Chapter 8: How Cells Release Stored Energy

ATP Is Universal Energy Source

- Photosynthesizers get energy from the sun
- Animals get energy second- or third-hand from plants or other organisms
- Regardless, the energy is converted to the chemical bond energy of ATP

Making ATP

- Plants make ATP during photosynthesis
- Cells of all organisms make ATP by breaking down carbohydrates, fats, and protein

Main Types of Energy-Releasing Pathways

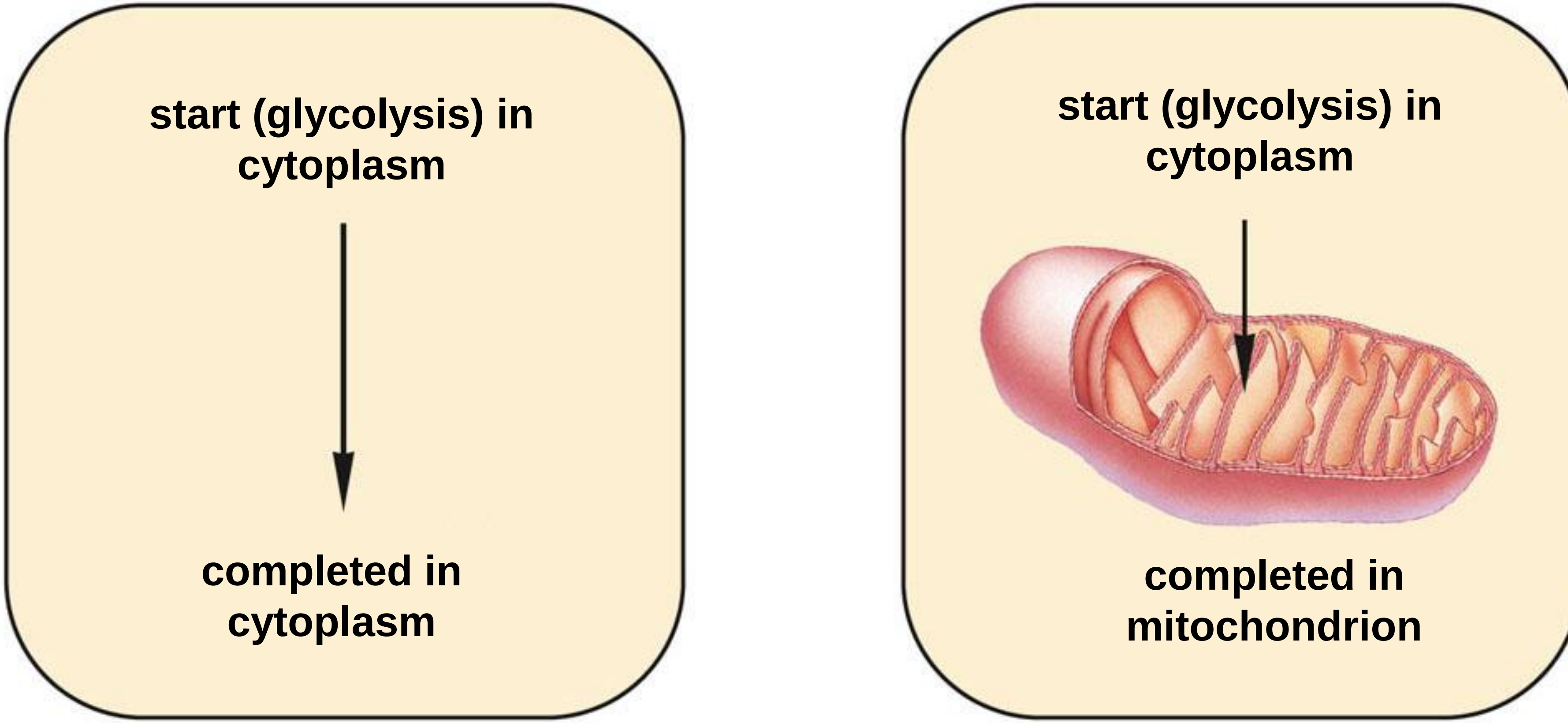
Anaerobic pathways

- Evolved first
- Don't require oxygen
- Start with glycolysis in cytoplasm
- Completed in cytoplasm

Aerobic pathways

- Evolved later
- Require oxygen
- Start with glycolysis in cytoplasm
- Completed in mitochondria

Main Types of Energy-Releasing Pathways



Anaerobic Energy-Releasing Pathways

Aerobic Respiration

Fig. 8-2, p.124

Summary Equation for Aerobic Respiration

$$C_6H_{12}0_6 + 6O_2 \longrightarrow 6CO_2 + 6H_20$$

glucose oxygen carbon dioxide water

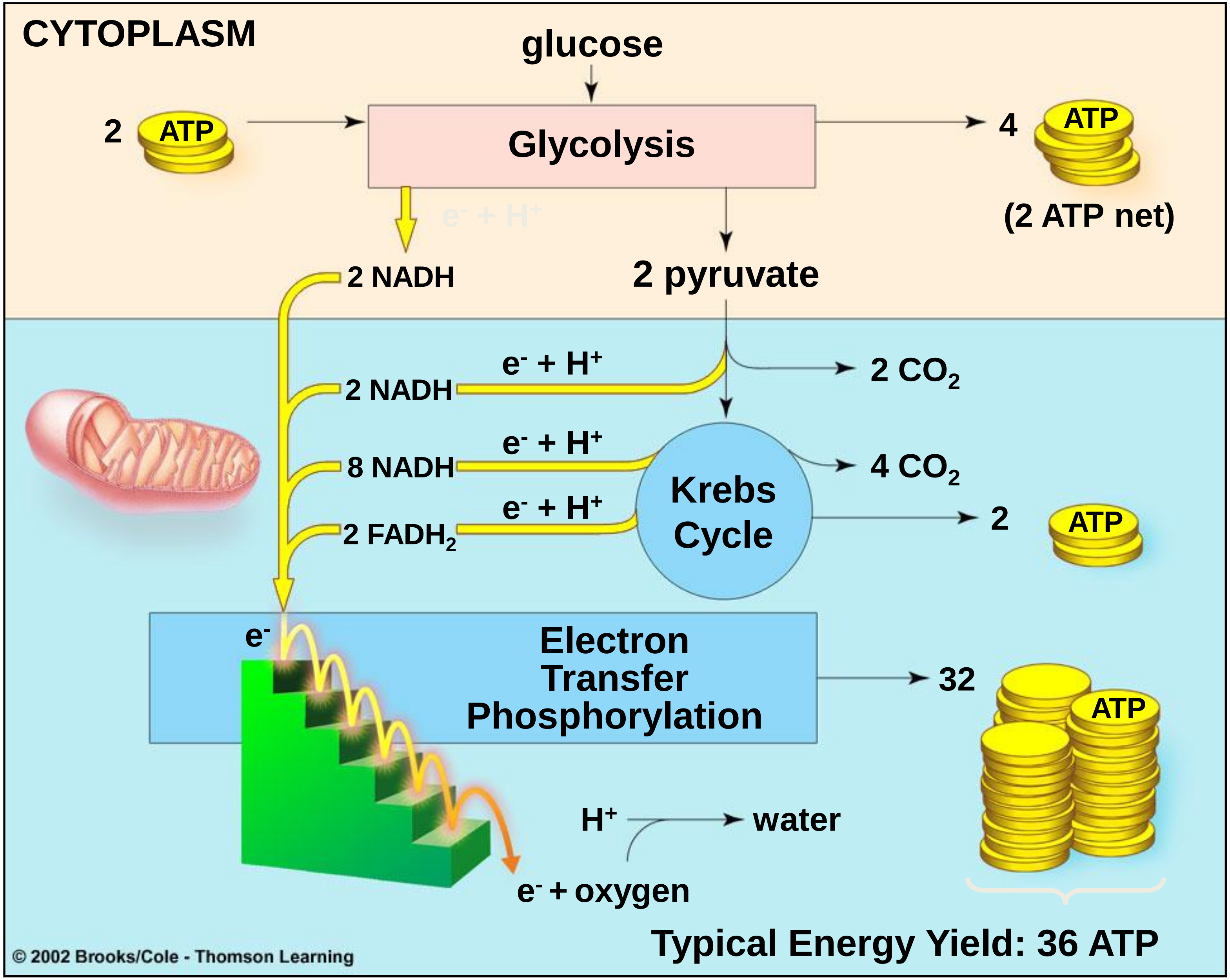

CYTOPLASM
glucose
2 ATP
Glycolysis
4 ATP
(2 ATP net)
e- + H+
2 NADH
2 pyruvate
e- + H+
2 NADH
2 CO2
e- + H+
8 NADH
4 CO2
e- + H+
2 FADH2
Krebs Cycle
2 ATP
e-
Electron Transfer Phosphorylation
32 ATP
H+
water
e- + oxygen
Typical Energy Yield: 36 ATP
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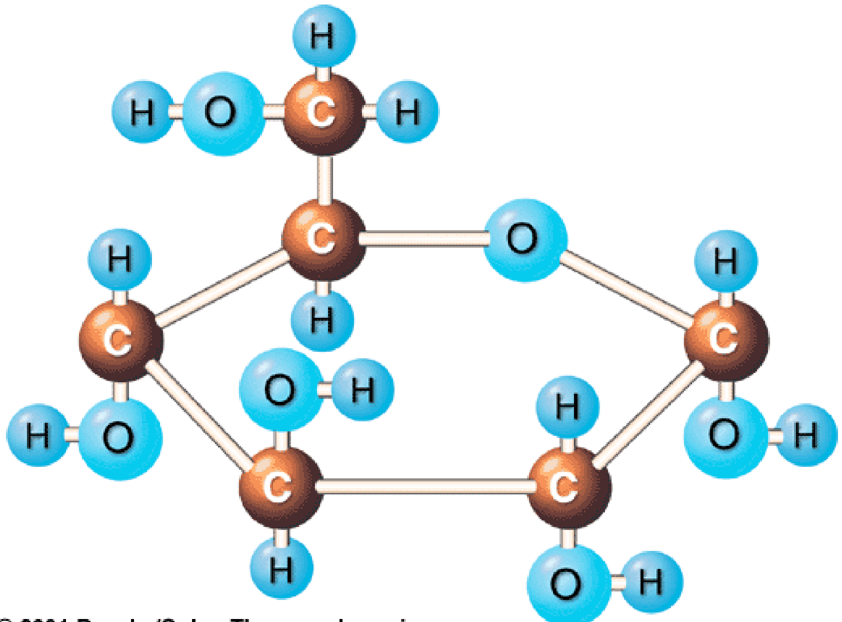
Fig. 8-3, p. 135

Glucose

- A simple sugar ($C_6H_{12}O_6$)
- Atoms held together by covalent bonds



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In-text figure
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Glycolysis Occurs in Two Stages

- **Energy-requiring steps**
  - ATP energy activates glucose and its six-carbon derivatives
- **Energy-releasing steps**
  - The products of the first part are split into three-carbon pyruvate molecules
  - ATP and NADH form

Glycolysis

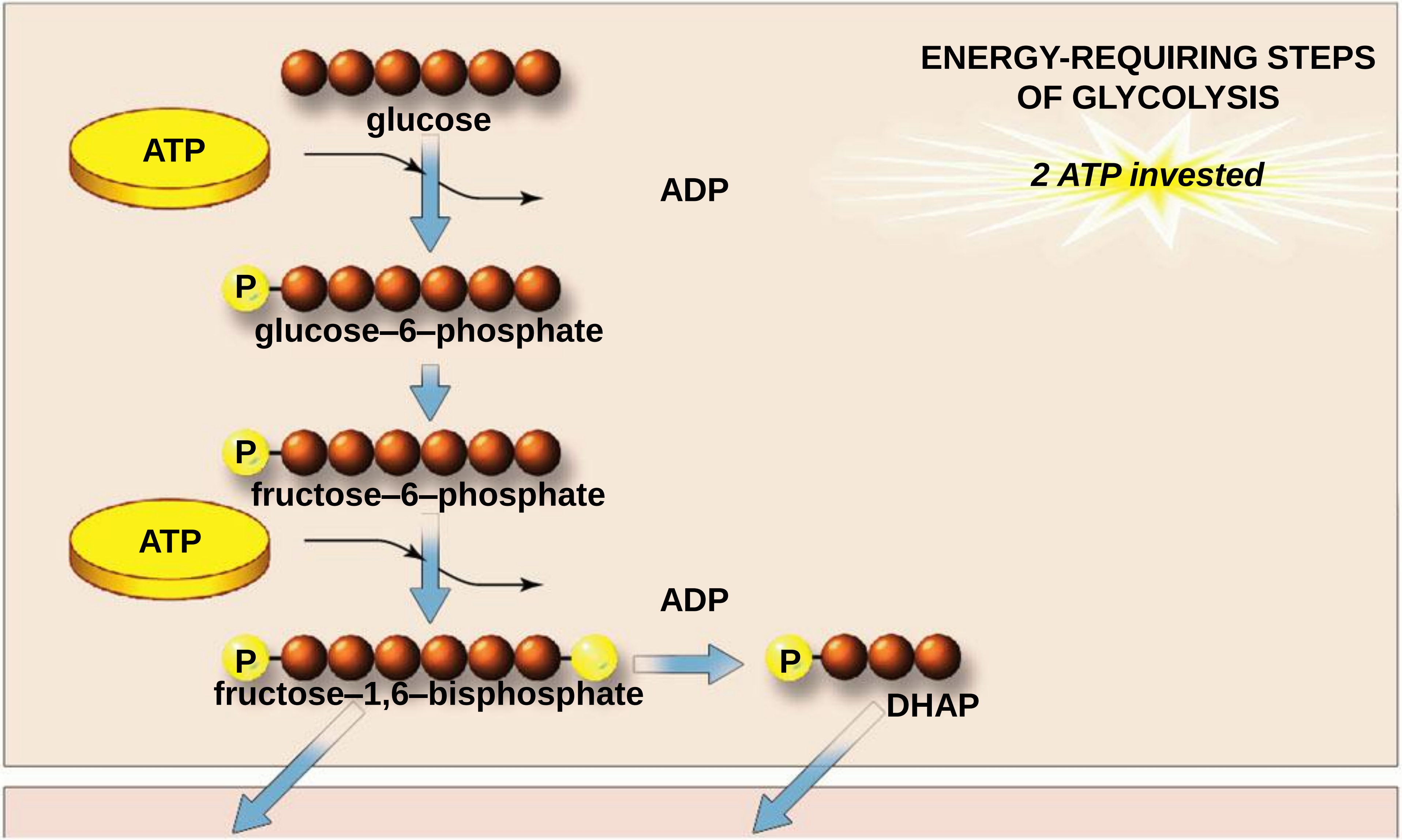

Fig. 8-4b, p.127

Glycolysis

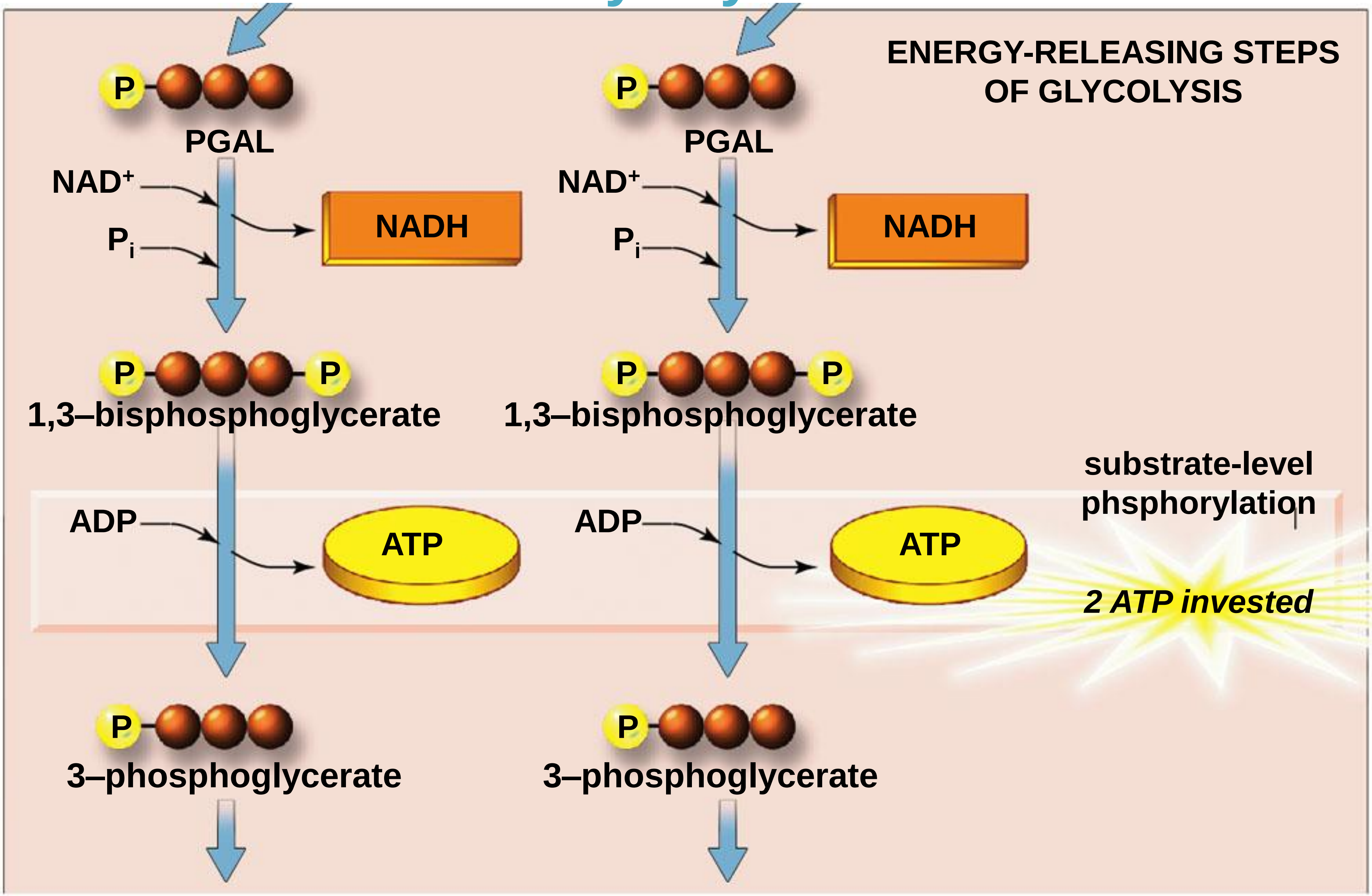

Fig. 8-4c, p.127

Glycolysis

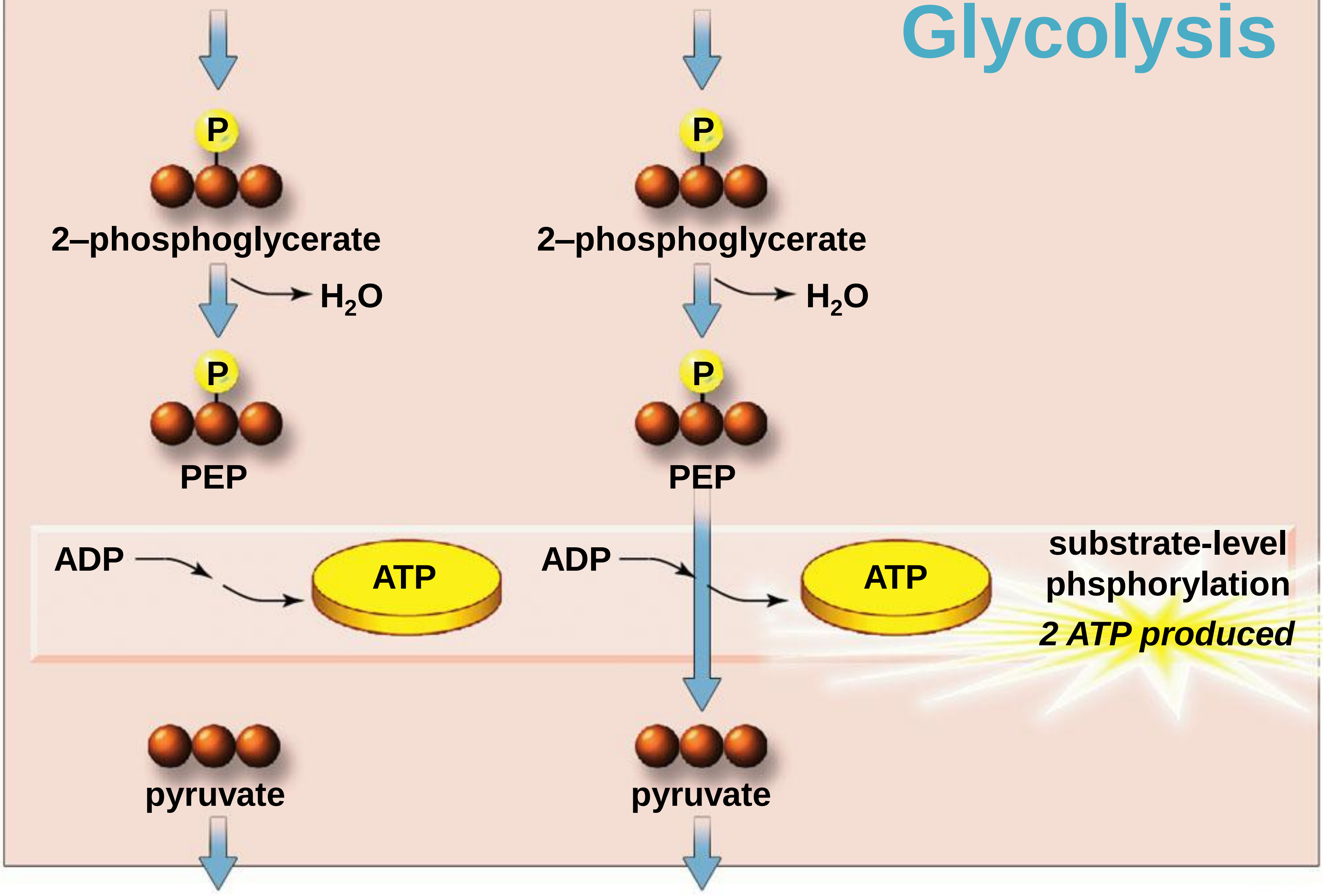

Fig. 8-4d, p.127

Energy-Requiring Steps of Glycolysis

2 ATP invested

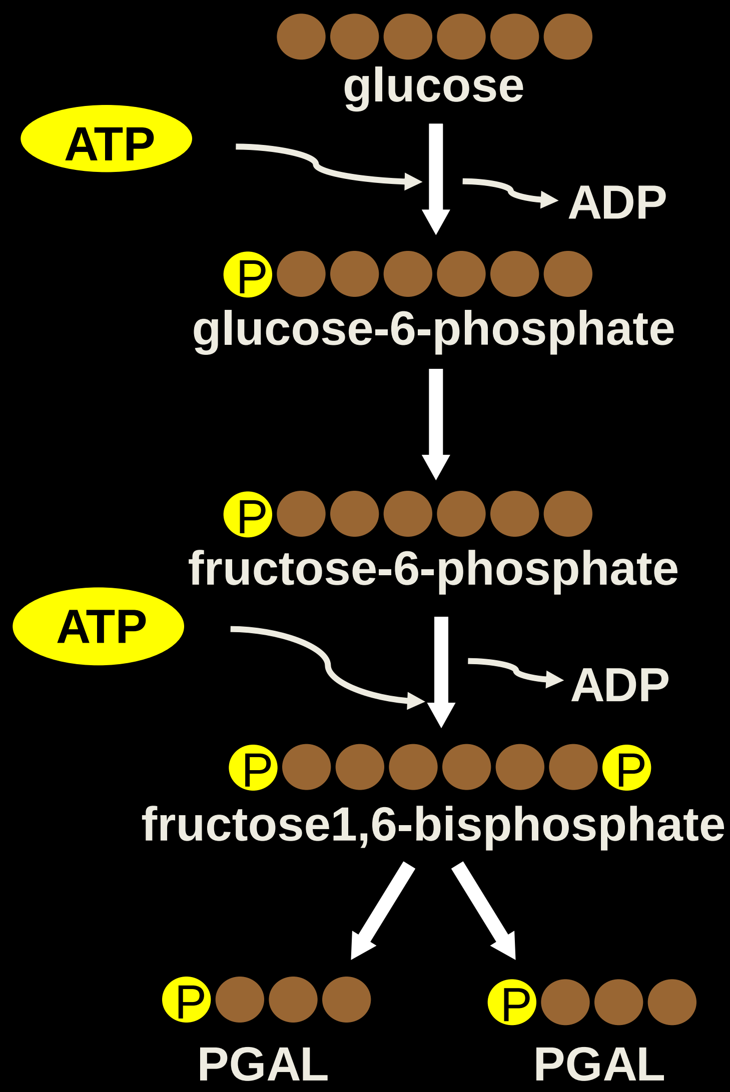

Figure 8-4(2)

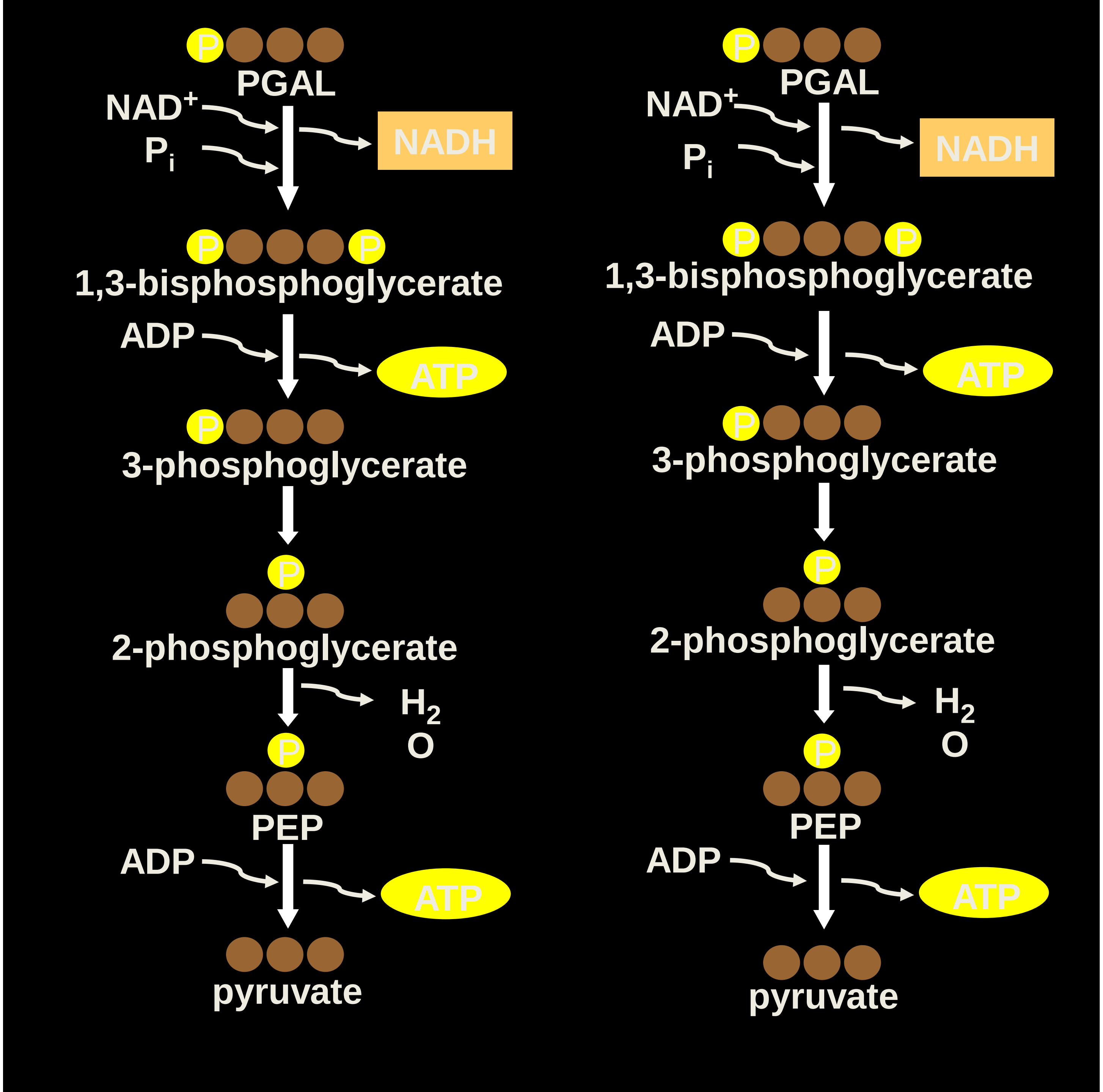

Figure 8-4

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Glycolysis: Net Energy Yield

Energy requiring steps:

2 ATP invested

Energy releasing steps:

2 NADH formed

4 ATP formed

Net yield is 2 ATP and 2 NADH

Second Stage Reactions

- Preparatory reactions
  - Pyruvate is oxidized into two-carbon acetyl units and carbon dioxide
  - NAD^+ is reduced
- Krebs cycle
  - The acetyl units are oxidized to carbon dioxide
  - NAD^+ and FAD are reduced

Second Stage Reactions

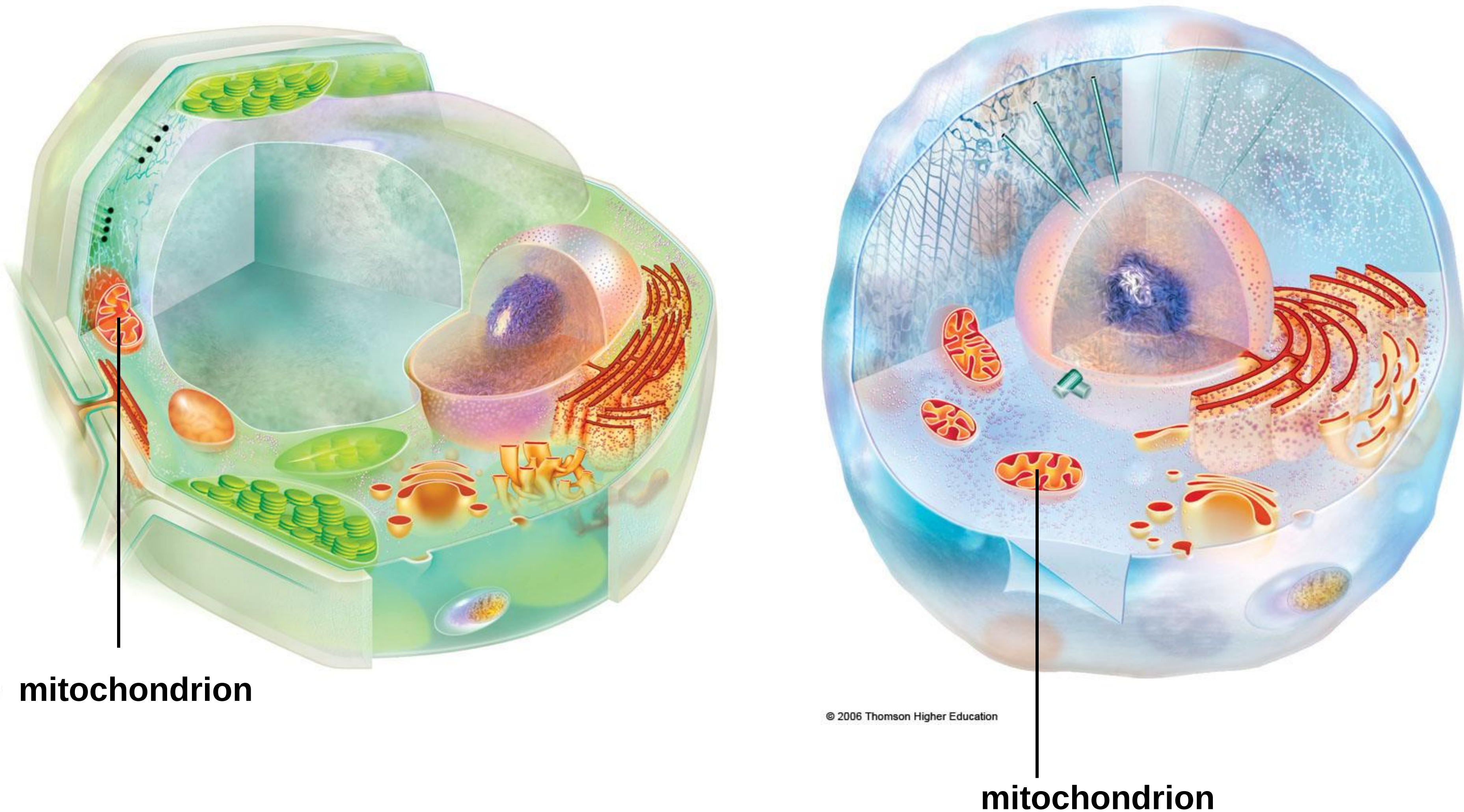


Fig. 8-5a, p.128

Second Stage Reactions

Fig. 8-5b, p.128

Second Stage Reactions

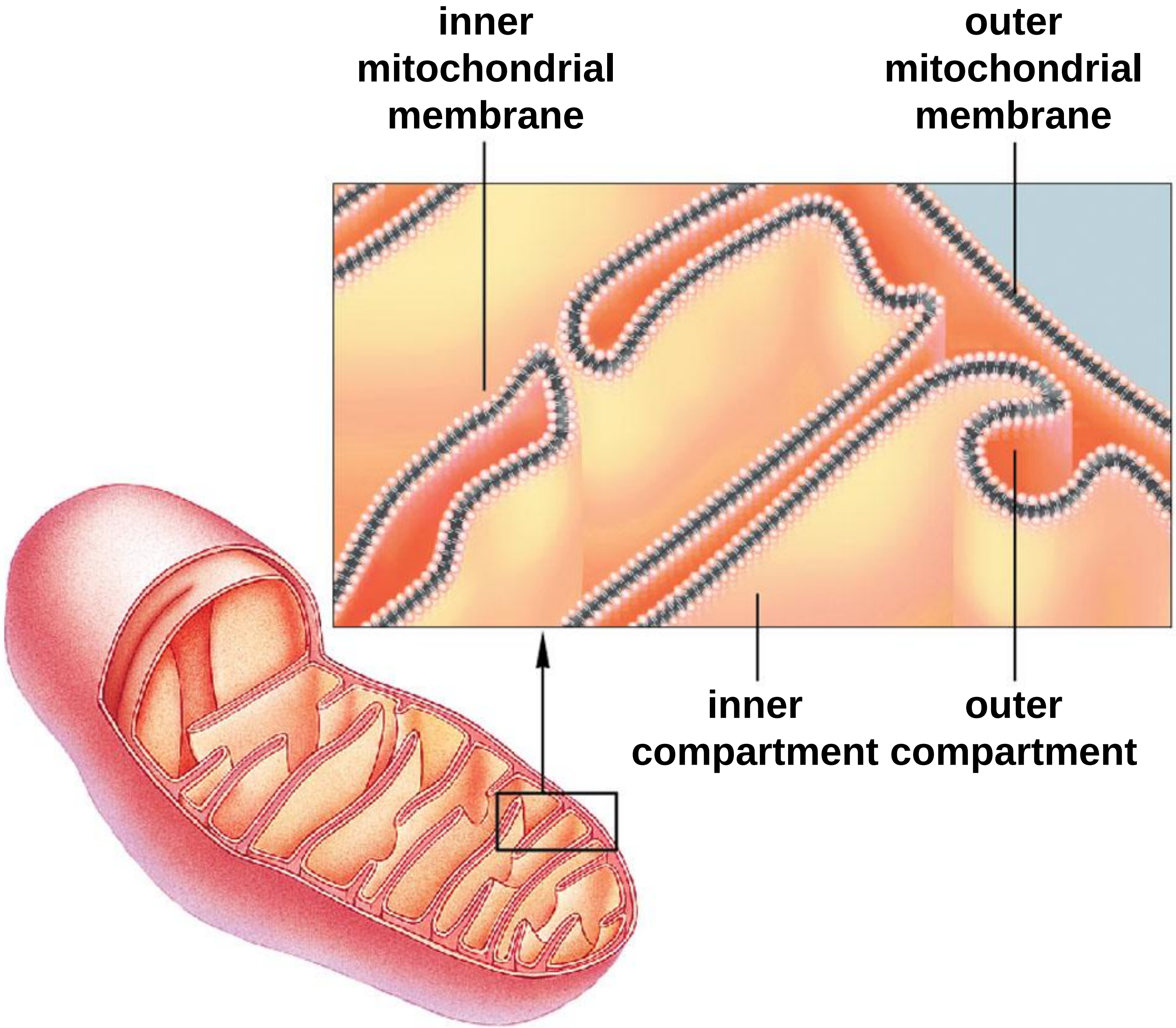
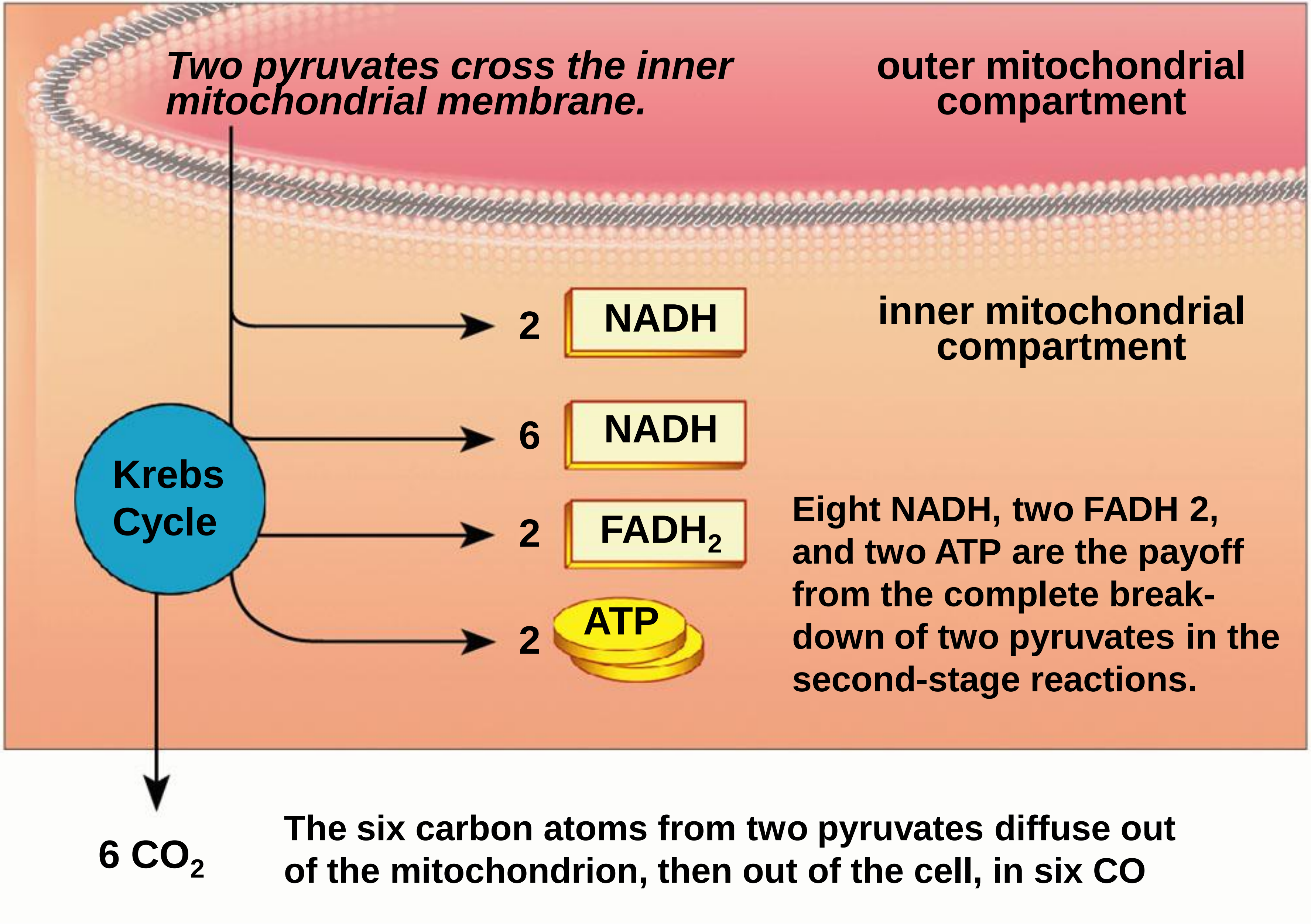


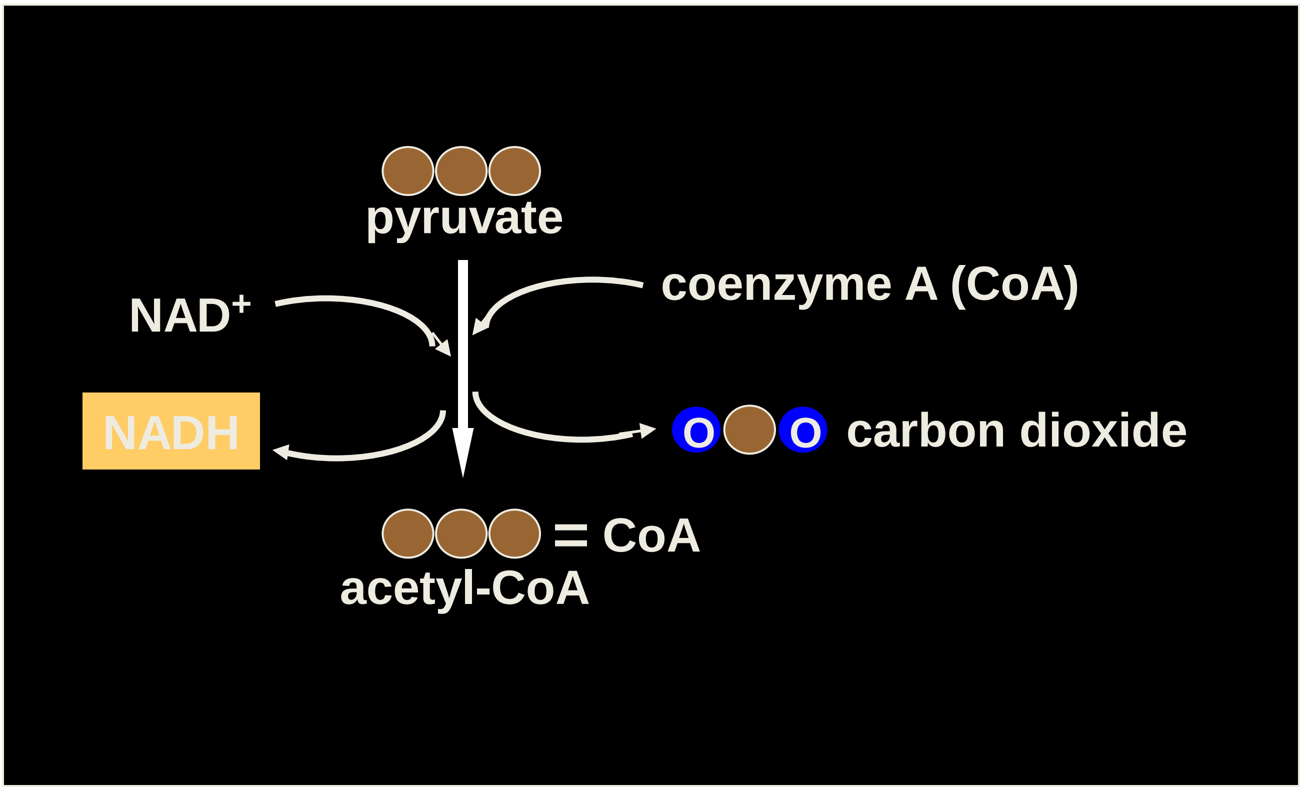
Fig. 8-6a, p.128



Two pyruvates cross the inner mitochondrial membrane.
outer mitochondrial compartment
inner mitochondrial compartment
2 NADH
6 NADH
2 FADH2
2 ATP
Krebs Cycle
Eight NADH, two FADH 2, and two ATP are the payoff from the complete break-down of two pyruvates in the second-stage reactions.
6 CO2
The six carbon atoms from two pyruvates diffuse out of the mitochondrion, then out of the cell, in six CO

Fig. 8-6b, p.128

Preparatory Reactions



Preparatory Reactions

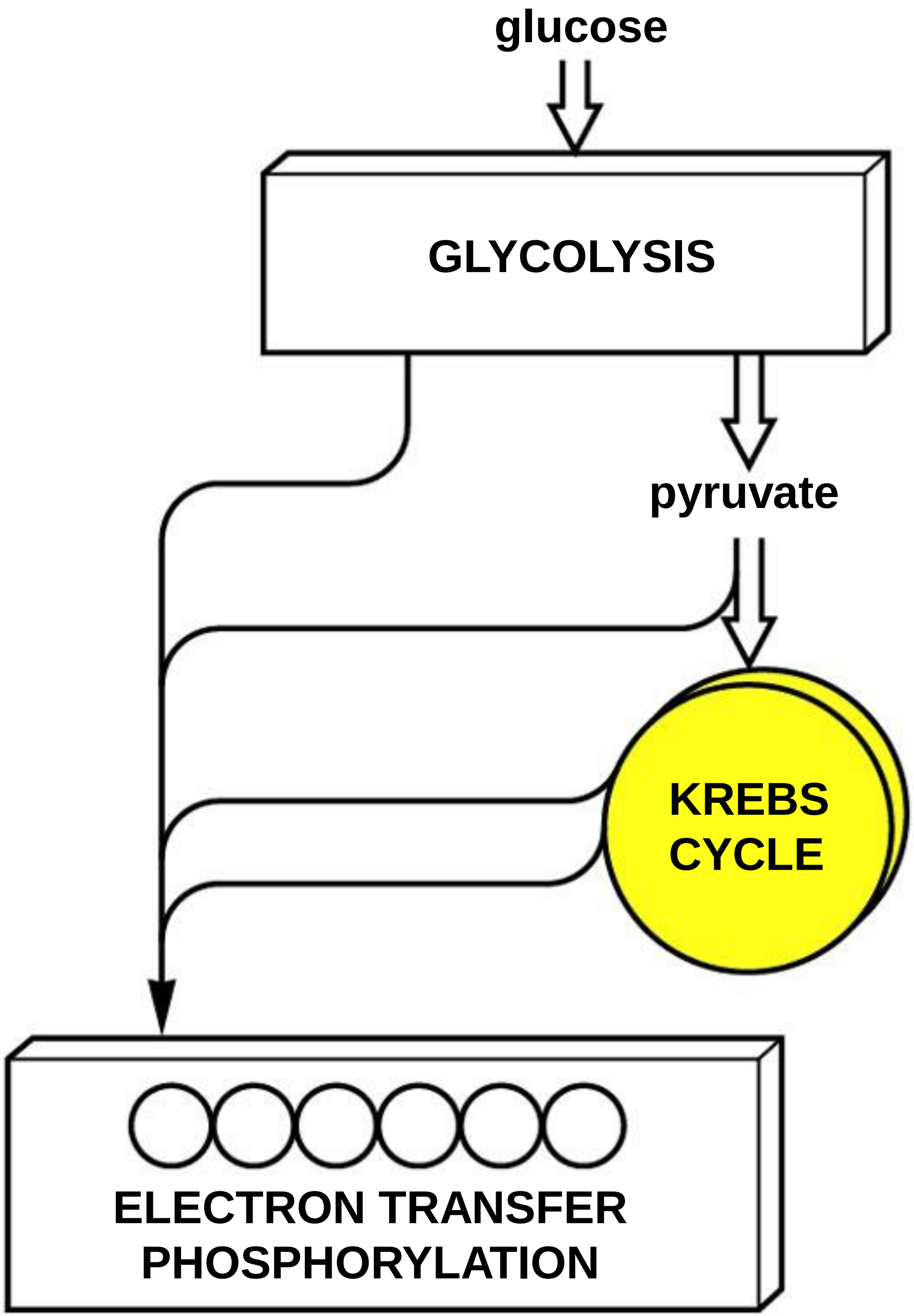


Fig. 8-7b, p.129

Krebs Cycle

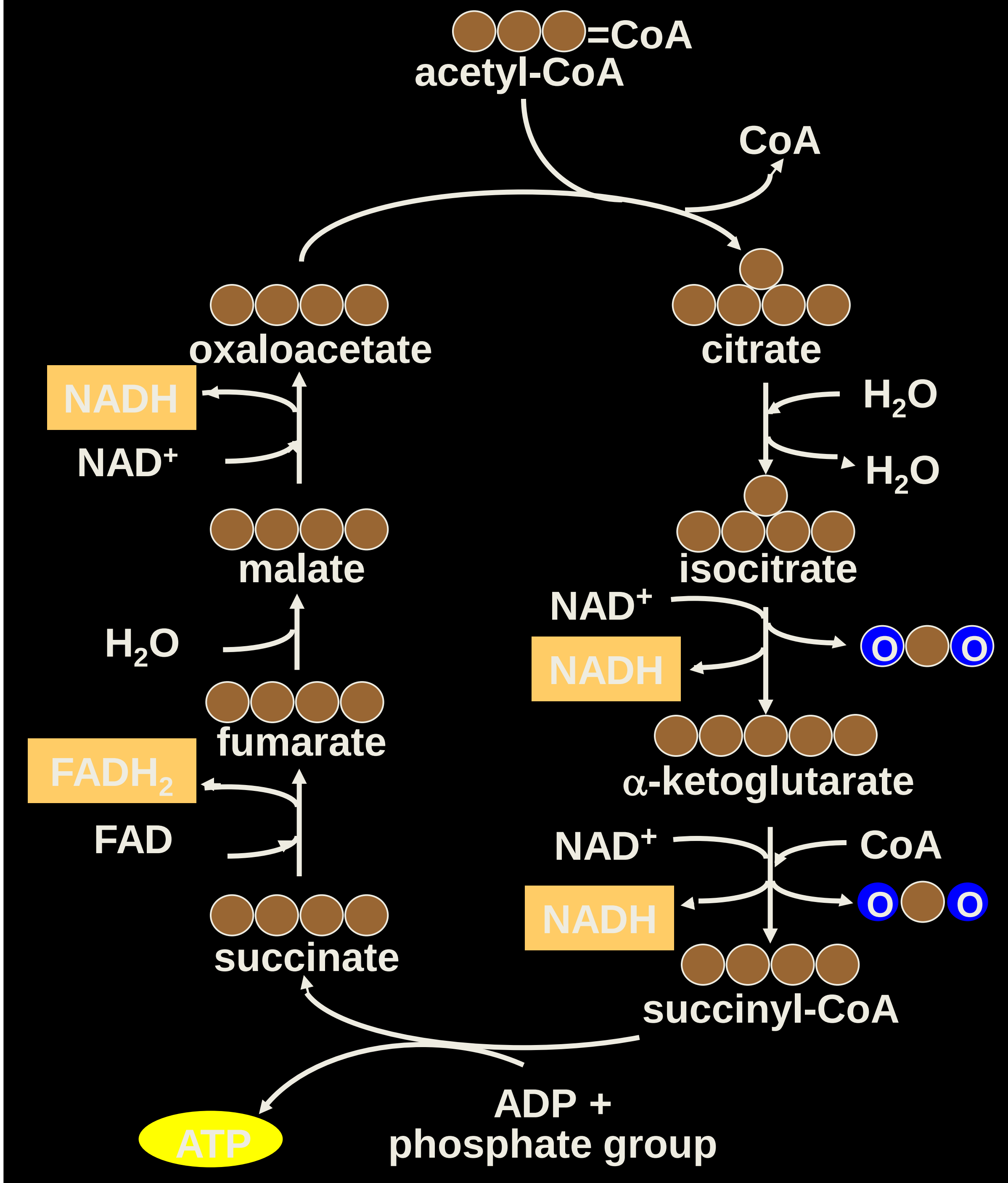


Figure 8-6

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The Krebs Cycle

Overall Reactants

- Acetyl-CoA
- 3 NAD^+
- FAD
- ADP and P_i

Overall Products

- Coenzyme A
- 2 CO_2
- 3 NADH
- $FADH_2$
- ATP

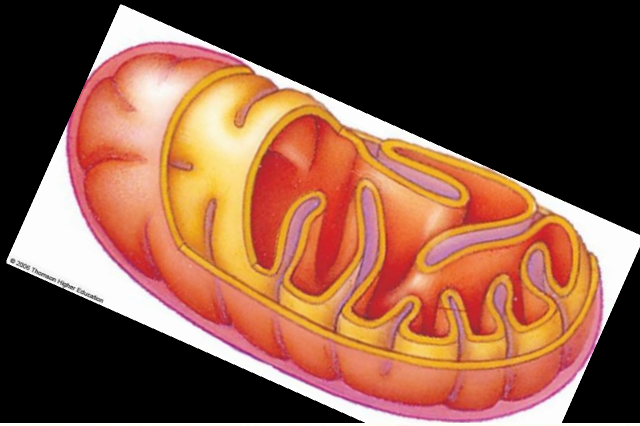
Results of the Second Stage

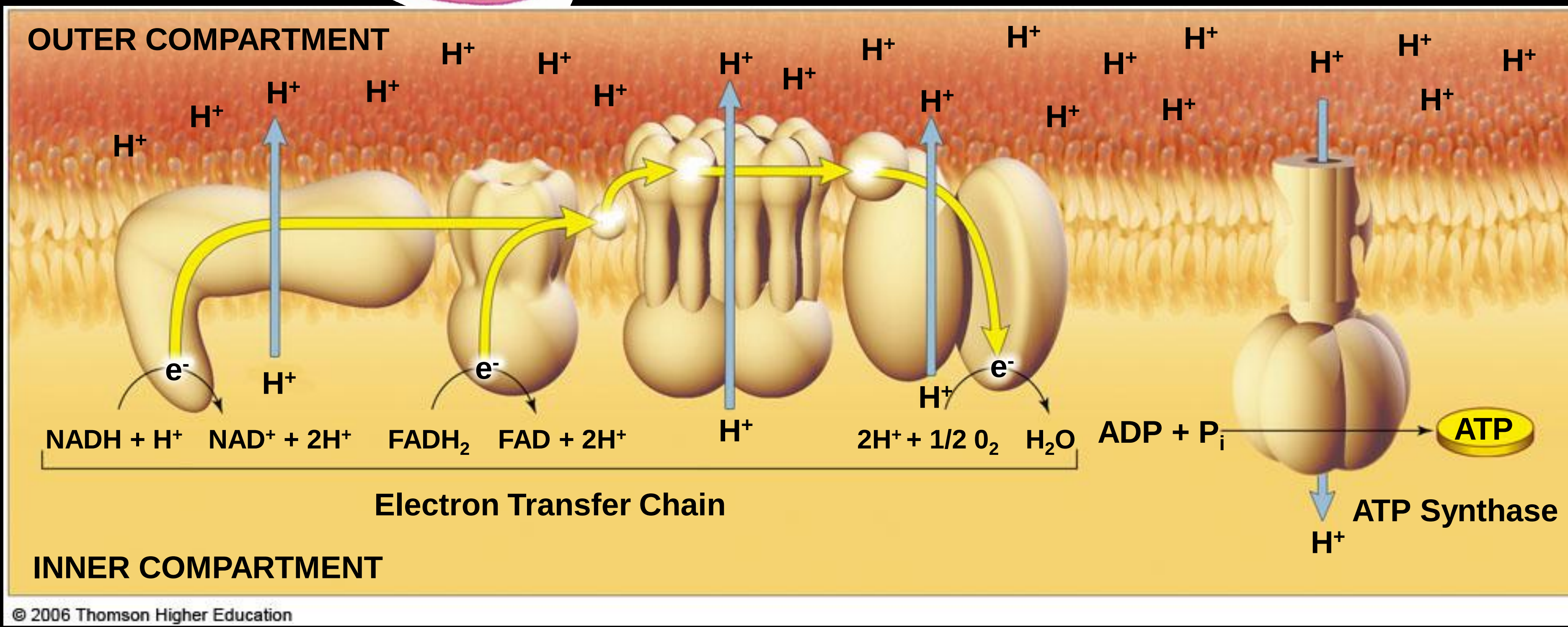
- All of the carbon molecules in pyruvate end up in carbon dioxide
- Coenzymes are reduced (they pick up electrons and hydrogen)
- One molecule of ATP forms
- Four-carbon oxaloacetate regenerates

Electron Transfer Phosphorylation

- Occurs in the mitochondria
- Coenzymes deliver electrons to electron transfer chains
- Electron transfer sets up H^+ ion gradients
- Flow of H^+ down gradients powers ATP formation

Phosphorylation





Phosphorylation

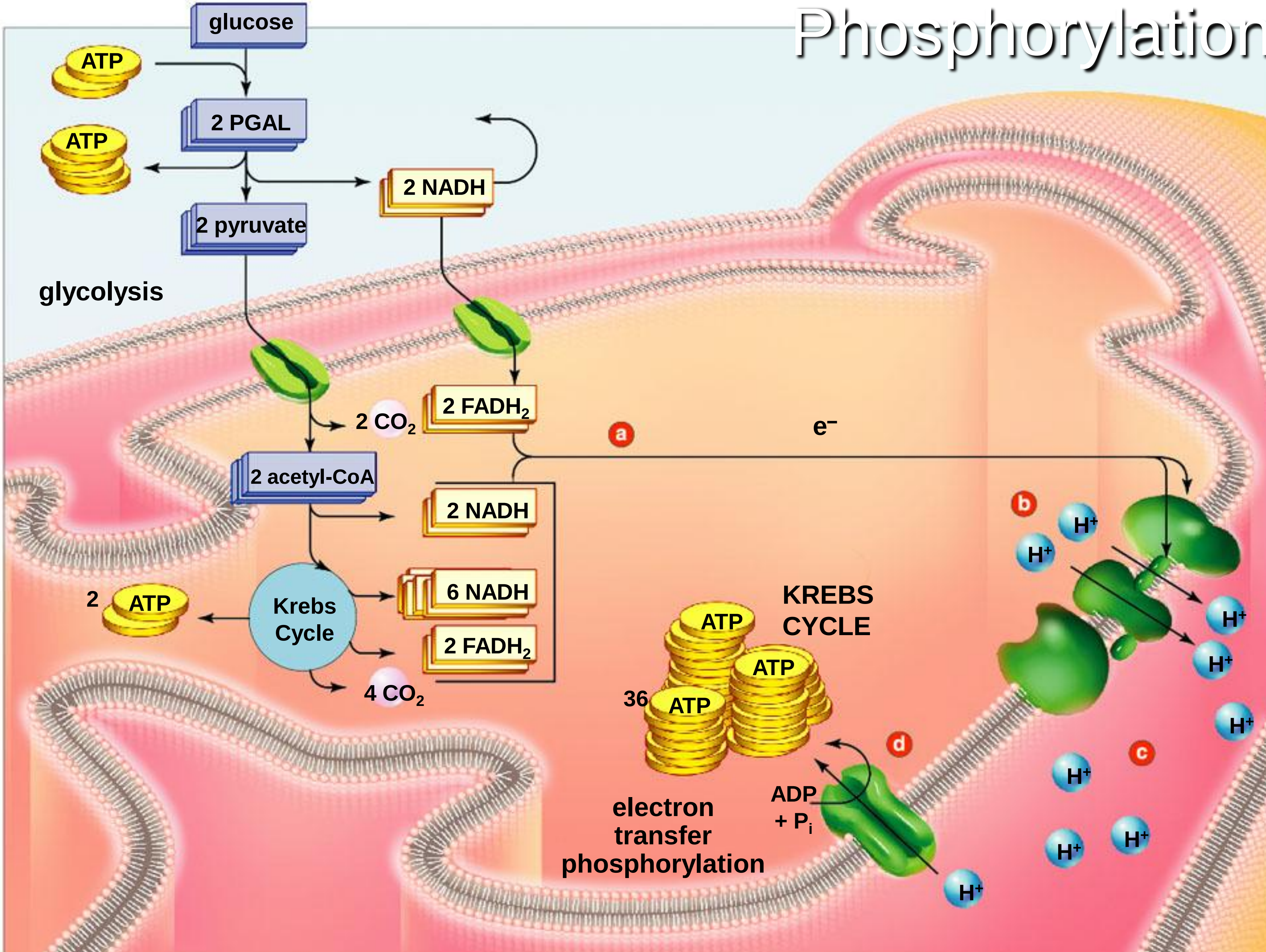
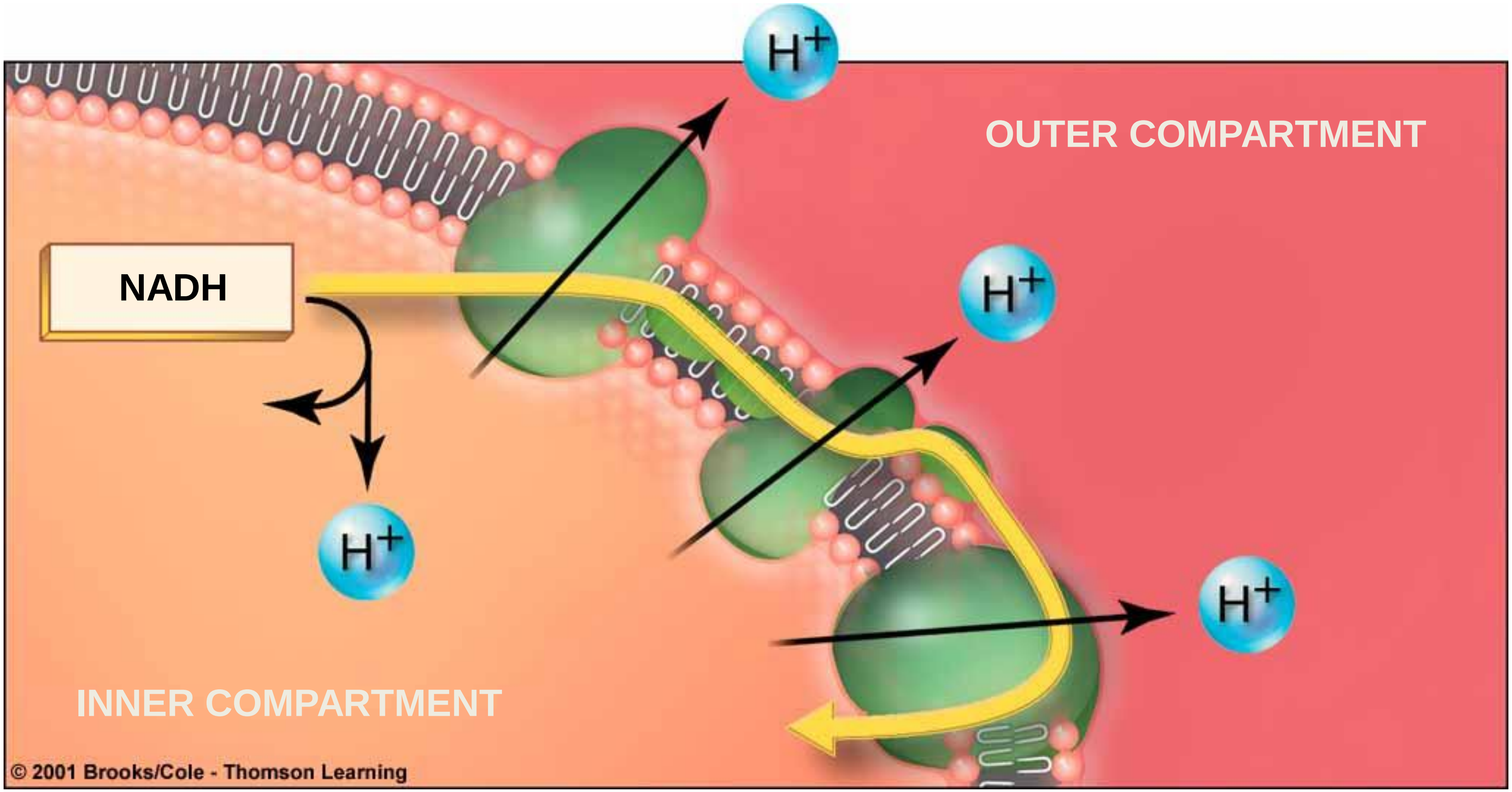
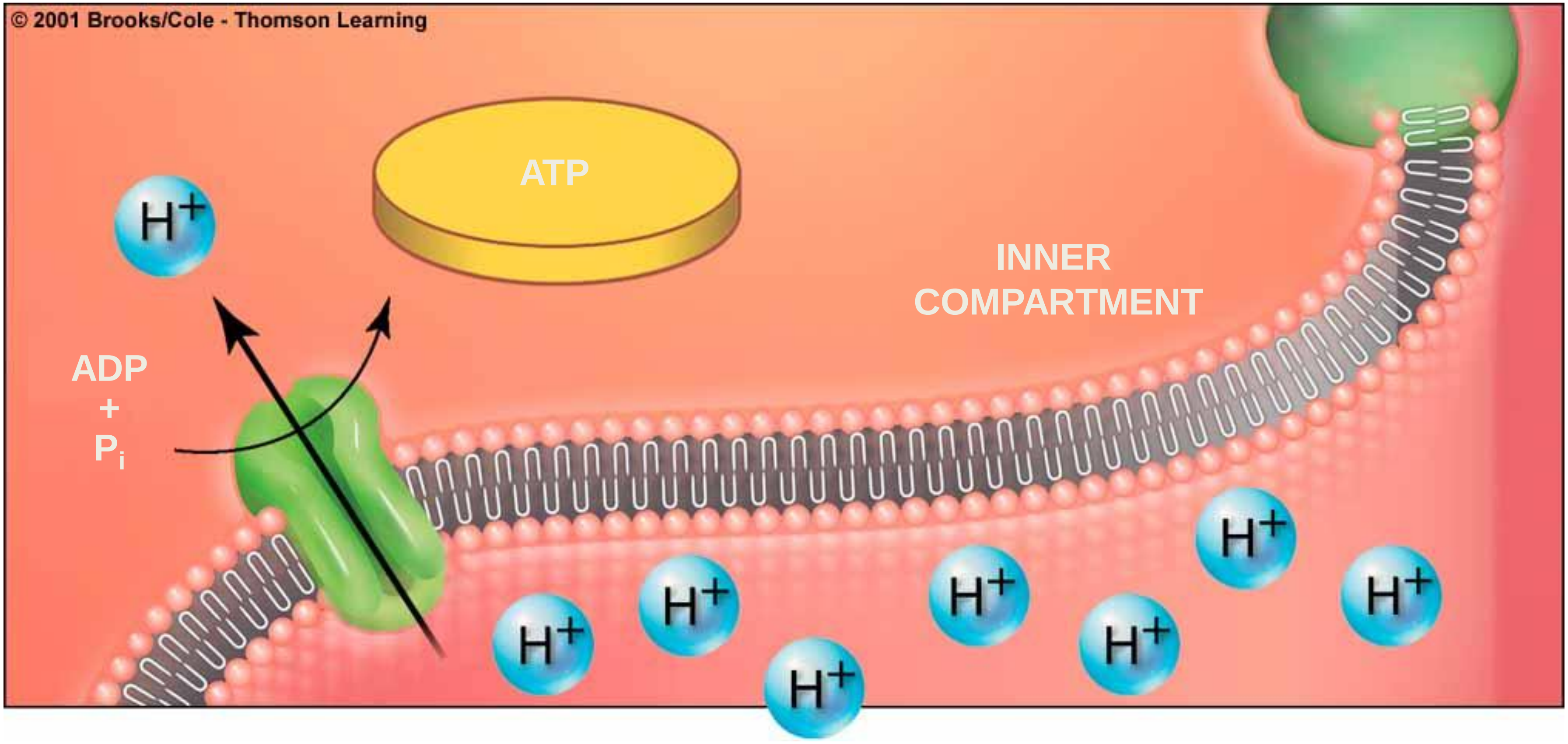


Fig. 8-9, p.131

Creating an H^+ Gradient



Making ATP: Chemiosmotic Model



Importance of Oxygen

- Electron transport phosphorylation requires the presence of oxygen

- Oxygen withdraws spent electrons from the electron transfer chain, then combines with H^+ to form water

Summary of Energy Harvest (per molecule of glucose)

- Glycolysis
  - 2 ATP formed by substrate-level phosphorylation
- Krebs cycle and preparatory reactions
  - 2 ATP formed by substrate-level phosphorylation
- Electron transport phosphorylation
  - 32 ATP formed

Efficiency of Aerobic Respiration

- 686 kcal of energy are released
- 7.5 kcal are conserved in each ATP
- When 36 ATP form, 270 kcal (36 X 7.5) are captured in ATP
- Efficiency is 270 / 686 X 100 = 39 percent
- Most energy is lost as heat

Anaerobic Pathways

- Do not use oxygen
- Produce less ATP than aerobic pathways
- Two types
  - Fermentation pathways
  - Anaerobic electron transport

Fermentation Pathways

- Begin with glycolysis
- Do not break glucose down completely to carbon dioxide and water
- Yield only the 2 ATP from glycolysis
- Steps that follow glycolysis serve only to regenerate NAD^+

Alcoholic Fermentation

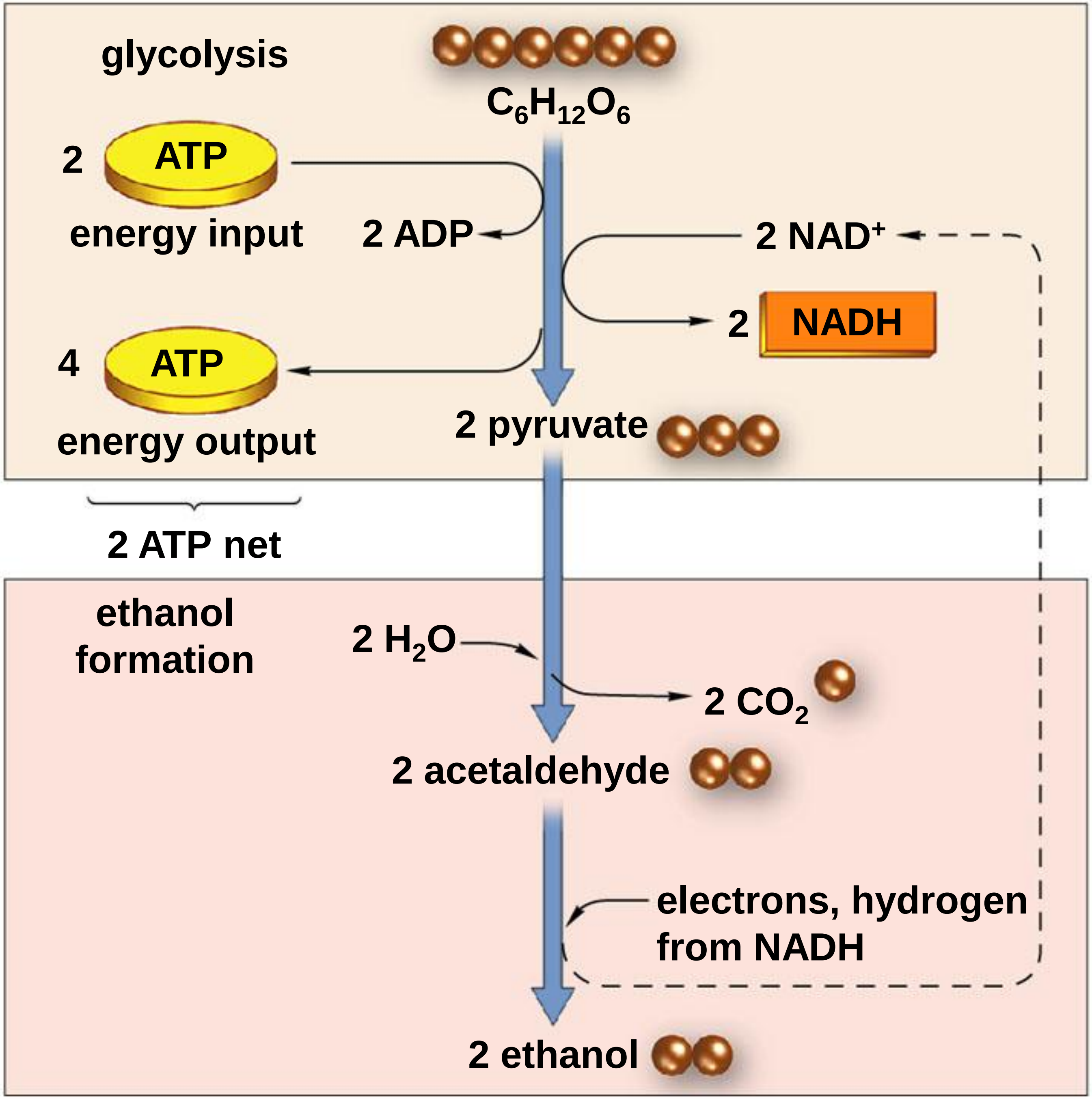


Fig. 8-10d, p.132

Alcoholic Fermentation

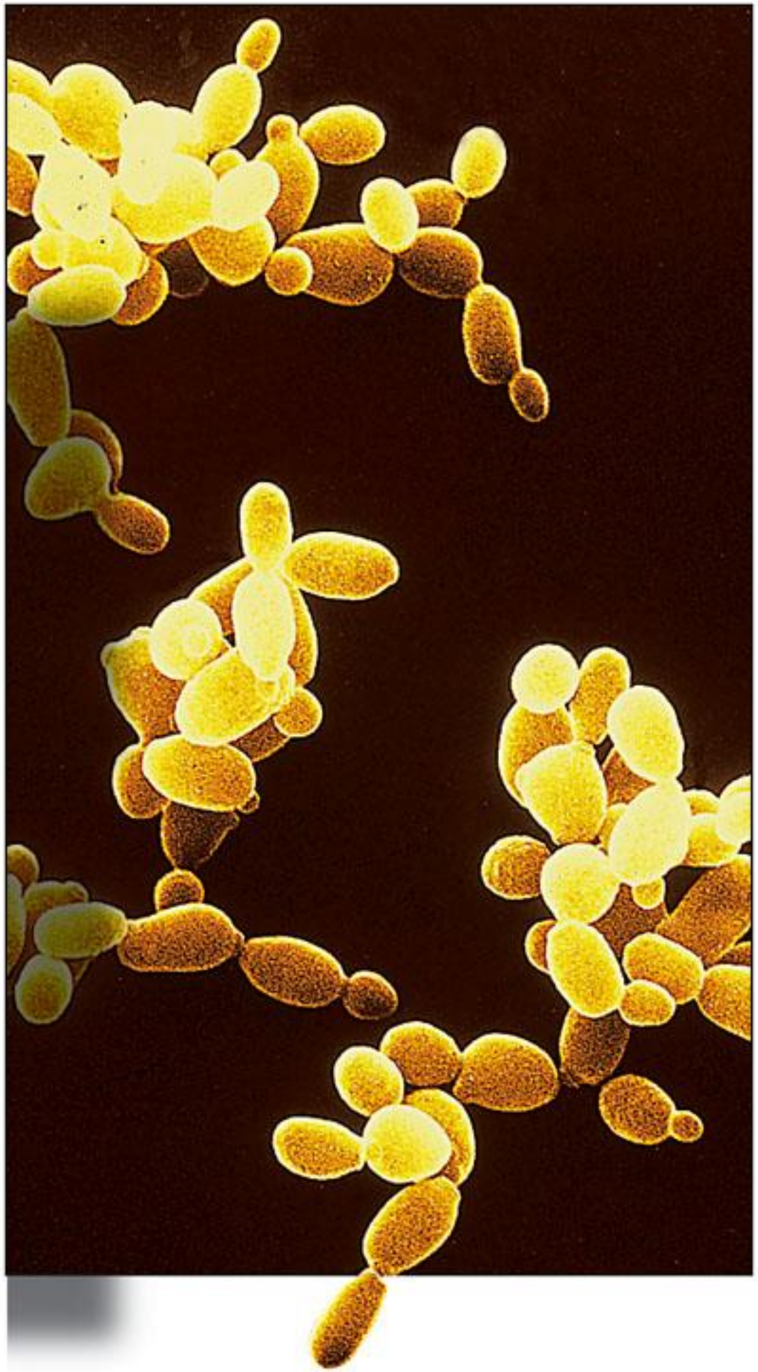


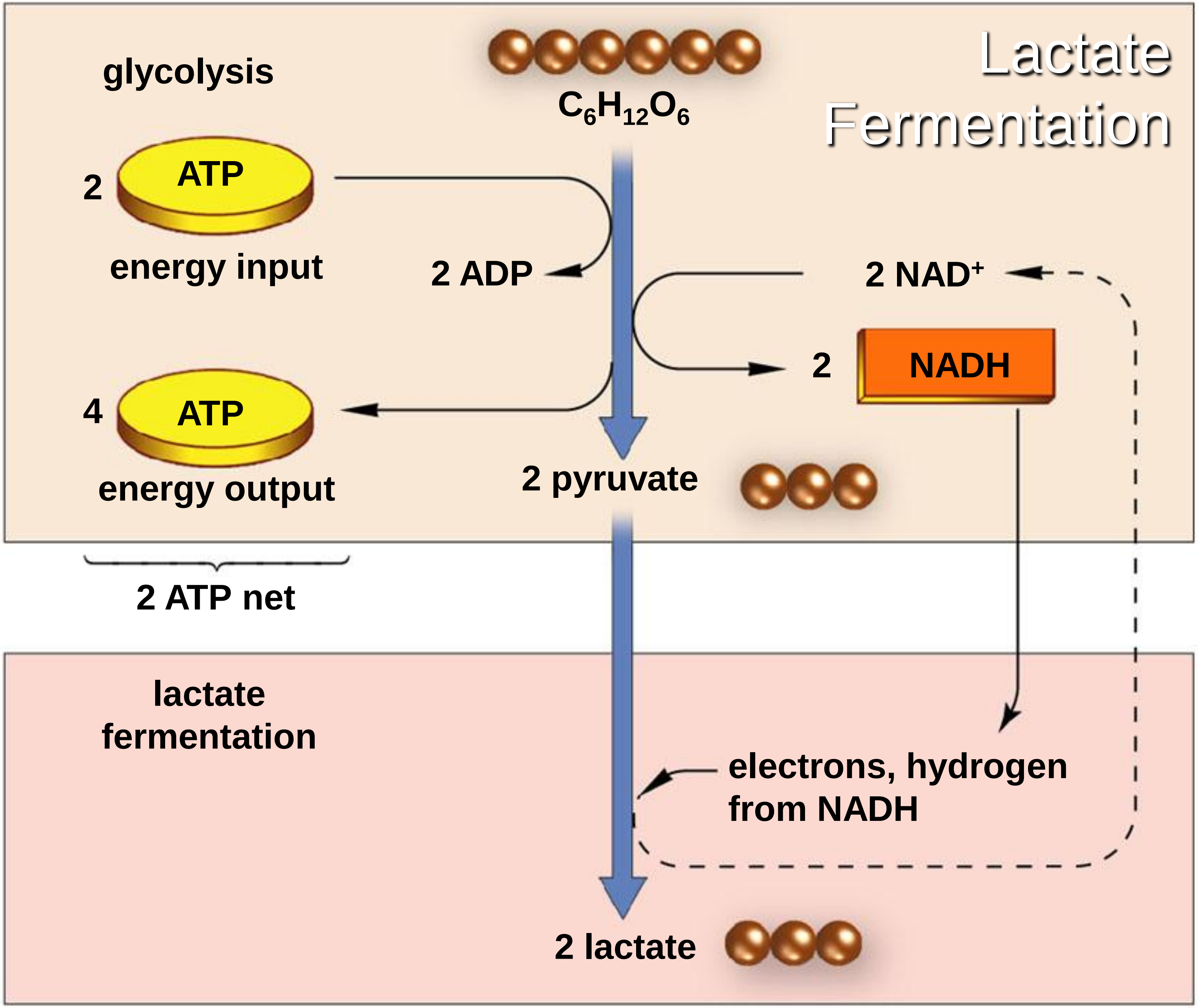
Fig. 8-10a, p.132

Alcoholic Fermentation

Fig. 8-10b, p.132

Alcoholic Fermentation

Fig. 8-10c, p.132



Lactate Fermentation
glycolysis
$C_6H_{12}O_6$
2 ATP
energy input
2 ADP
2 NAD^+
2 NADH
4 ATP
energy output
2 pyruvate
2 ATP net
lactate fermentation
electrons, hydrogen from NADH
2 lactate

Fig. 8-11, p.133

Lactate Fermentation

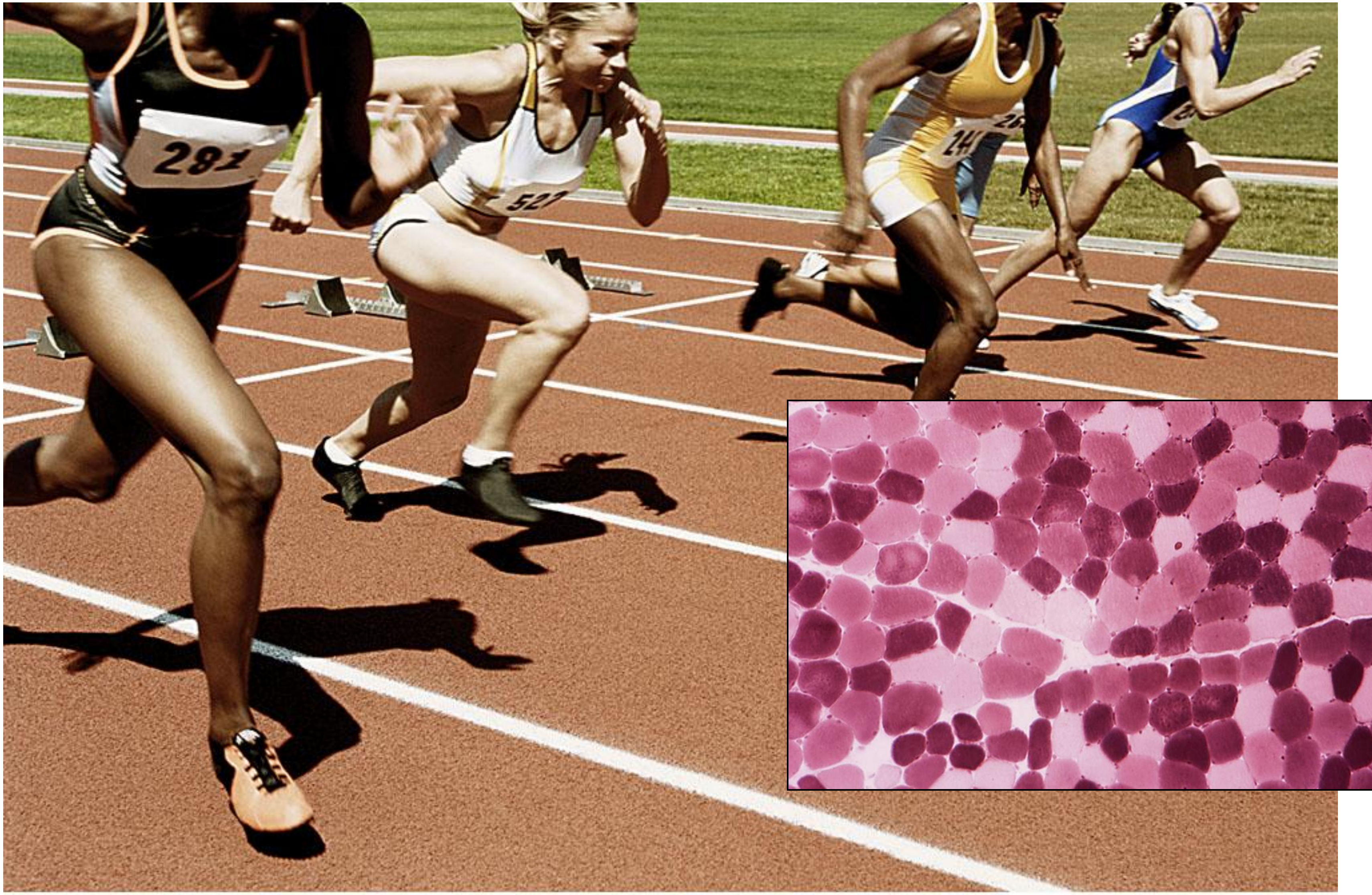
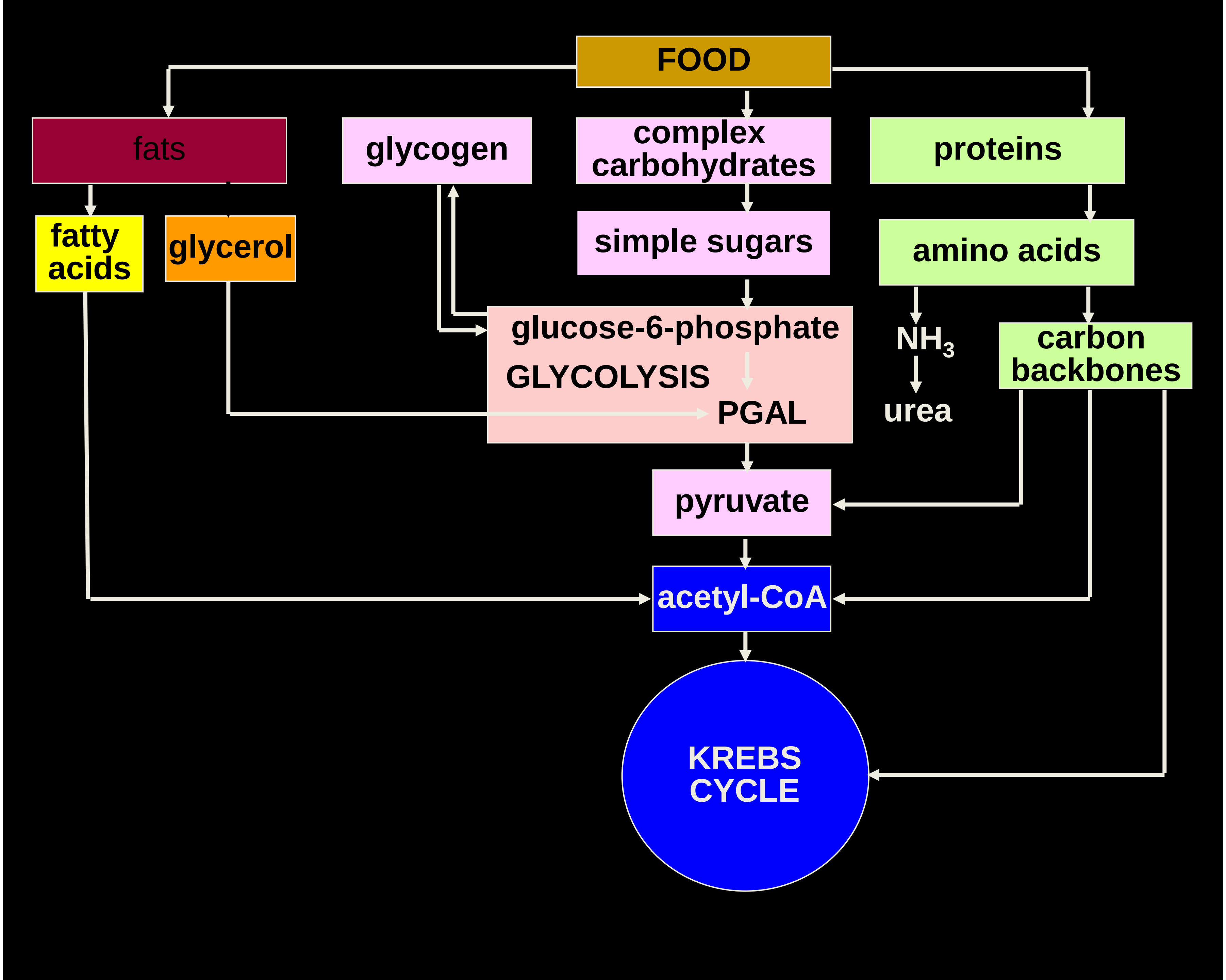


Fig. 8-12, p.133

Anaerobic Electron Transport

- Carried out by certain bacteria
- Electron transfer chain is in bacterial plasma membrane
- Final electron acceptor is compound from environment (such as nitrate), not oxygen
- ATP yield is low


FOOD
fats
glycogen
complex carbohydrates
proteins
fatty acids
glycerol
simple sugars
amino acids
glucose-6-phosphate
GLYCOLYSIS
PGAL
NH_3
urea
carbon backbones
pyruvate
acetyl-CoA
KREBS CYCLE

Alternative Energy Sources

Fig. 8-13a, p.135

Alternative Energy Sources

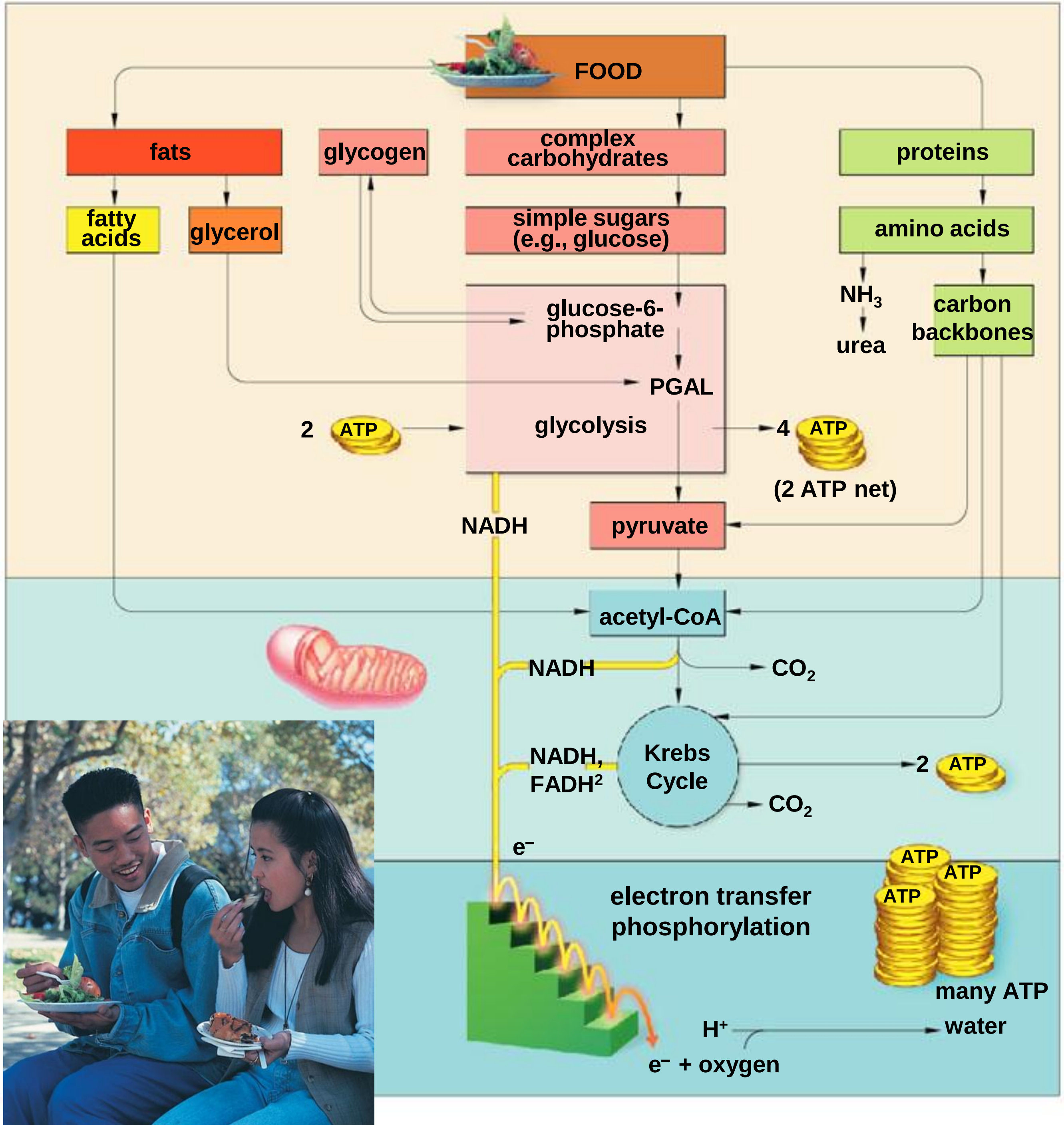


Fig. 8-13b, p.135

Evolution of Metabolic Pathways

- When life originated, atmosphere had little oxygen
- Earliest organisms used anaerobic pathways
- Later, noncyclic pathway of photosynthesis increased atmospheric oxygen
- Cells arose that used oxygen as final acceptor in electron transport

Processes Are Linked