In eukaryotes, cellular respiration

- harvests energy from food,
- yields large amounts of ATP, and
- Uses ATP to drive cellular work.

A similar process takes place in many prokaryotic organisms.
6.1 Photosynthesis and cellular respiration provide energy for life

- Mostly energy ultimately comes from the sun and producers perform photosynthesis.

- In cellular respiration
  - glucose is broken down to CO₂ and H₂O and
  - makes ATP.

- Takes place in the mitochondria of eukaryotic cells.
Figure 6.1

Sunlight energy

ECOSYSTEM

Photosynthesis in chloroplasts

CO₂ + H₂O → Glucose + O₂

Cellular respiration in mitochondria

(for cellular work) ATP

Heat energy
6.3 Cellular respiration banks energy in ATP molecules

- Cellular respiration - exergonic process that transfers energy from the bonds in glucose to form ATP.
- Cellular respiration
  - produces about 32-36 ATP molecules from 1 glucose molecule and
  - gets about 34% of the energy stored in glucose.
- Other foods (organic molecules) can also be used as a source of energy.
6.4 CONNECTION: The human body uses energy from ATP for all its activities

- Average adult human - ~ 2,200 kcal of energy per day.
  - ~75% of these calories are used to maintain a healthy body.
  - The remaining 25% is used to power physical activities.

- A kilocalorie (kcal) is
  - amount of heat required to raise the temperature of 1 (kg) of water by 1°C,
  - the same as a food Calorie, and
  - used to measure the nutritional values on food labels.

© 2012 Pearson Education, Inc.
<table>
<thead>
<tr>
<th>Activity</th>
<th>kcal consumed per hour by a 67.5-kg (150-lb) person*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running (8–9 mph)</td>
<td>979</td>
</tr>
<tr>
<td>Dancing (fast)</td>
<td>510</td>
</tr>
<tr>
<td>Bicycling (10 mph)</td>
<td>490</td>
</tr>
<tr>
<td>Swimming (2 mph)</td>
<td>408</td>
</tr>
<tr>
<td>Walking (4 mph)</td>
<td>341</td>
</tr>
<tr>
<td>Walking (3 mph)</td>
<td>245</td>
</tr>
<tr>
<td>Dancing (slow)</td>
<td>204</td>
</tr>
<tr>
<td>Driving a car</td>
<td>61</td>
</tr>
<tr>
<td>Sitting (writing)</td>
<td>28</td>
</tr>
</tbody>
</table>

*Not including kcal needed for body maintenance
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- When the carbon-hydrogen bonds of glucose are broken, electrons are transferred to oxygen.
  - Oxygen attracts electrons.
  - Loses energy when it “falls” to oxygen.

- The energy is dissipated as heat and light and is not available to living organisms.
Cellular respiration is the controlled breakdown of organic molecules.

Energy is
- gradually released in small amounts,
- captured by a biological system, and
- stored in ATP.
Figure 6.5A

Glucose $\text{C}_6\text{H}_{12}\text{O}_6$ + 6 $\text{O}_2$ $\rightarrow$ 6 $\text{CO}_2$ + 6 $\text{H}_2\text{O}$ + ATP

Loss of hydrogen atoms (becomes oxidized)

Gain of hydrogen atoms (becomes reduced)

+ Heat
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- Enzymes are necessary to oxidize glucose and other foods.

- NAD$^+$
  - is an important enzyme in oxidizing glucose,
  - accepts electrons, and
  - becomes reduced to NADH.
6.6 Overview: Cellular respiration occurs in three main stages (draw this together)

- Cellular respiration consists of a sequence of steps that can be divided into three stages.
  - Stage 1 – Glycolysis
  - Stage 2 – Pyruvate oxidation and citric acid cycle
  - Stage 3 – Oxidative phosphorylation
6.6 Overview: Cellular respiration occurs in three main stages (Draw this together)

- **Stage 1: Glycolysis**
  - occurs in the cytoplasm,
  - begins cellular respiration, and
  - breaks down glucose into two molecules of a three-carbon compound called pyruvate.
Stage 2: The citric acid cycle

- takes place in mitochondria,
- oxidizes pyruvate to a two-carbon compound, and
- supplies the third stage with electrons.
6.6 Overview: Cellular respiration occurs in three main stages (draw this together)

- Stage 3: Oxidative phosphorylation
  - involves electrons carried by NADH and FADH$_2$,
  - shuttles these electrons to the electron transport chain embedded in the inner mitochondrial membrane,
  - involves chemiosmosis, and
  - generates ATP through oxidative phosphorylation associated with chemiosmosis.
Figure 6.6_1

Glycolysis

Glucose → Pyruvate

Mitochondrion

Electrons carried by NADH

NADH

Oxidative Phosphorylation

(electron transport and chemiosmosis)

ATP

Substrate-level phosphorylation

Substrate-level phosphorylation

Oxidative phosphorylation

© 2012 Pearson Education, Inc.
6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate (DO NOT COPY)

- In glycolysis,
  - a single molecule of glucose is enzymatically cut in half through a series of steps,
  - two molecules of pyruvate are produced,
  - two molecules of NAD\(^+\) are reduced to two molecules of NADH, and
  - a net of two molecules of ATP is produced.
Glucose

2 ADP + 2 P → 2 ATP + 2 NADH + 2 H^+ → 2 Pyruvate

© 2012 Pearson Education, Inc.
6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate (DO NOT COPY)

- ATP is formed in glycolysis by substrate-level phosphorylation during which
  - an enzyme transfers a phosphate group from a substrate molecule to ADP and
  - ATP is formed.

- The compounds that form between the initial reactant, glucose, and the final product, pyruvate, are called intermediates.
Figure 6.7B

Enzyme + Substrate → Enzyme + Product

Substrate: P

Enzyme: P

ADP: ADP

Product: ATP

© 2012 Pearson Education, Inc.
Glycolysis harvests chemical energy by oxidizing glucose to pyruvate (DO NOT COPY)

- The steps of glycolysis can be grouped into two main phases.
  - In steps 1–4, the energy investment phase,
    - energy is consumed as two ATP molecules are used to energize a glucose molecule,
    - which is then split into two small sugars that are now primed to release energy.
  - In steps 5–9, the energy payoff,
    - two NADH molecules are produced for each initial glucose molecule and
    - ATP molecules are generated.
The pyruvate formed in glycolysis is transported from the cytoplasm into a mitochondrion where

- the citric acid cycle and
- oxidative phosphorylation will occur.
6.8 Pyruvate is oxidized prior to the citric acid cycle (DO NOT COPY)

- Two molecules of pyruvate are produced for each molecule of glucose that enters glycolysis.

- Pyruvate does not enter the citric acid cycle, but undergoes some chemical grooming in which
  - a carboxyl group is removed and given off as CO$_2$,
  - the two-carbon compound remaining is oxidized while a molecule of NAD$^+$ is reduced to NADH,
  - coenzyme A joins with the two-carbon group to form acetyl coenzyme A, abbreviated as acetyl CoA, and
  - acetyl CoA enters the citric acid cycle.
Figure 6.8

Pyruvate → \( \text{NAD}^{+} \) (reduction) → NADH + H⁺ → Acetyl coenzyme A + CO₂

1. Pyruvate dehydrogenase complex
2. NAD⁺ reduction to NADH
3. Formation of CO₂ and acetyl-CoA

© 2012 Pearson Education, Inc.
The citric acid cycle completes the oxidation of organic molecules, generating many NADH and FADH$_2$ molecules.

- The citric acid cycle is also called the Krebs cycle (after the German-British researcher Hans Krebs, who worked out much of this pathway in the 1930s),
- completes the oxidation of organic molecules, and
- generates many NADH and FADH$_2$ molecules.
6.9 The citric acid cycle completes the oxidation of organic molecules, generating many NADH and FADH$_2$ molecules (DO NOT COPY)

- During the citric acid cycle
  - the two-carbon group of acetyl CoA is added to a four-carbon compound, forming citrate,
  - citrate is degraded back to the four-carbon compound,
  - two CO$_2$ are released, and
  - 1 ATP, 3 NADH, and 1 FADH$_2$ are produced.
6.9 The citric acid cycle completes the oxidation of organic molecules, generating many NADH and FADH$_2$ molecules (DO NOT COPY)

- Remember that the citric acid cycle processes two molecules of acetyl CoA for each initial glucose.

- Thus, after two turns of the citric acid cycle, the overall yield per glucose molecule is
  - 2 ATP,
  - 6 NADH, and
  - 2 FADH$_2$. 
Figure 6.9B_s3

Step 1
Acetyl CoA stokes the furnace.

Steps 2 – 3
NADH, ATP, and CO₂ are generated during redox reactions.

Steps 4 – 5
Further redox reactions generate FADH₂ and more NADH.
6.10 Most ATP production occurs by oxidative phosphorylation (DO NOT COPY)

- Oxidative phosphorylation
  - involves electron transport and chemiosmosis and
  - requires an adequate supply of oxygen.
6.10 Most ATP production occurs by oxidative phosphorylation (DO NOT COPY)

- Electrons from NADH and FADH$_2$ travel down the electron transport chain to O$_2$.
- Oxygen picks up H$^+$ to form water.
- Energy released by these redox reactions is used to pump H$^+$ from the mitochondrial matrix into the intermembrane space.
- In chemiosmosis, the H$^+$ diffuses back across the inner membrane through ATP synthase complexes, driving the synthesis of ATP.
Figure 6.10

Oxidative Phosphorylation

Electron Transport Chain

Chemiosmosis

Intermembrane space

Inner mitochondrial membrane

Mitochondrial matrix

Protein complex of electron carriers

Mobile electron carriers

Electron flow

NADH

NAD+$^-$

FADH$_2$

FAD

2$H^+$ + $\frac{1}{2}O_2$

$H_2O$

$ADP + P \rightarrow ATP$

Oxidative Phosphorylation

© 2012 Pearson Education, Inc.
6.11 CONNECTION: Interrupting cellular respiration can have both harmful and beneficial effects

- Cellular poisons block the process of oxidative phosphorylation. These poisons

1. block the electron transport chain (for example, rotenone, cyanide, and carbon monoxide),

2. inhibit ATP synthase (for example, the antibiotic oligomycin), or

3. make the membrane leaky to hydrogen ions (called uncouplers, examples include dinitrophenol).
Brown fat is
- a special type of tissue associated with the generation of heat and
- more abundant in hibernating mammals and newborn infants.

In brown fat,
- the cells are packed full of mitochondria,
- the inner mitochondrial membrane contains an uncoupling protein, which allows \( H^+ \) to flow back down its concentration gradient without generating ATP, and
- ongoing oxidation of stored fats generates additional heat.
6.12 Review: Each molecule of glucose yields many molecules of ATP (DO NOT COPY)

- Recall that the energy payoff of cellular respiration involves
  1. glycolysis,
  2. alteration of pyruvate,
  3. the citric acid cycle, and
  4. oxidative phosphorylation.
6.12 Review: Each molecule of glucose yields many molecules of ATP (DO NOT COPY)

- The total yield is about 32 ATP molecules per glucose molecule.
- This is about 34% of the potential energy of a glucose molecule.
- In addition, water and CO$_2$ are produced.
Figure 6.12

Glycolysis

Glucose → Pyruvate

+ 2 ATP

by substrate-level phosphorylation

Pyruvate

Oxidation

2 Acetyl CoA

Citric Acid Cycle

+ 2 ATP

by substrate-level phosphorylation

Mitochondrion

Electron shuttles across membrane

NADH or FADH

2 NADH + 2 FADH

6 NADH + 2 FADH

Oxidative Phosphorylation (electron transport and chemiosmosis)

+ about 28 ATP

Maximum per glucose:

About 32 ATP

© 2012 Pearson Education, Inc.
6.13 Fermentation enables cells to produce ATP without oxygen

- Fermentation - harvests energy without oxygen. Fermentation
  - Uses glycolysis,
  - produces two ATP molecules per glucose, and
  - reduces NAD\(^+\) to NADH.

- The trick of fermentation is to provide an anaerobic path for recycling NADH back to NAD\(^+\).
6.13 Fermentation enables cells to produce ATP without oxygen

- Your muscle cells and certain bacteria can oxidize NADH through **lactic acid fermentation**, in which
  - NADH is oxidized to NAD$^+$ and
  - pyruvate is reduced to lactate.
The dairy industry uses lactic acid fermentation by bacteria to make cheese and yogurt.

Other types of microbial fermentation turn
- soybeans into soy sauce and
- cabbage into sauerkraut.
Glycolysis

Glucose → 2 Pyruvate

2 ATP

2 ADP + 2 P

2 NAD^+ → 2 NADH

2 Lactate

2 Pyruvate → 2 ATP

2 NADH → 2 NAD^+
6.13 Fermentation enables cells to produce ATP without oxygen

- The baking and winemaking industries have used **alcohol fermentation** for thousands of years.

- In this process yeasts (single-celled fungi)
  
  - oxidize NADH back to NAD\(^+\) and
  
  - convert pyruvate to \(\text{CO}_2\) and ethanol.
Glucose

2 NAD$^+$

2 NADH

2 ADP + 2 P

2 ATP

Glycolysis

2 Pyruvate

2 CO$_2$

2 NADH

2 NAD$^+$

2 Ethanol

© 2012 Pearson Education, Inc.
Fermentation enables cells to produce ATP without oxygen

- **Obligate anaerobes**
  - are poisoned by oxygen, requiring anaerobic conditions, and
  - live in stagnant ponds and deep soils.

- **Facultative anaerobes**
  - include yeasts and many bacteria, and
  - can make ATP by fermentation or oxidative phosphorylation.
Glycolysis is the universal energy-harvesting process of life.
- life long before oxygen was present,
- when only prokaryotes inhabited the Earth,
- about 3.5 billion years ago.

The ancient history of glycolysis is supported by its
- occurrence in all the domains of life and
- location within the cell, using pathways that do not involve any membrane-bounded organelles.
6.15 Cells use many kinds of organic molecules as fuel for cellular respiration

- ATP is generated using
  - carbohydrates,
  - fats, and
  - proteins.

- Fats - excellent cellular fuel because they
  - Have many hydrogen atoms and thus many energy-rich electrons and
  - yield more than twice as much ATP per gram than a gram of carbohydrate or protein.
Food, such as peanuts

Carbohydrates
- Sugars
  - Glucose → G3P → Pyruvate → Oxidation Acetyl CoA → Citric Acid Cycle → Oxidative Phosphorylation → ATP

Fats
- Glycerol Fatty acids
  - Pyruvate Oxidation Acetyl CoA → Citric Acid Cycle → Oxidative Phosphorylation → ATP

Proteins
- Amino acids
  - Amino groups
6.16 Food molecules provide raw materials for biosynthesis

- Cells use intermediates from cellular respiration for the biosynthesis of other organic molecules.
Figure 6.16

ATP needed to drive biosynthesis

- **Citric Acid Cycle**
- **Pyruvate Oxidation Acetyl CoA**
- **Glucose Synthesis**
  - Pyruvate → G3P → Glucose

Amino groups

- **Amino acids**
- **Fatty acids**
- **Glycerol**

- **Proteins**
- **Fats**
- **Carbohydrates**

Cells, tissues, organisms

ATP

Pyruvate

G3P

Glucose

Sugars
ATP needed to drive biosynthesis

Citric Acid Cycle

Pyruvate Oxidation Acetyl CoA

Glucose Synthesis
Pyruvate $\rightarrow$ G3P $\rightarrow$ Glucose

Amino groups
Amino acids
Fatty acids
Glycerol
Cells, tissues, organisms

Proteins
Fats
Carbohydrates
Sugars

ATP

© 2012 Pearson Education, Inc.