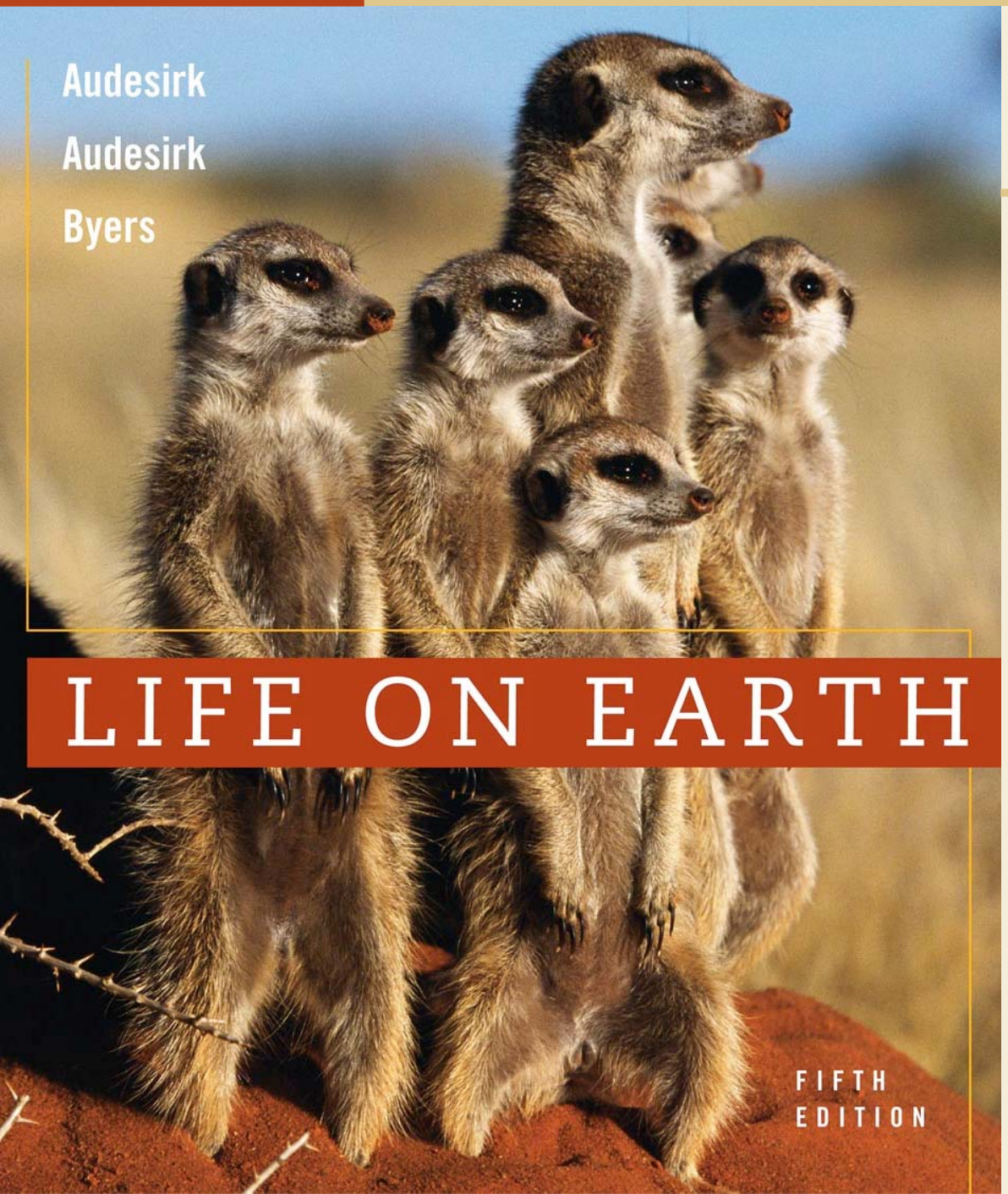

Chapter 7

Harvesting Energy: Glycolysis and Cellular Respiration

Including some materials
from lectures by
Gregory Ahearn
University of North Florida
Ammended by
John Crocker

Preliminary Review Questions Chapter 5-7

These questions need full and complete answers. Typically this will require a paragraph or two. If you are not certain if your answer is complete, ASK.

1. Define Energy, Chemical Energy, and Work.
2. What are the First and Second Laws of Thermodynamics? How do they impact growing complexity and decreasing entropy in living things on earth? (hint: is earth a closed system?)
3. Describe the process of photosynthesis. What is happening at a molecular and atomic level? (hint: electron carriers are at the molecular level, electrons are at the atomic level)
4. Compare and contrast exergonic and endergonic reactions and explain how they are related in coupled reactions.
5. Detail two coupled reactions involving ATP. (hint: detail should include all steps involved)
6. What are enzymes and how do they function? Be specific.
7. What environmental factors effect enzyme function? How do they effect enzyme function?
8. Describe allosteric regulation and feedback inhibition.
9. How does photosynthesis convert solar energy into energy usable by cells? Be specific. What are the chemical reactions? (Be more specific than $6\ CO_2 + 6H_2O + \text{sunlight energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$)
10. Describe the structure and location of chloroplasts within a leaf?
11. Detail the steps of PSI and PSII. How are they coupled?
12. What happens in the light reactions of photosynthesis? What happens in the dark reactions? How are light and dark reactions coupled?
13. What role does the color of photosynthetic pigments play in photosynthesis?
14. What is photorespiration? Why is it undesirable?
15. Compare and contrast photosynthesis and cellular respiration. Again be specific about reactions energy requirements etc.
16. How is cellular energy stored?
17. Describe in detail the processes of cellular metabolism. (glycolysis and cellular respiration)
18. Compare and contrast cellular respiration and fermentation. Once again be specific. What chemical processes are occurring in each and how are those similar and/or different?

7.1 What Is The Source Of A Cell's Energy?

- The energy for cellular activities is stored until use in bonds of molecules such as carbohydrates and fats.
- Stored energy is transferred to the bonds of energy-carrier molecules including ATP (adenosine triphosphate).
- Glucose is a key energy-storage molecule.

Source Of Cellular Energy

- Photosynthesis is the ultimate source of cellular energy.
- Photosynthetic cells capture and store sunlight energy
- This energy is later used by cells.
- These cells can be the photosynthetic organisms, or can be other organisms that consume photosynthetic organisms.

Source Of Cellular Energy

- Glucose metabolism and photosynthesis are complementary processes.
- The products of each reaction provide reactants for the other.
- The symmetry is visible in the equations that describe each process.
  - Photosynthesis:

    $6\ CO_2 + 6H_2O + \text{sunlight energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$
  - Glucose metabolism:

    $C_6H_{12}O_6 + 6O_2 \rightarrow 6\ CO_2 + 6\ H_20 + ATP + \text{heat energy}$

7.2 How Do Cells Harvest Energy From Glucose?

- Glucose metabolism occurs in stages
  - 1st stage is **glycolysis**.
  - 2nd stage, **cellular respiration**
  - Under **anaerobic** (no O_2) conditions the 2nd stage of glucose metabolism is **fermentation**.

Flash

Glucose

- Glucose is a key energy-storing molecule:
  - Nearly all cells metabolize glucose for energy
  - Glucose metabolism is fairly simple
  - Other organic molecules are converted to glucose for energy harvesting

Glucose

- During glucose breakdown, all cells release the solar energy that was originally captured by plants through photosynthesis, and use it to make ATP
- The overall equation for the complete breakdown of glucose is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$$

Overview of Glucose Breakdown

- The main stages of glucose metabolism are:
  - **Glycolysis**
  - **Cellular respiration**

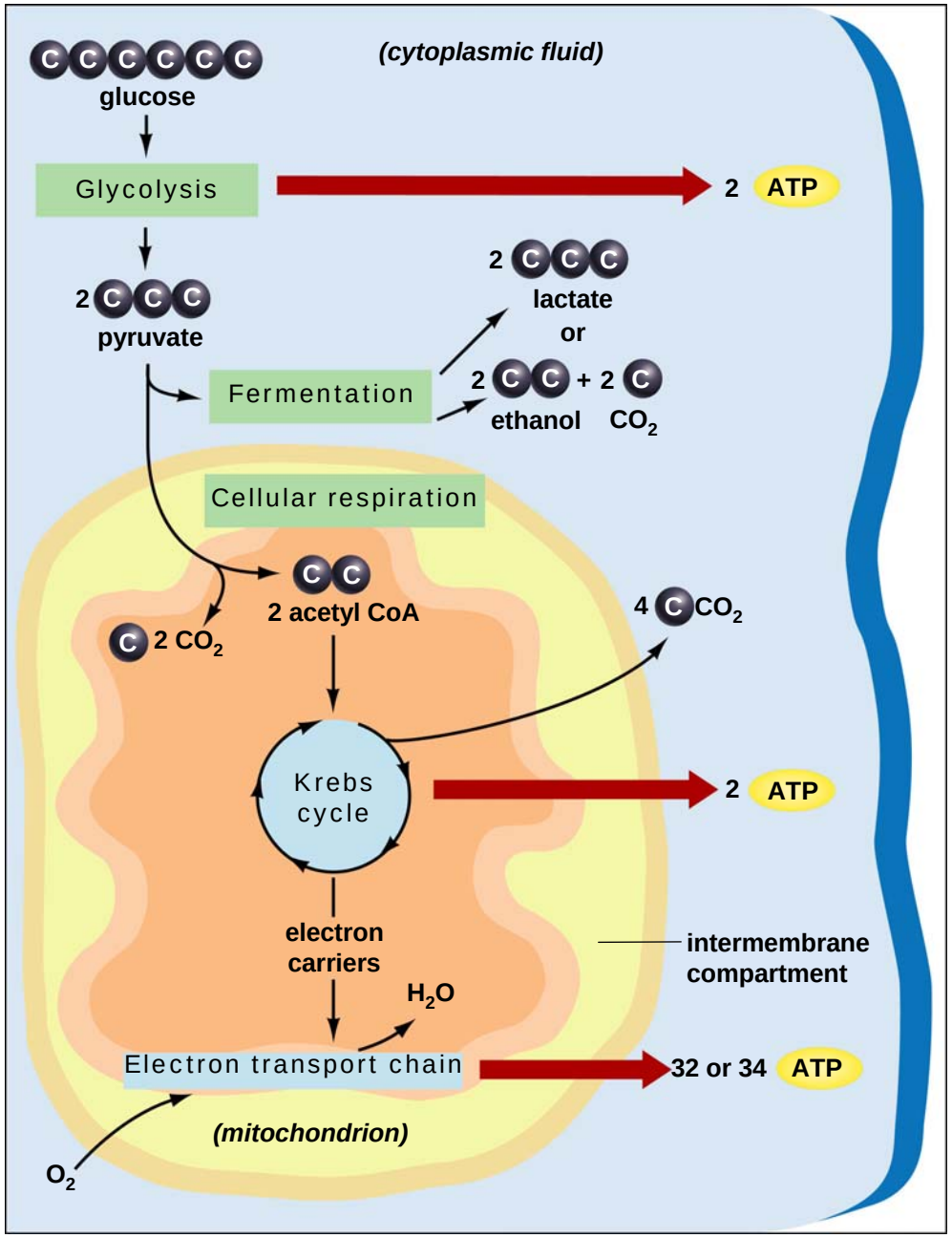

Fig. 7-1

Overview of Glucose Breakdown

- Stage 1: Glycolysis.
  - Glycolysis occurs in the cytoplasm of cells.
  - Does not require oxygen
  - Glucose (6 C sugar) is split into two pyruvate molecules (3 C each).
  - Yields two molecules of ATP per molecule of glucose.

Overview of Glucose Breakdown

- Stage 2: Cellular respiration
  - Occurs in **mitochondria** (in eukaryotes)
  - Requires oxygen (**aerobic**)
  - Breaks down pyruvate into CO_2 and H_20
  - Produces an additional 32 or 34 ATP molecules, depending on the cell type

Overview of Glucose Breakdown

- If oxygen is absent fermentation occurs
  - Pyruvate remains in the cytoplasm
  - Pyruvate may be converted into either lactate, or ethanol and CO_2
  - No ATP is produced
- If oxygen is present cellular respiration occurs

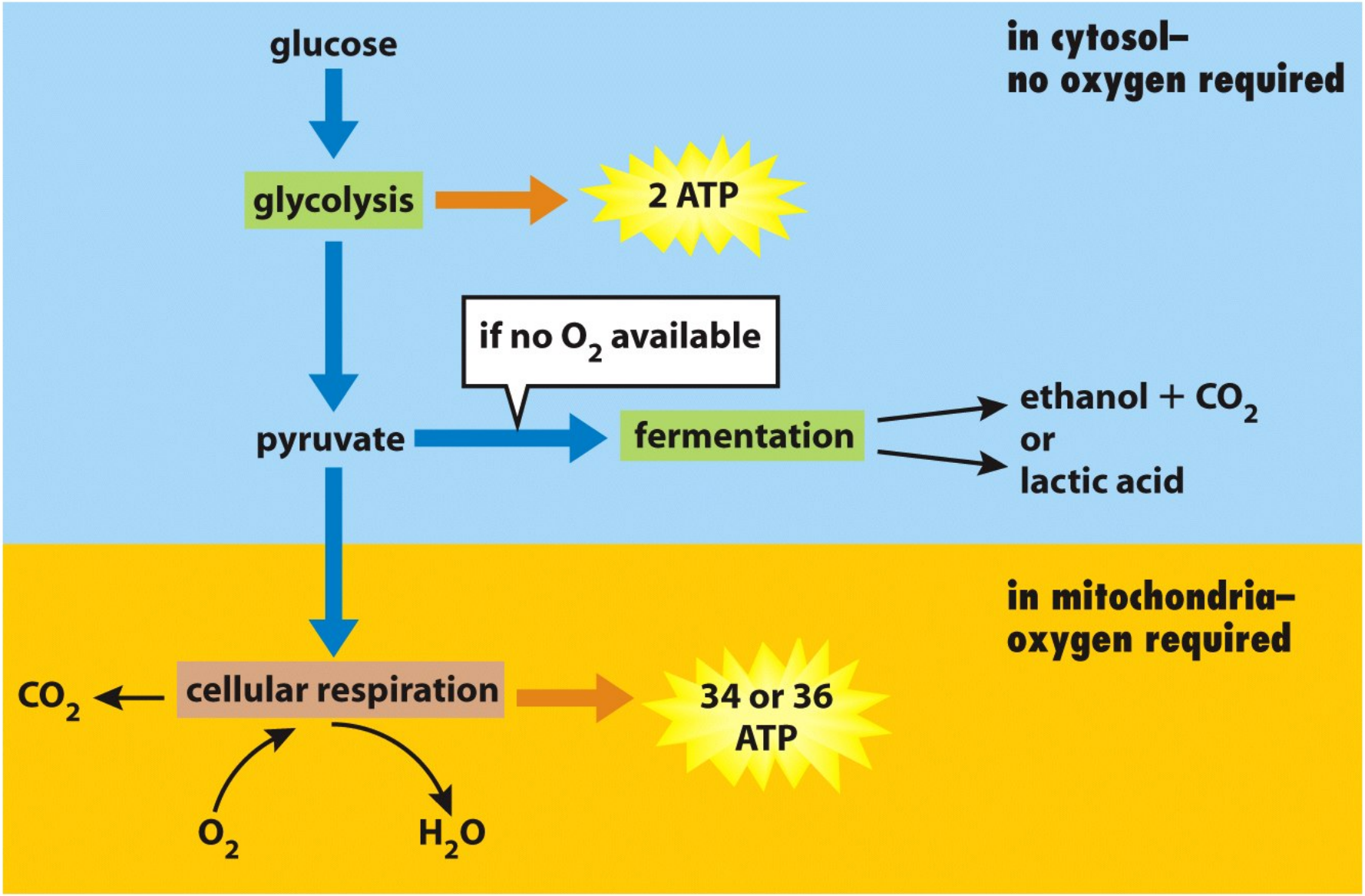

Figure 8-1 Biology: Life on Earth, 8/e
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7.3 What Happens During Glycolysis?

- Glycolysis splits one molecule of glucose into two molecules of pyruvate.
- During glycolysis, one molecule of glucose yields two ATP and two molecules of nicotinamide adenine dinucleotide (NADH) an electron carrier .
- Glycolysis involves two major steps:
  - Glucose activation
  - Energy harvest

Flash

Glycolysis

1. Glucose activation phase
   - Glucose molecule converted into the highly reactive fructose bisphosphate
   - Two enzyme-catalyzed reactions drive the conversion
   - Yields 2 ATP molecules

Glycolysis

- Two ATP power the phosphorylation of glucose to form fructose bisphosphate.

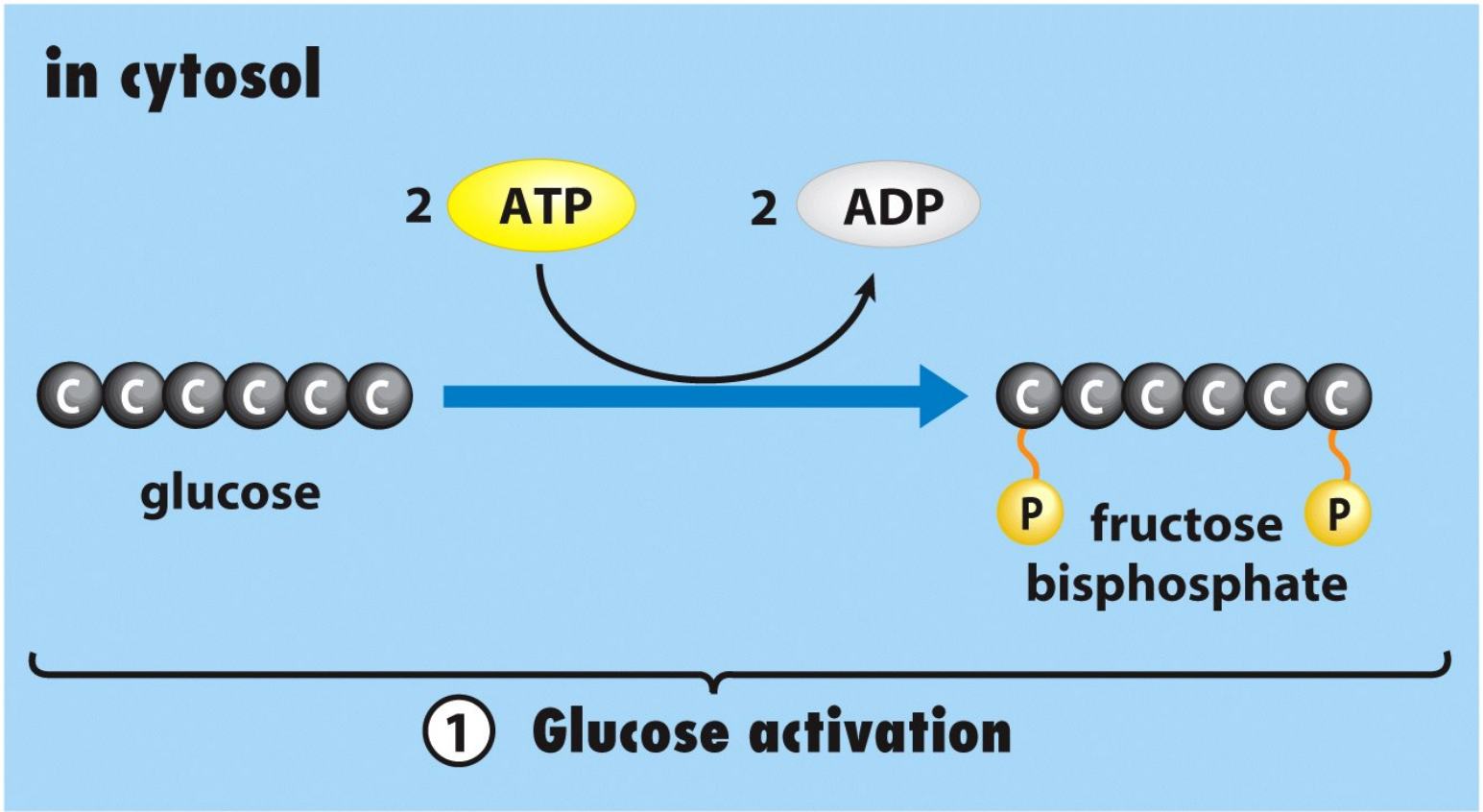

Figure 8-2 part 1 Biology: Life on Earth, 8/e

Glycolysis

2. Energy harvesting phase
   - Fructose bisphosphate is split into two three-carbon molecules of glyceraldehyde 3-phosphate (G3P)
   - In a series of reactions, each G3P molecule is converted into a pyruvate, generating two ATPs per conversion (4 total ATPs)
   - Because two ATPs were used to activate the glucose molecule there is a net gain of two ATPs per glucose molecule

Glycolysis

2. Energy harvesting phase (continued)
   - As each G3P is converted to pyruvate, two high-energy electrons and a hydrogen ion are added to an “empty” electron-carrier NAD+ to make the high-energy electron-carrier molecule NADH
   - Because two G3P molecules are produced per glucose molecule, two NADH carrier molecules are formed

Glycolysis

- Four ATP (net 2) and 2 NADH are harvested in the conversion of 2 G3P molecules to 2 pyruvate molecules

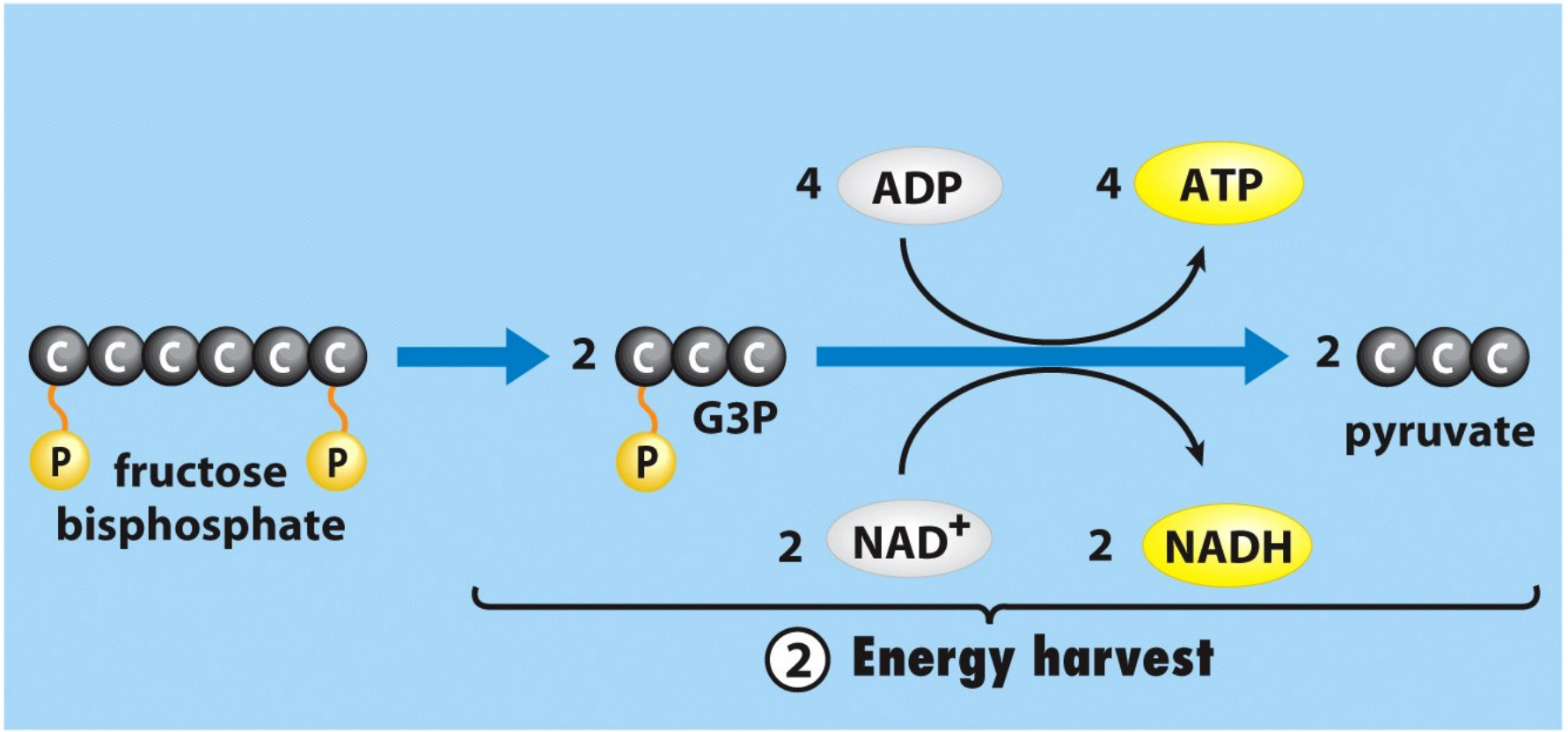

Figure 8-2 part 2 Biology: Life on Earth, 8/e

Glycolysis

- Energy harvest from glycolysis
  - Two ATPs are used to activate glucose.
  - Two ATPs are made for each pyruvate (four total).
  - Each conversion to pyruvate forms one molecule of NADH (two total).
  - Net gain from glycolysis: 2ATP + 2 NADH

Glycolysis

- Summary of glycolysis:
  - Each molecule of glucose is broken down to two molecules of pyruvate
  - A net of two ATP molecules and two NADH (high-energy electron carriers) are formed

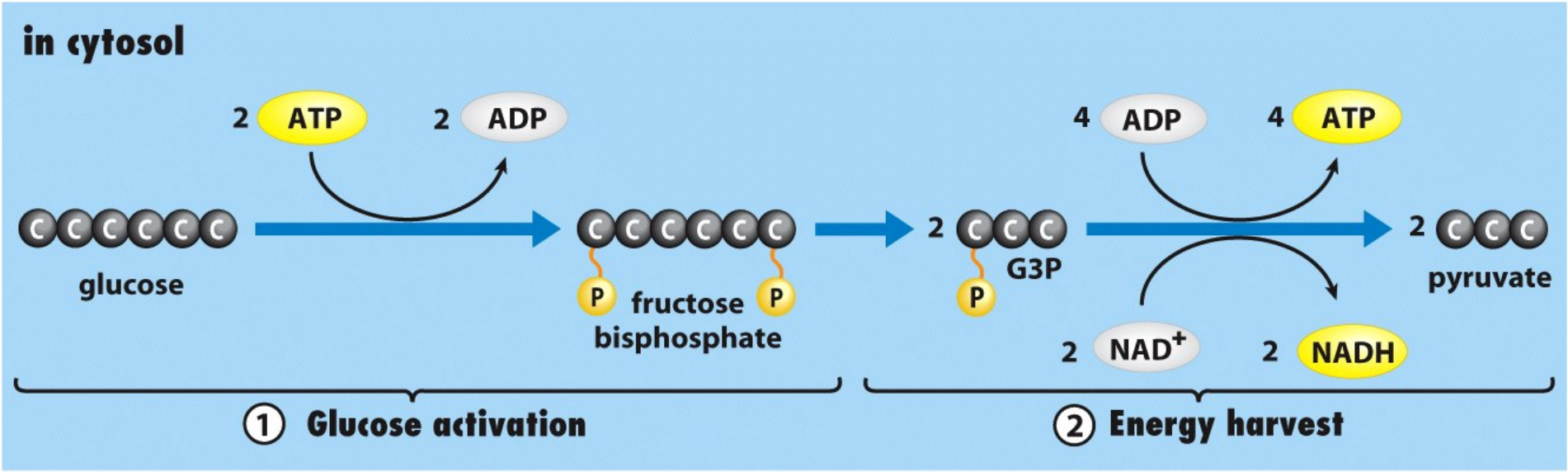

Figure 8-2 Biology: Life on Earth, 8/e

7.4 What Happens During Cellular Respiration?

- Cellular respiration is the second stage of glucose metabolism
- Only occurs in the presence of O_2 (aerobic).
- Occurs in the mitochondria.
- Converts pyruvate to CO_2 and H_2O.
- Large amounts of ATP are produced

Flash

Cellular Respiration

- Steps of Cellular Respiration
  - Step 1: Two molecules of pyruvate produced by glycolysis are transported into the matrix of a mitochondrion.
  - Step 2: Each pyruvate is split into CO_2 and acetyl CoA, which enters the Krebs cycle.
    - The Krebs cycle produces one ATP from each pyruvate, and donates electrons to NADH and flavin adenine dinucleotide ($FADH_2$).

Flash

Cellular Respiration

- Steps of cellular respiration *(continued)*
  - Step 3: NADH and $FADH_2$ donate energized electrons to the electron transport chain of the inner membrane.
  - Step 4: In the electron transport chain, electron energy is used to transport hydrogen ions (H^+) from the matrix to the intermembrane compartment.
  - Step 5: Electrons combine with O_2 and H^+ to form H_2O.

Flash

Cellular Respiration

- Steps of cellular respiration *(continued)*
  - Step 6: Hydrogen ions in the intermembrane compartment diffuse across the inner membrane, down their concentration gradient.
  - Step 7: The flow of ions into the matrix provides the energy to produce ATP from ADP.
  - Step 8: ATP moves out of mitochondrion into the cytoplasm.

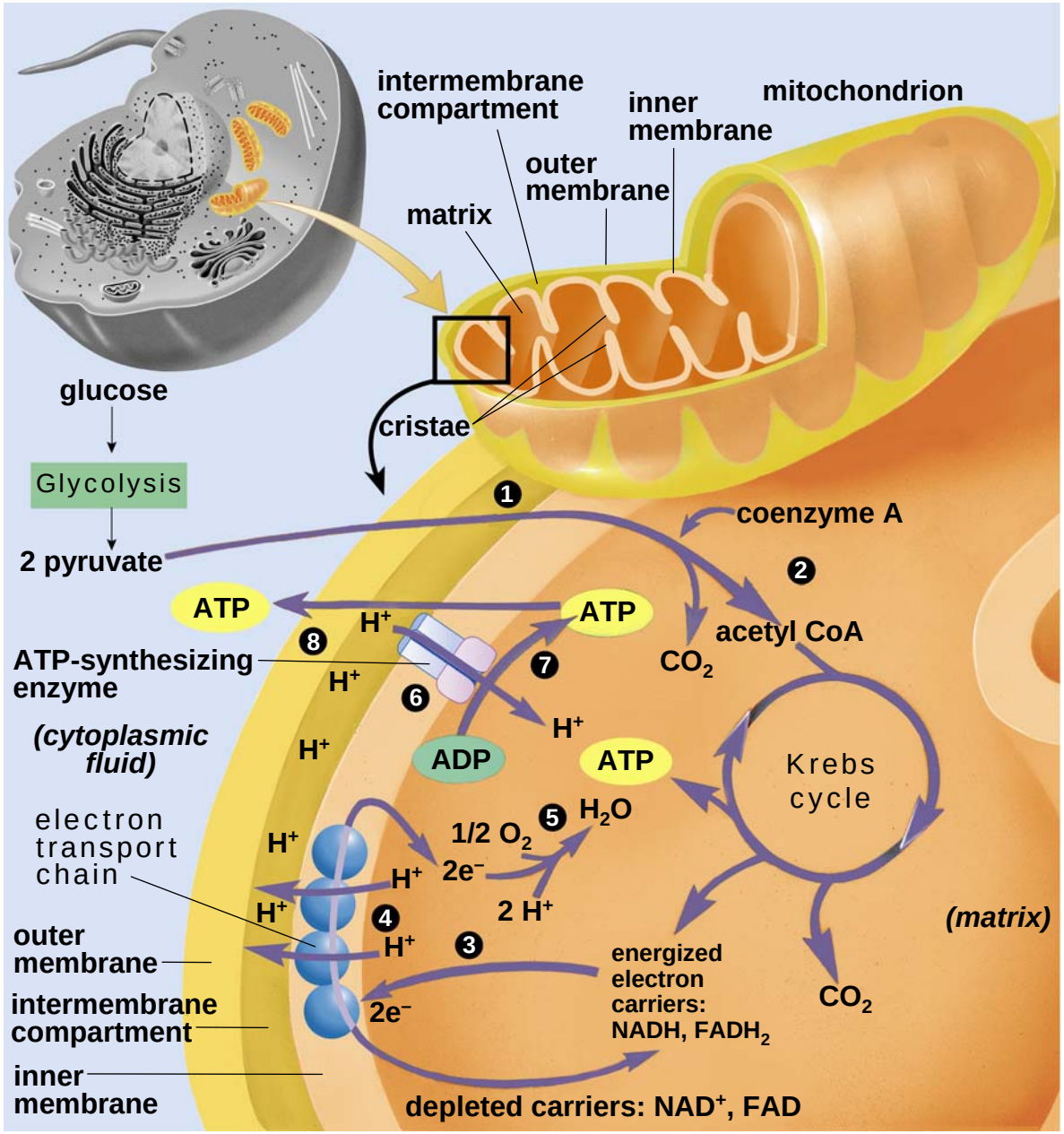

Fig. 7-3

Cellular Respiration

- The Krebs cycle breaks down pyruvate in the mitochondrial matrix.
  - Pyruvate produced by glycolysis reaches the matrix and reacts with coenzyme A, forming acetyl CoA.
  - During this reaction, two electrons and a H^+ are transferred to NAD^+ to form NADH.
  - Acetyl CoA enters the Krebs cycle and produces one ATP, one $FADH_2$, and three NADH.

Cellular Respiration

- The reactions in the mitochondrial matrix

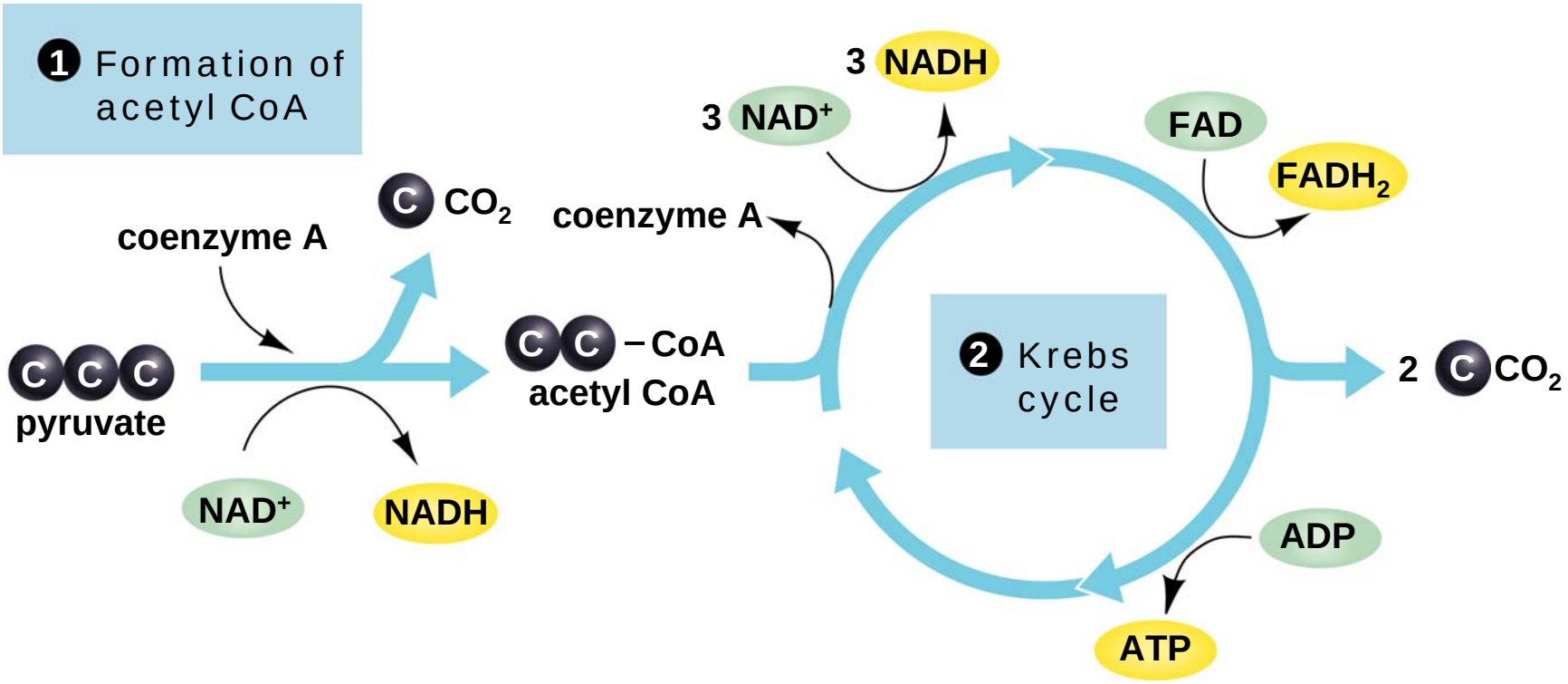

Fig. 7-4

Cellular Respiration

- Energetic electrons are carried to the electron transport chain.
  - Step 1: Energized carriers deposit their electrons in the electron transport chains (ETC) in the inner mitochondrial membrane.
  - Step 2: Electrons in the ETC move from one molecule to the next, transferring energy that is used to pump H^+ out of the matrix and into the intermembrane compartment.
  - Step 3: At the end of the ETC, oxygen atoms combine with two H^+ and two depleted electrons to form H_2O.

Cellular Respiration

- Energetic electrons are carried to the electron transport chain *(continued).*
  - Oxygen accepts electrons after they have passed through the ETC and given up most of their energy.
  - If O_2 is not present, electrons accumulate in the ETC, H^+ pumping out of the matrix stops, and cellular respiration ceases.

Cellular Respiration

- The electron transport chain in the mitochondrial matrix

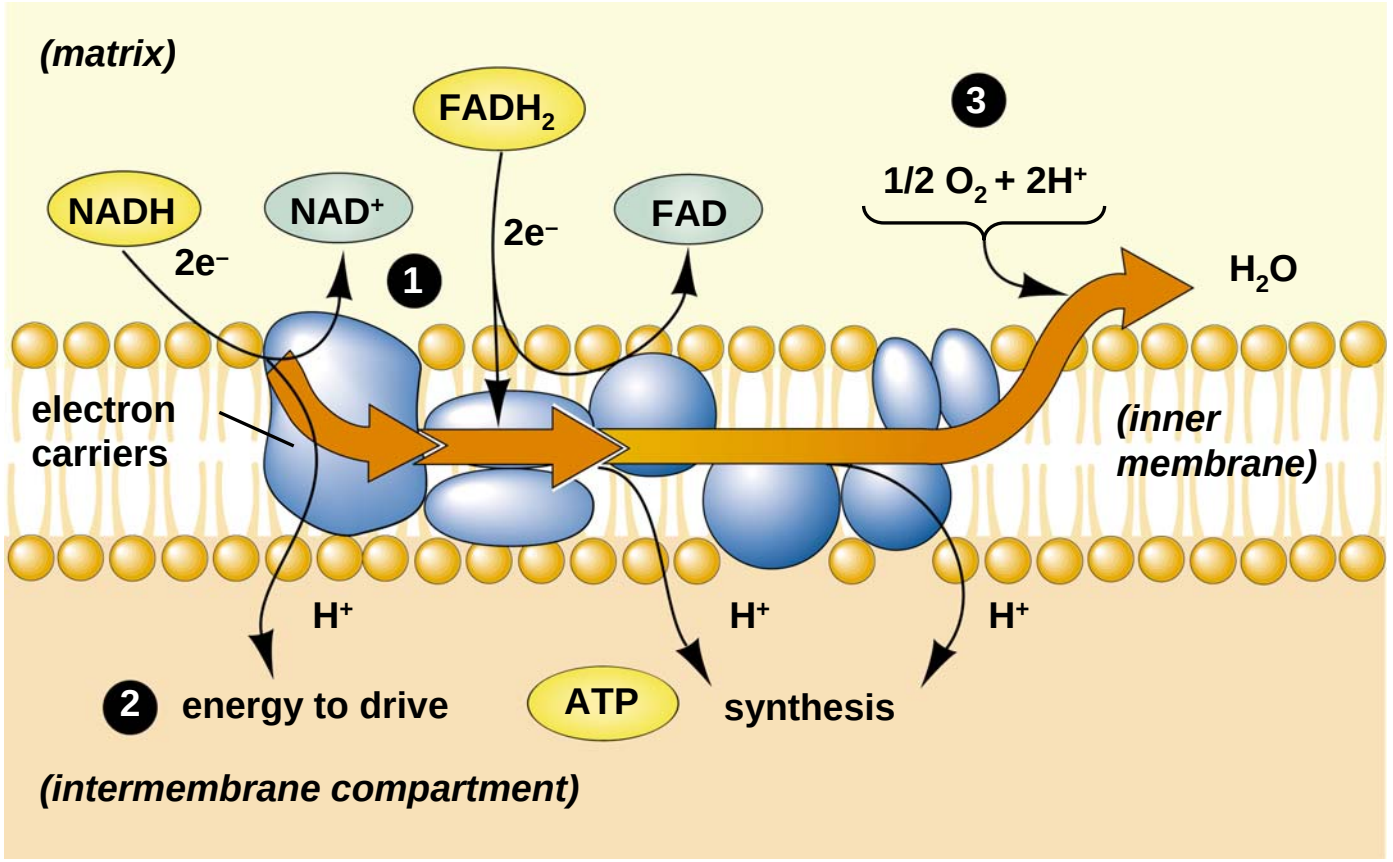

Fig. 7-5

Cellular Respiration

- Energy from a hydrogen-ion gradient is used to produce ATP.
  - Hydrogen ions accumulate in the intermembrane compartment and diffuse back into the matrix.
  - The energy released when hydrogen ions move down their concentration gradient is used to make ATP in a process called chemiosmosis.
  - During chemiosmosis, 32 to 34 molecules of ATP are produced from each molecule of glucose.
  - This ATP is transported from the matrix to the cytoplasm, where it is used to power metabolic reactions.

7.5 What Happens During Fermentation?

- Under anaerobic conditions (no O_2), glucose cannot be metabolized by cellular respiration; instead, fermentation takes place.
- Unlike cellular respiration, fermentation generates no ATP, but instead, regenerates NAD^+ that is used to generate ATP from glycolysis.

Flash

Fermentation

- In fermentation, pyruvate acts as an electron acceptor from the NADH produced during glycolysis.
- When pyruvate accepts electrons from NADH, it recycles the NAD^+ so that more glucose can be converted to pyruvate, generating a small amount of ATP in the process.
- When no O_2 is present, glycolysis becomes the main source of ATP and NADH production.

Fermentation

- There are two types of fermentation: one converts pyruvate to ethanol and CO_2, and the other converts pyruvate to lactate.
  - Alcoholic fermentation is the primary mode of metabolism in many microorganisms.
  - The reactions use hydrogen ions and electrons from NADH, thereby regenerating NAD^+.
  - Alcoholic fermentation is responsible for the production of many economic products, such as wine, beer, and bread.

Fermentation

- Glycolysis followed by alcoholic fermentation

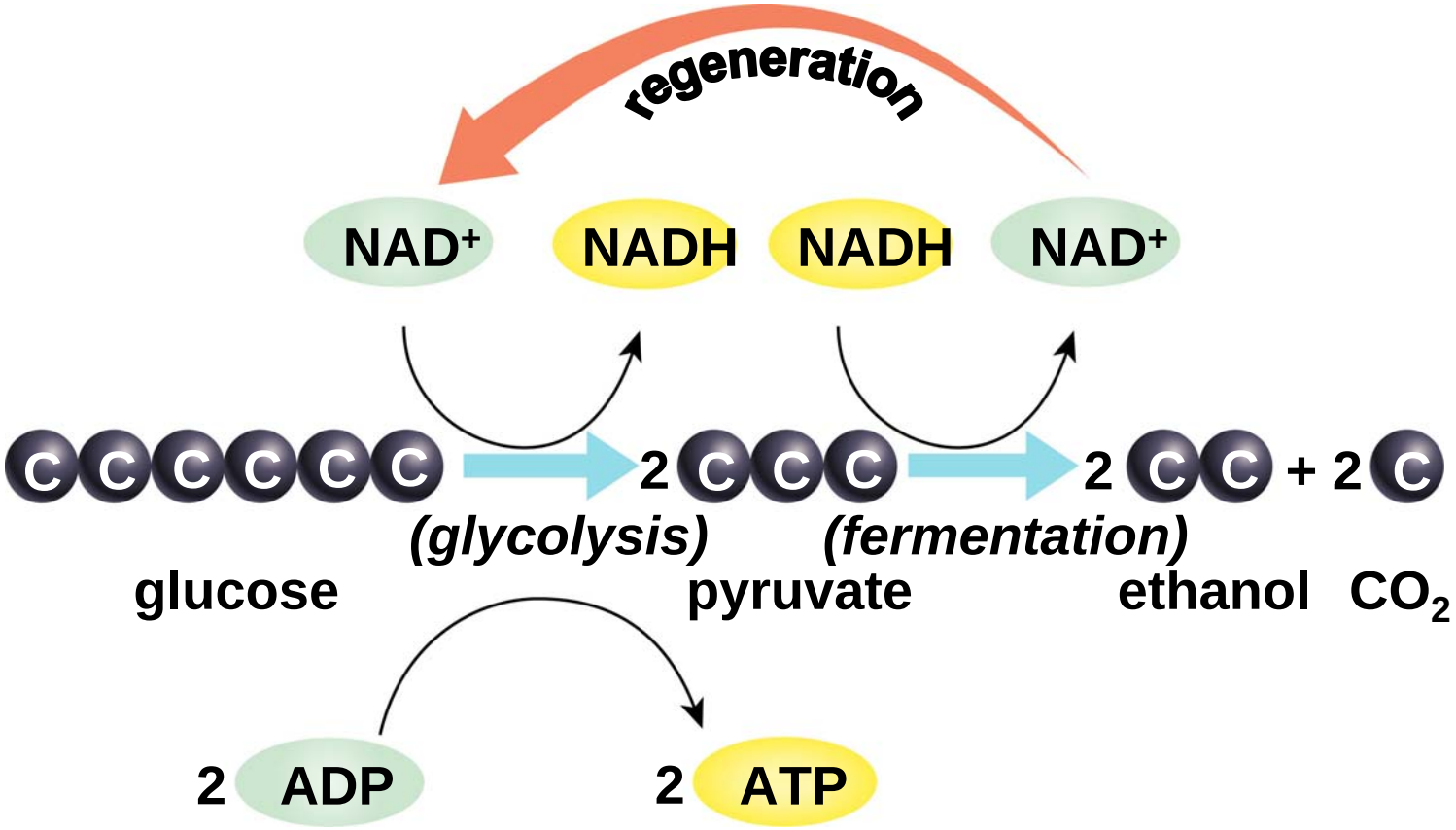

Fig. 7-6

Fermentation

- Other cells ferment pyruvate to lactate, and include microorganisms that produce yogurt, sour cream, and cheese.
- Lactate fermentation also occurs in aerobic organisms when cells are temporarily deprived of oxygen, such as muscle cells during vigorous exercise.
- These muscle cells ferment pyruvate to lactate, which uses H^+ and electrons from NADH to regenerate NAD^+.

Fermentation

- Glycolysis followed by lactate fermentation

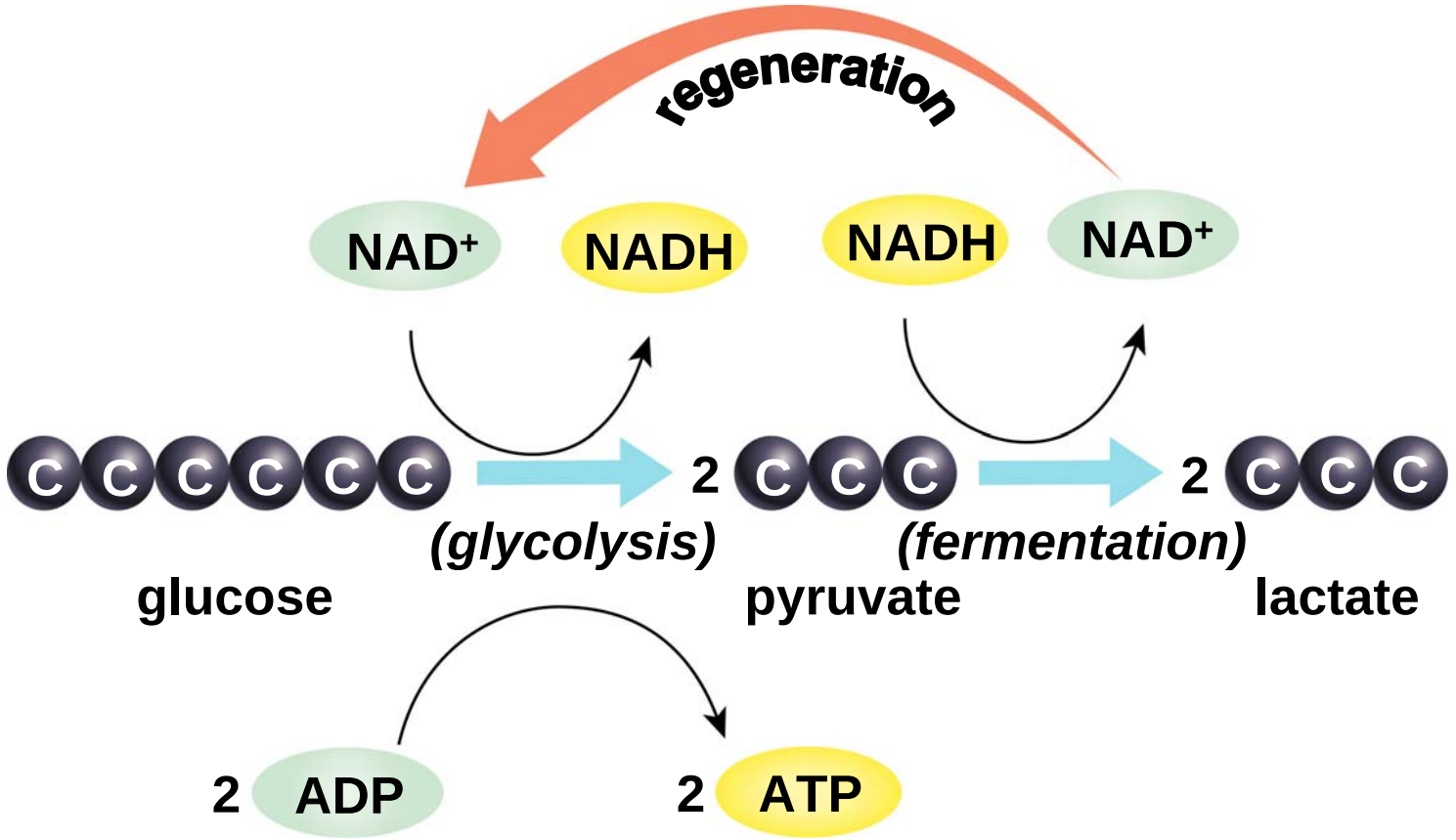

Fig. 7-8

Fermentation

- Fermentation limits human muscle performance.
  - During a sprint muscles use more ATP than can be delivered by cellular respiration because O_2 cannot be delivered to muscles fast enough.
  - Glycolysis can deliver a small amount of ATP to rapidly contracting muscles, but toxic buildup of lactate will occur.
  - Long distance runners must therefore pace themselves so that cellular respiration can power their muscles for most of the race.

Fermentation

- Some microbes ferment pyruvate to other acids (as seen in making of cheese, yogurt, sour cream)
- Some microbes perform fermentation exclusively (instead of aerobic respiration)
- Yeast cells perform **alcoholic fermentation**

Figure 8-3b Biology: Life on Earth, 8/e
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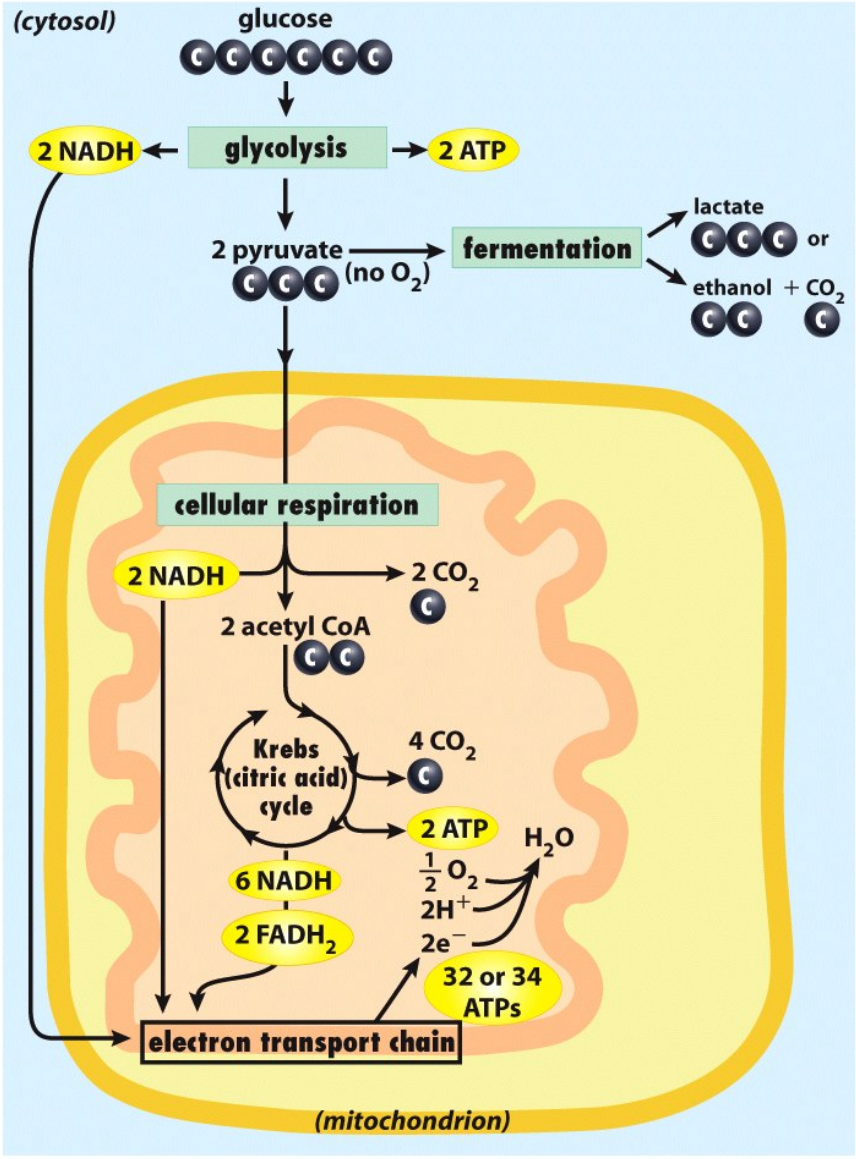
Summary of Glucose Breakdown

- **Figure 8-9**, p. 142, summarizes the process of glucose metabolism in a eukaryotic cell with oxygen present…



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Flash

Summary of Glucose Breakdown

- **Figure 8-10**, p. 143, shows the energy produced by each stage of glucose breakdown…

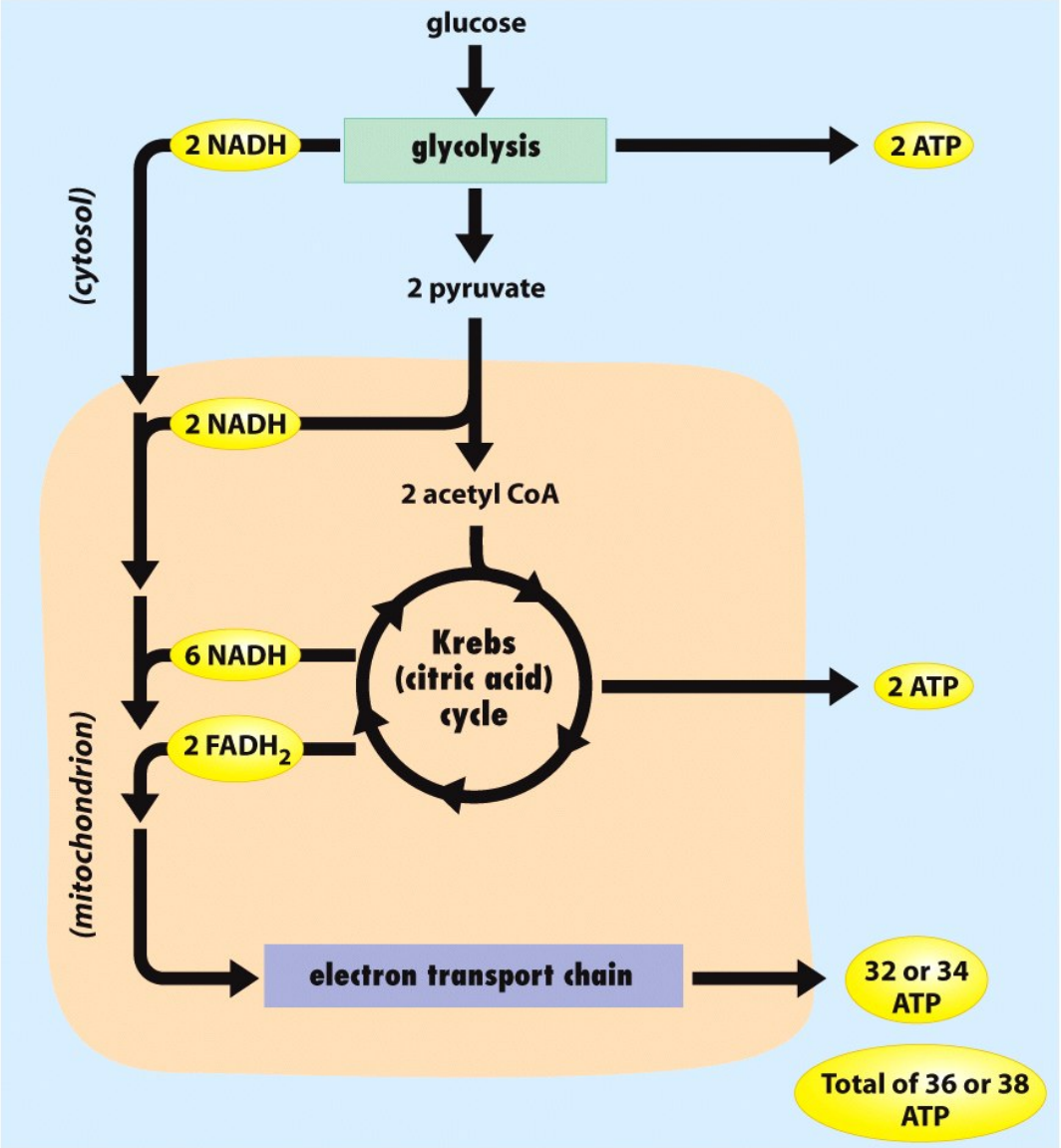

Figure 8-10 Biology: Life on Earth, 8/e
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Influence on How Organisms Function

- Metabolic processes in cells are heavily dependent on ATP generation (cyanide kills by preventing this)
- Muscle cells switch between fermentation and aerobic cell respiration depending on O_2 availability