How Cells Release Chemical Energy

Chapter 7

Learning Objectives:

1. What is the relationship between cellular respiration and breathing?
2. List the balanced chemical equation that summarizes the complete oxidation (aerobic breakdown) of glucose.
3. List and describe the major characteristics of the 4 subpathways in the oxidation of glucose (Where do they occur in the cells, what goes in, what comes out, are the steps aerobic or anaerobic, and what is the net production of ATP?)
4. List and describe the roles of coenzymes used in the respiratory pathway (NAD, FAD, CoA).
5. Describe how a concentration gradient is used to generate ATP in mitochondria, and compare this process with the function of chloroplasts.
6. What is fermentation and what are the possible products (for animal cells and yeast)? How is fermentation accomplished, and why is it performed?
7. List the food molecules that may be oxidized for energy (using the same metabolic machinery) if glucose is not available. Describe, in general terms, how this happens.
Producing ATP: the Universal Currency of Life

All energy-releasing pathways...
- require characteristic starting materials
  - Including unstable molecules, and in some cases ATP itself!
- yield predictable products and by-products
  - These chemical reactions are organized by _______.
- yield a net production of ATP

What food molecule is your 'best' source of chemical energy? Why?

Plants make some ATP during photosynthesis

How is this ATP used in photosynthesis?

Cells of all organisms make ATP by breaking down carbohydrates, fats, and protein

How do plant cells make most of their ATP to perform work?
What is Cellular Work?

How is this different from the “work” of diffusion?

Main Types of Energy-Releasing Pathways

<table>
<thead>
<tr>
<th>Anaerobic pathways:</th>
<th>Aerobic pathways:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolved first</td>
<td>Evolved later</td>
</tr>
<tr>
<td>Don’t require oxygen</td>
<td>Require oxygen</td>
</tr>
<tr>
<td>Start with glycolysis in cytoplasm</td>
<td>Start with glycolysis in cytoplasm</td>
</tr>
<tr>
<td>Finished in cytoplasm</td>
<td>Completed in mitochondria</td>
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</tbody>
</table>

What type of cell is only capable of this kind of ATP production?

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Glucose

- A simple sugar $(C_6H_{12}O_6)$

- Atoms held together by covalent bonds

Enzymes break the bonds to help harvest $H$ from this molecule, which are then delivered in high concentration to mitochondria. How do the $H$ get to mitochondria?

Carbohydrate Pathway Starts with Glycolysis

- Glycolysis occurs in cytoplasm
- Reactions are catalyzed by enzymes

\[
\text{Glucose (6C)} \rightarrow 2 \text{Pyruvate (3C)}
\]
1. Energy-requiring steps
   - ATP energy activates glucose

2. Energy-releasing steps
   - The carbon skeleton of glucose is split into two 3C pyruvate molecules
   - ATP and NAD\text{red} form

**Glycolysis**

\[ \text{Glucose (6C)} \rightarrow \text{Glucose-6-phosphate ("energized")} \]
\[ \rightarrow 2 \text{ Pyruvate (3C)} + 2 \text{ATP} + 4 \text{H} + \text{heat} \]

*If oxygen is available for future aerobic reactions, where do the 4H go, and how do they get there?*

*What happens if O\text{2} is not available?*

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(if conditions remain anaerobic)

**Fermentation:**

\[ 2 \text{ Pyruvate (3C)} + 2 \text{ATP} + 2 \text{NAD}\text{red} + \text{heat} \]
\[ \rightarrow 2 \text{ Ethanol (2C)} + \text{CO}_2 + 2 \text{NAD}\text{ox} \quad \text{ (Yeast)} \]

*or*

\[ 2 \text{ Lactate (3C)} + 2 \text{NAD}\text{ox} \quad \text{ (Animal cells)} \]
Transitioning to Aerobic Reactions

- Occur in the mitochondria
- Pyruvate is broken down to CO$_2$ + H
- More ATP is formed
- More coenzymes are needed to shuttle H

Aerobic Respiration

- Transition reactions
  - (3C) Pyruvate is oxidized into (2C) acetyl units and CO$_2$
  - NAD$_{red}$ brings H to Oxidative Phosphorylation
- Krebs cycle
  - The acetyl units are oxidized to carbon dioxide
  - NAD$_{red}$ and FAD$_{red}$ shuttle more H to Oxidative Phosphorylation
Overview of Aerobic Respiration

• One of the carbons from each pyruvate is released in CO₂.

How many total CO₂ are released in this step per molecule of glucose 6C?

• Two carbons are attached to coenzyme A and continue on to the Krebs cycle.

Transition Reactions

2 Pyruvate (3C) + 2 Coenzyme A

2 Acetyl-CoA (2C) + 4H + 2 CO₂ + heat (active acetate) Fate?

• One of the carbons from each pyruvate is released in CO₂.

How many total CO₂ are released in this step per molecule of glucose 6C?

• Two carbons are attached to coenzyme A and continue on to the Krebs cycle.
Krebs Cycle

Why is this set of reactions described as a cycle?

What is left of the original glucose molecule at the end of 2 “turns” of the Krebs cycle?

What can be done with the ATP that is produced?

Two pyruvates cross the inner mitochondrial membrane.

Intermembrane space

Krebs Cycle

2 NAD\text{_{red}}

inner mitochondrial compartment

6 NAD\text{_{red}}

2 FAD\text{_{red}}

Eight NAD\text{_{red}}, two FAD\text{_{red}}, and two ATP are the payoff from the complete breakdown of two pyruvates in the early reactions.

2 ATP

The six carbon atoms from two pyruvates diffuse out of the mitochondrion, then out of the cell, as six CO\text{_2}.

6 CO\text{_2}
Oxidative Phosphorylation

Electrons donated by NADH, released energy used to pump $H^+$ across the inner mitochondrial membrane. This energy then drives the synthesis of ATP.

Back to glycolysis and Krebs cycle.
Creating an H⁺ Gradient

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ATP Formation:
Using the potential energy in a H⁺ gradient

Why is it so important that O₂ be available for the subpathways called “aerobic”? 

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Summary of Aerobic Respiration

1. Glycolysis:
   - Glucose to 2 pyruvate
   - 2 NADH, 2 ATP

2. Pyruvate oxidation to Acetyl-CoA:
   - 2 acetyl-CoA
   - 4 CO₂, 2 ATP

3. Krebs Cycle:
   - 2 + 4 CO₂, 6 NADH, 2 FADH₂
   - 10 ATP

4. Electron Transfer Chain:
   - 2 NADH, 2 FADH₂
   - 36 ATP

5. ATP formation:
   - ADP + Pi
   - H+ transfer

The Links between Photosynthesis, Glycolysis, and Aerobic Respiration

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Entrance of other nutrients & Biosynthesis

Glycolysis:

- Glucose 6-phosphate
- 2 Phosphoglycerate (PGAL)
- Glyceraldehyde
- Pyruvate

Transition Reactions:

- 2 Pyruvate + 2 Oxaloacetate
- 2 Acetyl-CoA
- Fatty acids (2C to 7C)

Kreb's Cycle:

- Alpha-ketoglutarate (A-KG)
- Oxaloacetate (OAA)

Oxidative Phosphorylation:

- ATP + ADP + Heat

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