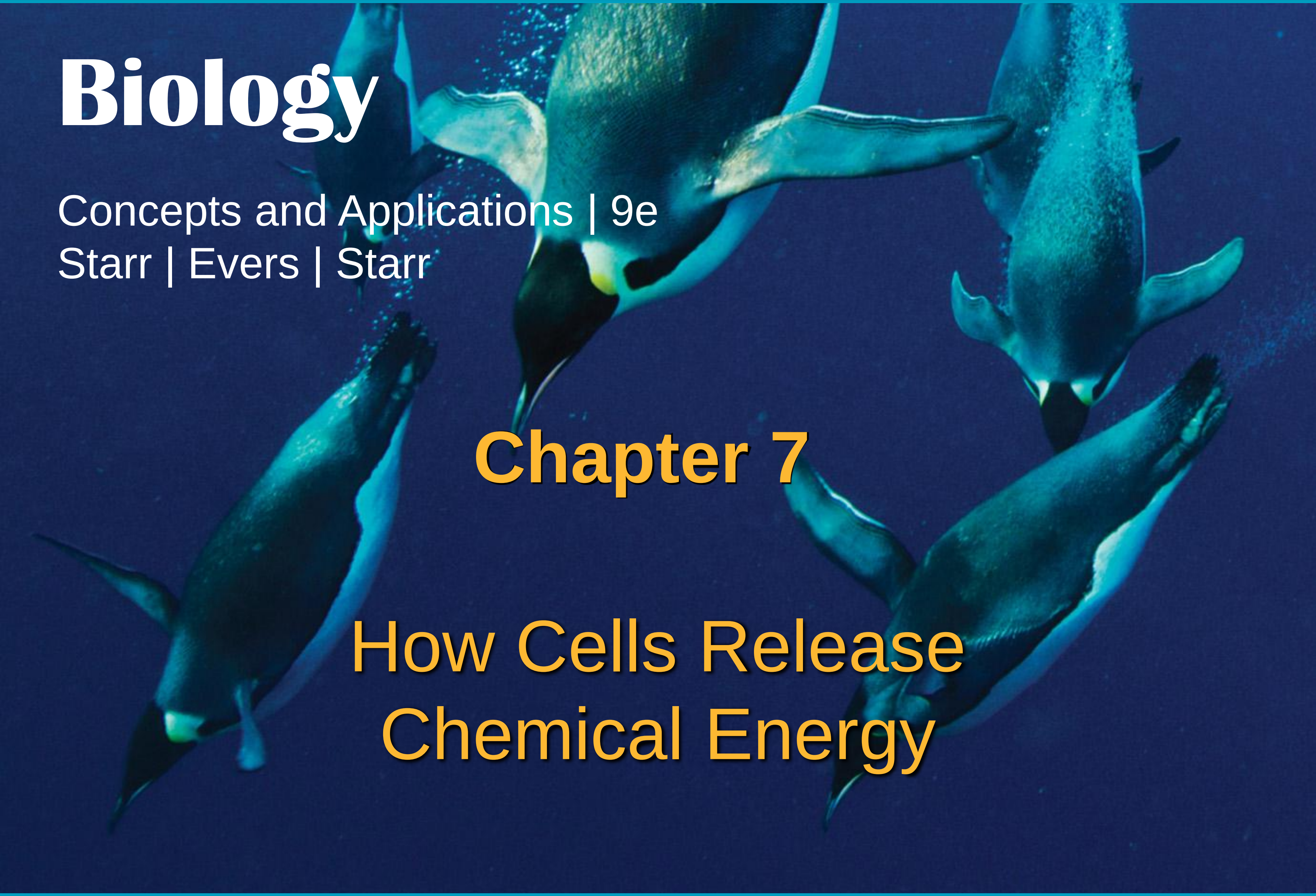

Biology

Concepts and Applications | 9e

Starr | Evers | Starr

Chapter 7

How Cells Release Chemical Energy

7.1 How Do Cells Access the Chemical Energy in Sugars?

- In order to use the energy stored in sugars, cells must first transfer it to ATP
  - The energy transfer occurs when the bonds of a sugar's carbon backbone are broken, driving ATP synthesis

How Do Cells Access the Chemical Energy in Sugars? (cont'd.)

- There are two main mechanisms by which organisms break down sugars to make ATP:
  - Aerobic respiration
  - Fermentation

Aerobic Respiration and Fermentation Compared (cont'd.)

- Aerobic respiration: requires oxygen to break down sugars to make ATP
  - Main energy-releasing pathway in nearly all eukaryotes and some bacteria

Aerobic Respiration and Fermentation Compared (cont'd.)

- The three stages of aerobic respiration produce thirty-six ATP:
  - Glycolysis
    - Occurs in the cytoplasm; net yield is two ATP
  - Krebs cycle
    - Occurs in the mitochondria; net yield is two ATP
  - Electron transfer phosphorylation
    - Occurs in the mitochondria; net yield is thirty-two ATP

Animation: Where Pathways Start and Finish

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Aerobic Respiration and Fermentation Compared (cont'd.)

- Fermentation: sugar breakdown pathway that does not require oxygen to make ATP
  - Like aerobic respiration, fermentation begins with glycolysis in cytoplasm
  - Unlike aerobic respiration, fermentation occurs entirely in cytoplasm, and does not include electron transfer chains
  - Net yield is two ATP, which provides enough ATP to sustain many single-celled species

7.2 How Did Energy-Releasing Pathways Evolve?

- The first cells we know of appeared on Earth about 3.4 billion years ago
  - These ancient organisms did not use sunlight
- Eventually, the cyclic pathway of photosynthesis evolved
  - Sunlight offered an unlimited supply of energy

How Did Energy-Releasing Pathways Evolve? (cont'd.)

- A new noncyclic pathway of photosynthesis evolved
  - Water molecules were split into hydrogen and oxygen
  - Oxygen gas (O_2) began seeping out of photosynthetic prokaryotes
  - O_2 began to accumulate in the ocean and the atmosphere – changing the world of life!

How Did Energy-Releasing Pathways Evolve? (cont'd.)

- When O_2 first accumulated, it caused catastrophic pollution
  - Free radicals form when O_2 reacts with metal cofactors
  - Free radicals damage DNA and other biological molecules
  - Cells with no way to cope with free radicals quickly died out

How Did Energy-Releasing Pathways Evolve? (cont'd.)

- Following the early accumulation of O_2, only a few lineages persisted
  - Life persisted in deep water, muddy sediments, and other *anaerobic* (oxygen-free) habitats
  - Antioxidants evolved in these survivors, giving rise to the first *aerobic* (oxygen using) organisms

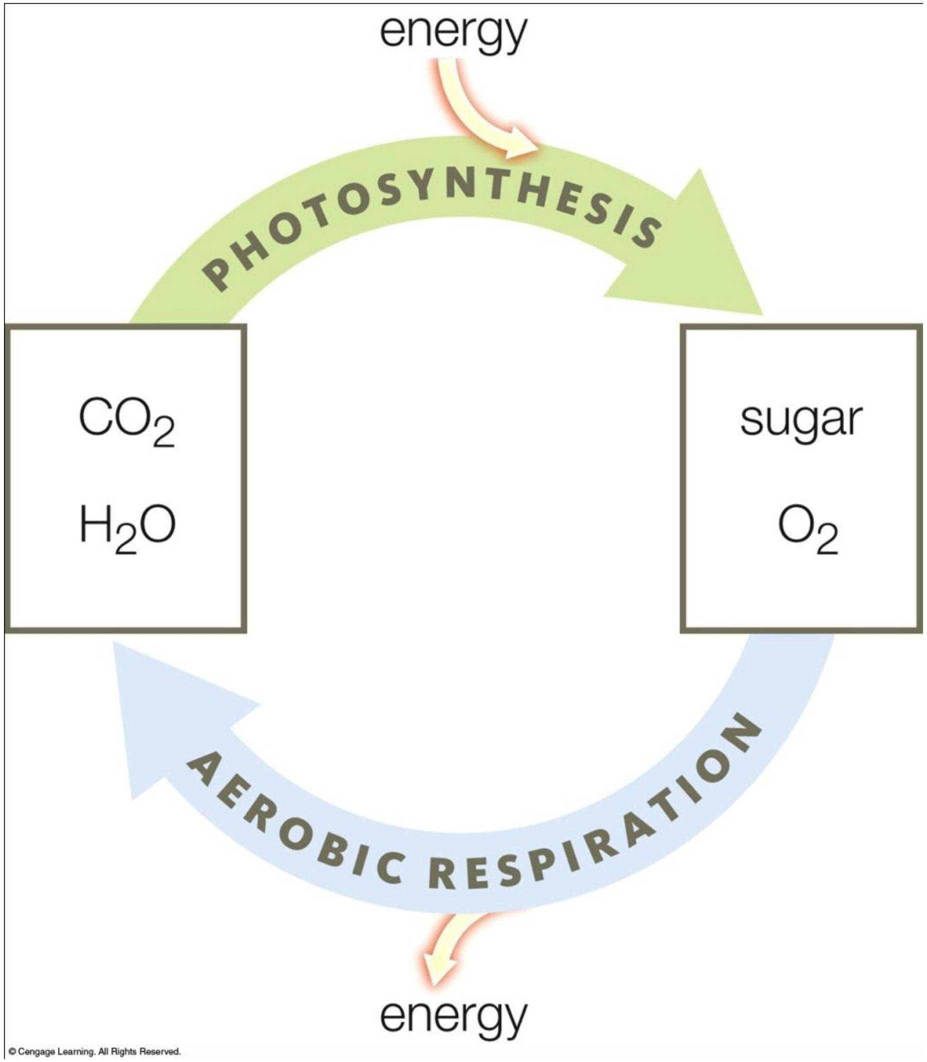
How Did Energy-Releasing Pathways Evolve? (cont'd.)

- The newly evolved aerobic organisms put the reactive properties of oxygen to use in aerobic respiration pathways
  - Aerobic respiration involves the reverse reactions of photosynthesis:
    - Uses oxygen and produce carbon dioxide
    - Combines molecular oxygen with hydrogen ions and electrons

How Did Energy-Releasing Pathways Evolve? (cont'd.)

- The cycling of carbon, hydrogen, and oxygen through living things came full circle with the evolution of aerobic organisms

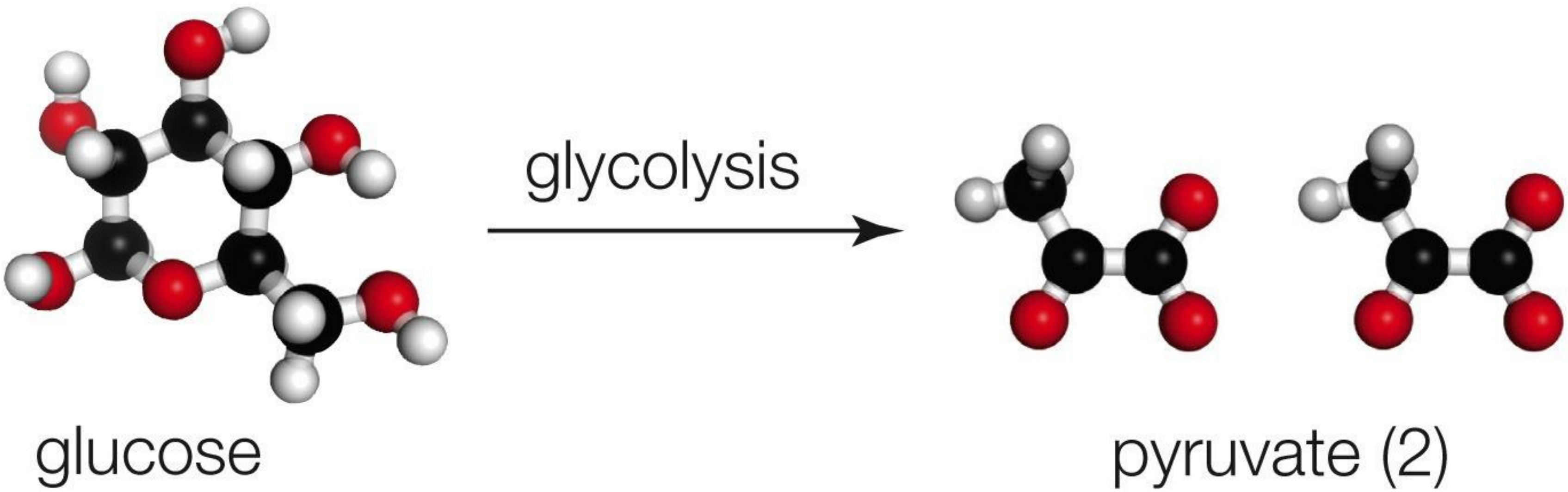
How Did Energy-Releasing Pathways Evolve? (cont'd.)



7.3 What Is Glycolysis?

- Glycolysis: series of reactions that begin the sugar breakdown pathways of aerobic respiration and fermentation
  - Convert one six-carbon molecule of sugar (such as glucose) into two molecules of *pyruvate*: an organic compound with a three-carbon backbone

What Is Glycolysis? (cont'd.)



What Is Glycolysis? (cont'd.)

- Steps of glycolysis:
  - A phosphate group is transferred from ATP to glucose, forming glucose-6-phosphate
  - Glucose-6-phosphate accepts a phosphate group from another ATP
    - Two PGAL (phosphoglyceraldehyde) form

What Is Glycolysis? (cont'd.)

- Steps of glycolysis (cont'd.):
  - Each PGAL receives a second phosphate group, and each gives up two electrons and a hydrogen ion
    - Two molecules of PGA (phosphoglycerate) form
    - The electrons and hydrogen ions are accepted by two NAD+, forming NADH (required for third step of aerobic respiration)

What Is Glycolysis? (cont'd.)

- Steps of glycolysis (cont'd.):
  - A phosphate group is transferred from each PGA to ADP, so two ATP form
    - The direct transfer of a phosphate group from a substrate to ADP is called *substrate-level phosphorylation*
  - Glycolysis ends with the formation of two more ATP by substrate-level phosphorylation

What Is Glycolysis? (cont'd.)

- Net yield of glycolysis is two ATP per molecule of glucose
  - A total of four ATP form, but two ATP were invested to begin the reactions of glycolysis
- Glycolysis also produces two three-carbon pyruvate molecules

Animation: Glycolysis

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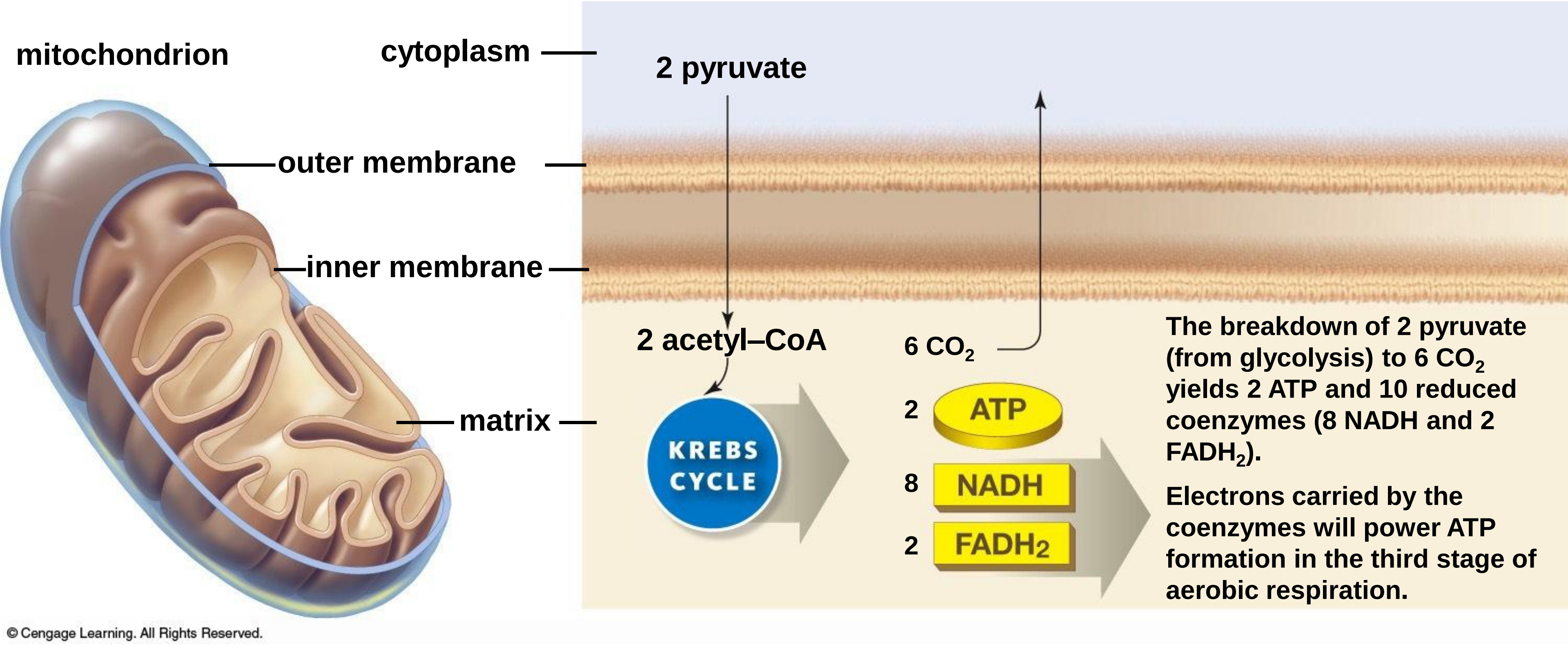
7.4 What Happens During the Second Stage of Aerobic Respiration?

- The second stage of aerobic respiration occurs inside mitochondria
  - Includes two sets of reactions, acetyl–CoA formation and the Krebs cycle
  - These pathways break down the pyruvate produced during glycolysis

What Happens During the Second Stage of Aerobic Respiration? (cont'd.)



Acetyl–CoA Formation

- Steps of acetyl-CoA formation:
  - Pyruvate is transported into the mitochondrial matrix
  - Pyruvate is split into CO_2 and a two-carbon acetyl group ($—COCH_3$)
  - CO_2 diffuses out of the cell and the acetyl group combines with coenzyme A (CoA), forming acetyl-CoA
    - Electrons and hydrogen ions released by the reaction combine with NAD+, so NADH also forms

The Krebs Cycle

- Steps of the Krebs cycle:
  - Two carbon atoms of acetyl–CoA are transferred to oxaloacetate, forming citrate
  - Two CO_2 form and depart the cell
  - Two NAD^+ are reduced when they accept hydrogen ions and electrons, forming two NADH

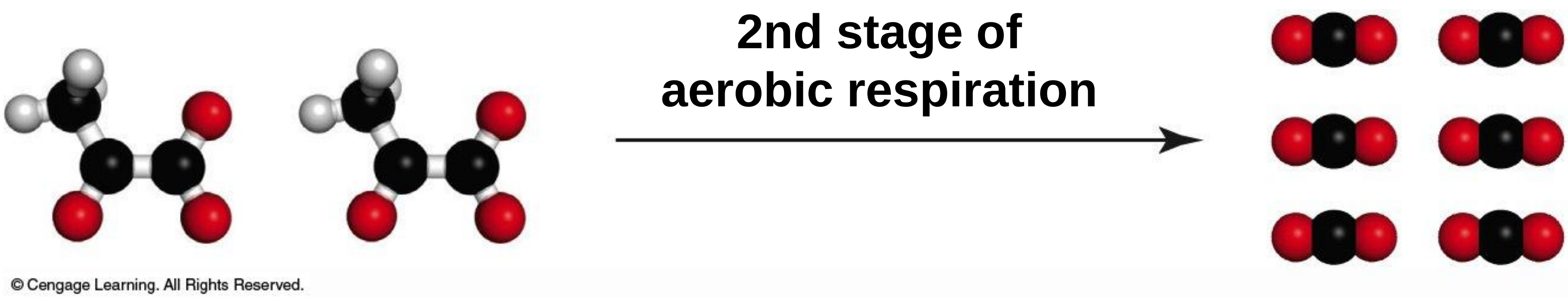
The Krebs Cycle (cont'd.)

- Steps of the Krebs cycle (cont'd.):
  - ATP forms by substrate-level phosphorylation
  - Two coenzymes are reduced: an FAD (flavin adenine dinucleotide) and another NAD^+
  - Oxaloacetate is regenerated

The Krebs Cycle (cont'd.)

- The combined second-stage reactions of aerobic respiration break down two pyruvate to six CO_2
- Net yield of second-stage reactions is two ATP
- Ten coenzymes (eight NAD^+ and two FAD) are reduced
  - Provides electrons to the third stage of aerobic respiration

The Krebs Cycle (cont'd.)



pyruvate (2) **carbon dioxide (6)**

Animation: The Krebs Cycle–Details

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7.5 What Happens During the Third Stage of Aerobic Respiration?

- The third stage of aerobic respiration occurs at the inner mitochondrial membrane
- NADH and $FADH_2$ (produced during the first two stages of aerobic respiration) deliver electrons and hydrogen ions to electron transfer chains

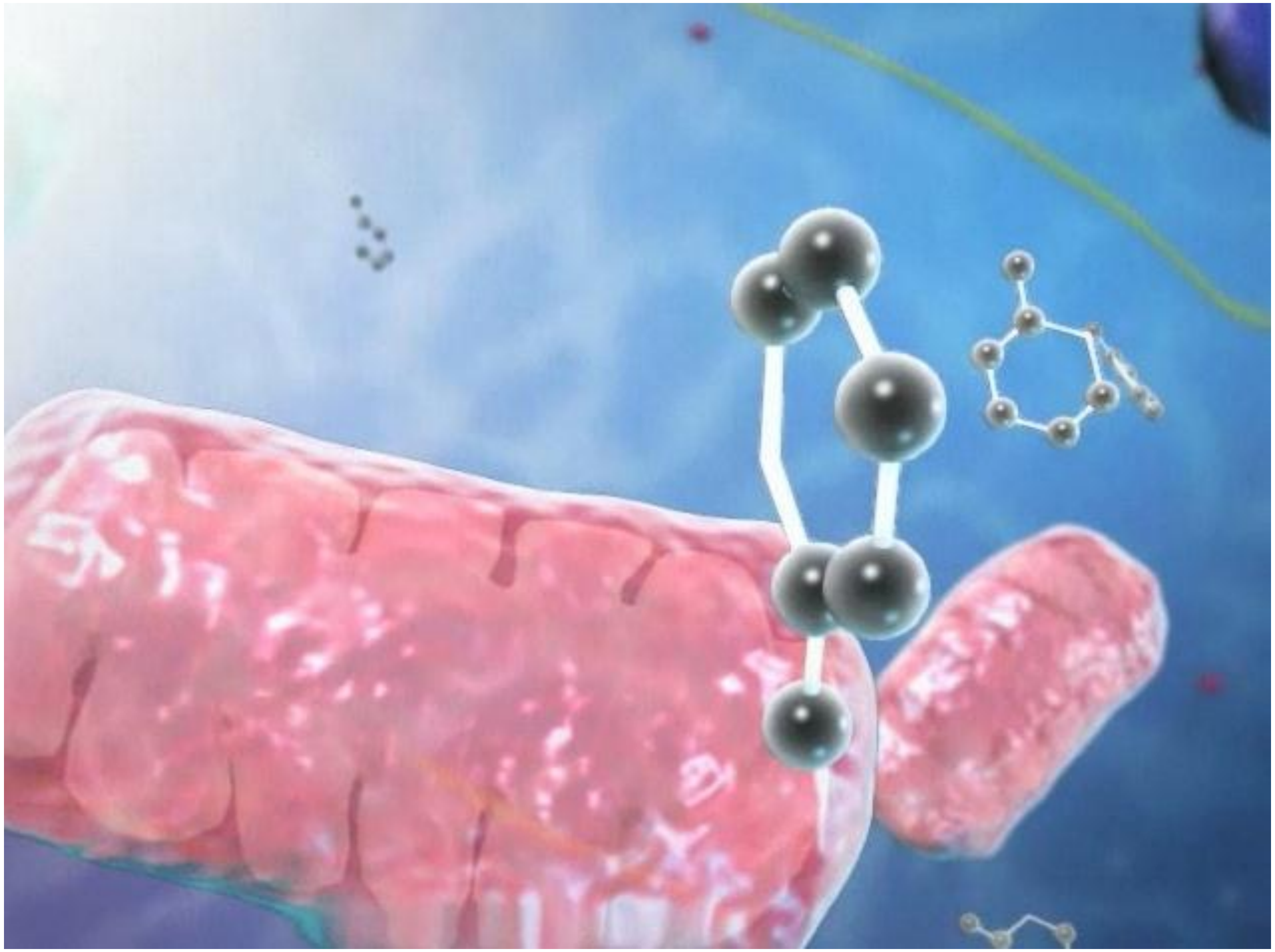
What Happens During the Third Stage of Aerobic Respiration? (cont'd.)

- As the electrons move through the chains, they give up energy little by little
- Hydrogen ions are actively transported across the inner membrane
  - The resulting hydrogen ion gradient causes the ions to flow through the ATP synthase, driving the formation of ATP

What Happens During the Third Stage of Aerobic Respiration? (cont'd.)

- Oxygen accepts electrons at the end of mitochondrial electron transfer chains
  - Water is formed as a byproduct
- About thirty-two ATP form during the third-stage reactions

3D ANIMATION: Cellular Respiration



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7.5 What Happens During the Third Stage of Aerobic Respiration? (cont'd.)

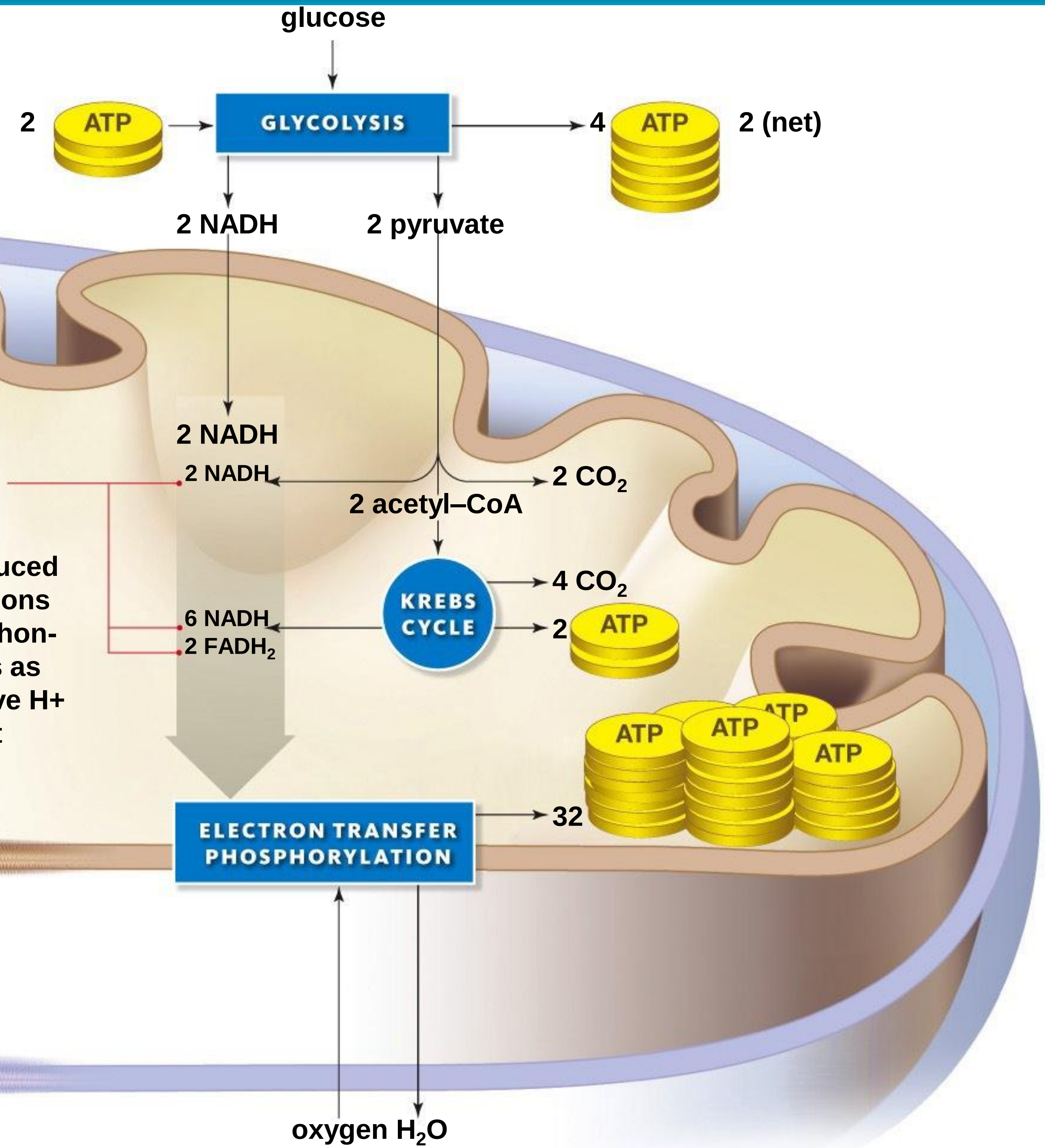
- Summary of aerobic respiration:
  - For each glucose molecule, four ATP form in the first- and second-stage reactions
  - The twelve coenzymes reduced in the first two stages deliver enough electrons to fuel synthesis of about thirty-two additional ATP during the third stage
  - Thirty-six net ATP are produced in total

What Happens During the Third Stage of Aerobic Respiration? (cont'd.)

Stage 1
Glycolysis in cytoplasm splits a glucose molecule into 2 pyruvate; 2 NADH and 4 ATP also form. An investment of 2 ATP began the reactions, so the net yield is 2 ATP.

Stage 2
Acetyl–CoA formation and the Krebs cycle in the mitochondrial matrix break down the pyruvate to CO2, which leaves the cell. Ten additional coenzymes are reduced. Two ATP form.

Stage 3
In electron transfer phosphorylation, the reduced coenzymes give up electrons and hydrogen ions to electron transfer chains in the inner mitochondrial membrane. Energy lost by the electrons as they move through the chains is used to move H+ across the membrane. The resulting gradient causes H+ to flow through ATP synthases, which drives ATP synthesis.



7.6 What Is Fermentation?

- Like aerobic respiration, fermentation begins with glycolysis in the cytoplasm
  - In fermentation, pyruvate is not fully broken down to CO_2
  - Electrons do not move through electron transfer chains, so no additional ATP forms
  - NAD^+ is regenerated, allowing glycolysis to continue
  - The net yield is two ATP

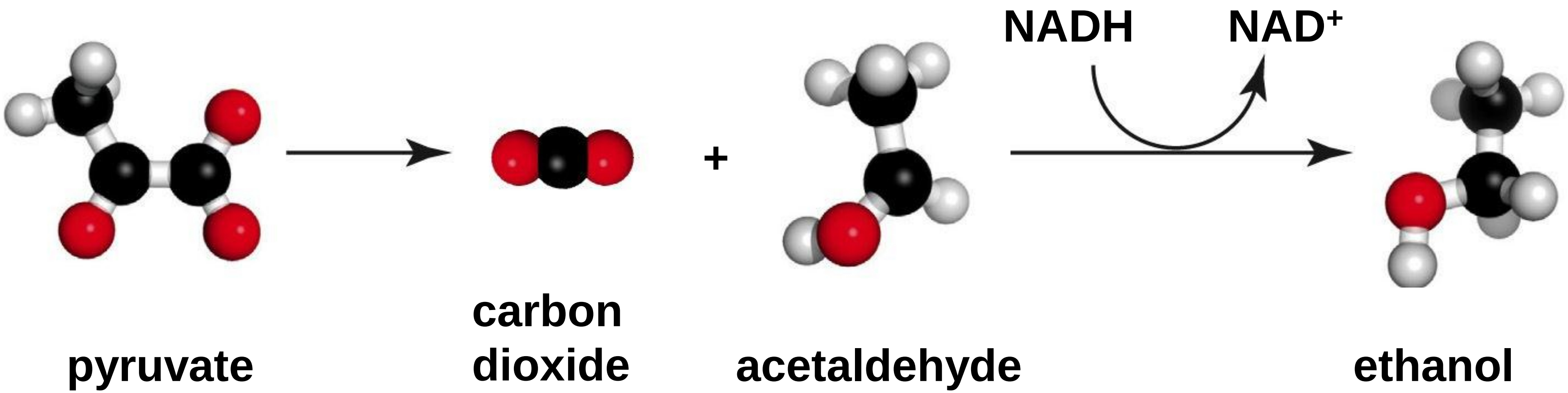
What Is Fermentation? (cont'd.)

- Two fermentation pathways:
  - Alcoholic fermentation: anaerobic sugar breakdown pathway that produces ATP, CO_2, and ethanol
  - Lactate fermentation: anaerobic sugar breakdown pathway that produces ATP and lactate

Alcoholic Fermentation

- Steps of alcoholic fermentation:
  - 3-carbon pyruvate is split into carbon dioxide and 2-carbon acetaldehyde
  - Electrons and hydrogen are transferred from NADH to the acetaldehyde, forming NAD^+ and ethanol

Alcoholic Fermentation (cont'd.)



ANIMATION: The fermentation reactions

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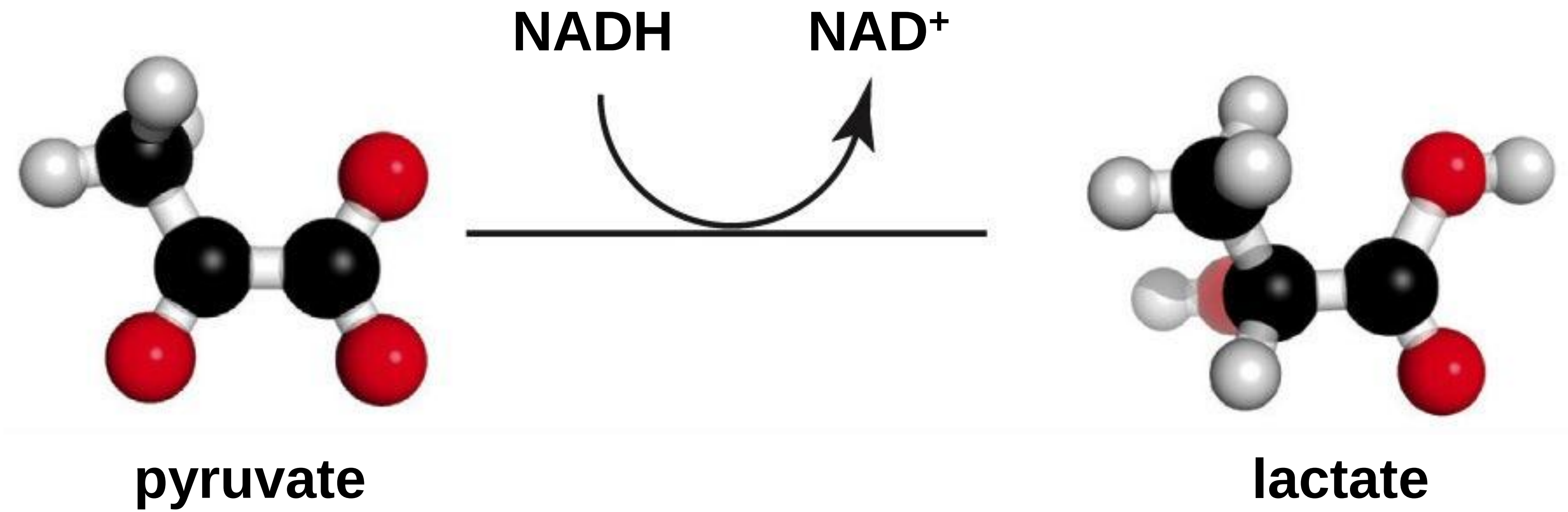
Alcoholic Fermentation (cont'd.)

- Alcoholic fermentation in a fungus, *Saccharomyces cerevisiae,* sustains these yeast cells as they grow and reproduce
  - Used to produce beer, wine, and bread

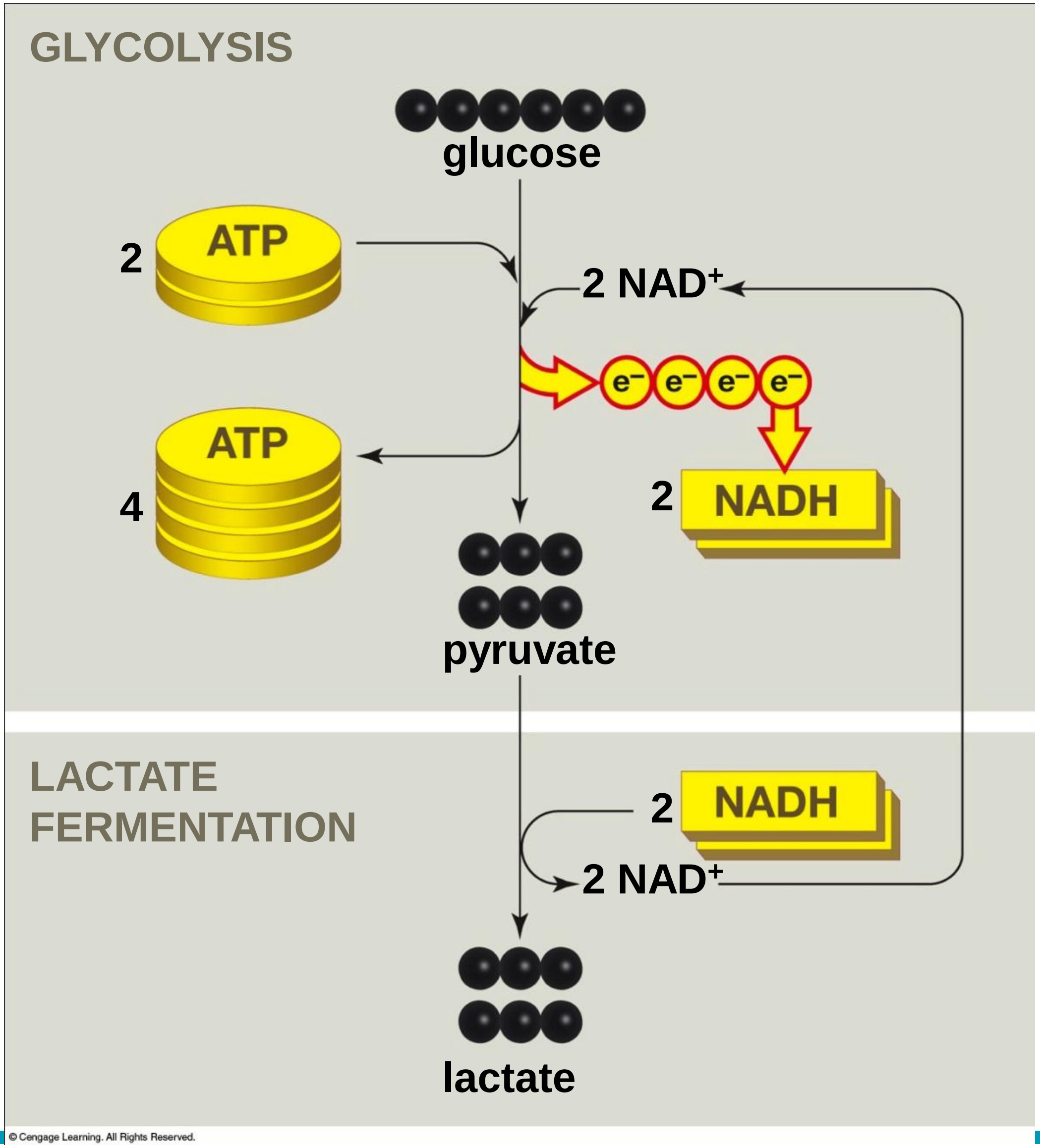
Lactate Fermentation

- Steps of lactate fermentation:
  - The electrons and hydrogen ions carried by NADH are transferred directly to pyruvate
  - Pyruvate is converted to 3-carbon lactate
  - NADH is converted to NAD^+

Lactate Fermentation (cont'd.)



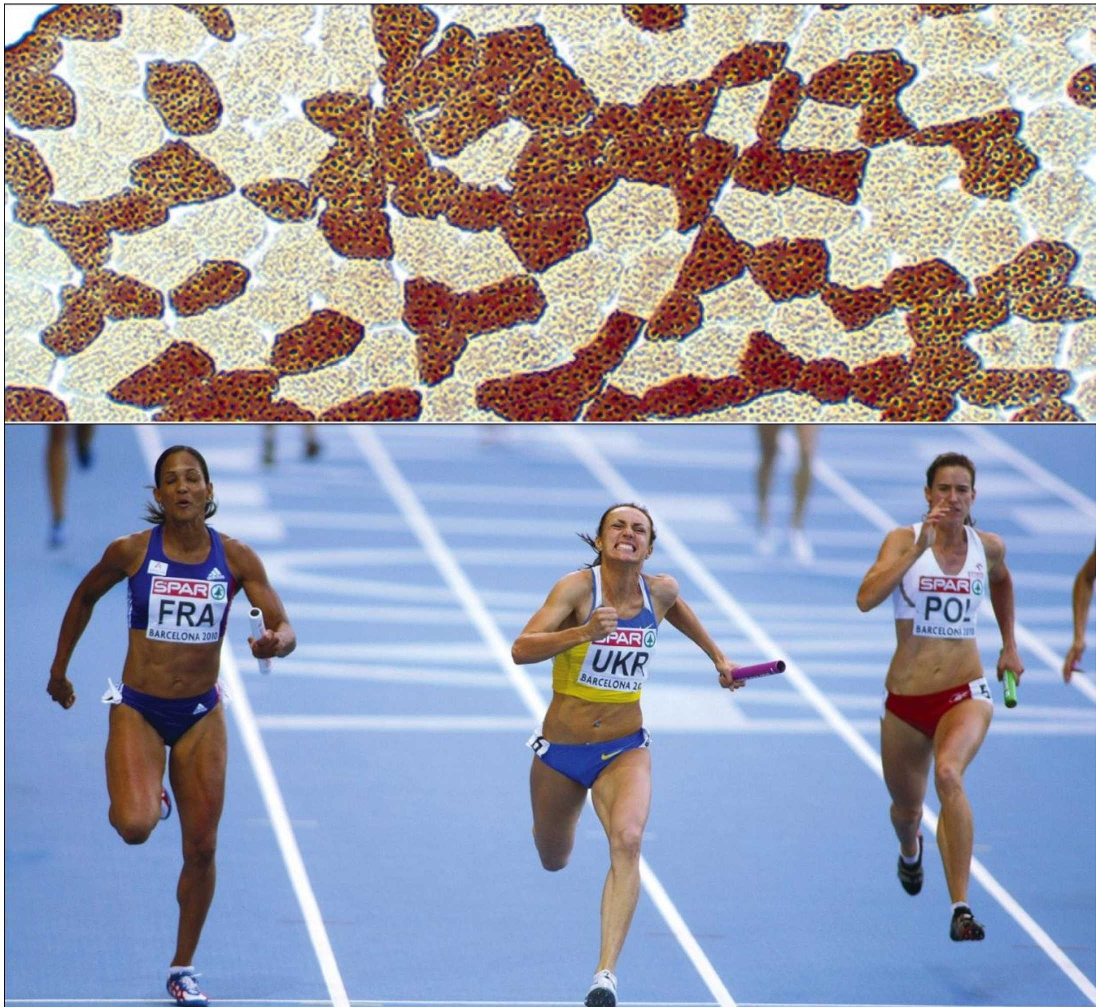
Lactate Fermentation (cont'd.)



Lactate Fermentation (cont'd.)

- Animal muscle cells carry out aerobic respiration and/or lactate fermentation
  - Red muscle fibers: many mitochondria and myoglobin; produce ATP mainly by aerobic respiration
    - Sustains prolonged activity
  - White muscle fibers: contain few mitochondria and no myoglobin; most ATP produced by lactate fermentation
    - Useful for quick, strenuous activities

Lactate Fermentation (cont'd.)



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7.7 Can the Body Use Any Organic Molecule for Energy?

- Energy from dietary molecules
  - Aerobic respiration generates a lot of ATP by fully oxidizing glucose, completely dismantling it carbon by carbon
    - Cells also dismantle other organic molecules by oxidizing them
  - Complex carbohydrates, fats, and proteins in food can be converted to molecules that enter glycolysis or the Krebs cycle

Complex Carbohydrates

- Starches and other complex carbohydrates are broken down into monosaccharides
- Sugars are converted to glucose-6-phosphate for glycolysis
  - A high concentration of ATP causes glucose-6-phosphate to be diverted away from glycolysis and into the formation of glycogen stores

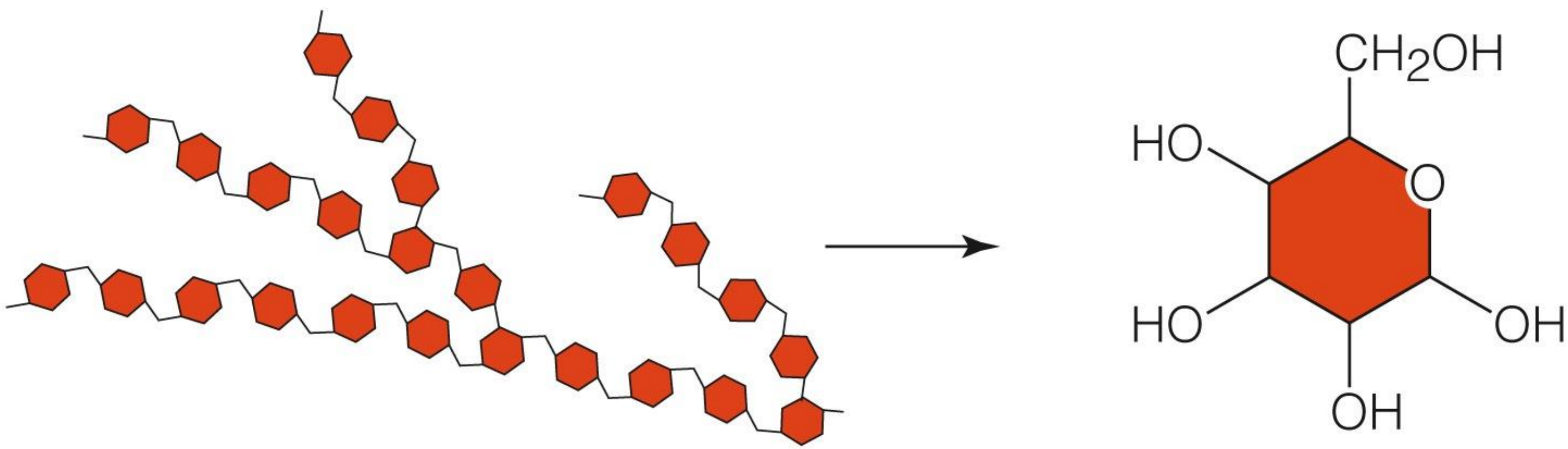
Fats

- Fats are dismantled by first breaking the bonds that connect the fatty acid tails to the glycerol head
- Free fatty acids are oxidized by splitting their backbones into two-carbon fragments
  - These fragments are converted to acetyl–CoA, which can enter the Krebs cycle
- Glycerol gets converted to PGAL, an intermediate of glycolysis

Proteins

- Dietary proteins are split into their amino acid subunits
  - Ammonia (NH_3), formed as a waste product, is eliminated in urine
  - The carbon backbone is split, and acetyl–CoA, pyruvate, or an intermediate of the Krebs cycle forms
  - These molecules enter aerobic respiration’s second stage

7.7 Can the Body Use Any Organic Molecule for Energy? (cont'd.)



starch (a complex carbohydrate) **glucose**

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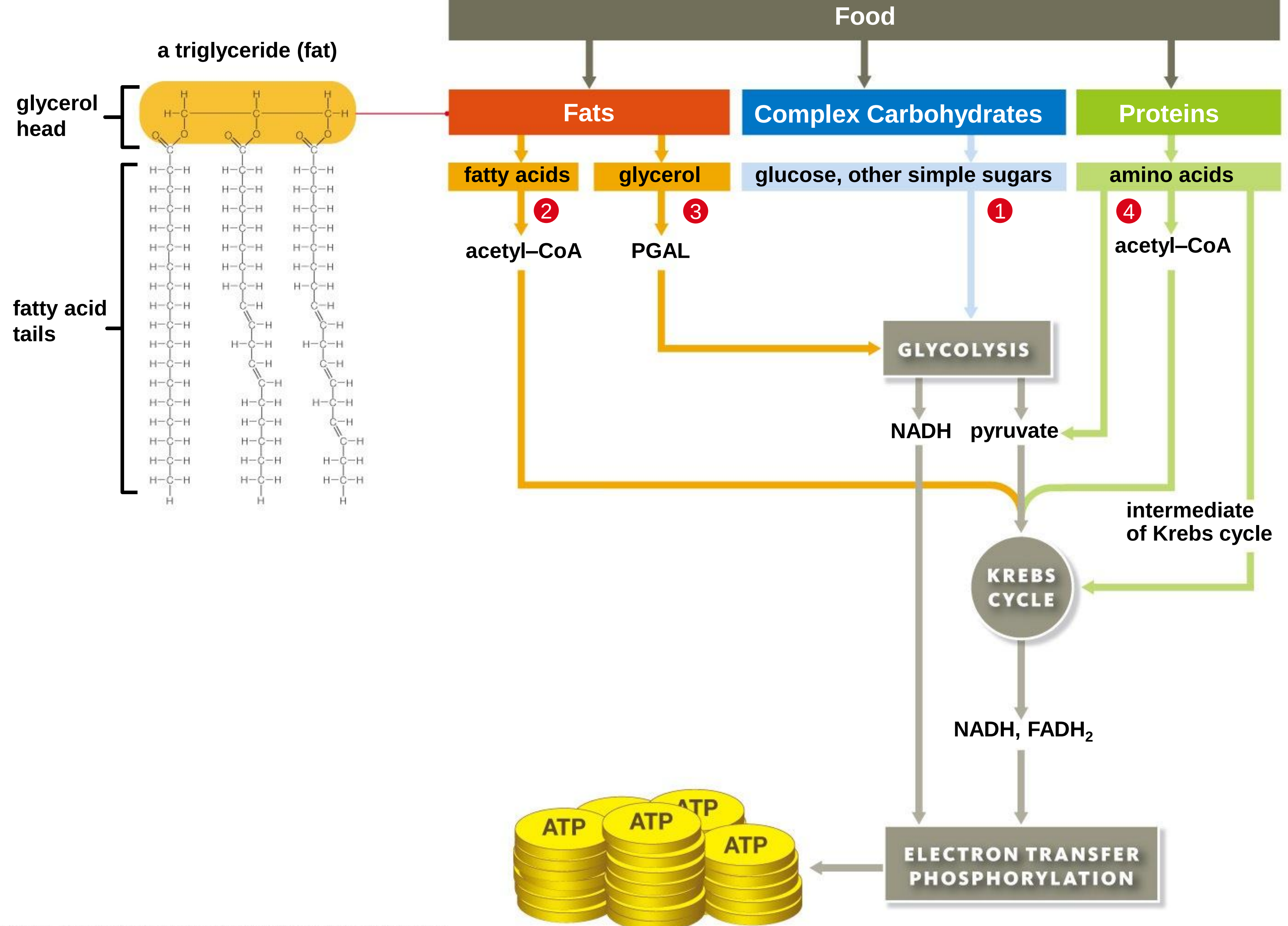
Food
a triglyceride (fat)
glycerol head
fatty acid tails
Fats
Complex Carbohydrates
Proteins
fatty acids
glycerol
glucose, other simple sugars
amino acids
2
3
1
4
acetyl–CoA
PGAL
acetyl–CoA
GLYCOLYSIS
NADH
pyruvate
intermediate of Krebs cycle
KREBS CYCLE
NADH, FADH2
ATP
ATP
ATP
ATP
ELECTRON TRANSFER PHOSPHORYLATION

7.8 Application: Mitochondrial Malfunction

- Sometimes when oxygen enters an electron transfer chain, it escapes as a free radical
  - Free radicals cause damage by oxidizing biological molecules and breaking carbon backbones
- Antioxidants in the cytoplasm detoxify free radicals

Application: Mitochondrial Malfunction (cont'd.)

- A genetic disorder or encounter with a toxin can result in a missing antioxidant or defective electron transfer chain
  - Free radicals accumulate and destroy first the function of mitochondria, then the cell
    - This tissue damage is called oxidative stress
  - Hundreds of incurable disorders are associated with such defects
    - Cancer, hypertension, Alzheimer's, and Parkinson's diseases

Application: Mitochondrial Malfunction (cont'd.)