Module 2E – How Cells Harvest Energy

- All cells can harvest energy from organic molecules. To do this, they catabolize (break down) organic molecules and use the energy that is released to make ATP from ADP and phosphate.
- In this module, we will look at several ways cells can catabolize glucose and use the energy that is released to make ATP.

Objective # 28

Identify the following terms and explain how each is involved in the transfer of energy within a cell:

a) oxidation-reduction reactions
b) electron carriers
c) electron transport chain
d) ATP

Objective 28a

- Reactions that involve a transfer of electrons from one atom or molecule to another are called oxidation-reduction (redox) reactions.
- The substance that loses electrons is oxidized and the substance that gains electrons is reduced.

Objective 28a

- Redox reactions play a key role in the flow of energy within cells because electrons have energy. Therefore, when electrons are transferred, energy is transferred along with them.
- The amount of energy an electron has depends on the energy level it occupies. Light and other forms of energy can boost electrons to a higher energy level. High energy electrons can be used to make ATP.

Objective 28a

- During redox reactions, H+ ions are often transferred along with electrons.
- Since a hydrogen atom consists of one H+ ion (proton) and one electron, a substance that loses hydrogen atoms is oxidized (loses electrons) and a substance that gains hydrogen atoms is reduced.

Objective 28a

- Cells use reduced organic molecules (molecules rich in hydrogen) as fuel.
- Cells extract energy from these molecules by oxidizing them i.e. removing hydrogen atoms.
- Energy stored in the electrons of removed hydrogen atoms can be used to make molecules of ATP.
Objective 28b

- Electron carriers are molecules that help transfer electrons from one substance to another within the cell. They pick up electrons from substances being oxidized and donate them to substances being reduced.
- As mentioned previously, H⁺ ions are often transferred along with the electrons.

For example, during the breakdown of glucose:
- Enzymes remove 2 H atoms (2 H⁺ and 2e⁻) from glucose
- Both electrons and one H⁺ are picked up by NAD⁺ to form NADH
- The other H⁺ is released as a free ion

Some Important Electron Carriers

<table>
<thead>
<tr>
<th>Oxidized Form</th>
<th>Add →</th>
<th>Remove ←</th>
<th>Reduced Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAD⁺</td>
<td>2e⁻ and 2H⁺</td>
<td>NADH + H⁺</td>
<td></td>
</tr>
<tr>
<td>FAD</td>
<td>2e⁻ and 2H⁺</td>
<td>FADH₂</td>
<td></td>
</tr>
<tr>
<td>NADP⁺</td>
<td>2e⁻ and 2H⁺</td>
<td>NADPH + H⁺</td>
<td></td>
</tr>
</tbody>
</table>

Objective 28c

- An electron transport chain (ETC) is a series of electron carriers that are embedded in a membrane and that pass electrons from one carrier to the next in a specific sequence:

Electron Transport Chain

- NADH dehydrogenase
- bc₁ complex
- Cytochrome oxidase complex
- H⁺ + 1/2O₂ → H₂O
- Inner mitochondrial membrane
- Intermembrane space
Objective 28c

- As electrons are passed from one carrier to the next in the ETC, some of their energy is released. This energy can be used to make ATP.
- In the case of aerobic respiration, the final electron acceptor is oxygen, which joins with $2H^+$ to form water.

Objective 28d

- ATP:
  - plays a key role in short-term storage and release of energy within the cell
  - is sometimes called the “energy currency” of the cell because it is the immediate source of energy for most cell activities
  - is made by adding a phosphate group (phosphorylating) ADP

Objective # 29

Describe the following methods that are used by cells to make ATP:

a) substrate-level phosphorylation
b) electron transport phosphorylation (also called chemiosmotic phosphorylation or chemiosmosis)

Objective 29a

- During substrate-level phosphorylation, a high-energy phosphate group is enzymatically transferred from an organic molecule (such as the sugar PEP) directly to ADP to form ATP:
Objective 29a

Enzymatic transfer of a phosphate group from PEP to ADP, forming pyruvate and ATP:

![Diagram](https://example.com/diagram.png)

Objective 29b

Chemiosmotic phosphorylation occurs in 2 stages:
1) An ETC uses energy from electrons to pump H⁺ across a membrane against their concentration gradient. This builds up a store of potential energy.

Objective 29b
2) As the H⁺ ions move back through the membrane down their concentration gradient, through special protein complexes, the stored energy is released and used to make ATP from ADP and phosphate.

Objective # 30

Explain why chemiosmotic phosphorylation is sometimes called oxidative phosphorylation.

Objective 30

Chemiosmotic phosphorylation is called oxidative phosphorylation if the electrons are accepted by oxygen when they reach the end of the ETC.
Distinguish between aerobic respiration, anaerobic respiration, and fermentation.

Aerobic respiration, anaerobic respiration, and fermentation refer to different ways of breaking down glucose (glucose catabolism).

The chemical bond energy of glucose (and all other molecules) is stored in the electrons that make up the covalent bonds.

During glucose catabolism, high energy electrons are stripped from glucose and picked up by the electron carriers NAD$^+$ and FAD.

In most cases, the electrons are passed to an ETC where their energy is used to make ATP by chemiosmosis.

Eventually, the electrons, along with H$^+$, are passed to a final acceptor.

If molecular oxygen ($O_2$) is the final electron acceptor, the process is called aerobic respiration.

If some other inorganic molecule is the final electron acceptor, the process is called anaerobic respiration.

If an organic molecule is the final electron acceptor, the process is called fermentation.

First we will examine the process of aerobic respiration, then we will take a brief look at anaerobic respiration, and finally we will discuss the process of fermentation.

Write a summary chemical equation for aerobic respiration and describe the origin and fate of each substance involved.
Objective 32

Aerobic respiration:

\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \]

- some of the released energy is captured and stored in molecules of ATP.

Objective # 33

Identify the 4 main stages of aerobic respiration. For each stage discuss:

a) the cellular location
b) the main events that take place
c) starting substances and end products
d) the major enzymes involved and the type of reaction each catalyzes
e) the number of ATPs, NADHs, and FADH_2s, produced (or used up) per glucose molecule

Objective 33

The 4 main stages of aerobic respiration are:

1) Glycolysis
2) Pyruvate Oxidation
3) The Krebs Cycle (Citric Acid Cycle)
4) Oxidative Phosphorylation (ETC)

1st Stage - Glycolysis:

- Glucose (6C) is broken down into 2 molecules of pyruvate (3C each).
- 2 ATP are used for activation energy and 4 ATP are produced by substrate level phosphorylation resulting in a net gain of 2 ATP.
- The oxidation of glucose releases 4 high energy electrons which are used to reduce 2 NAD+ to form 2 NADH.
2nd Stage - Pyruvate Oxidation:
- Each pyruvate (3C) from glycolysis is broken down into 1 CO₂ (1C) and 1 acetyl group (2C)
- The acetyl group joins with coenzyme A to form acetyl-CoA
- The oxidation of each pyruvate releases 2 high energy electrons which are used to reduce 1 NAD+ to form 1 NADH.

3rd Stage - Krebs Cycle:
- Each acetyl group (2C) from pyruvate oxidation is broken down into 2 molecules of carbon dioxide (1C)
- The breakdown of each acetyl group releases enough energy to form 1 ATP by substrate level phosphorylation
- The oxidation of each acetyl group releases enough high energy electrons to form 3 NADH and 1 FADH₂

4th Stage - Oxidative Phosphorylation:
- NADH and FADH₂ (produced during glycolysis, pyruvate oxidation, and the Krebs cycle) donate high energy electrons to an electron transport chain
- As the electrons are passed along the ETC, their energy is used to make ATP by chemiosmosis
- At the end of the ETC, electrons join with oxygen and 2H+ to form water

Objective 33
- The theoretical yield of ATP from the breakdown of one molecule of glucose by aerobic respiration is 38.
- In eukaryotes, this is reduced to 36 ATP because NADH generated by glycolysis in the cytoplasm has to be actively transported into the mitochondria. This costs the cell 1 ATP per NADH transported.
Objective 33
Theoretical ATP Yield from Aerobic Respiration

- Glucose \( \rightarrow \) 2 ATP
- Glycolysis
- Pyruvate \( \rightarrow \) 2 ATP
- Pyruvate oxidation
- Krebs Cycle
- Total net ATP yield = 38 (36 in eukaryotes)

Objective 33
- The actual yield for eukaryotes is reduced to approximately 30 ATP per glucose molecule for 2 reasons:
  - The inner mitochondrial membrane is “leaky” allowing some protons to pass through without passing through ATP synthase.
  - Energy stored in the proton gradient is used for other purposes besides generation of ATP.

Objective # 34
Describe the process of anaerobic respiration.

- During aerobic respiration, cells use O\(_2\) as the final electron acceptor at the end of the electron transport chain.
- Many bacteria can respire without O\(_2\), using CO\(_2\), SO\(_4\), nitrates, or other inorganic compounds as the final electron acceptor in place of O\(_2\). This process is called anaerobic respiration.

Objective # 35
Describe the process of fermentation and distinguish between alcoholic fermentation and lactic acid fermentation.

- In some cases, the high energy electrons picked up by NAD\(^+\) during glycolysis are not donated to an ETC.
- Instead, NADH donates its extra electrons and H\(^+\) directly to an organic molecule, which serves as the final electron acceptor. This process is called fermentation.
Objective 35

Although bacteria can carry out more than a dozen kinds of fermentation, eukaryotes are capable of only a few:

● Alcoholic fermentation:
  > occurs in single-celled fungi called yeast
  > a terminal CO₂ is removed from the pyruvic acid (3C) produced during glycolysis, producing acetaldehyde (2C)
  > acetaldehyde accepts 2 e⁻ and a H⁺ from NADH, producing ethanol and NAD⁺

Objective 35

Lactic Acid Fermentation:
  > used by most animal cells when O₂ is not available
  > NADH donates 2 e⁻ and a H⁺ directly to the pyruvate (3C) produced during glycolysis, producing lactate (3C) and NAD⁺

Objective 35

Alcoholic fermentation and lactic acid fermentation each generate 2 ATP per glucose molecule (generated by substrate level phosphorylation during glycolysis) compared to the theoretical maximum of 36 ATP per glucose during aerobic respiration in eukaryotes.