How Cells Release Chemical Energy – Cellular Respiration

Overview of Carbohydrate Breakdown Pathways

- Photoautotrophs make ATP during photosynthesis and use it to synthesize glucose and other carbohydrates

- Most organisms, including photoautotrophs, make ATP by breaking down glucose and other organic compounds

Comparison of the Main Pathways

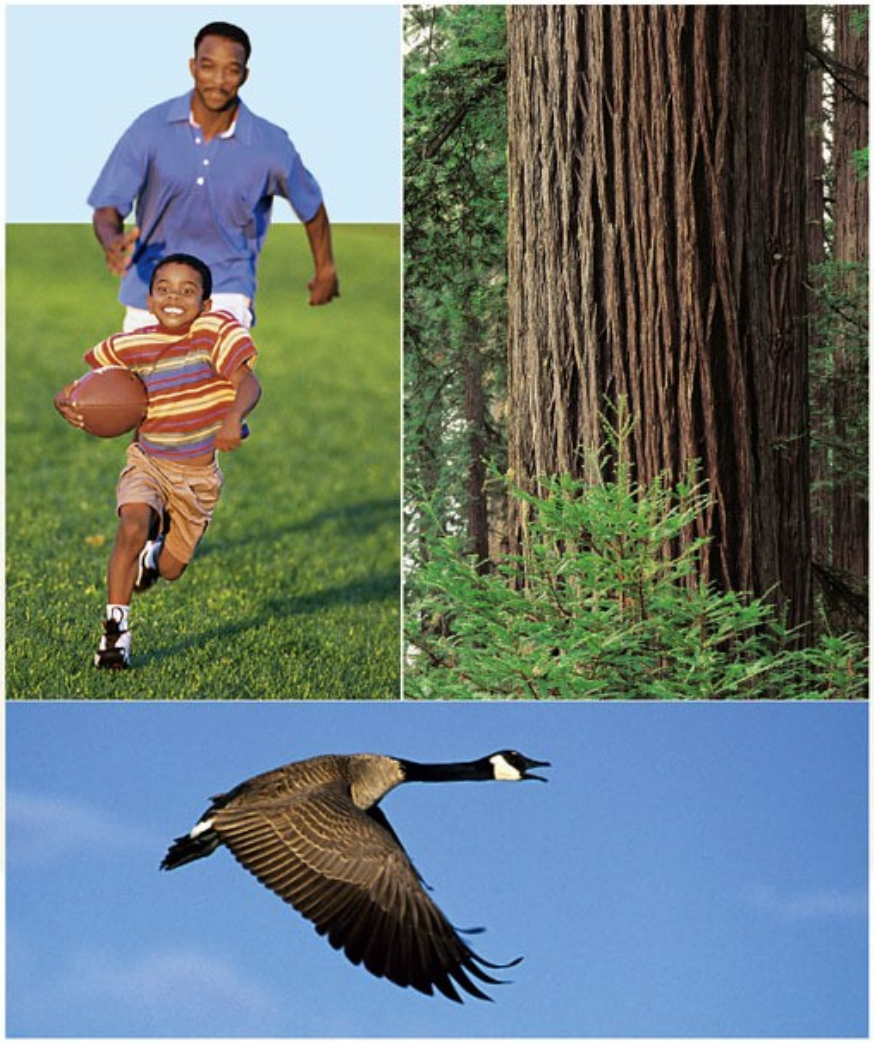
- **Aerobic respiration**
  - **Aerobic** metabolic pathways (using oxygen) are used by most eukaryotic cells
- **Fermentation**
  - **Anaerobic** metabolic pathways (occur in the absence of oxygen) are used by prokaryotes and protists in anaerobic habitats

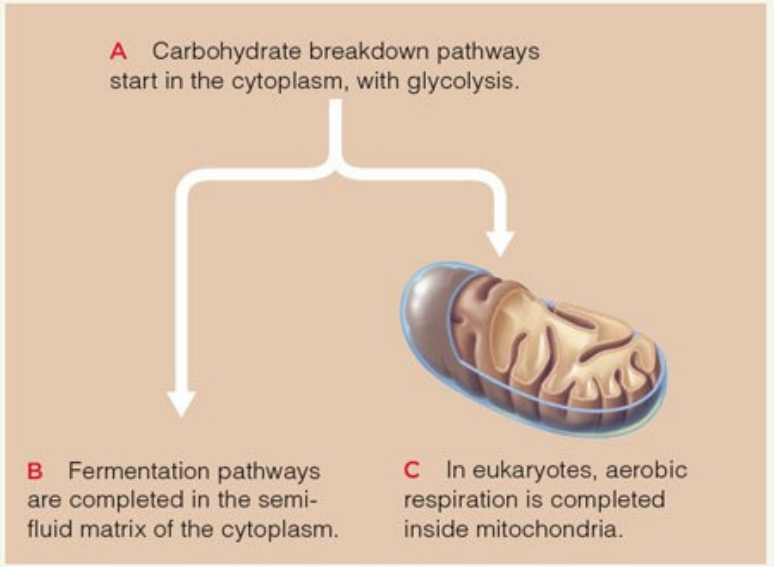
Comparison of the Main Pathways

- Aerobic respiration and fermentation both begin with **glycolysis**, which converts one molecule of glucose into two molecules of **pyruvate**

- After glycolysis, the two pathways diverge
  - Fermentation is completed in the cytoplasm, yielding 2 ATP per glucose molecule
  - Aerobic respiration is completed in mitochondria, yielding 36 ATP per glucose molecule

Comparison of the Main Pathways





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Overview of Aerobic Respiration

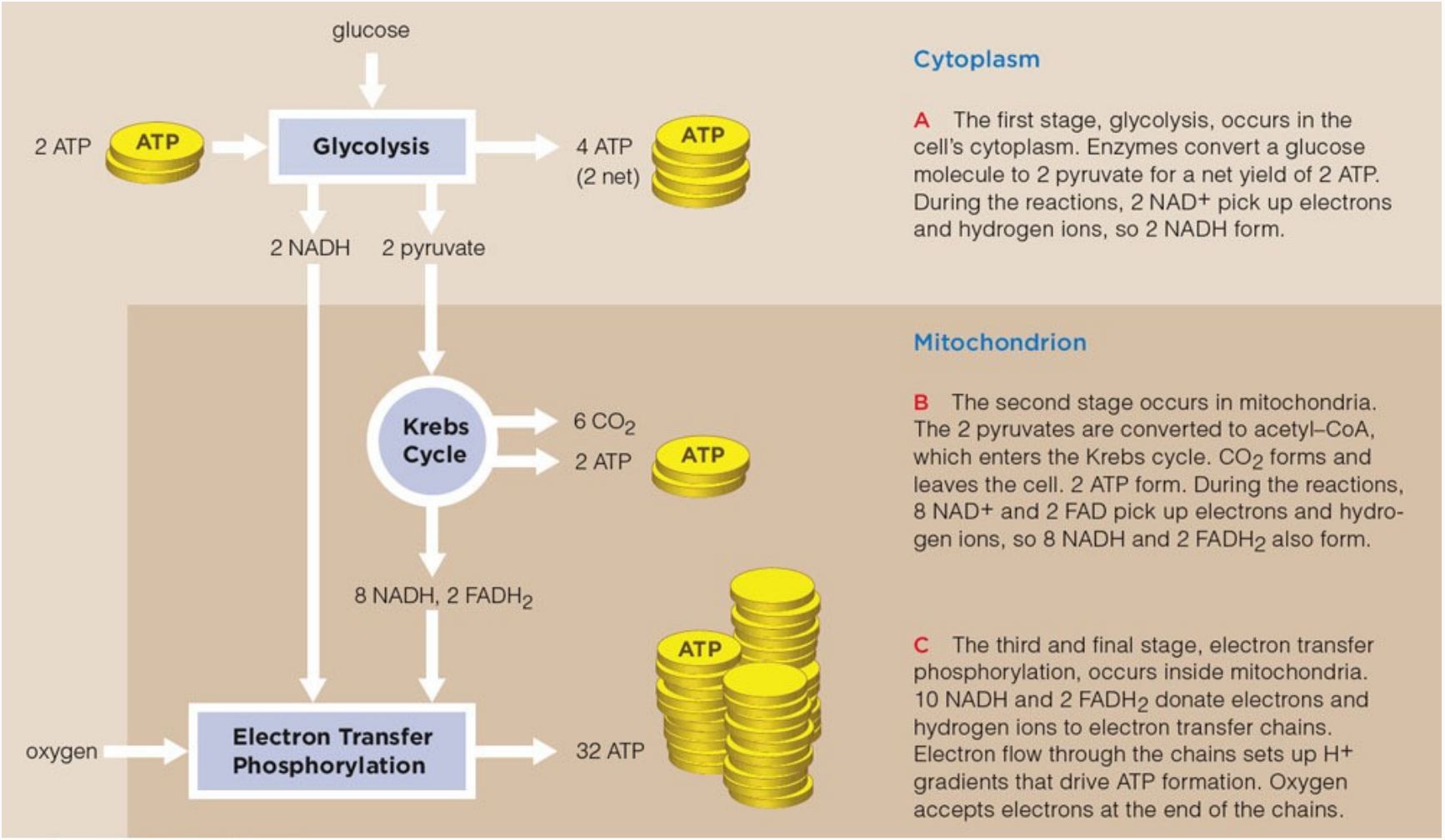
- Three stages
  - Glycolysis
  - Acetyl-CoA formation and Krebs cycle
  - Electron transfer phosphorylation (ATP formation)

$C_6H_{12}O_6$ (glucose) + O_2 (oxygen) $\longrightarrow$

CO_2 (carbon dioxide) + H_2O (water)

  - Coenzymes NADH and $FADH_2$ carry electrons and hydrogen

Overview of Aerobic Respiration



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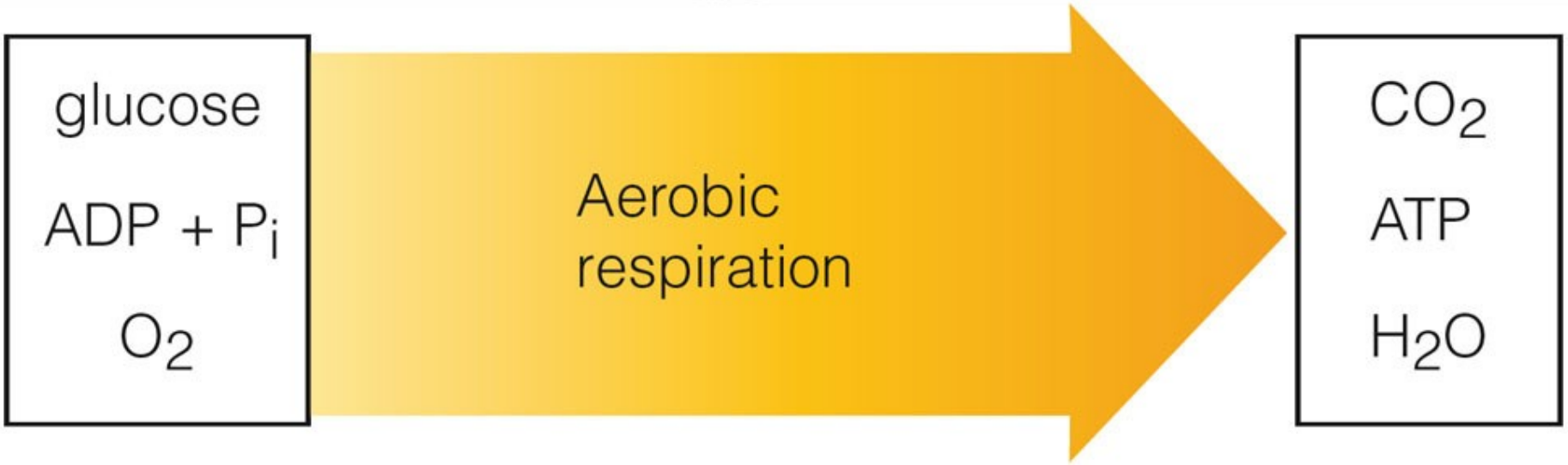

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Animation: Overview of aerobic respiration

http://
www.youtube.com/v/SoRyBftF3O0

Key Concepts:
Energy From Carbohydrate Breakdown

- *Various degradative pathways convert the chemical energy of glucose and other organic compounds to the chemical energy of ATP*

- *Aerobic respiration yields the most ATP from each glucose molecule; in eukaryotes, it is completed inside mitochondria*

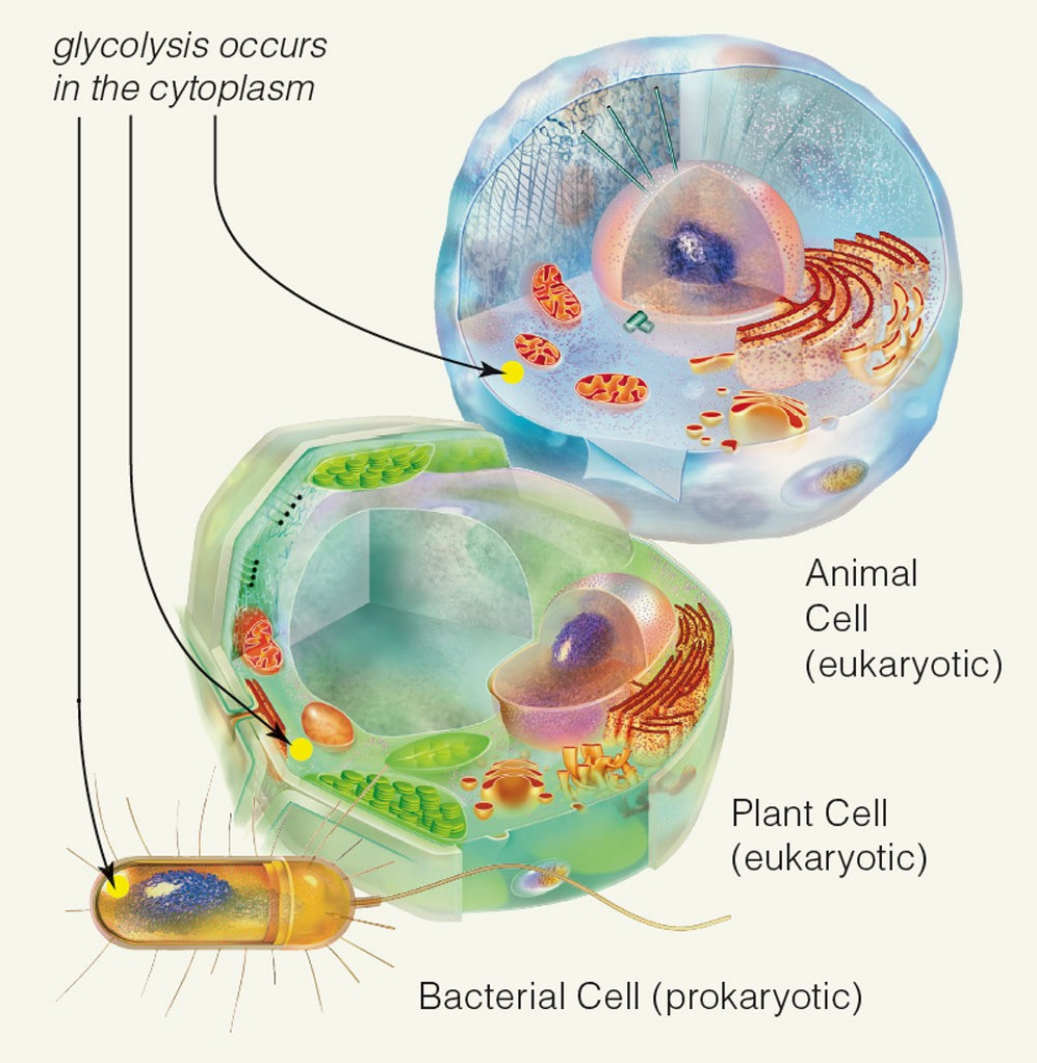
Glycolysis – Glucose Breakdown Starts

- Glycolysis starts and ends in the cytoplasm of all prokaryotic and eukaryotic cells
- An energy investment of ATP starts glycolysis

Glycolysis

- Two ATP are used to split glucose and form 2 PGAL, each with one phosphate group
- Enzymes convert 2 PGAL to 2 PGA, forming 2 NADH
- Four ATP are formed by **substrate-level phosphorylation** (net 2 ATP)
- Enzymes of glycolysis use two ATP to convert one molecule of glucose to two molecules of three-carbon pyruvate

Glycolysis


glycolysis occurs
in the cytoplasm
Animal
Cell
(eukaryotic)
Plant Cell
(eukaryotic)
Bacterial Cell (prokaryotic)
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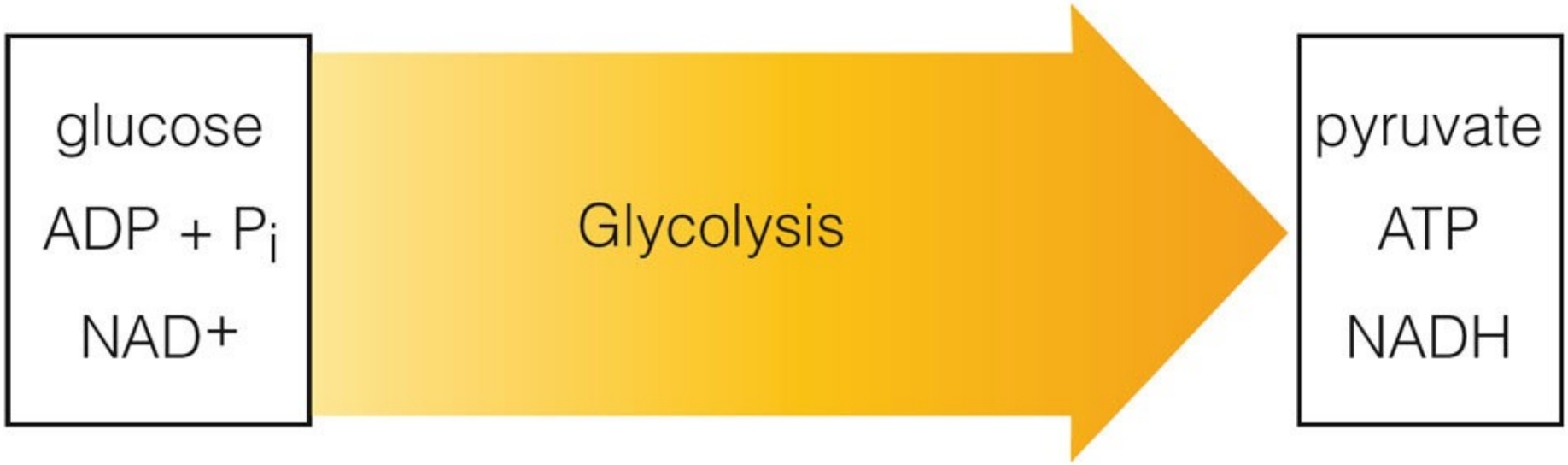
Products of Glycolysis

- Net yield of glycolysis:
  - 2 pyruvate, 2 ATP, and 2 NADH per glucose
- Pyruvate may:
  - Enter fermentation pathways in cytoplasm
  - Enter mitochondria and be broken down further in aerobic respiration



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Glycolysis Occurs in Two Stages

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

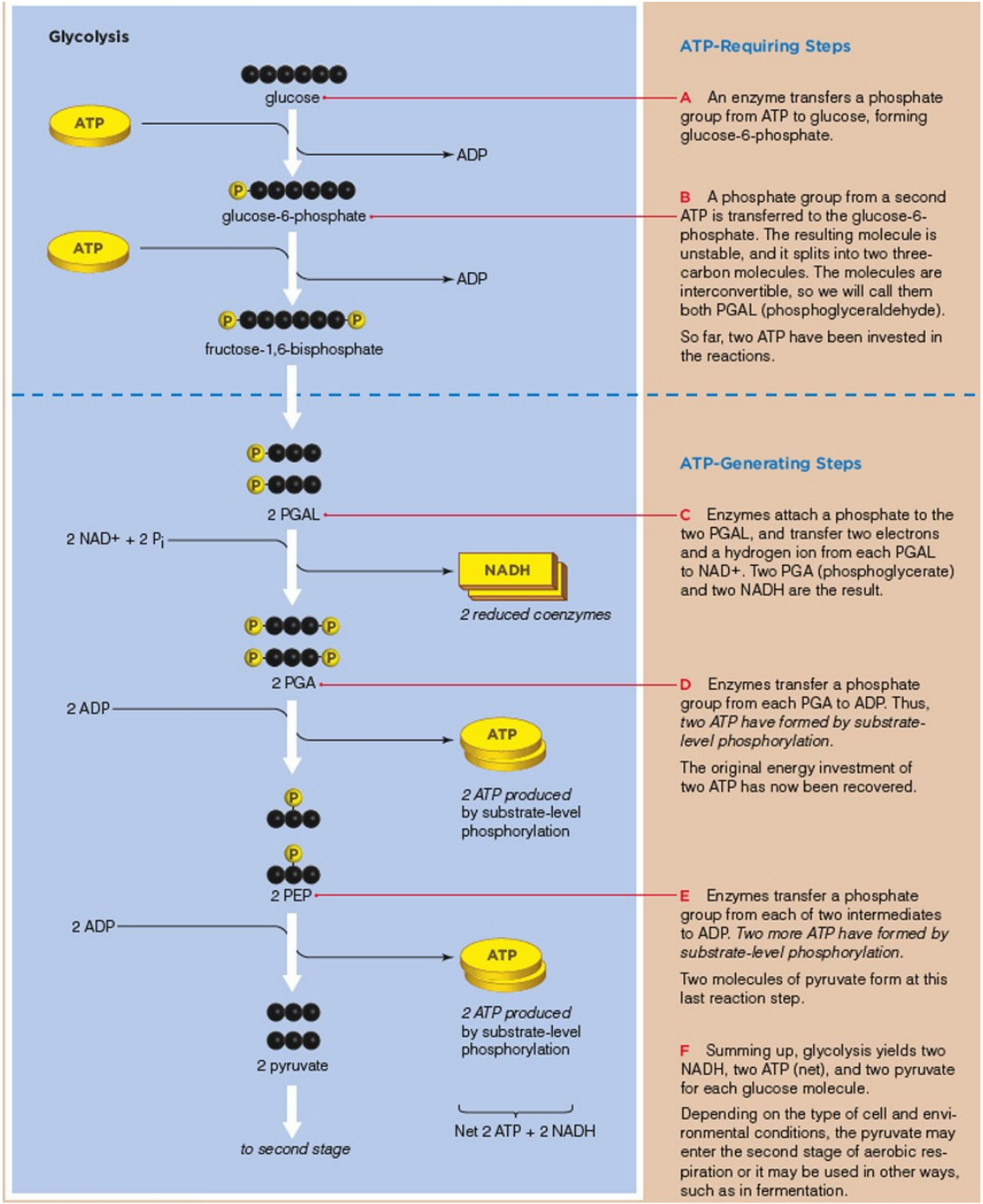

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Fig. 8-4b, p. 127

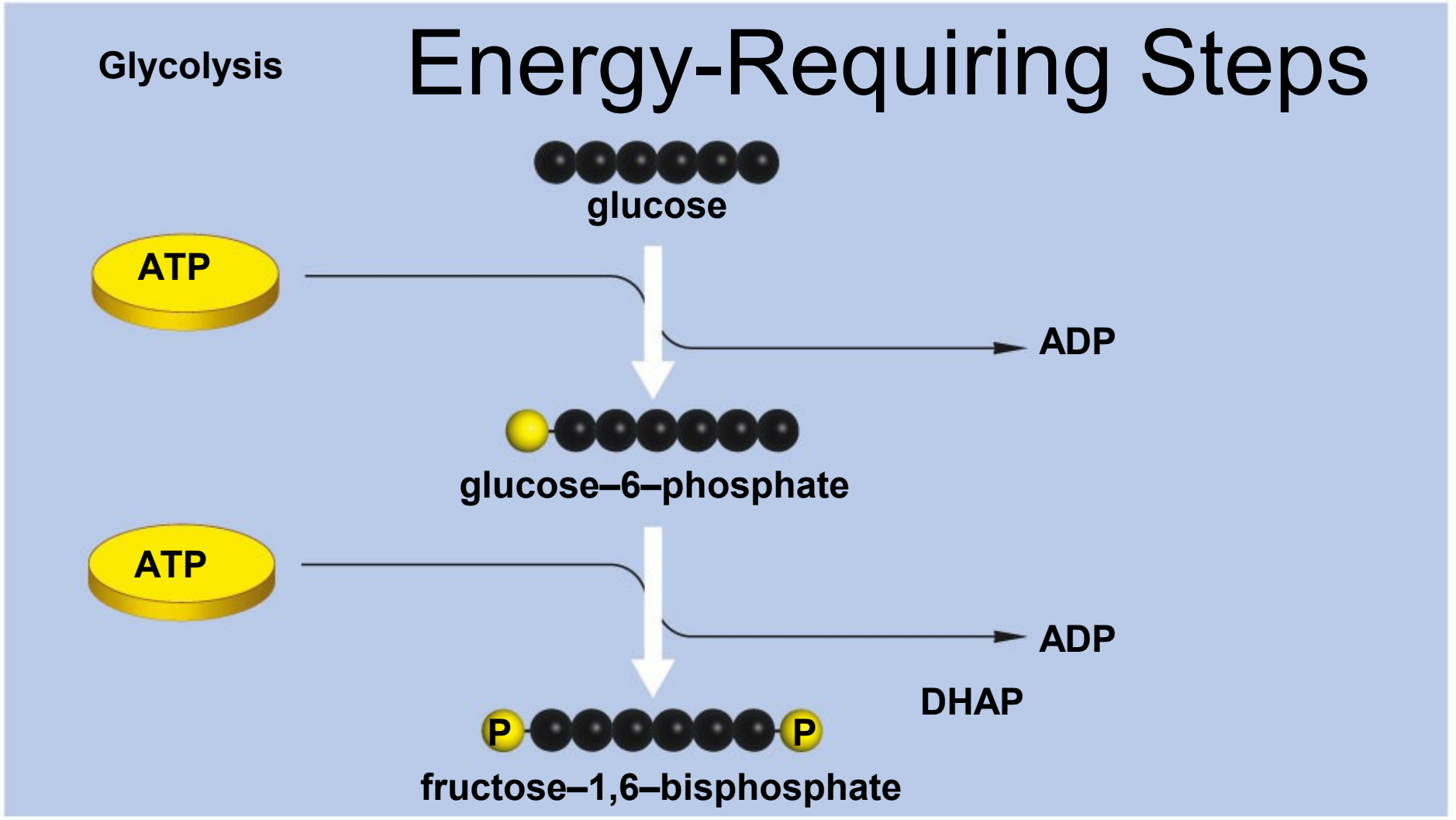

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Fig. 7.4c1, p.111

Energy-Releasing Steps

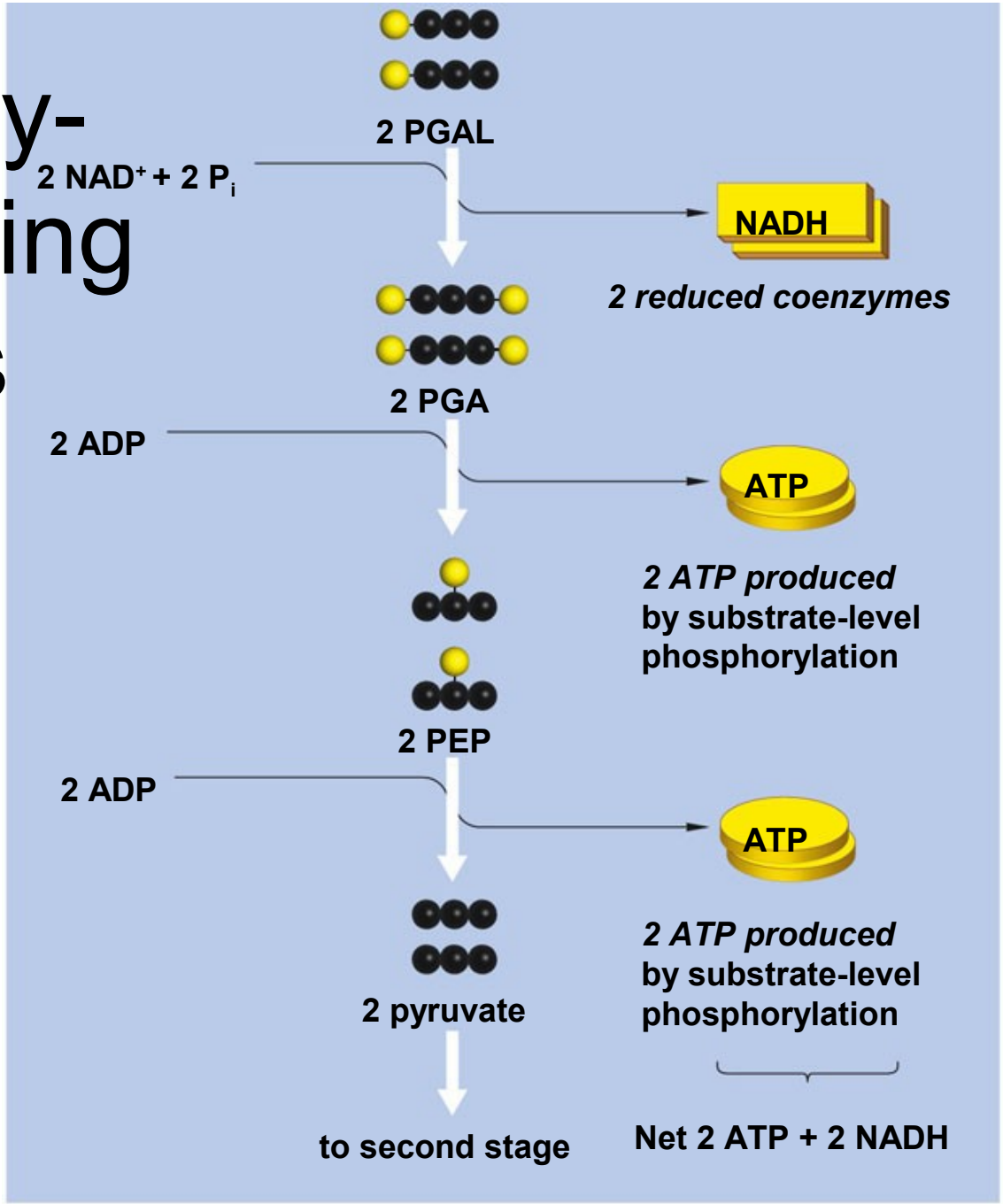

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Fig. 7.4c2, p.111

Key Concepts:
Glycolysis

- *Glycolysis is the first stage of aerobic respiration and of anaerobic routes such as fermentation pathways*
- *Enzymes of glycolysis convert glucose to pyruvate*
- *As enzymes break down glucose to pyruvate, the coenzyme NAD^+ picks up electrons and hydrogen atoms*
- *Net energy yield is two ATP*

Second Stage of Aerobic Respiration

- The second stage of aerobic respiration finishes breakdown of glucose that began in glycolysis
- More ATP is formed
- More coenzymes are reduced
- Occurs in mitochondria
- Includes two stages: acetyl CoA formation and the Krebs cycle (each occurs twice in the breakdown of one glucose molecule)

Acetyl CoA Formation

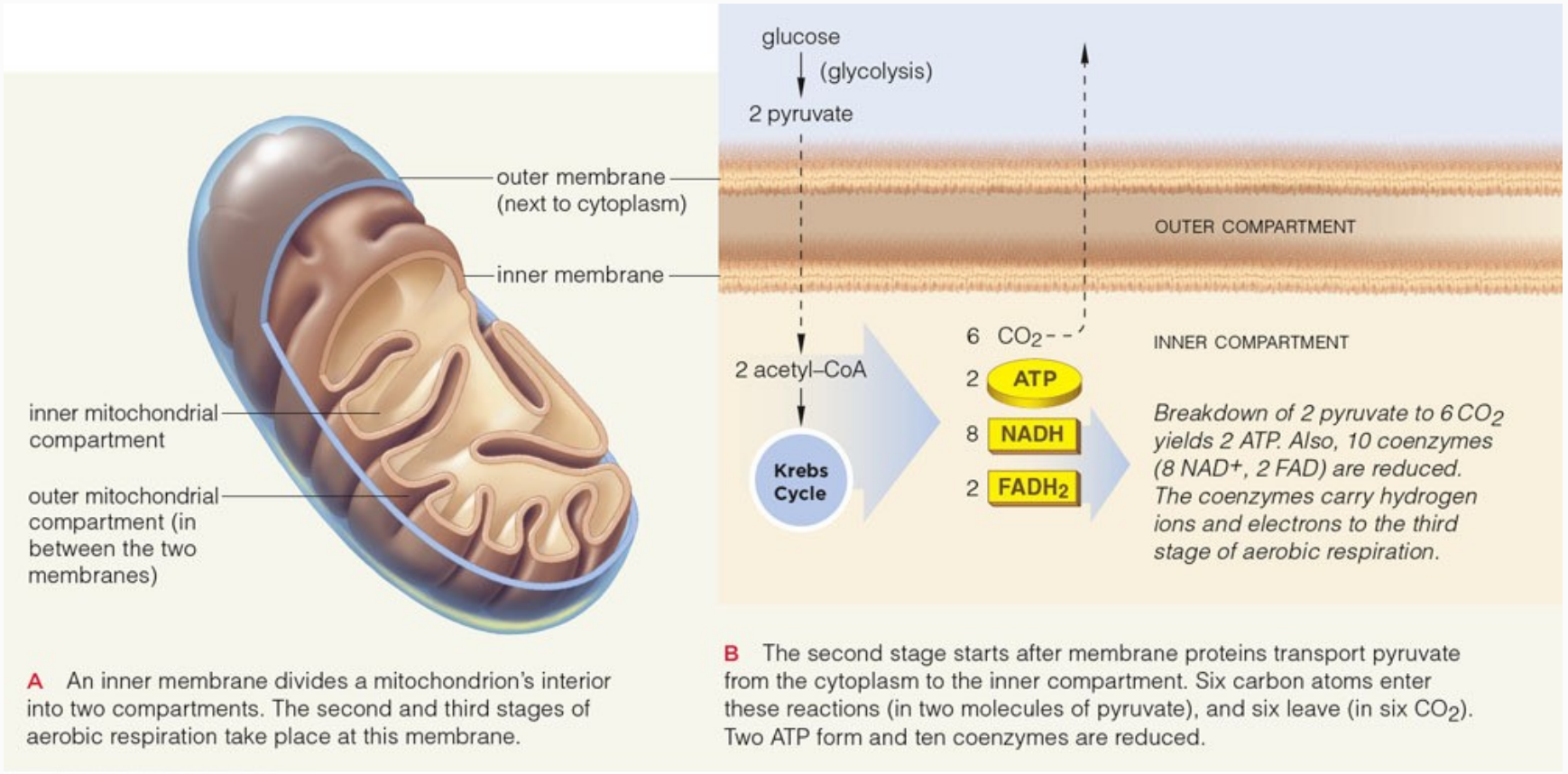
- In the inner compartment of the mitochondrion, enzymes split pyruvate, forming acetyl CoA and CO_2 (which diffuses out of the cell)

- NADH is formed

The Krebs Cycle – 10.05, 10.06

- **Krebs cycle**
  - A sequence of enzyme-mediated reactions that break down 1 acetyl CoA into 2 CO_2
  - Oxaloacetate is used and regenerated
  - 3 NADH and 1 $FADH_2$ are formed
  - 1 ATP is formed
  - DOUBLE THIS FOR EACH MOLECULE OF GLUCOSE!!!

Inside a Mitochondrion



A An inner membrane divides a mitochondrion's interior into two compartments. The second and third stages of aerobic respiration take place at this membrane.

B The second stage starts after membrane proteins transport pyruvate from the cytoplasm to the inner compartment. Six carbon atoms enter these reactions (in two molecules of pyruvate), and six leave (in six CO_2). Two ATP form and ten coenzymes are reduced.

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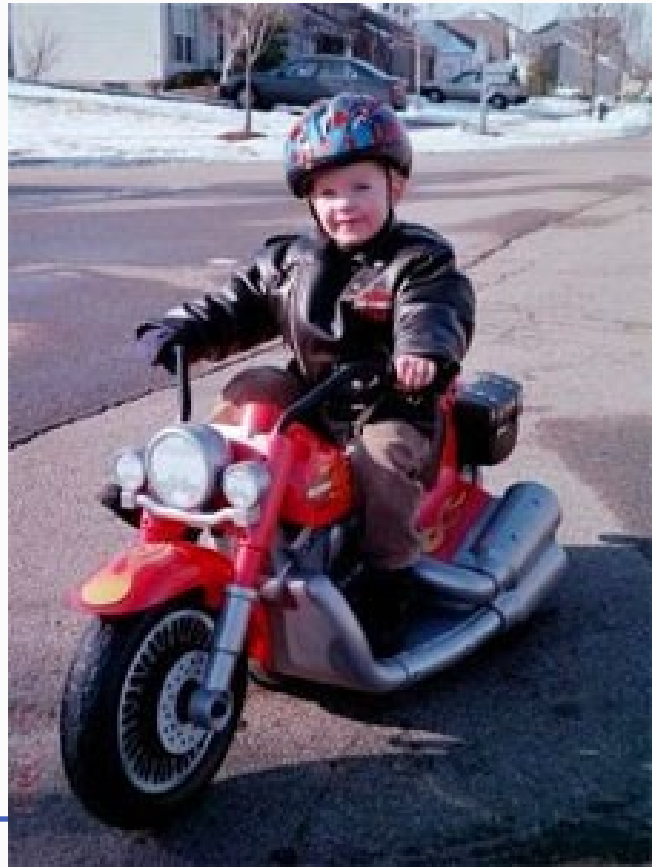
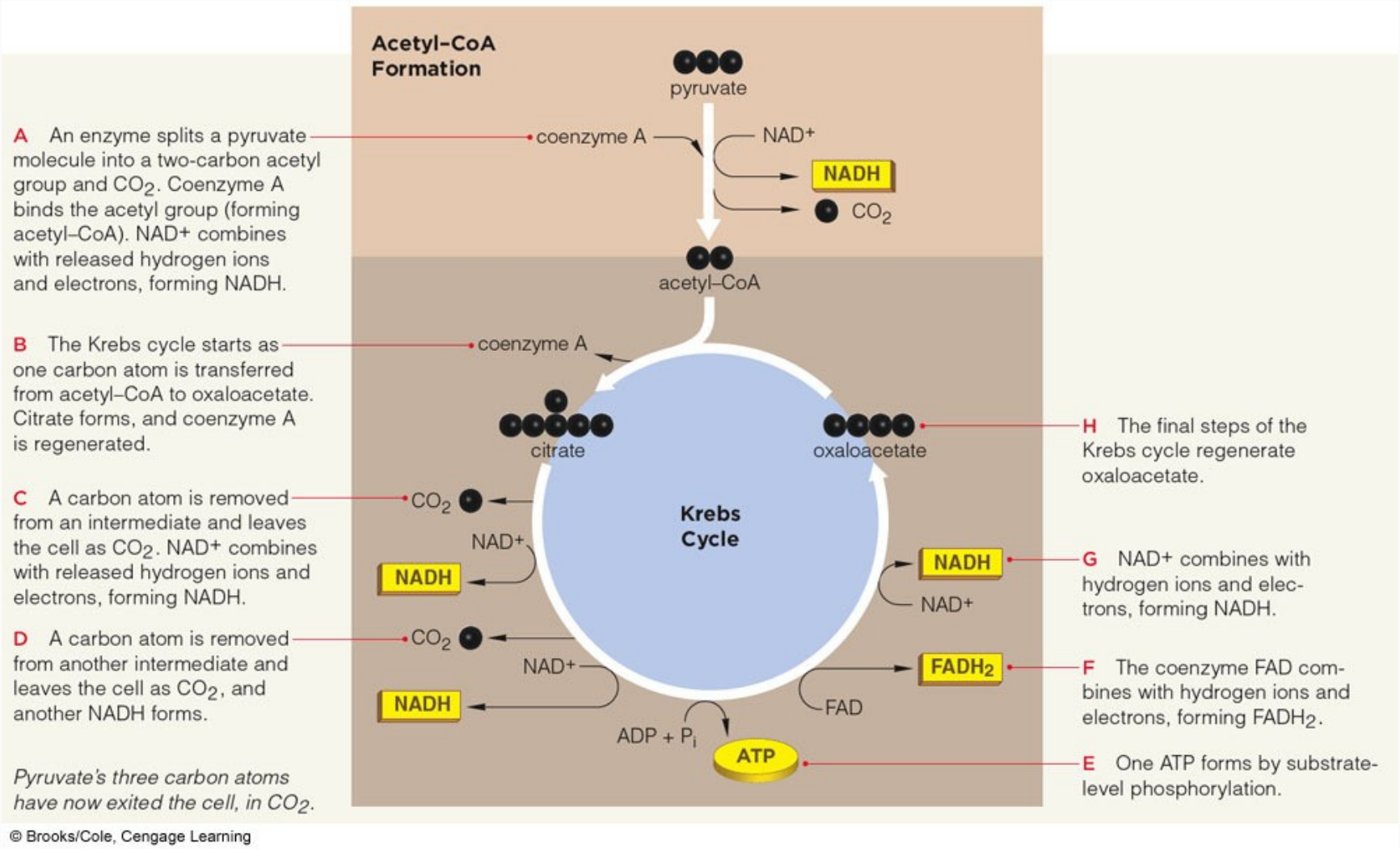
Krebs Cycle

- Each turn of the Krebs cycle, one acetyl-CoA is converted to two molecules of CO_2
  - DOUBLE THIS FOR EACH MOLECULE OF GLUCOSE!
- After two cycles
  - Two pyruvates are dismantled
  - Glucose molecule that entered glycolysis is fully broken down

Little Johnny Krebs



Acetyl CoA Formation and the Krebs Cycle



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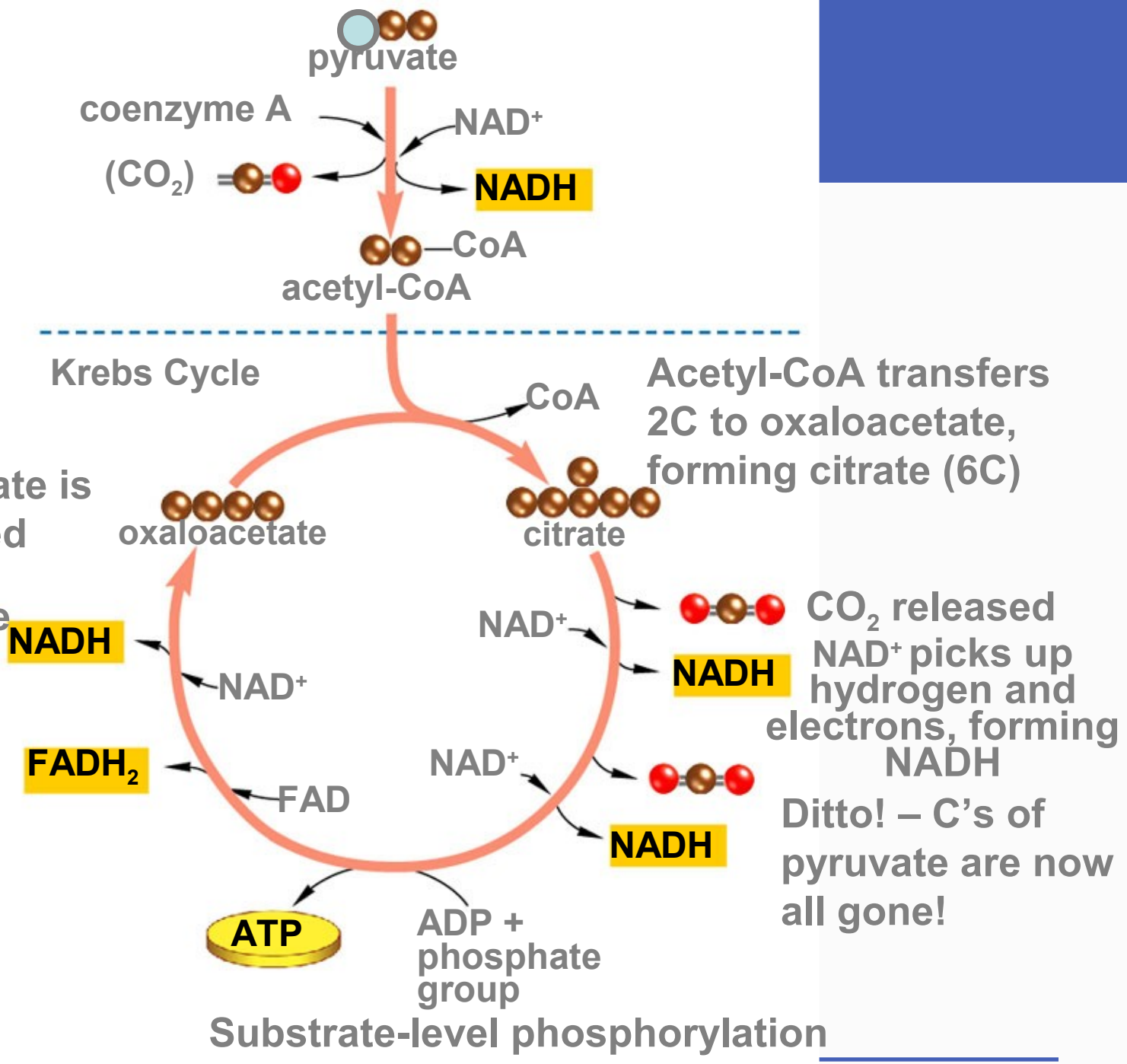
1. Remember that there are 2 pyruvate molecules from glycolysis!!!



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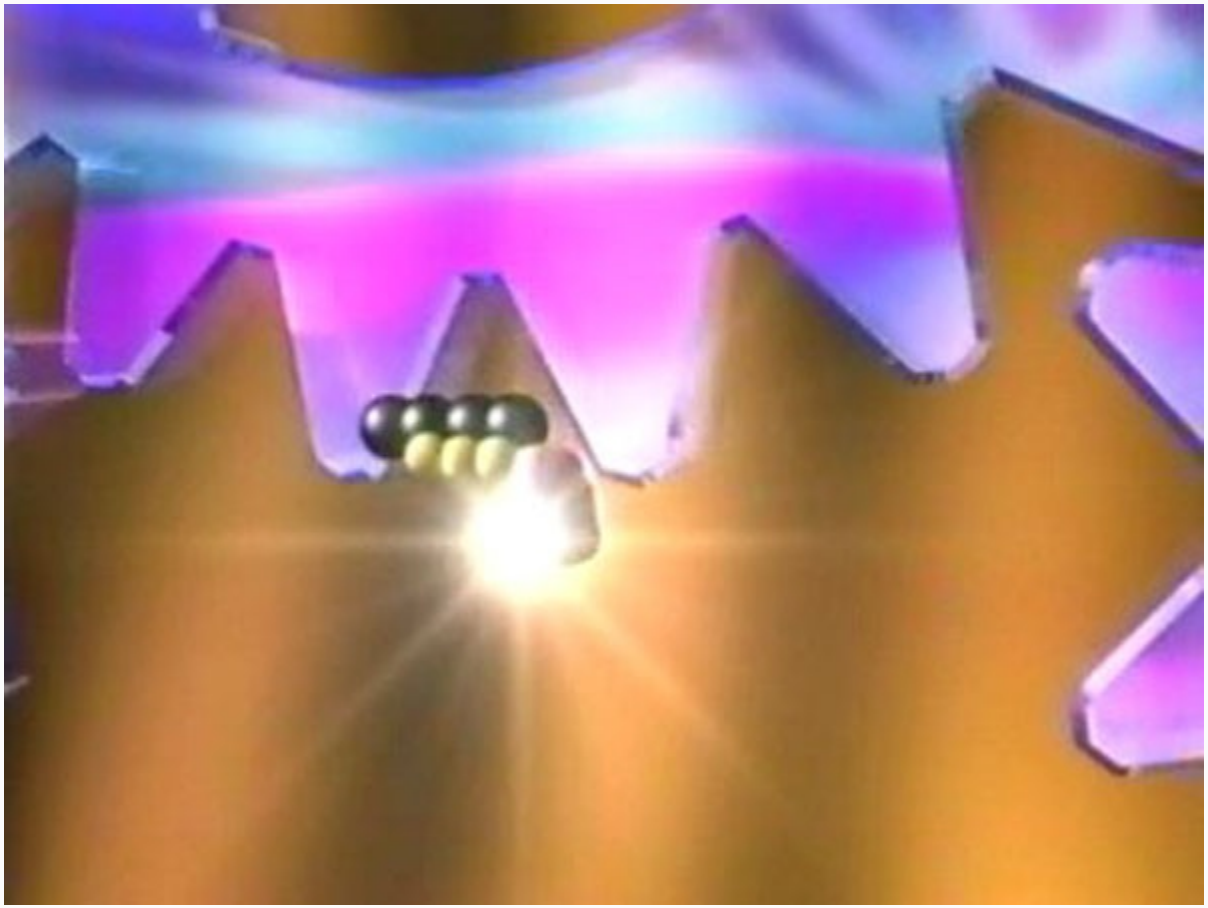
Net Results

- Second stage of aerobic respiration results in
  - Six CO_2, two ATP, eight NADH, and two $FADH_2$ for every two pyruvates
- Adding the yield from glycolysis, the total is
  - Twelve reduced coenzymes and four ATP for each glucose molecule
- Coenzymes deliver electrons and hydrogen to the third stage of reactions

Animation: Krebs cycle overview



http://www.youtube.com/v/aCypoN3X7KQ

Aerobic Respiration's Big Energy Payoff

- Many ATP are formed during the third and final stage of aerobic respiration

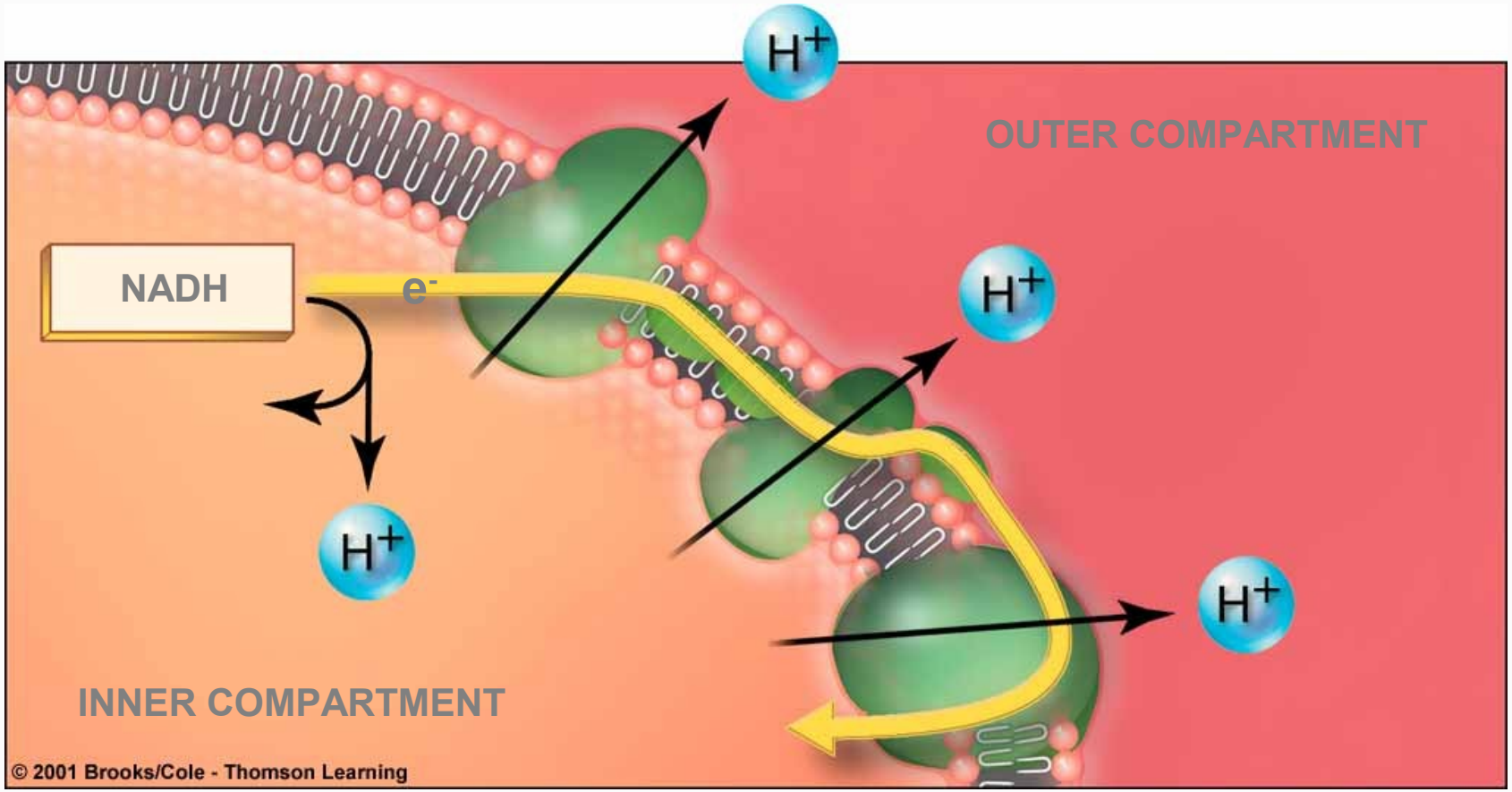
- **Electron transfer phosphorylation**
  - Occurs in mitochondria
  - Results in attachment of phosphate to ADP to form ATP

Electron Transfer Phosphorylation

- Coenzymes NADH and $FADH_2$ donate electrons and H^+ to electron transfer chains
- Active transport forms a H^+ concentration gradient in the outer mitochondrial compartment
- H^+ follows its gradient through ATP synthase, which attaches a phosphate to ADP
- Finally, oxygen accepts electrons and combines with H^+, forming water

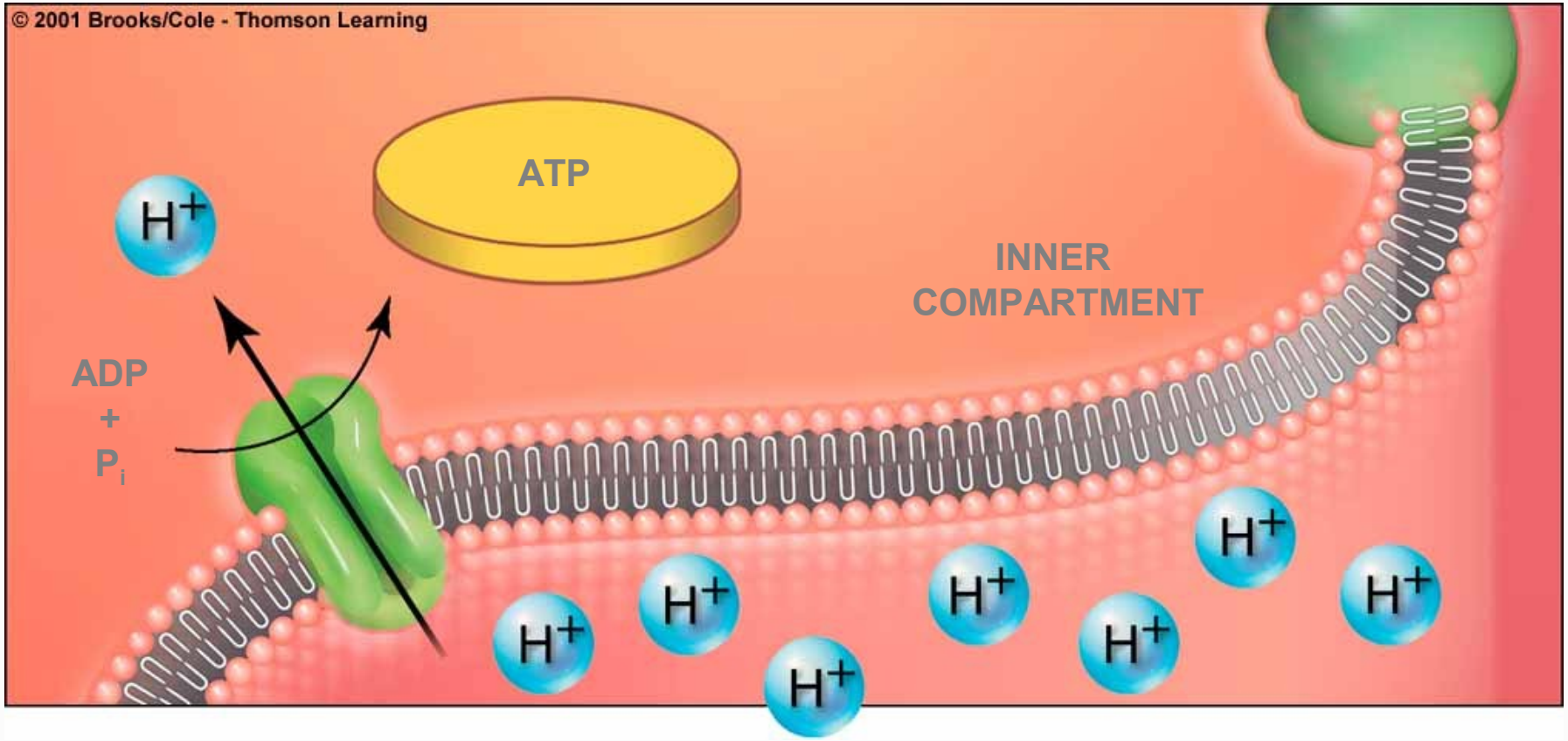
Creating an H^+ Gradient

As electrons go through the transport chain (supplied by NADH & $FADH_2$), H^+ gets shuttled out

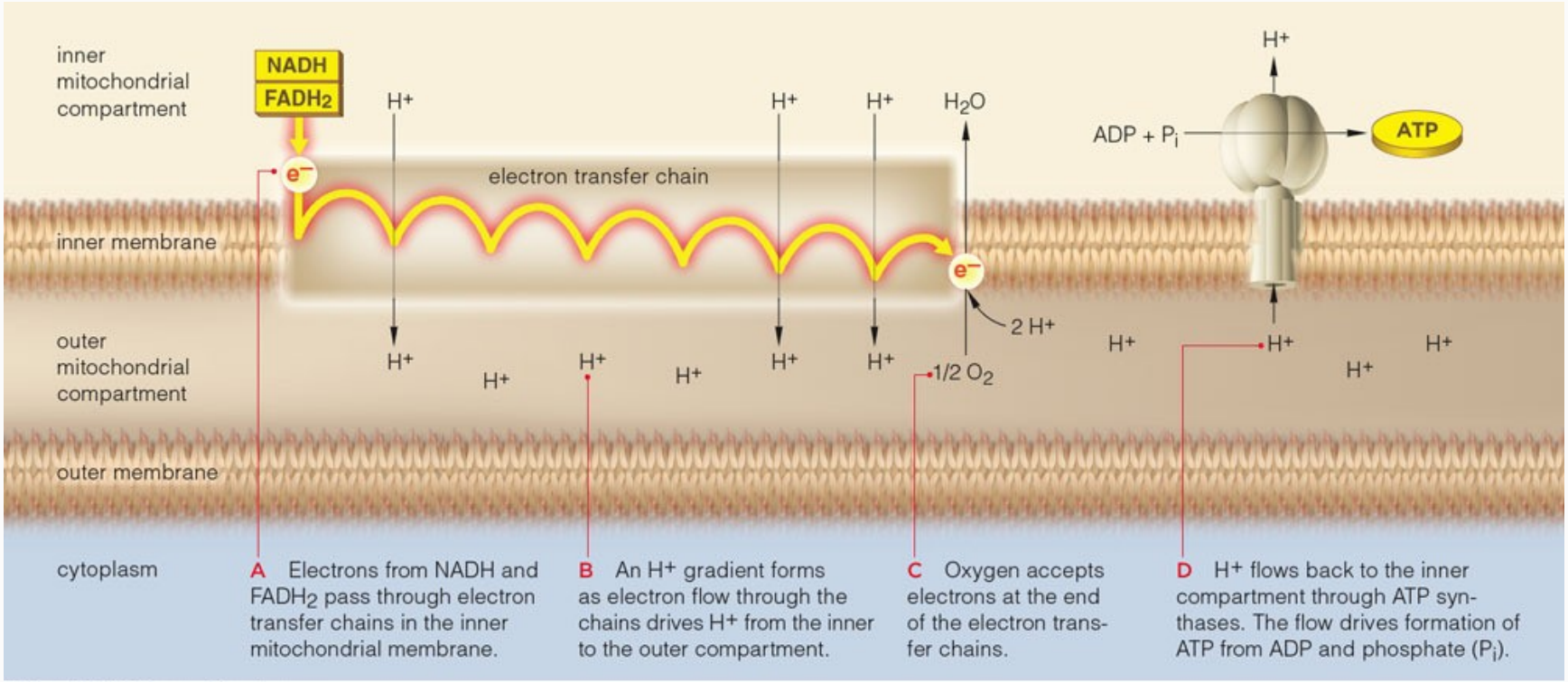


ATP Formation

H^+ concnetration is now greater in the outer compartment. H^+ follows these gradients through ATP synthases to the interior, forming ATP



Electron Transfer Phosphorylation



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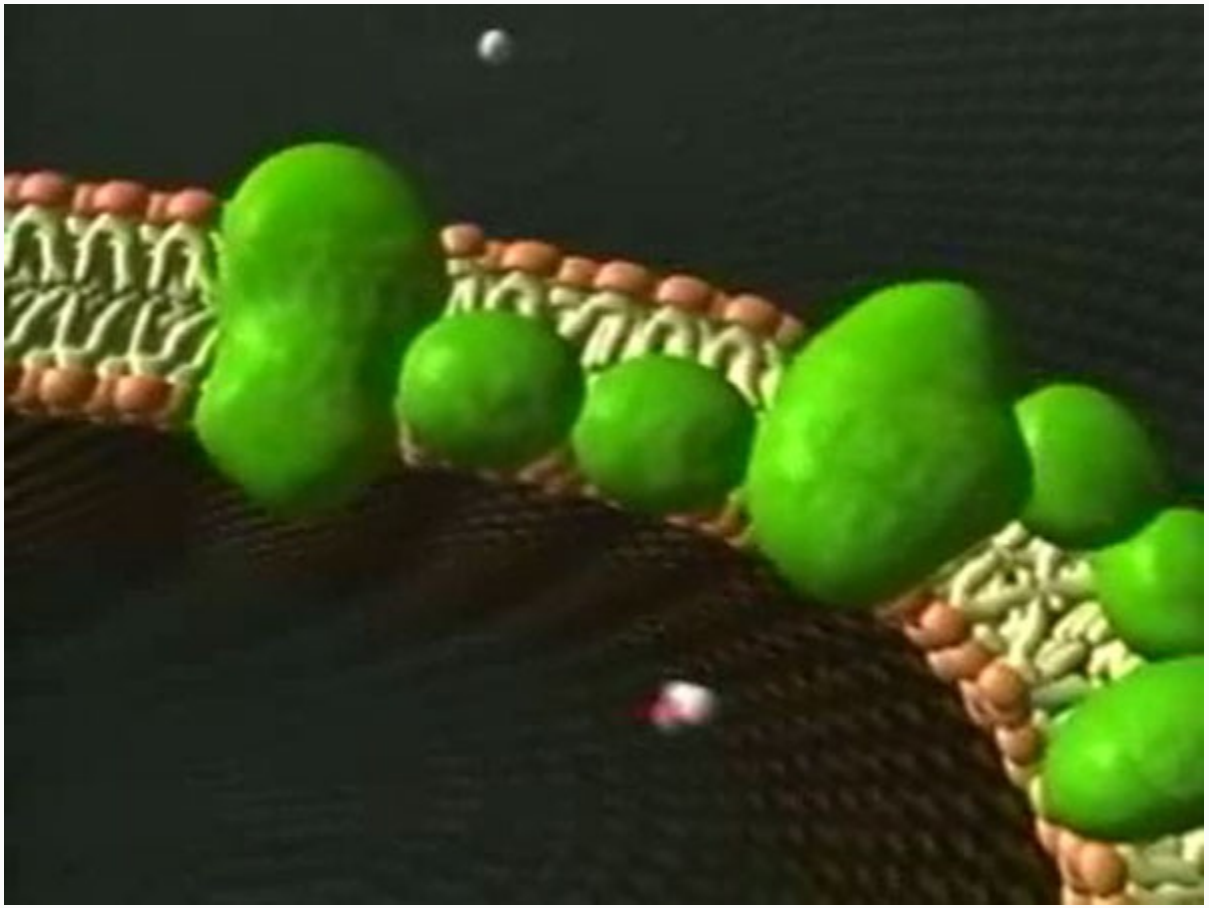
Animation: Electron transfer phosphorylation

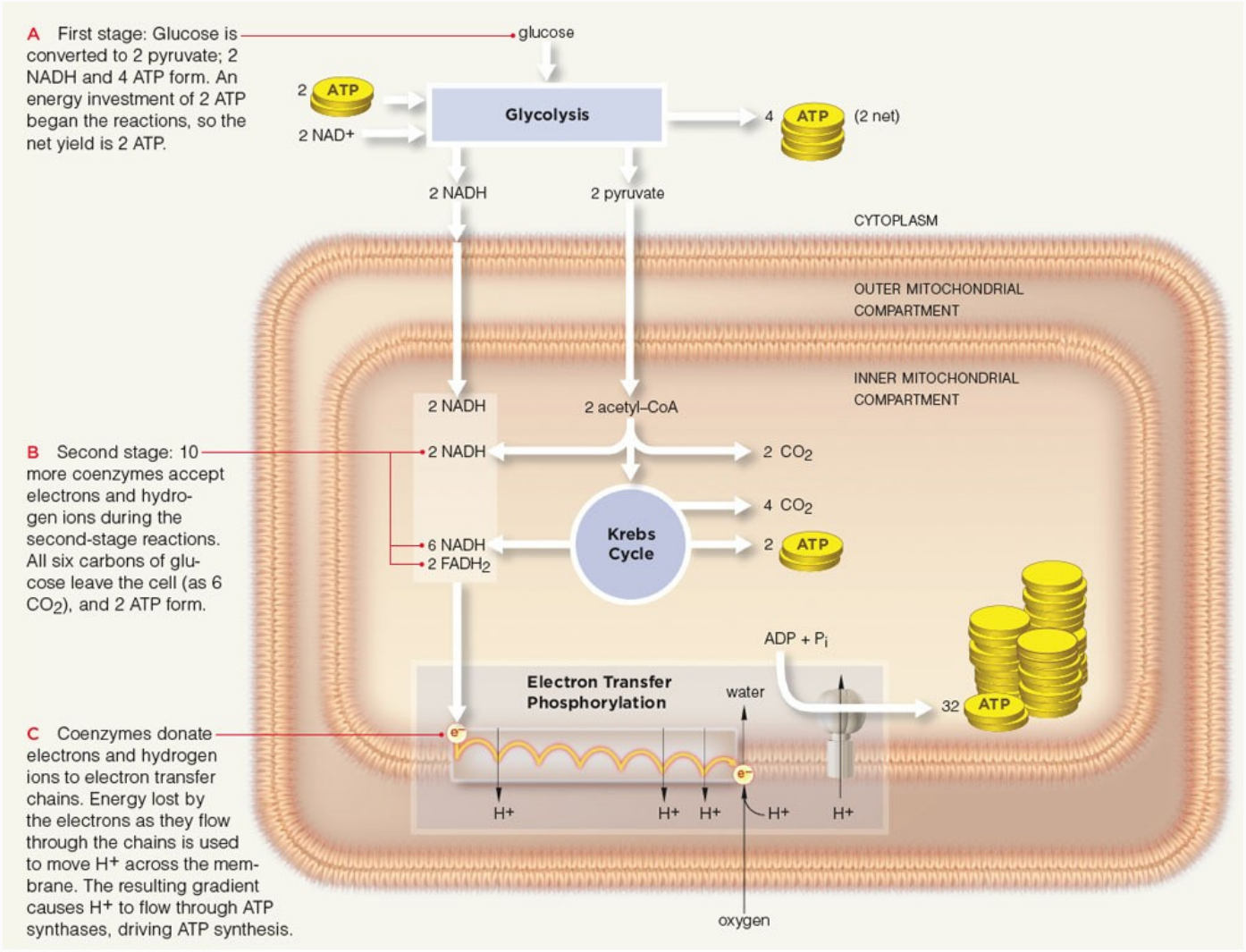


http://www.youtube.com/v/Idy2XAlZIVA

Summary: The Energy Harvest

- Typically, the breakdown of one glucose molecule yields 36-38 (for the class, we'll call it 36) ATP based on the type of cell.
  - Glycolysis: 2 ATP
  - Acetyl CoA formation and Krebs cycle: 2 ATP
  - Electron transfer phosphorylation: 32 ATP

Summary: Aerobic Respiration



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Key Concepts:
How Aerobic Respiration Ends

- *The final stages of aerobic respiration break down pyruvate to CO_2*
- *Many coenzymes that become reduced deliver electrons and hydrogen ions to electron transfer chains; energy released by electrons flowing through the chains is captured in ATP*
- *Oxygen accepts electrons at ends of the chains*

Anaerobic Energy-Releasing Pathways

- Fermentation pathways break down carbohydrates without using oxygen

- The final steps in these pathways regenerate NAD^+ but do not produce ATP

- Only used by simple organisms. You'll never see an anaerobic Renfield

Fermentation Pathways

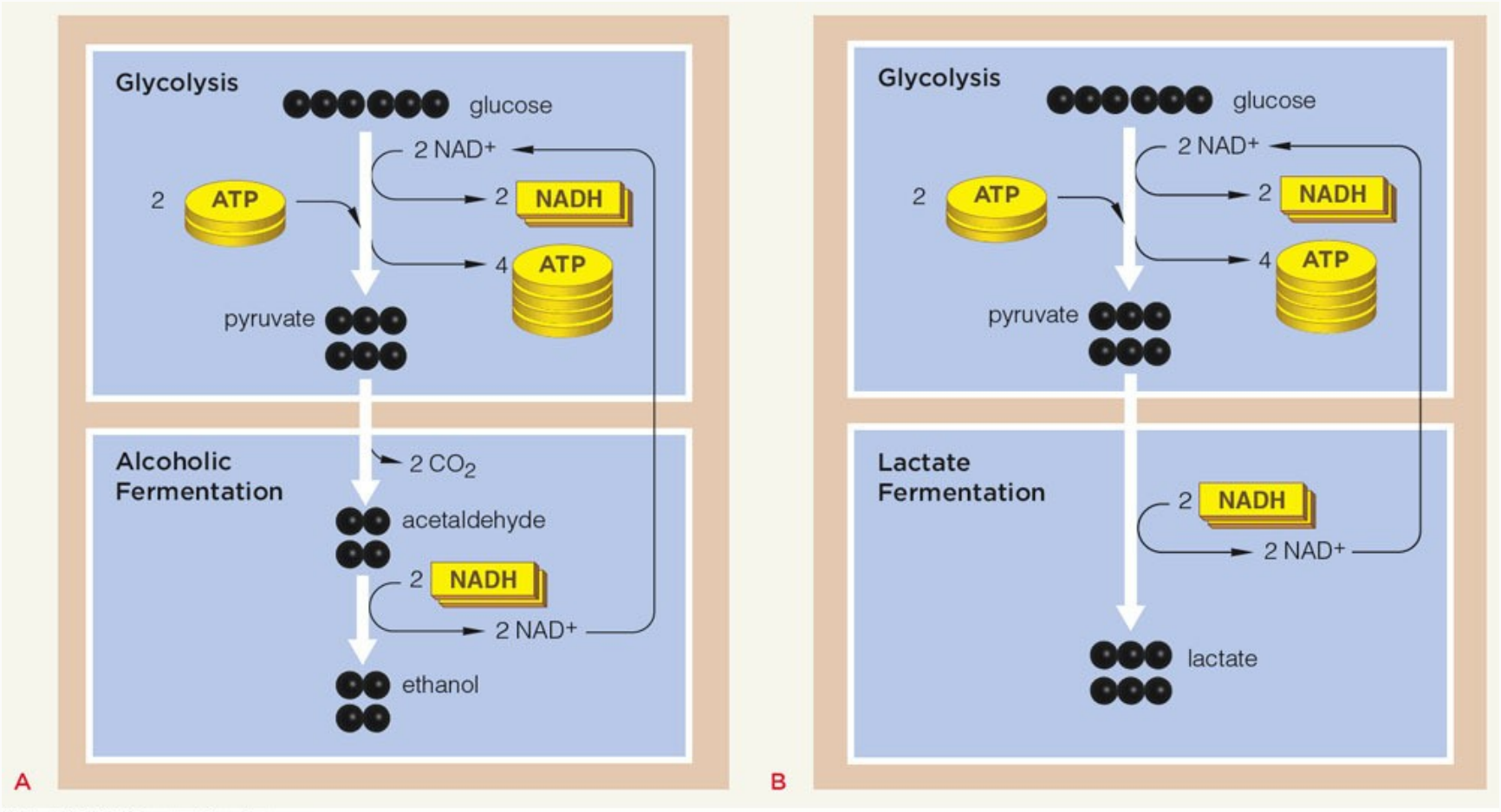
- Glycolysis is the first stage of fermentation
  - Forms 2 pyruvate, 2 NADH, and 2 ATP
- Pyruvate is converted to other molecules, but is not fully broken down to CO_2 and water
  - Regenerates NAD^+ but doesn't produce ATP
- Provides enough energy for some single-celled anaerobic species

Two Pathways of Fermentation

- **Alcoholic fermentation**
  - Pyruvate is split into acetaldehyde and CO_2
  - Acetaldehyde receives electrons and hydrogen from NADH, forming NAD^+ and ethanol

- **Lactate fermentation**
  - Pyruvate receives electrons and hydrogen from NADH, forming NAD^+ and lactate

Two Pathways of Fermentation



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Alcoholic Fermentation

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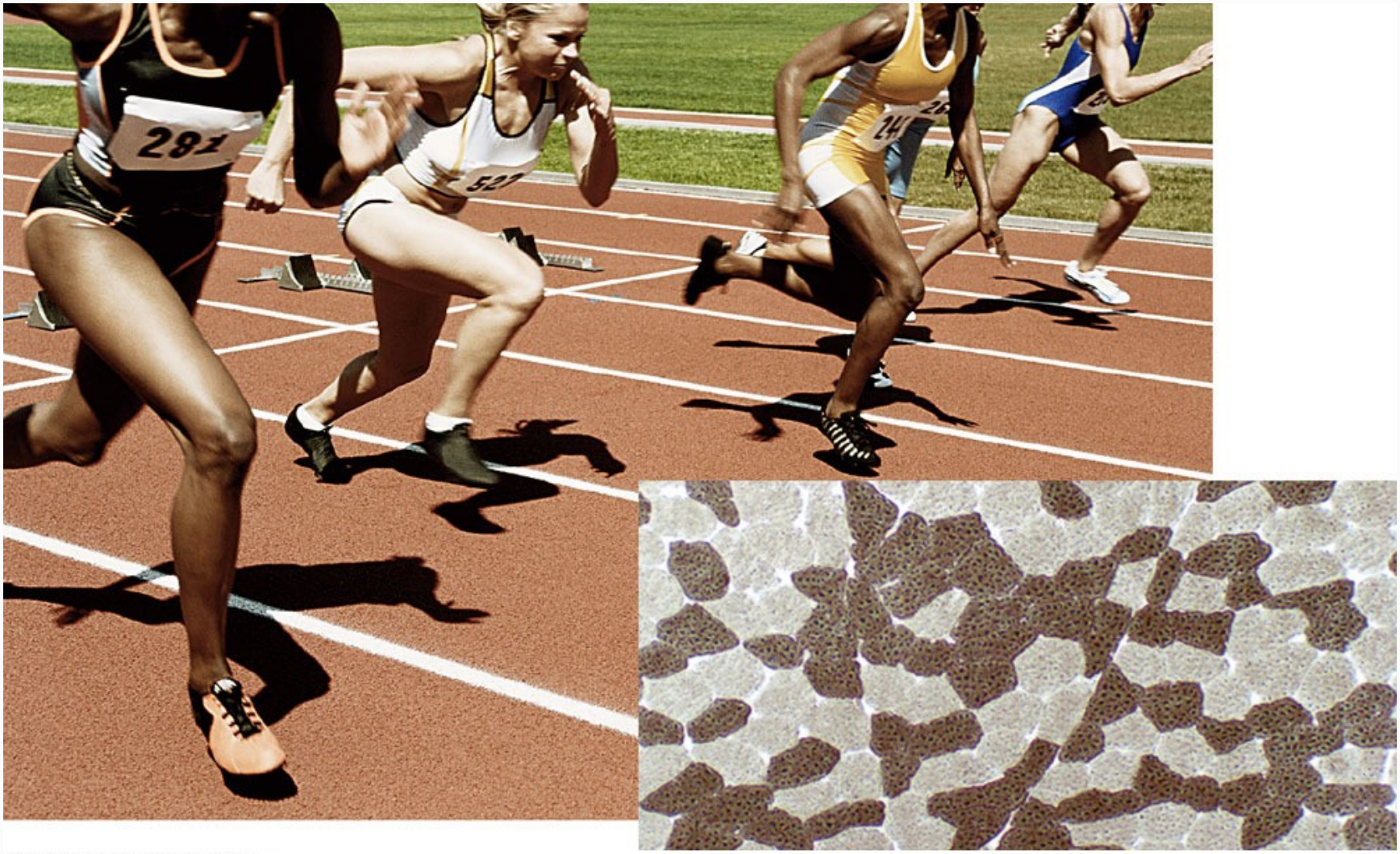
The Twitchers

- Slow-twitch muscle fibers (“red” muscles) make ATP by aerobic respiration
  - Have many mitochondria
  - Dominate in prolonged activity
- Fast-twitch muscle fibers (“white” muscles) make ATP by lactate fermentation
  - Have few mitochondria and no myoglobin
  - Sustain short bursts of activity

Sprinters and Lactate Fermentation



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Key Concepts:
How Anaerobic Pathways End

- *Fermentation pathways start with glycolysis*
- *Substances other than oxygen accept electrons at the end of the pathways*
- *Compared with aerobic respiration, the net yield of ATP from fermentation is small*

Reflections on Life's Unity

- Life's diversity and continuity arise from unity at the level of molecules and energy
  - Energy inputs drive the organization of molecules into cells (one-way flow of energy)

- Energy from the sun sustains life's organization
  - Photosynthesizers use energy from the sun to feed themselves and other forms of life
  - Aerobic respiration balances photosynthesis

Links Between Photosynthesis and Aerobic Respiration