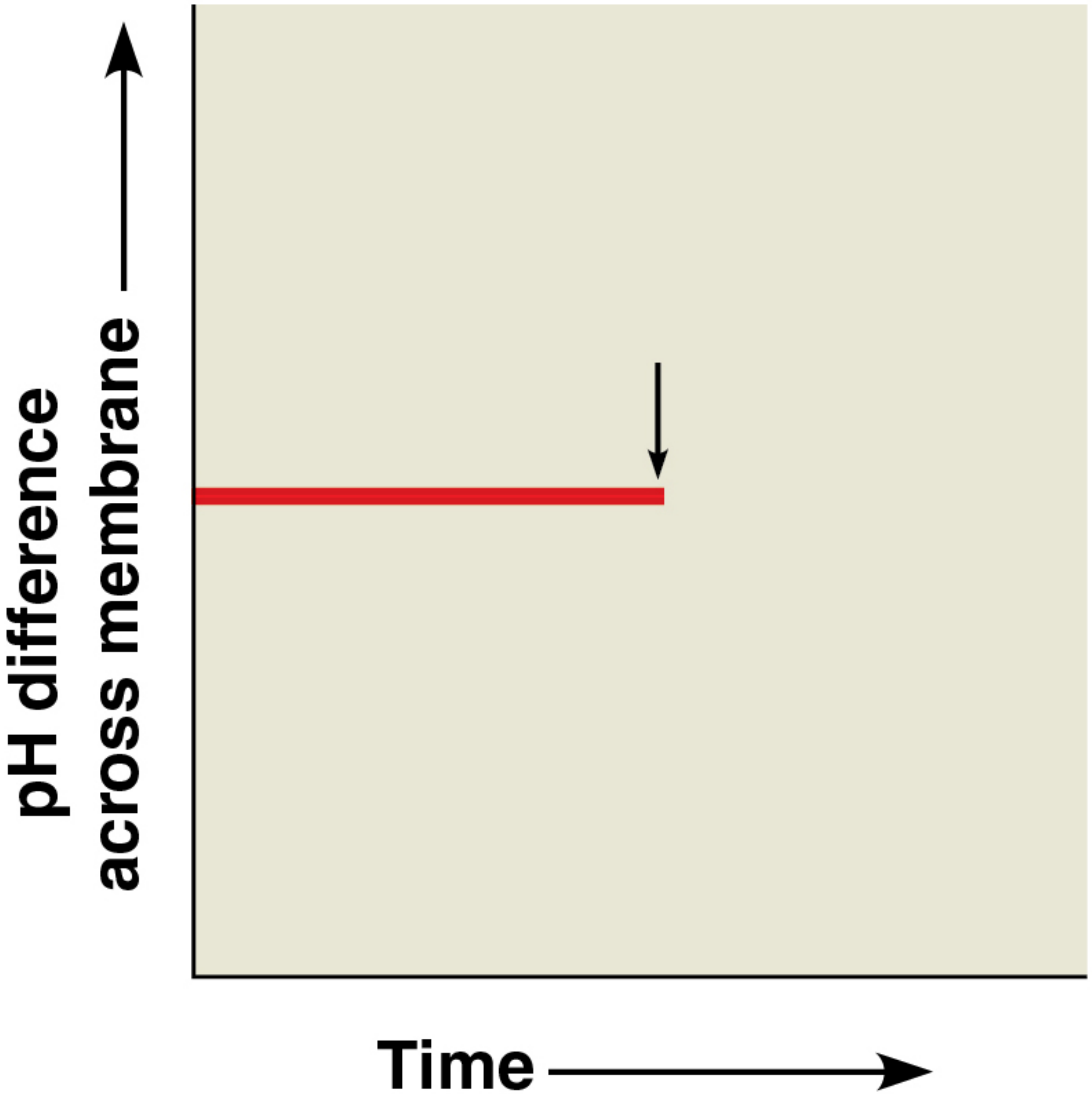


Figure 9.UN22