Cellular Respiration: Aerobic Harvesting of Energy

6.1 Photosynthesis and Cellular Respiration Provide Energy for Life (1 of 2)

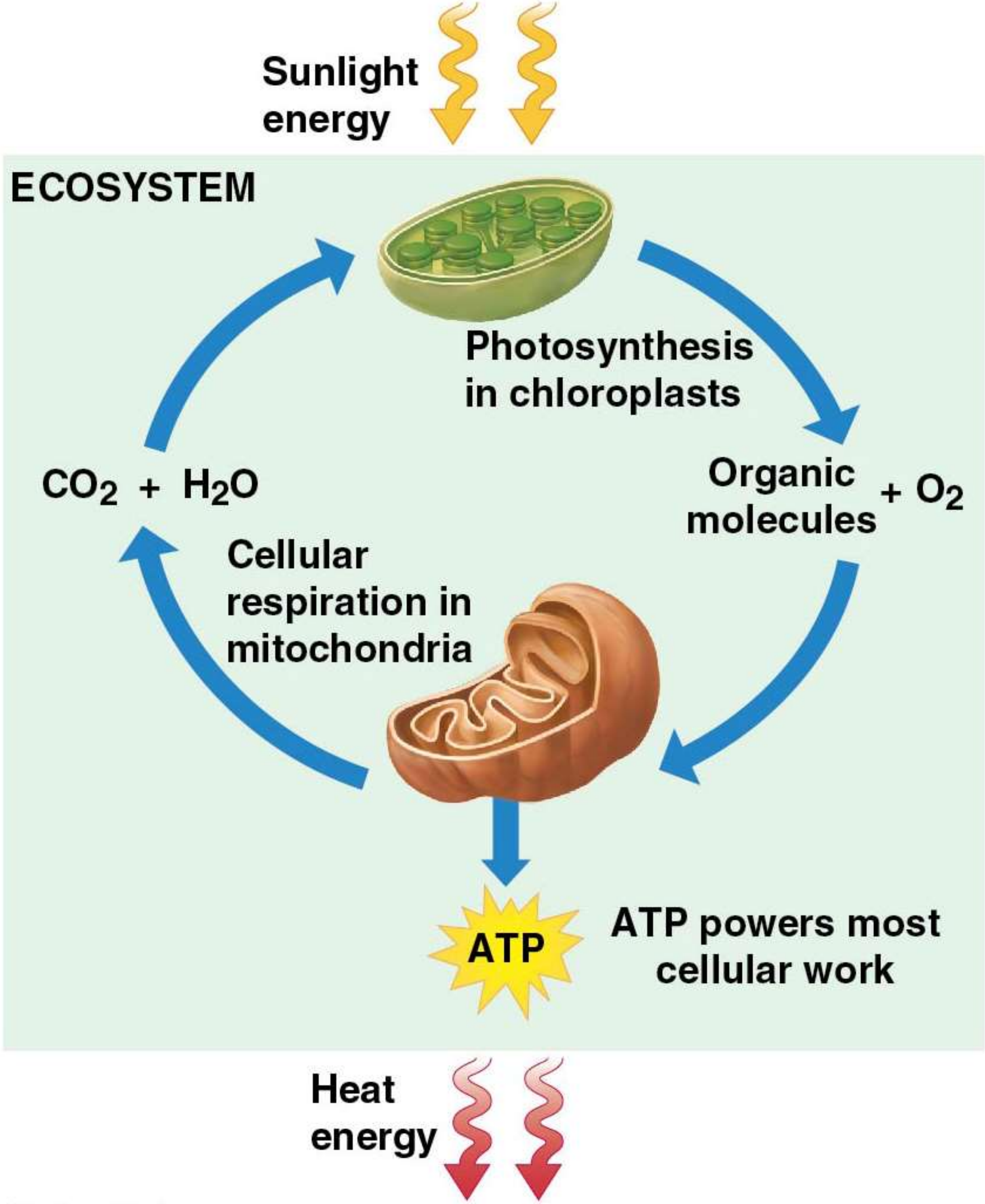
- Life requires energy.
- In almost all ecosystems, energy ultimately comes from the sun.
- **In photosynthesis,**
  - the energy of sunlight is used to rearrange the atoms of carbon dioxide (CO_2) and water (H_20),
  - producing organic molecules, and
  - releasing oxygen (O_2).

6.1 Photosynthesis and Cellular Respiration Provide Energy for Life (2 of 2)

- In **cellular respiration,**
  - O_2 is consumed as organic molecules are broken down to CO_2 and H_2O and
  - the cell captures the energy released as ATP.

Checkpoint question What is misleading about the following statement? “Plant cells perform photosynthesis, and animal cells perform cellular respiration.”

Figure 6.1



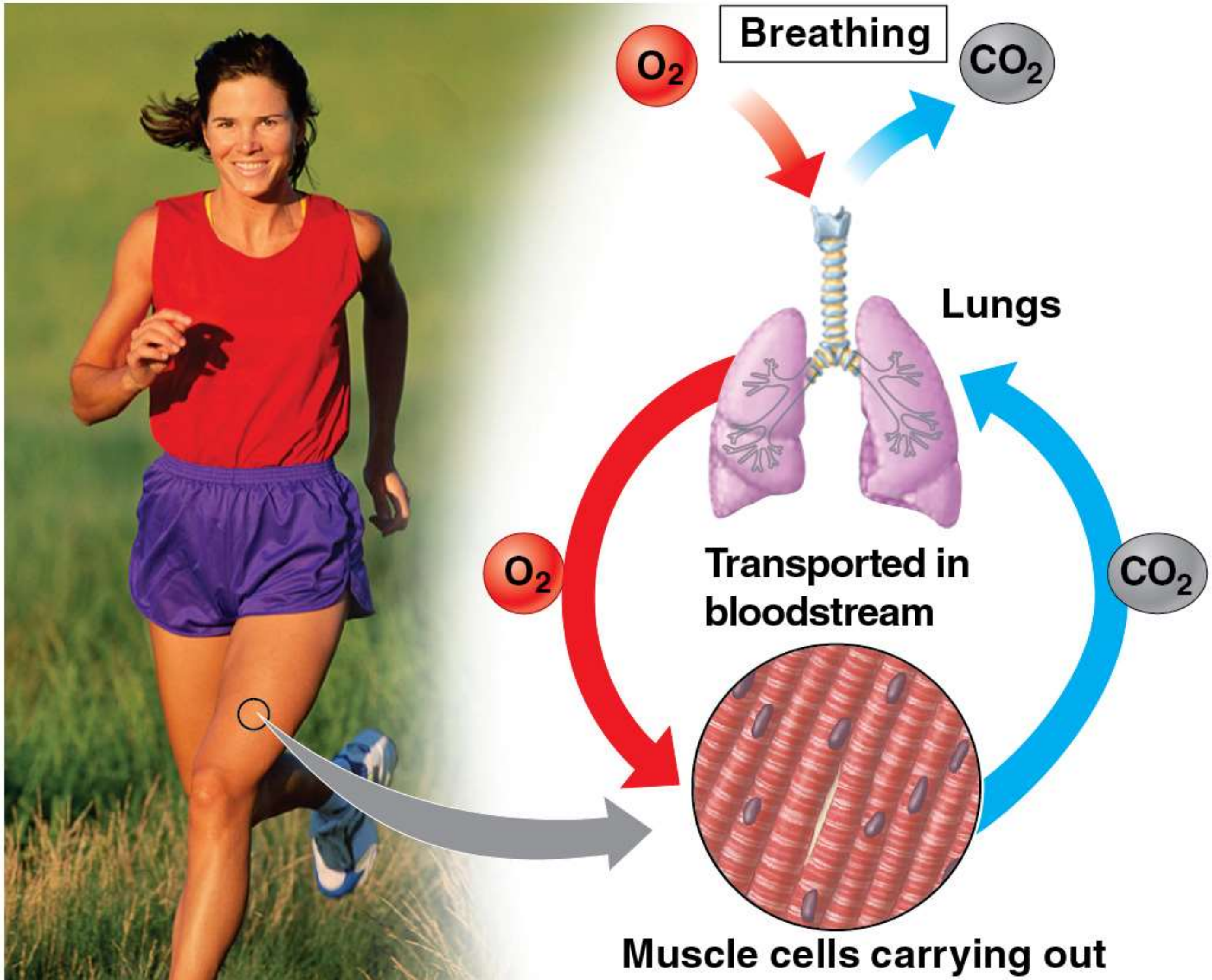
Sunlight energy
ECOSYSTEM
Photosynthesis in chloroplasts
Organic molecules + O_2
CO_2 + H_2O
Cellular respiration in mitochondria
ATP
ATP powers most cellular work
Heat energy

6.2 Breathing Supplies O_2 for Use in Cellular Respiration and Removes CO_2

- Respiration, often used as a synonym for "breathing," refers to an exchange of gases.
  - An organism obtains O_2 from its environment and
  - Releases CO_2 as a waste product.
- Breathing and cellular respiration are closely related.

Checkpoint question Are the oxygen atoms a runner exhales the same oxygen atoms she inhaled from the environment?

Figure 6.2



Cellular Respiration

$$\text{Glucose} + O_2 \rightarrow CO_2 + H_2O + \text{ATP}$$

6.3 Cellular Respiration Banks Energy in ATP Molecules

- Cellular respiration
  - is an exergonic (energy-releasing) process that transfers energy from glucose to form ATP and
  - captures about 34% of the available energy originally stored in glucose with the rest of the energy lost as heat.

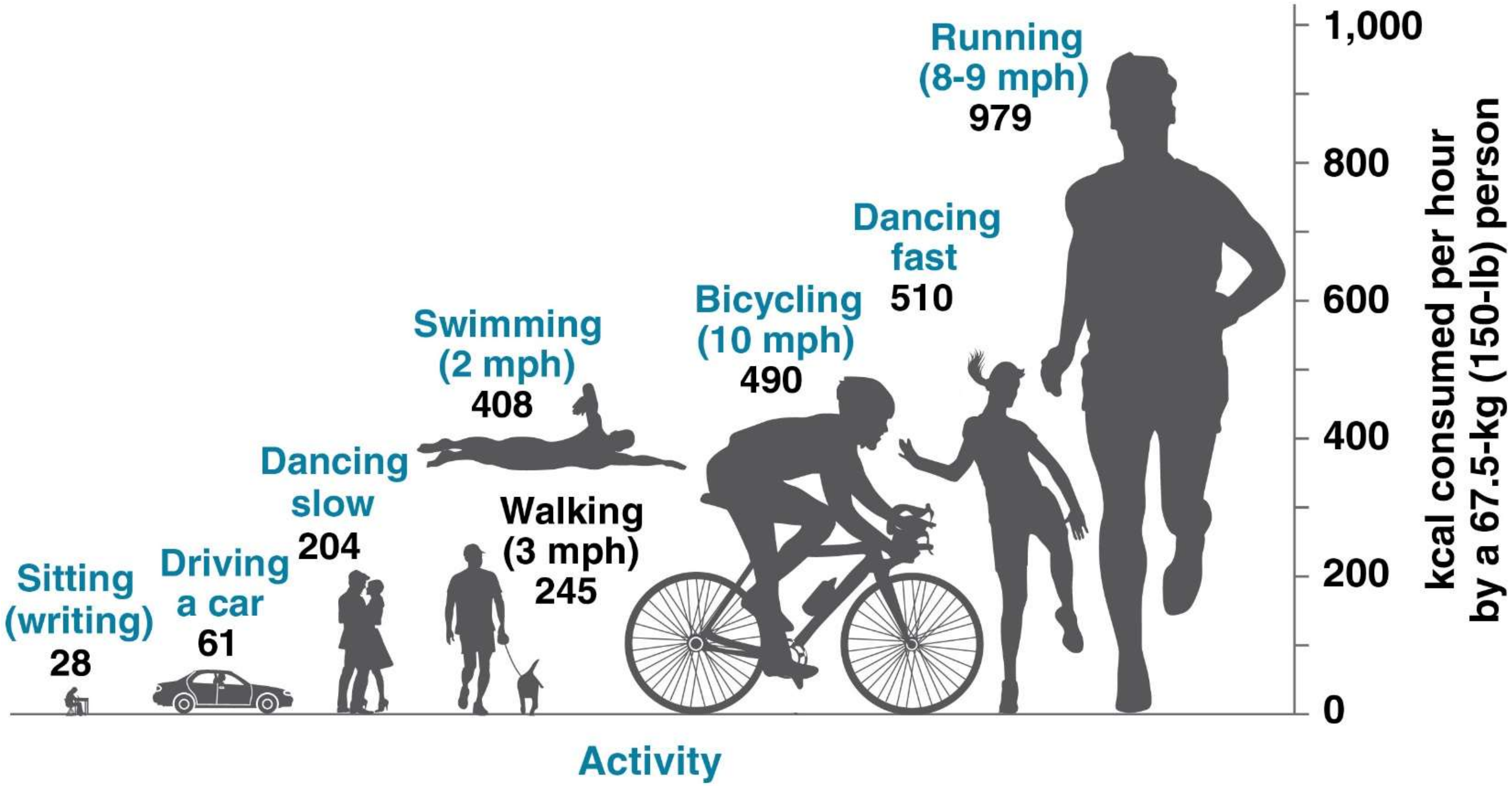
Checkpoint question Are the oxygen atoms a runner exhales the same oxygen atoms she inhaled from the environment?

If the inhibitor binds to the enzyme with covalent bonds, the inhibition is usually irreversible. When weak chemical interactions bind inhibitor and enzyme, the inhibition is reversible.

6.4 Connection: The Human Body Uses Energy from ATP for All Its Activities (1 of 2)

- Your body requires a continuous supply of energy.
- Cellular respiration provides energy for body maintenance and voluntary activities.
- A balance of energy intake and expenditure is required to maintain a healthy weight.

6.4 Connection: The Human Body Uses Energy from A T P for All Its Activities (2 of 2)



Checkpoint question While walking at 3 mph, how far would you have to travel to “burn off” the equivalent of an extra slice of pizza, which has about 475 kcal? How long would that take? You would have to walk about 6 miles, which would take you about 2 hours.

6.5 Cells Capture Energy from Electrons “Falling” from Organic Fuels to Oxygen (1 of 2)

- How do your cells extract energy from fuel molecules? The answer involves the transfer of electrons in chemical reactions.
- Electrons removed from fuel molecules **(oxidation)** are transferred to **NAD+ (reduction).**
- NADH passes electrons to an **electron transport chain**. As electrons “fall” from carrier to carrier and finally to O_2, energy is released.

Figure 6.5a

Loss of hydrogen atoms
(becomes oxidized)

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

(Glucose)

Gain of hydrogen atoms
(becomes reduced)

Pearson

Figure 6.5b

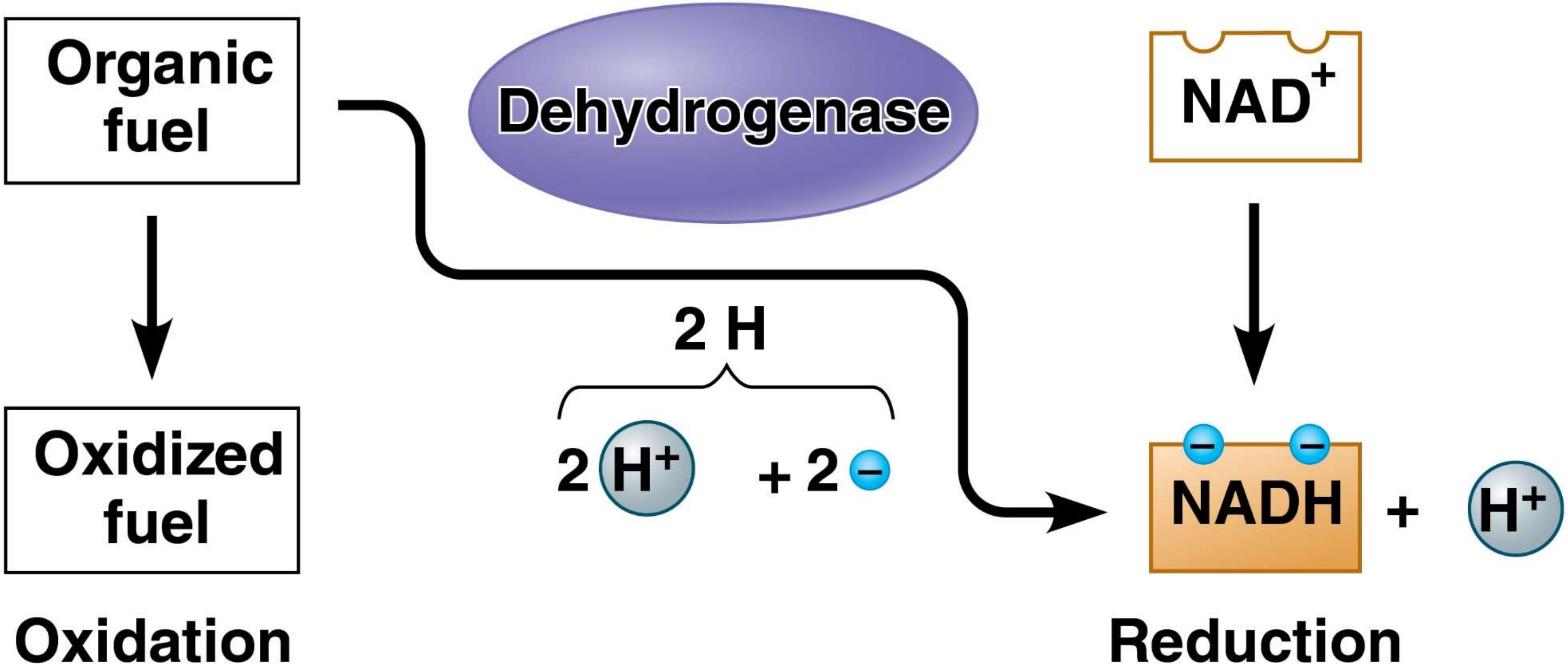
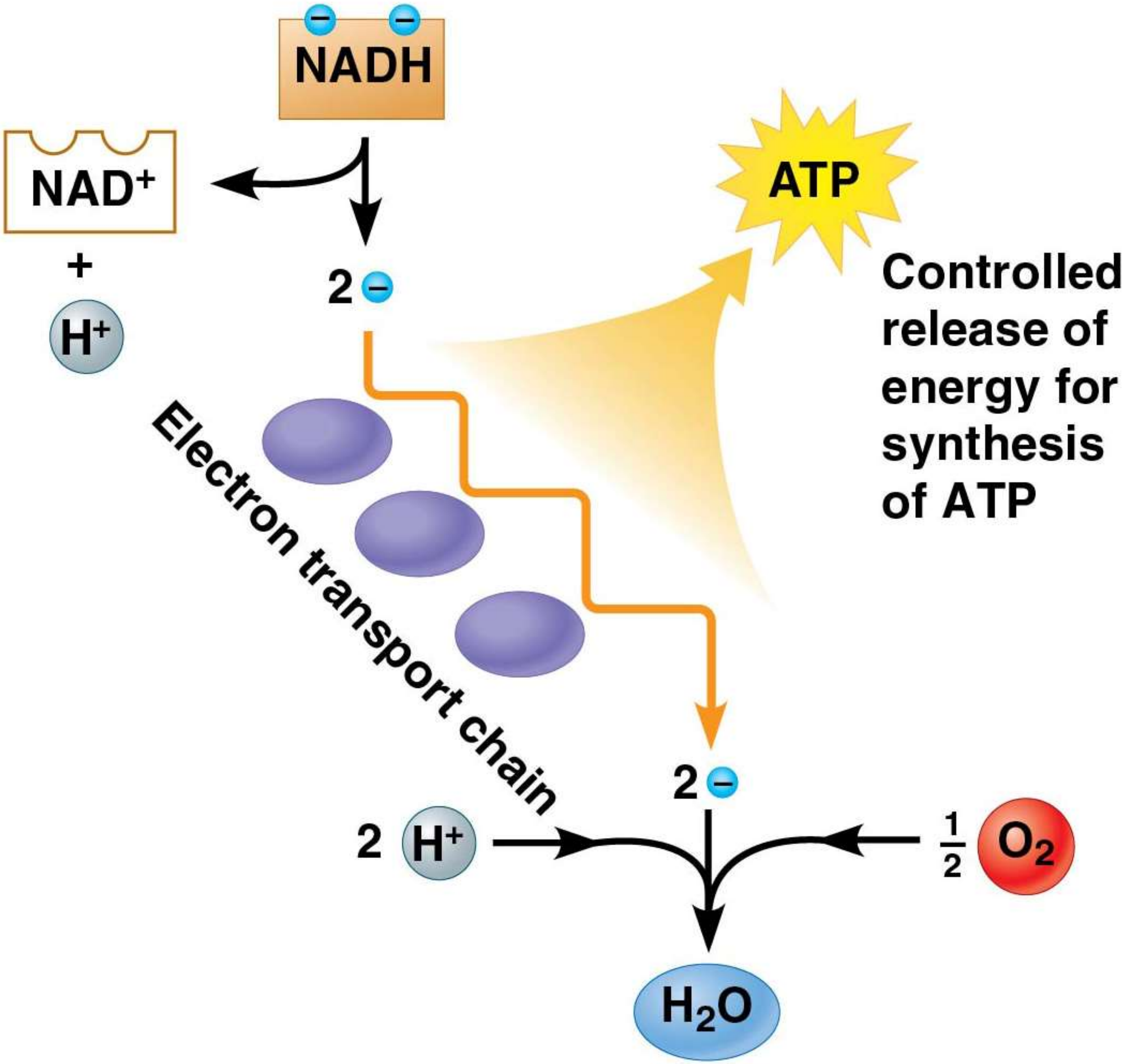

Organic fuel
Dehydrogenase
NAD+
2 H
2 H+ + 2 –
Oxidized fuel
NADH + H+
Oxidation
Reduction

Figure 6.5c


NADH
NAD+
+
H+
2
ATP
Controlled release of energy for synthesis of ATP
Electron transport chain
2
2 H+
1/2 O2
H2O

6.5 Cells Capture Energy from Electrons “Falling” from Organic Fuels to Oxygen (2 of 2)

Checkpoint question What chemical characteristic of the element oxygen accounts for its function in cellular respiration?

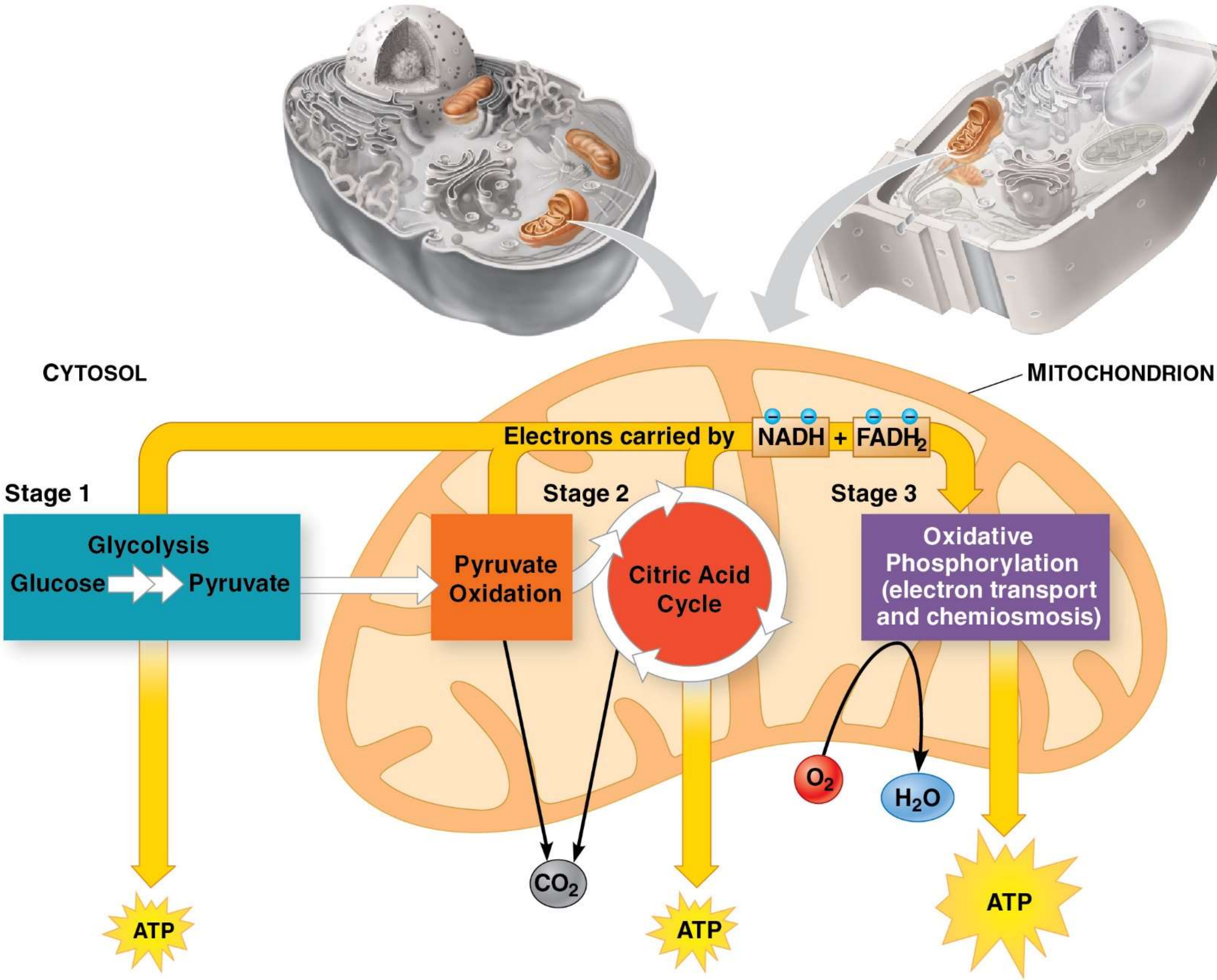
Oxygen is extremely electronegative (see Module 2.6), making it very powerful in pulling electrons down the electron transport chain.

Stages of Cellular Respiration

6.6 Overview: Cellular Respiration Occurs in Three Main Stages (1 of 3)

- Stage 1: **Glycolysis**
  - occurs in the cytosol,
  - begins cellular respiration, and
  - breaks down glucose into two molecules of a three-carbon compound called pyruvate.
- Stage 2: **Pyruvate oxidation** and the **citric acid cycle**
  - take place in mitochondria,
  - complete the breakdown of glucose to carbon dioxide, and
  - supply the third stage of respiration with electrons.

Figure 6.6



CYTOSOL
MITOCHONDRION
Electrons carried by NADH + $FADH_2$
Stage 1
Glycolysis
Glucose
Pyruvate
Stage 2
Pyruvate Oxidation
Citric Acid Cycle
Stage 3
Oxidative Phosphorylation (electron transport and chemiosmosis)
ATP
CO_2
ATP
O_2
H_2O
ATP

6.6 Overview: Cellular Respiration Occurs in Three Main Stages (2 of 3)

- Stage 3: **Oxidative phosphorylation** involves electron transport and **chemiosmosis**.
  - NADH and a related electron carrier, $FADH_2$, shuttle electrons to electron transport chains embedded in the inner mitochondrial membrane.
  - Most of the ATP produced by cellular respiration is generated by oxidative phosphorylation.
  - The electrons are finally passed to oxygen, which becomes reduced to H_2O.

6.6 Overview: Cellular Respiration Occurs in Three Main Stages (3 of 3)

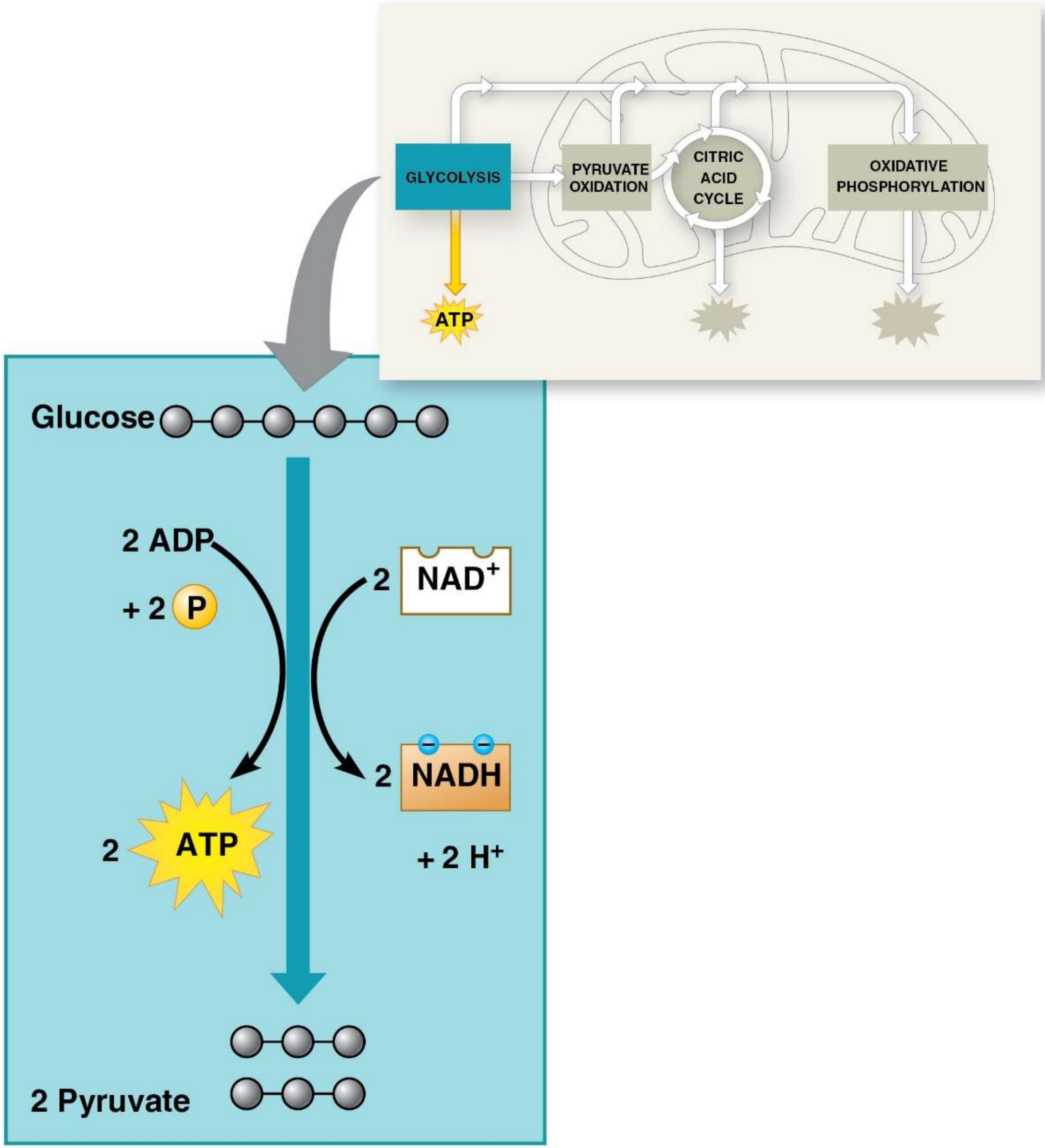
Checkpoint question Of the three main stages of cellular respiration, which one does not take place in the mitochondria?

Stage 1, glycolysis, occurs in the cytosol.

6.7 Stage 1: Glycolysis Harvests Chemical Energy by Oxidizing Glucose to Pyruvate (1 of 2)

- ATP is used to prime a glucose molecule, which is split in two.
- These three-carbon **intermediates** are oxidized to two molecules of pyruvate, yielding a net of 2 ATP and 2 NADP H.
- ATP is formed by **substrate-level phosphorylation**, in which a phosphate group is transferred from an organic molecule to ADP.

Figure 6.7a


GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION
ATP
Glucose
2 ADP
+ 2 P
2 NAD+
2 NADH
+ 2 H+
2 ATP
2 Pyruvate

6.7 Stage 1: Glycolysis Harvests Chemical Energy by Oxidizing Glucose to Pyruvate (2 of 2)

Checkpoint question For each glucose molecule processed, what are the net molecular products of glycolysis?

Two molecules of pyruvate, two molecules of ATP, and two molecules of NADH

6.8 Multiple Reactions in Glycolysis Split Glucose into Two Molecules (1 of 2)

- Figure 6.8 shows simplified structures for the organic compounds in the nine chemical reactions of glycolysis.
- The sequential steps of glycolysis illustrate how, in a metabolic pathway, each chemical step feeds into the next. In other words, the product of one reaction serves as the reactant for the next.
- Compounds that form between an initial reactant and a final product are known as **intermediates**.

6.8 Multiple Reactions in Glycolysis Split Glucose into Two Molecules (2 of 2)

- The energy investment phase actually consumes energy.
  - In this phase, two molecules of ATP are used to add a phosphate group to each glucose molecule,
  - which is then split into two small sugars.
- Steps 1–4 consume energy.
- Steps 5–9 yield energy.

Pearson

Figure 6.8_2

Energy Investment Phase

Steps 1–3 Glucose is energized, using ATP.

Step 4 A six-carbon intermediate splits into two three-carbon intermediates.

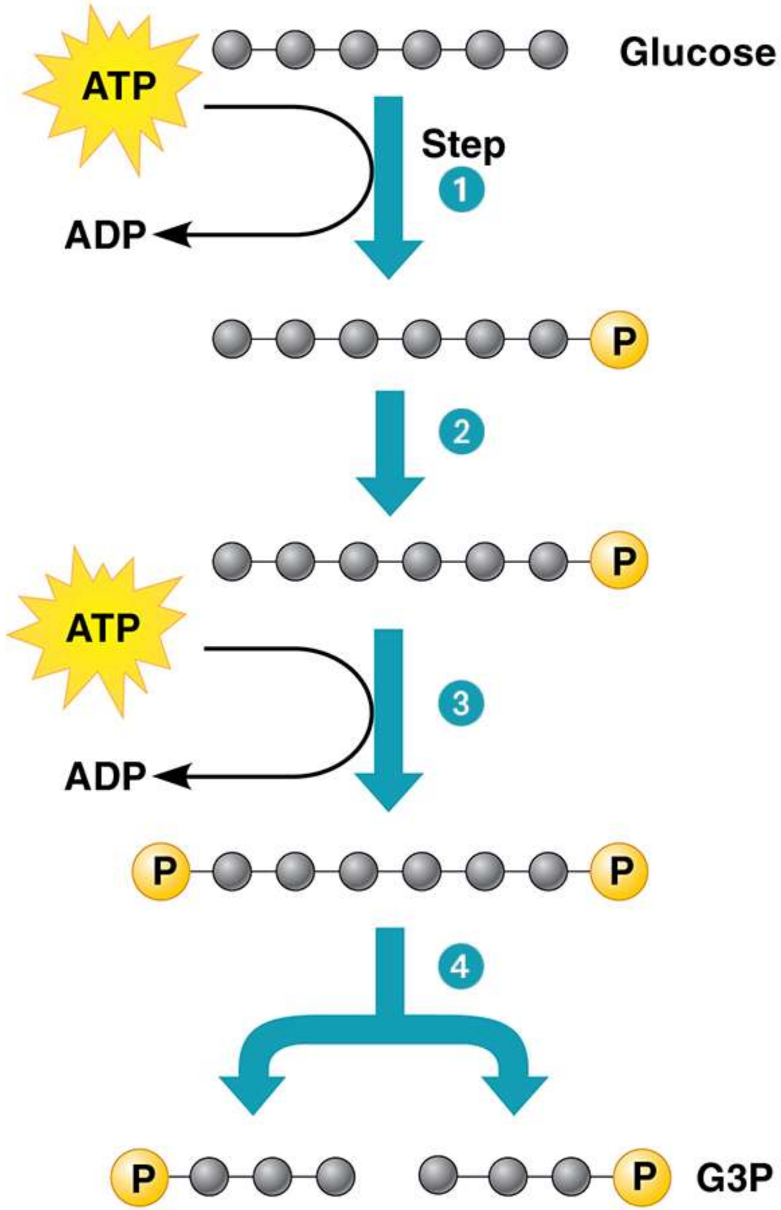
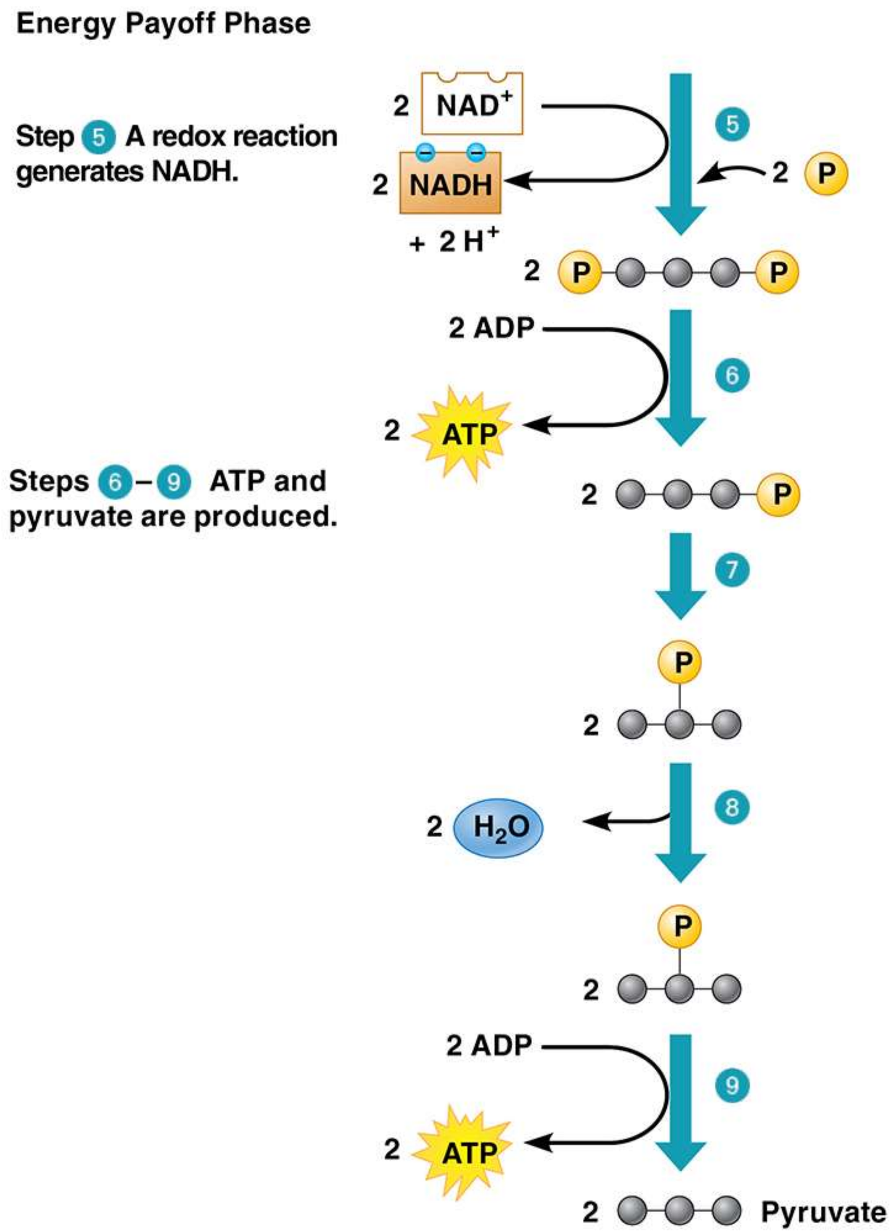


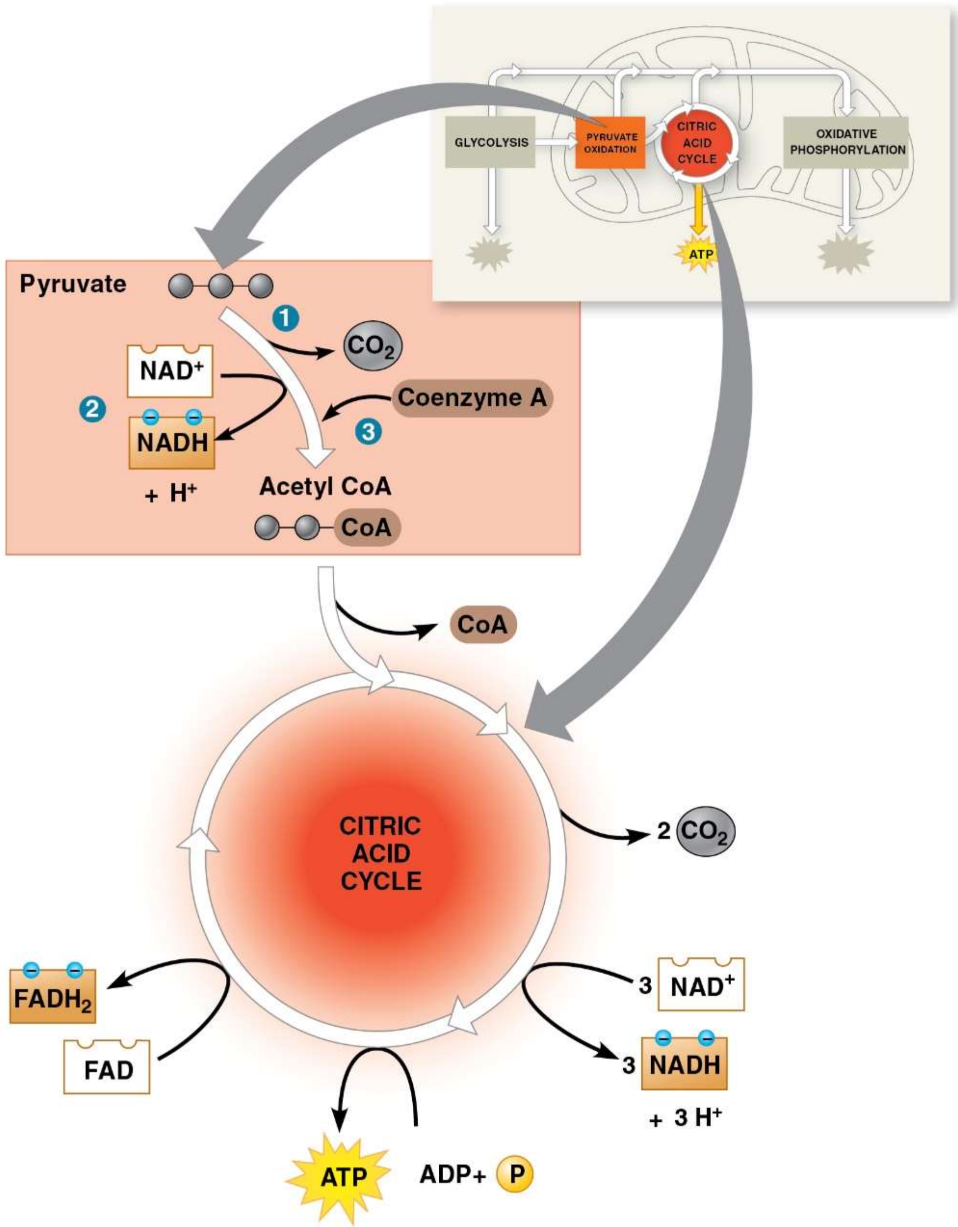
Figure 6.8_4


Energy Payoff Phase
Step 5 A redox reaction generates NADH.
Steps 6–9 ATP and pyruvate are produced.
2 NAD+
2 NADH
+ 2 H+
5
2 P
2
2 ADP
6
2 ATP
2
7
P
2
2 H2O
8
P
2
2 ADP
9
2 ATP
2 Pyruvate

6.9 Stage 2: The Citric Acid Cycle Completes the Energy-Yielding Oxidation of Organic Molecules

- The oxidation of pyruvate yields **acetyl CoA**, CO_2, and NA DH.
- For each turn of the citric acid cycle,
  - two carbons from acetyl CoA are added,
  - $2CO_2$ are released, and
  - 3NADH and $1FADH_2$ are produced.

Figure 6.9

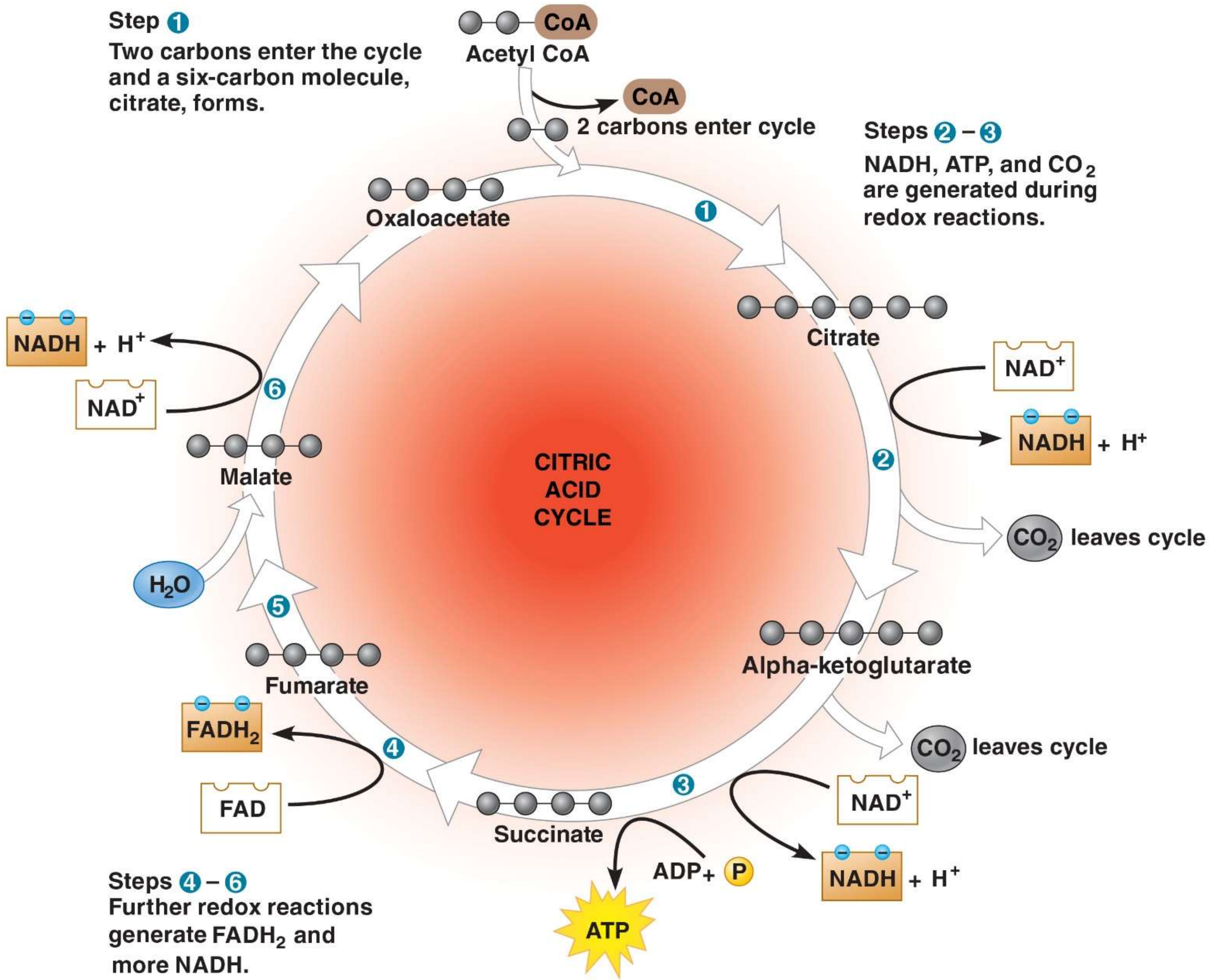


GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION
ATP
Pyruvate
1
CO_2
NAD^+
2
NADH
+ H^+
Coenzyme A
3
Acetyl CoA
CoA
CoA
CITRIC ACID CYCLE
2 CO_2
3 NAD^+
3 NADH
+ 3 H^+
$FADH_2$
FAD
ATP
ADP+ P

6.10 The Multiple Reactions of the Citric Acid Cycle Finish Off the Dismantling of Glucose

- Figure 6.10 shows the six major steps of the citric acid cycle.

Figure 6.10

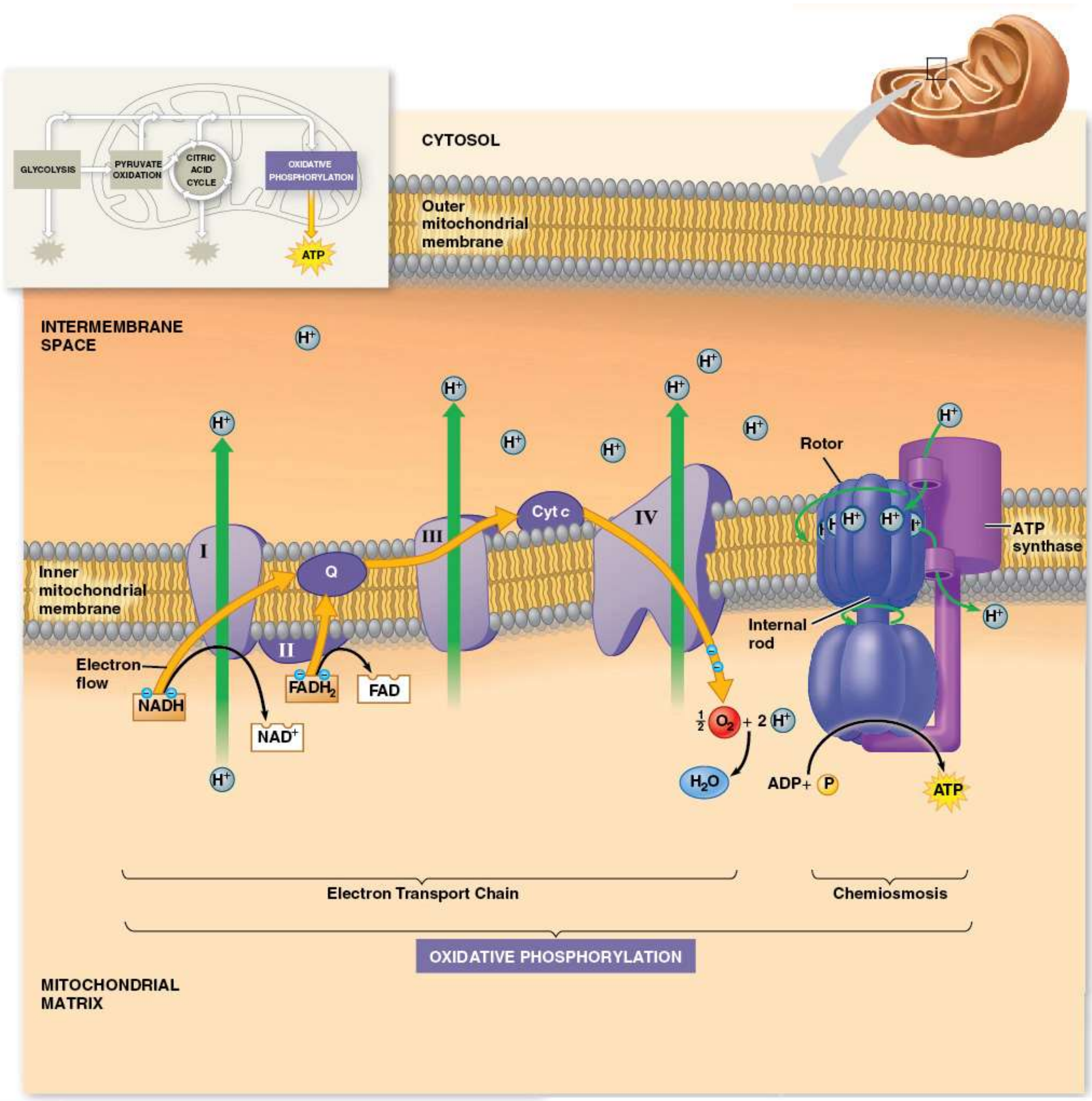


Pearson

6.11 Stage 3: Visualizing the Concept: Most A T P Production Occurs by Oxidative Phosphorylation (1 of 2)

- In mitochondria, electrons from NADH and $FADH_2$ are passed down the electron transport chain to O_2, which picks up H^+ to form water.
- Energy released by these redox reactions is used to pump H^+ into the intermembrane space.
- In chemiosmosis, the H^+ gradient drives H^+ back through the enzyme complex **ATP synthase** in the inner membrane, synthesizing ATP.

Figure 6.11



GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYLATION
ATP
CYTOSOL
Outer mitochondrial membrane
INTERMEMBRANE SPACE
Inner mitochondrial membrane
I
II
III
IV
Q
Cyt c
Electron flow
NADH
NAD+
FADH2
FAD
H+
1/2 O2 + 2 H+
H2O
Rotor
ATP synthase
Internal rod
ADP + P
ATP
Electron Transport Chain
Chemiosmosis
OXIDATIVE PHOSPHORYLATION
MITOCHONDRIAL MATRIX

6.11 Stage 3: Visualizing the Concept: Most A T P Production Occurs by Oxidative Phosphorylation (2 of 2)

Checkpoint question What effect would an absence of oxygen (O_2) have on the process of oxidative phosphorylation?

Without oxygen to "pull" electrons down the electron transport chain, the energy stored in NADH and $FADH_2$ could not be harnessed for ATP synthesis.

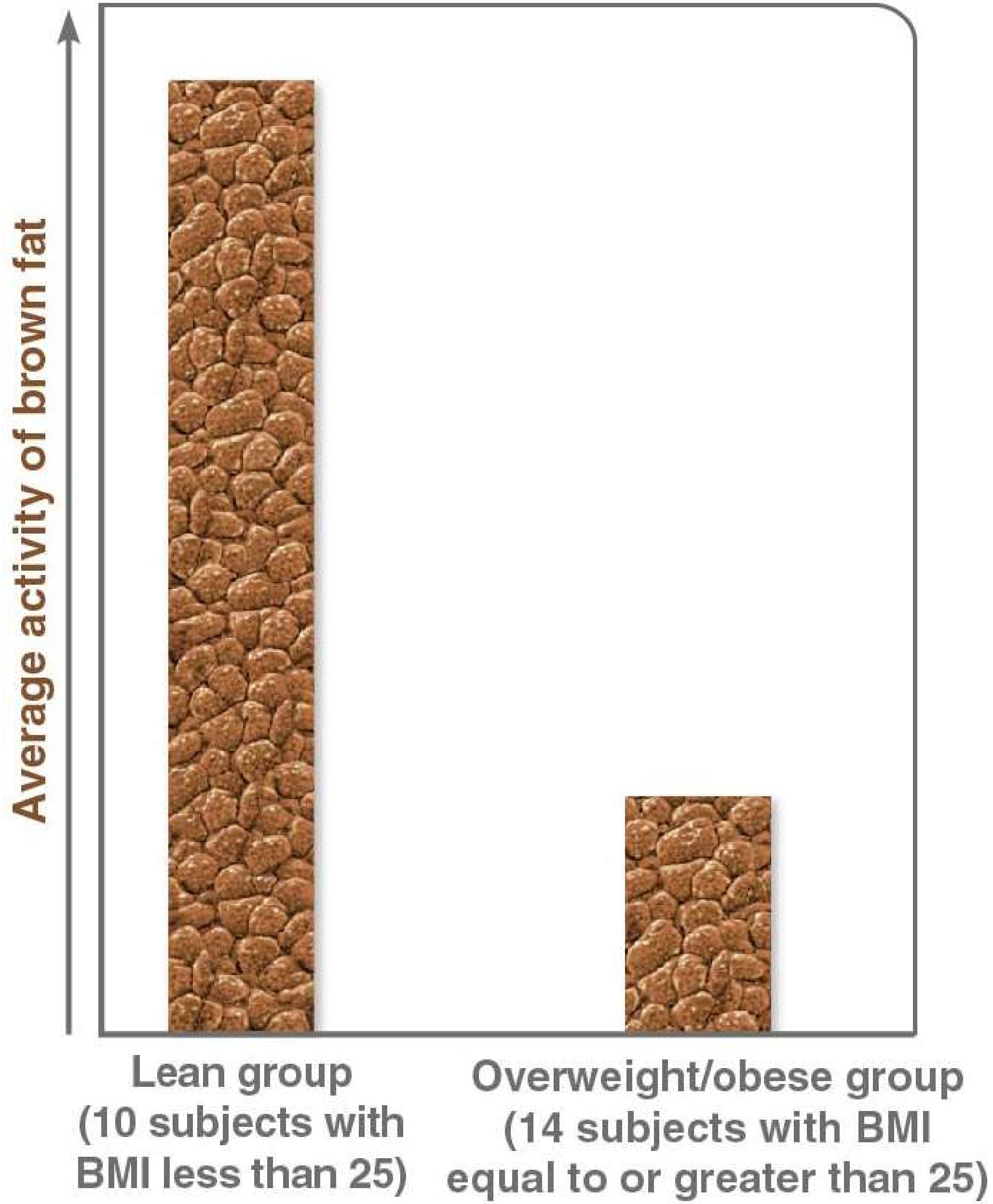
6.12 Scientific Thinking: Scientists Have Discovered Heat-Producing, Calorie-burning Brown Fat in Adults (1 of 3)

- Mitochondria in brown fat can burn fuel and produce heat without making ATP.
- Ion channels spanning the inner mitochondrial membrane
  – allow H^+ to flow freely across the membrane and
  – dissipate the H^+ gradient that the electron transport chain produced, which does not allow ATP synthase to make ATP.
  – All the energy from the burning of fuel molecules would be released as heat.

6.12 Scientific Thinking: Scientists Have Discovered Heat-Producing, Calorie-burning Brown Fat in Adults (2 of 3)

- Until recently, brown fat in humans was thought to disappear after infancy.
- Recent research indicates that brown fat may be present in most people and when activated by cold, the brown fat of lean individuals is more active (burns more calories).

Figure 6.12


Average activity of brown fat
Lean group
(10 subjects with
BMI less than 25)
Overweight/obese group
(14 subjects with BMI
equal to or greater than 25)

6.12 Scientific Thinking: Scientists Have Discovered Heat-Producing, Calorie-burning Brown Fat in Adults (3 of 3)

Checkpoint question The initial study discussed identified brown fat in less than 10% of the patients whose scans were analyzed. The second study identified brown fat in 96% of participants. What accounts for this difference in research results?

Brown fat was activated and thus identified in response to the cold temperature treatment of the second study.

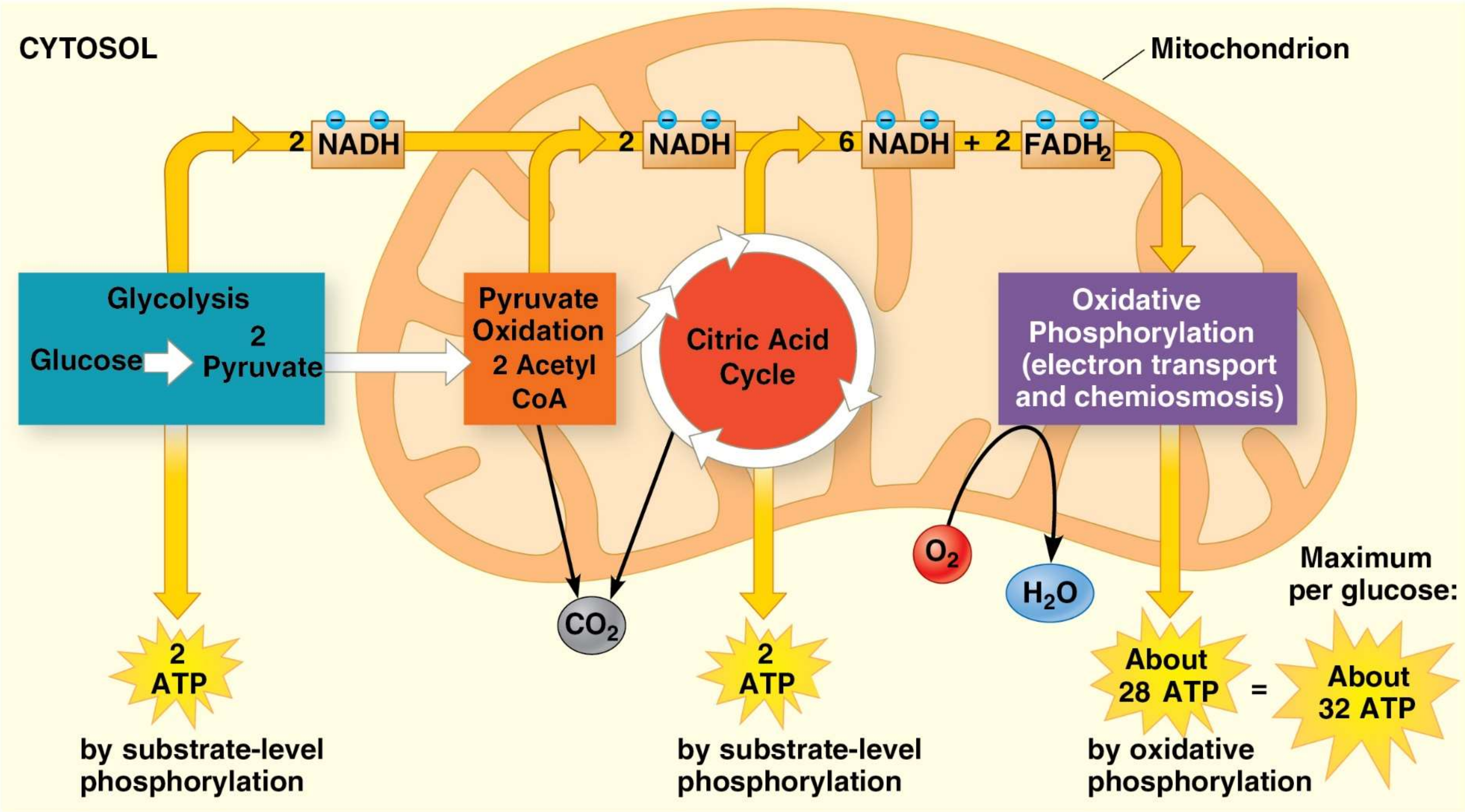
6.13 Review: Each Molecule of Glucose Yields Many Molecules of ATP

- Substrate-level phosphorylation and oxidative phosphorylation produce up to 32 ATP molecules for every glucose molecule oxidized in cellular respiration.

Checkpoint question Explain where O_2 is used and CO_2 is produced in cellular respiration.

O_2 accepts electrons at the end of the electron transport chain. CO_2 is released during the oxidation of intermediate compounds in pyruvate oxidation and the citric acid cycle.

Figure 6.13



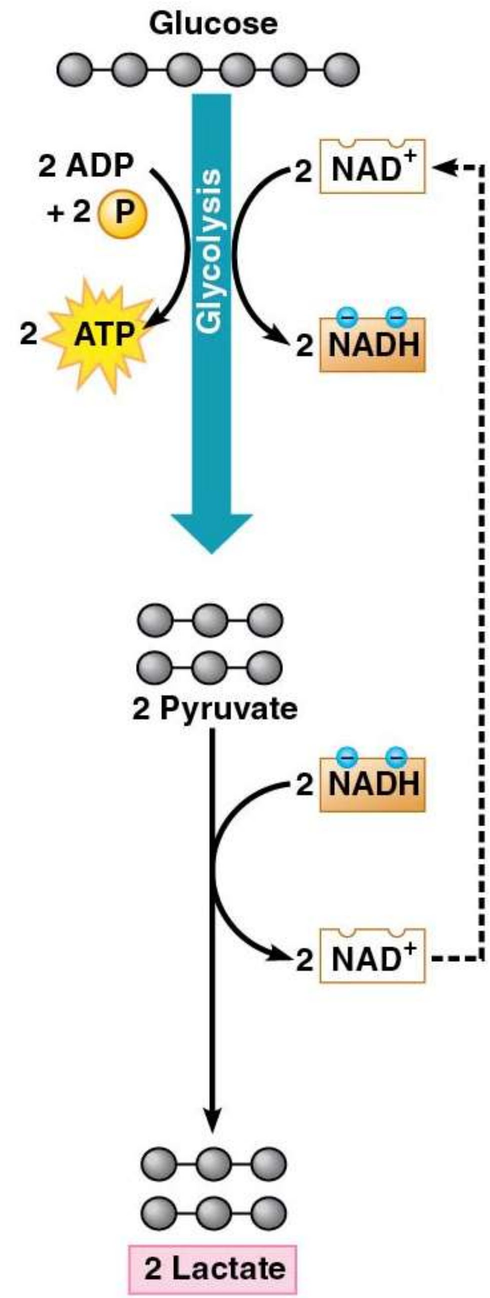
CYTOSOL
Mitochondrion
2 NADH
2 NADH
6 NADH + 2 FADH2
Glycolysis
Glucose
2 Pyruvate
Pyruvate Oxidation
2 Acetyl CoA
Citric Acid Cycle
Oxidative Phosphorylation (electron transport and chemiosmosis)
CO2
O2
H2O
2 ATP
by substrate-level phosphorylation
2 ATP
by substrate-level phosphorylation
About 28 ATP
by oxidative phosphorylation
=
Maximum per glucose:
About 32 ATP

Fermentation: Anaerobic Harvesting of Energy

6.14 Fermentation Enables Cells to Produce A T P Without Oxygen (1 of 2)

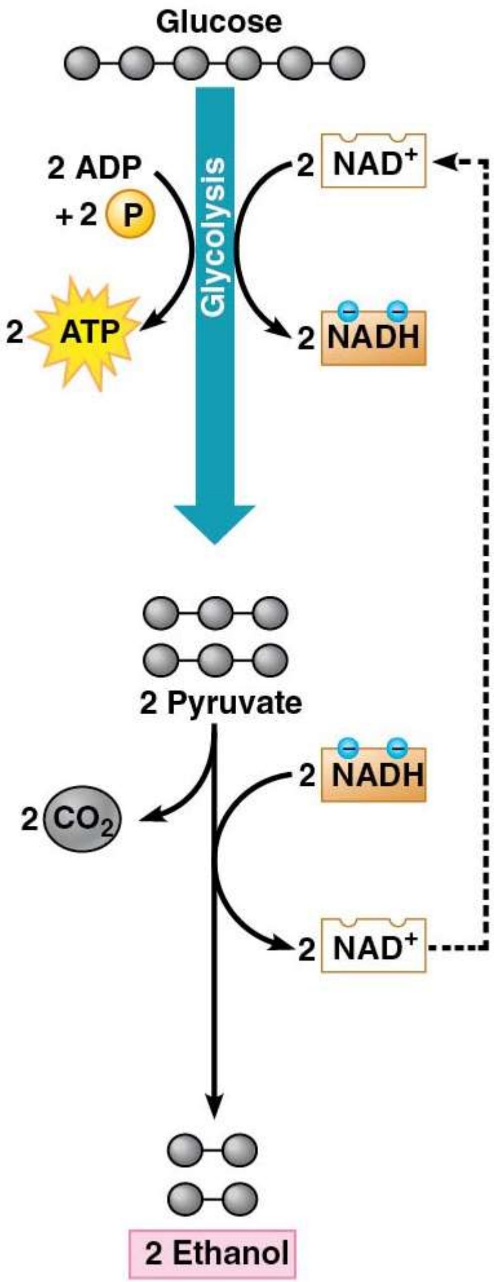
- Fermentation is a way of harvesting energy that does not require oxygen.
- Under anaerobic conditions, muscle cells, yeasts, and certain bacteria produce ATP by glycolysis.
- NAD^+ is recycled from NADH as pyruvate is reduced to
  - lactate (**lactic acid fermentation**) or
  - alcohol and CO_2 (**alcohol fermentation**).

Figure 6.14a



Glucose
Glycolysis
2 ADP
+ 2 P
2 ATP
2 NAD+
2 NADH
2 Pyruvate
2 NADH
2 NAD+
2 Lactate

Figure 6.14b



Glucose
Glycolysis
2 ADP
+ 2 P
2 ATP
2 NAD+
2 NADH
2 Pyruvate
2 CO2
2 NADH
2 NAD+
2 Ethanol

6.14 Fermentation Enables Cells to Produce ATP Without Oxygen (2 of 2)

Checkpoint question A glucose-fed yeast cell is moved from an aerobic environment to an anaerobic one. For the cell to continue generating ATP at the same rate, how would its rate of glucose consumption need to change?

The cell would have to consume glucose at a rate about 16 times the consumption rate in the aerobic environment (2 ATP per glucose molecule is made by fermentation versus 32 ATP by cellular respiration.)

6.15 Evolution Connection: Glycolysis Evolved Early in the History of Life on Earth

- Glycolysis occurs in the cytosol of the cells of nearly all organisms and is thought to have evolved in ancient prokaryotes.

Checkpoint question List some of the characteristics of glycolysis that indicate that it is an ancient metabolic pathway.

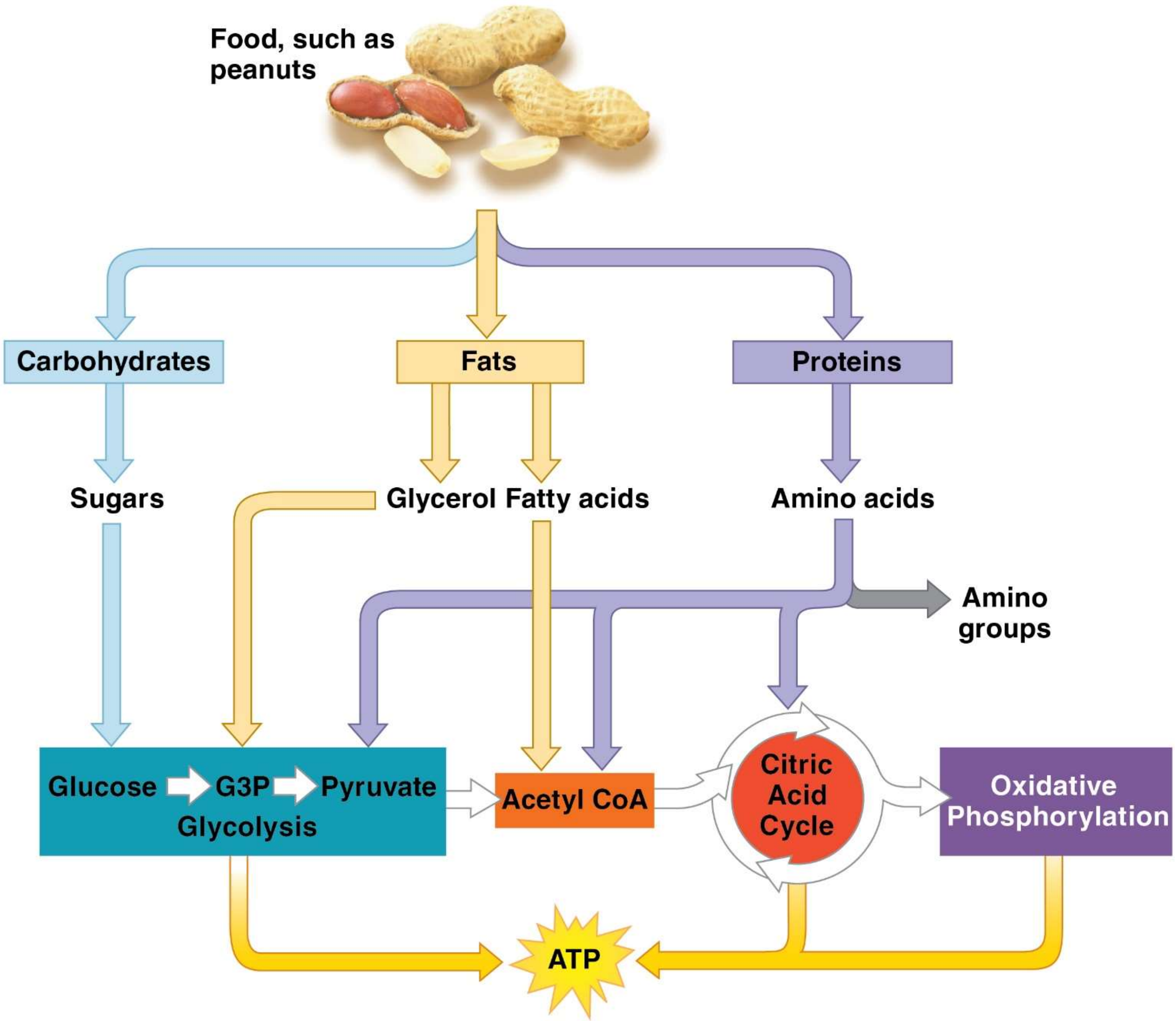
Glycolysis occurs universally (functioning in both fermentation and respiration), does not require oxygen, and does not occur in a membrane-enclosed organelle.

Connections Between Metabolic Pathways

6.16 Cells Use Many Kinds of Organic Molecules as Fuel for Cellular Respiration (1 of 2)

- You obtain most of your calories as
  - carbohydrates (such as sucrose and other disaccharide sugars and starch, a polysaccharide),
  - fats, and
  - proteins.
- A cell can use these three types of molecules to make ATP.

Figure 6.16



Food, such as peanuts
Carbohydrates
Fats
Proteins
Sugars
Glycerol
Fatty acids
Amino acids
Amino groups
Glucose
G3P
Pyruvate
Glycolysis
Acetyl CoA
Citric Acid Cycle
Oxidative Phosphorylation
ATP

6.16 Cells Use Many Kinds of Organic Molecules as Fuel for Cellular Respiration (2 of 2)

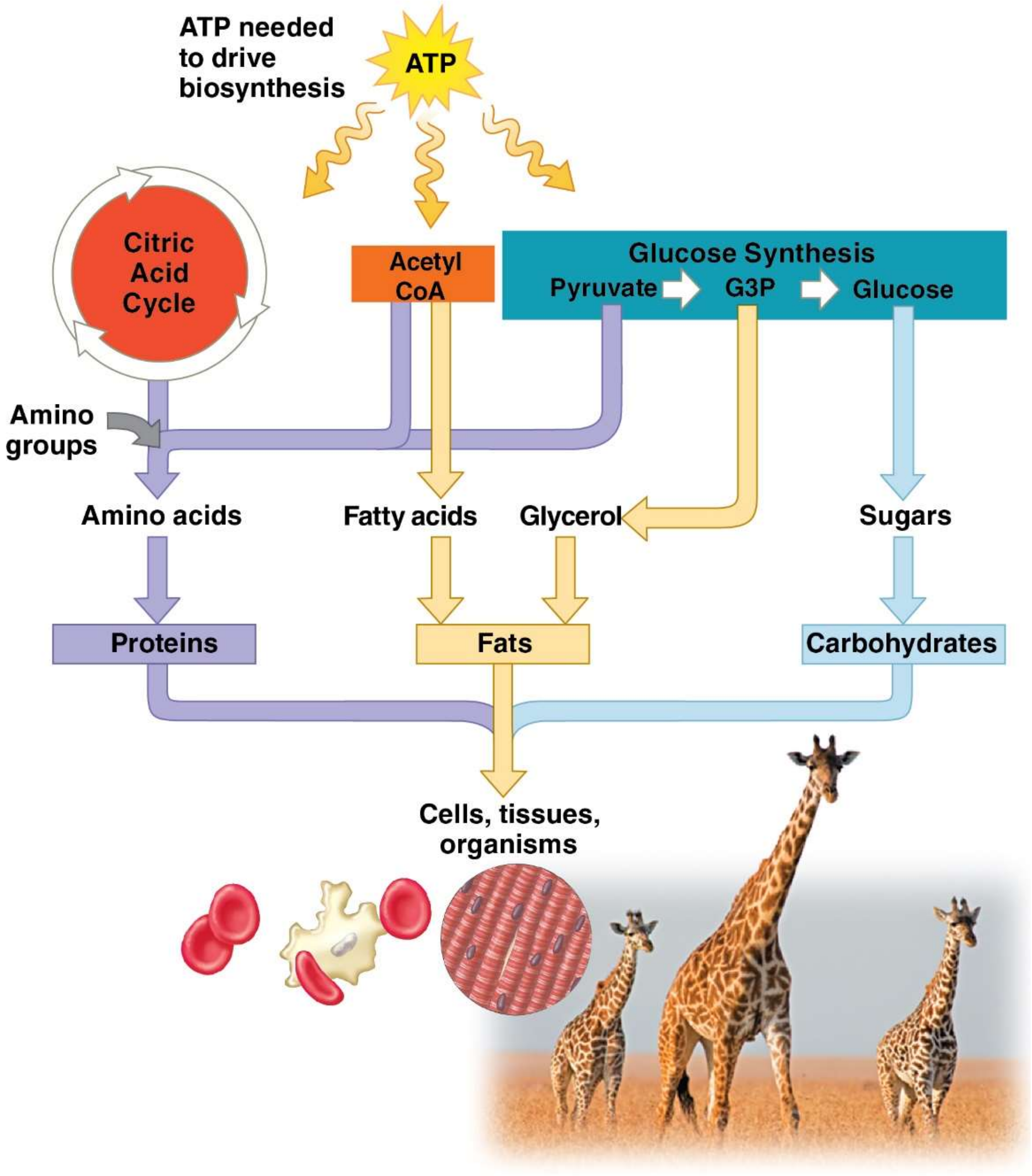
Checkpoint question Can a human survive on a diet consisting primarily of fats and proteins and almost no sugar?

Yes. Breakdown products from fats and proteins enter the cellular respiration pathway through glycolysis and the citric acid cycle to make ATP.

6.17 Organic Molecules from Food Provide Raw Materials for Biosynthesis (1 of 2)

- Cells use intermediates from cellular respiration and ATP for biosynthesis of other organic molecules.
- Metabolic pathways are often regulated by feedback inhibition.

Figure 6.17


ATP needed to drive biosynthesis
ATP
Citric Acid Cycle
Acetyl CoA
Glucose Synthesis
Pyruvate
G3P
Glucose
Amino groups
Amino acids
Fatty acids
Glycerol
Sugars
Proteins
Fats
Carbohydrates
Cells, tissues, organisms

6.17 Organic Molecules from Food Provide Raw Materials for Biosynthesis (2 of 2)

Checkpoint question Explain how someone can gain weight and store fat even when on a low-fat diet.

If caloric intake is excessive, body cells use metabolic pathways to convert the excess to fat. The glycerol and fatty acids of fats are made from G3P and acetyl CoA, respectively, both produced from the oxidation of carbohydrates.