Chapter 9
Cellular Respiration: Harvesting Chemical Energy
Is this a process of turning food into energy?
How does food give us energy?

- Transfers of electrons during chemical reactions (oxidation–reduction reactions)

- Relocation of electrons in food molecules releases energy → which can be used to synthesize ATP
  - ATP is used to do ALL types of cellular work
Cells recycle the ATP they use for work.

**Transport work: ATP phosphorylates transport proteins**
- Membrane protein
- Solute
- Solute transported

**Mechanical work: ATP phosphorylates motor proteins**
- Motor protein
- Protein moved

**Chemical work: ATP phosphorylates key reactants**
- Reactants
- Product made

ATP → ADP + Pi

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Light energy

ECOSYSTEM

Photosynthesis in chloroplasts

\[ \text{CO}_2 + \text{H}_2\text{O} \]

Cellular respiration in mitochondria

\[ \text{Organic molecules} + \text{O}_2 \]

ATP powers most cellular work

ATP

Heat energy
Respiration – Equation

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} \]

and energy (ATP + heat)

The energy is released from the chemical bonds in the complex organic molecules.

- Breakdown of glucose is exergonic
  - \( \Delta G = -686 \text{ kcal/mol} \)
  - Products store less energy than reactants, so energy is given off
Respiration – Preview

- The process of releasing Energy from food.
- Food – Stored Energy in chemical bonds.
- ATP – Useable Energy for cell work.
Cellular respiration does not happen in a single explosive step to release energy. Glucose is broken down gradually in a series of enzyme-catalyzed steps.

(a) Uncontrolled reaction

(b) Cellular respiration
1. **Purpose** – what is the reaction supposed to do?
2. **Location** – where is it at?
3. **Requirements** – what is needed to make it run?
4. **Products** – what does it produce?
Oxidation – definitions

- Loss of electrons.
- Loss of energy.
- Loss of Hydrogens from Carbons.
Reduction – definitions

- Gain of electrons.
- Gain of energy.
- Gain of Hydrogens to Carbons.

Comment – be careful not to use “reduction” in lay terms.
Figure 9.3

Reactants

\[ \text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + \text{Energy} + 2 \text{H}_2\text{O} \]

- Methane (reducing agent)
- Oxygen (oxidizing agent)

Products

- Carbon dioxide
- Water

Methane becomes oxidized to carbon dioxide.

Oxygen becomes reduced to water.
Electrons “fall” from organic molecules to oxygen during cellular respiration

- \( \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} \)
  - Glucose is **oxidized** (Oxygen is added)
  - Oxygen is **reduced** (Hydrogen is added)
  - Electrons lose potential energy, which is used to build ATP

- Molecules with lots of H atoms are good fuels
$\text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{Energy}$
Redox reactions

- Reactions are usually paired or linked together.
- Look for these links as we study Cellular Respiration.
- Many of the reactions will be done by phosphorylation.
Phosphorylation

- Adding a phosphate group to a molecule.
- The phosphate group adds “energy” to the molecule for chemical reactions.
Substrate-Level Phosphorylation

Enzyme

Substrate (PEP)

Product (pyruvate)

ADP

+ ATP

Adenosine

Adenosine
Cell Respiration – parts

1. Glycolysis
2. Krebs Cycle
3. Electron Transport Chain
Glycolysis

- Glyco- glucose.
- -lysis: to split
- Universal step in all Respiration types.
- Likely to be earliest type of cell energy processes.
Glycolysis

- **Function** – To split glucose and produce NADH and ATP.
- **Location** – Cytoplasm.
GLYCOLYSIS

Glucose $\rightarrow$ Pyruvate

Cytosol

ATP

Substrate-level phosphorylation

Mitochondrion
Molecules that transport or shuttle electrons within the cell.

Exist in two forms:
- Oxidized (ox)
- Reduced (red)
Nicotinamide Adenine Dinucleotide

NAD$^+$ + 2 e$^-$ $\rightleftharpoons$ NADH

NAD$^+$ = oxidized form
NADH = reduced form
Glycolysis – Requirements

- Glucose
- 2 ATP
- 4 ADP
- 2 NAD$^+$
Glycolysis – Products

- 2 Pyruvic Acids/Pyruvates (a 3C acid)
- 2 ADP
- 4 ATP
- 2 NADH
Net Result

- 2 ATP per glucose
- 2 NADH
- Does NOT require $O_2$
Energy Investment Phase

Glucose → 2 ADP

Energy Payoff Phase

4 ADP → 4 ATP
2 NAD⁺ → 2 NADH

Net:

Glucose → 2 Pyruvate + 2H₂O
2 ADP + 2Pᵢ → 2 ATP
2 NAD⁺ → 2 NADH + 2H⁺
Energy Investment Phase

Kinase = enzyme that transfers a phosphate group

- ATP
- ADP
- Glucose
- Hexokinase
- Glucose-6-phosphate
- Phosphoglucoisomerase
- Fructose-6-phosphate
- Phosphofructokinase
- ATP
- ADP

- Fructose-1, 6-bisphosphate
- Aldolase
- Dihydroxyacetone phosphate
- Isomerase
- Glyceraldehyde-3-phosphate
Energy Harvest Phase

2 NAD⁺ + 2 H⁺ → 2 NADH + 2 P_i

1, 3-Bisphosphoglycerate

2 ADP → 2 ATP

Phosphoglycerokinase

2 Phosphoglycerate → 2 ATP

Phosphoglyceromutase

2 ATP

2-Phosphoglycerate → Enolase

2 H₂O

Phosphoenolpyruvate

2 ADP → 2 ATP

Pyruvate kinase

2 ATP

Pyruvate
Formation of Acetyl CoA
(connects glycolysis w/ the Krebs Cycle)

**CYTOSOL**

Transport protein

**MITOCHONDRIUM**

1. Pyruvate
2. NAD\(^+\) → NADH + H\(^+\)
3. CO\(_2\)

**Acetyl CoA**
Krebs Cycle

- Also called:
  - Citric Acid Cycle
  - Tricarboxylic Acid Cycle
Krebs Cycle

- **Function**: Oxidize pyruvic acid to $\text{CO}_2$ & Produce NADH and FADH$_2$
- **Location**: Mitochondria matrix
GLYCOLYSIS

Glucose ➔ Pyruvate

Cytosol

Substrate-level phosphorylation

ATP

KREBS CYCLE

Mitochondrion

Substrate-level phosphorylation

ATP
Krebs Cycle – Requirements

- Pyruvic acid (3C acid)
- Coenzyme A
- 4 NAD\(^+\)
- 1 ADP
- 1 FAD
- Double this list for each glucose.
Krebs Cycle – Products

- 3 CO₂
- Acetyl CoA
- 4 NADH
- 1 ATP
- 1 FADH₂
- Double this list for each glucose.
Pyruvate (from glycolysis, 2 molecules per glucose)

\[ \text{Pyruvate} \rightarrow \text{NAD}^+ \rightarrow \text{CO}_2 \]

\[ \text{NADH} + \text{CoA} \rightarrow \text{Acetyl CoA} \]

\[ \text{FADH}_2 \rightarrow \text{FAD} \rightarrow \text{NAD}^+ \rightarrow \text{NADH} + \text{CoA} \]

\[ \text{KREBS CYCLE} \]

\[ \text{ATP} \rightarrow \text{ADP} + \text{P}_i \]

\[ \text{CO}_2 \rightarrow 2 \text{CO}_2 \]

\[ 3 \text{NAD}^+ + 3 \text{H}^+ \rightarrow 3 \text{NADH} \]
Krebs Cycle

- Produces most of the cell's energy in the form of NADH and FADH$_2$
- Does NOT require O$_2$
The ATPs produced directly in Krebs Cycle and in Glycolysis are by:
- Substrate–level phosphorylation
- The Phosphate group ($P_i$) is transferred from a substrate to ADP.

- How many ATPs so far?
  - 2 (glycolysis) +
  - 2 (Krebs Cycle) = 4 ATP
Electron Transport Chain

- ETC or Electron Transport System (ETS).
- A collection of proteins that are structurally linked into units.
ETC

- Uses sets of **Cytochromes**, Fe containing proteins to pass electrons.
- The Cytochromes alternate between RED and OX forms and pass electrons down to $O_2$
ETC

- **Function**: Transfer energy in NADH and FADH$_2$ to ATP.
- **Location**: Mitochondria cristae (inner membrane).
ETC – Requirements

- NADH and/or FADH$_2$
- ADP
- O$_2$
ETC – Products

- NAD\(^+\) and FAD
- ATP
- H\(_2\)O
ETC – ATP Yields

- Each NADH -- 3 ATP
- Each FADH$_2$ -- 2 ATP
ETC energy is used to move/pump $H^+$ (protons) across the cristae membrane.
ATP is generated as the $H^+$ diffuse back into the matrix.
ATP Synthase

- Uses the flow of H$^+$ to make ATP.
- Works like an ion pump in reverse, or like a waterwheel under the flow of H$^+$ “water”.

ATP Synthase Animation

- http://www.youtube.com/watch?v=PjdPTY1wHdQ
- You may also wish to watch other animations on Youtube.
Figure 9.16

Electron shuttles span membrane

**Glycolysis**

Glucose → 2 Pyruvate

**Pyruvate oxidation**

2 Pyruvate → 2 Acetyl CoA

**Citric acid cycle**

2 NADH + 2 FADH₂

**Oxidative phosphorylation: electron transport and chemiosmosis**

6 NADH + 2 FADH₂ → + about 26 or 28 ATP

+ 2 ATP

**Respiration = 34% efficient**

Where does the other 66% go?

Automobile = only 25% efficient

**Flow of energy during respiration:**

Glucose → NADH → ETC → H⁺ gradient → ATP

**Maximum per glucose:**

About 30 or 32 ATP
Fermentation

- Without a constant supply of oxygen to accept electrons, the ETC backs up and ATP synthesis ceases.

- Fermentation is used to oxidize food and make ATP w/o oxygen.
  - Consists of glycolysis + reactions that regenerate NAD⁺.
    - 2 Types—Alcohol Fermentation & Lactic Acid Fermentation.
Alcoholic Fermentation

- Done by yeast, a kind of fungus, and some bacteria
(a) Alcohol fermentation
Alcoholic Fermentation

- Uses only Glycolysis.
- An incomplete oxidation – energy is still left in the products (alcohol).
- Does **NOT** require $O_2$
- Produces ATP when $O_2$ is not available.
Lactic Acid Fermentation

- Uses only Glycolysis.
- An incomplete oxidation – energy is still left in the products (lactic acid).
- Does **NOT** require O₂
- Produces ATP when O₂ is not available.
Glucose \rightarrow \text{GLYCOLYSIS} \rightarrow 2 \text{Lactate}

2 \text{ADP} + 2 \text{P}_i \rightarrow 2 \text{ATP}

2 \text{NAD}^+ \rightarrow 2 \text{NADH} + 2 \text{H}^+

2 \text{Pyruvate}
Lactic Acid Fermentation

- Animals, fungi, & bacteria do this
- Done by human muscle cells under oxygen debt.
Fermentation – Summary

- Way of regenerating NAD$^+$ so Glycolysis can still run.
- Provides ATP to a cell even when $O_2$ is absent.
Glucose

Cytosol

Pyruvate

No O₂

O₂

Ethanol or lactate

Acetyl CoA

KREBS CYCLE

Mitochondrion

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Aerobic Respiration – Rs with $O_2$

Anaerobic Respiration – Rs without $O_2$ (uses different final electron acceptor)

Fermentation – uses glycolysis only
Strict vs. Facultative

- **Strict** – can only do Rs this one way.
- **Facultative** – can switch Rs types depending on $O_2$ availability. Ex – yeast
Question

- Since yeast can do both aerobic and anaerobic Rs, which is the better process if given a choice?
- Check the ATP yields from both processes.
ATP yields by Rs type

- Fermentation – Glycolysis only gets 2 ATPs per glucose.
- Aerobic – Glycolysis, Krebs, and ETC. Generates many more ATPs per glucose.
Figure 9.16

Electron shuttles span membrane

2 NADH or 2 FADH$_2$

Glycolysis
Glucose → 2 Pyruvate

Pyruvate oxidation
2 Acetyl CoA

Citric acid cycle

2 NADH
6 NADH
2 FADH$_2$

Oxidative phosphorylation: electron transport and chemiosmosis

+ 2 ATP + 2 ATP + about 26 or 28 ATP

Maximum per glucose: About 30 or 32 ATP
Yeast

- Would rather do aerobic Rs; it has 16x more energy per glucose.
- But, anaerobic will keep you alive if oxygen is not present.
Importance of Rs

- Convert food to ATP.
- Provides materials for use in other cellular pathways.
Other Importances of Respiration

- Alcohol Industry – almost every society has a fermented beverage.
- Baking Industry – many breads use yeast to provide CO$_2$ bubbles to raise the dough.
Why is the alcohol content of wine always around 12–14%?

Alcohol is toxic and kills the yeast at high concentrations.
Swiss Cheese

- Holes are bubbles of CO$_2$ from fermentation.
Regulation

- AMP Stimulates
- ATP and Citrate Inhibits

Speeds up or slows down entire process of respiration as needed for efficiency
Which part of the equation represent which of the 3 Rs reactions?
Summary

- Know the 3 main parts of Rs and the required items for each.
- Differentiate between aerobic respiration, anaerobic respiration, and fermentation.
- Appreciate the importance of Rs.