

## Ch. 6 How Cells Harvest Chemical Energy

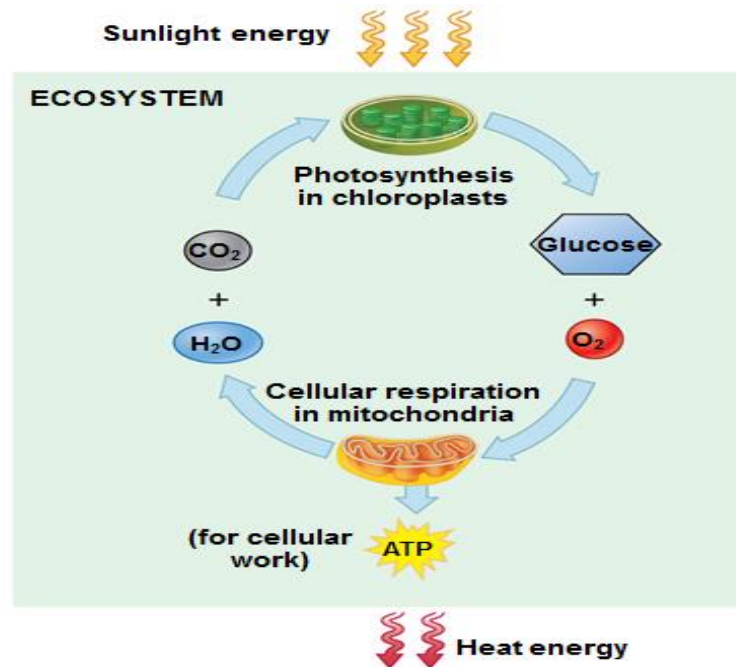
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### Introduction

- A. In eukaryotes, cellular respiration occurs in the mitochondria of cells
  - 1. harvests energy from food,
  - 2. yields large amounts of ATP
  - 3. uses ATP to drive cellular work.
- B. A similar process takes place in many prokaryotic organisms.

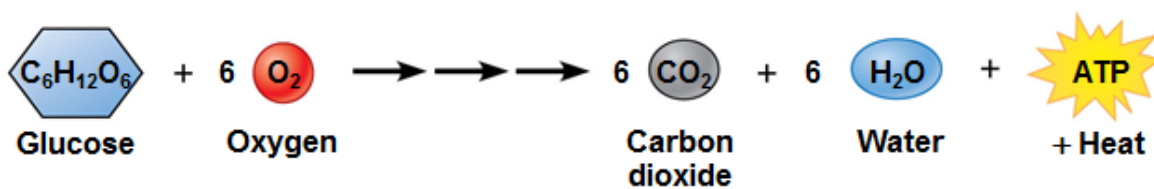
### Cellular Respiration: Aerobic Harvesting of Energy

#### 6.1 Photosynthesis and cellular respiration provide energy for life



- 1. Life requires energy.
  - 2. In almost all ecosystems, energy ultimately comes from the sun.
  - 3. In photosynthesis,
    - a. some of the energy in sunlight is captured by chloroplasts,
    - b. atoms of carbon dioxide and water are rearranged
    - c. glucose and oxygen are produced.
  - 4. In cellular respiration
    - a. glucose is broken down to carbon dioxide and water
    - b. the cell captures some of the released energy to make ATP.
- 6.2 Breathing supplies O<sub>2</sub> for use in cellular respiration and removes CO<sub>2</sub>
- 1. Respiration, as it relates to breathing, and cellular respiration are not the same.
    - a. Respiration, in the breathing sense, refers to an exchange of gases. Usually an organism brings in oxygen from the environment and releases waste CO<sub>2</sub>.
    - b. Cellular respiration is the aerobic (oxygen requiring) harvesting of energy from food molecules by cells.

### 6.3 Cellular respiration banks energy in ATP molecules



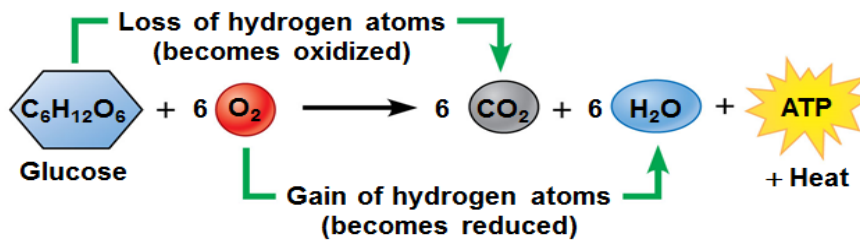
1. Cellular respiration is an exergonic process that transfers energy from the bonds in glucose to form ATP.
2. Cellular respiration produces about 32 ATP molecules from each glucose molecule and captures only about 34% of the energy originally stored in glucose.
3. Other foods (organic molecules) can also be used as a source of energy.

### 6.4 The human body uses energy from ATP for all its activities

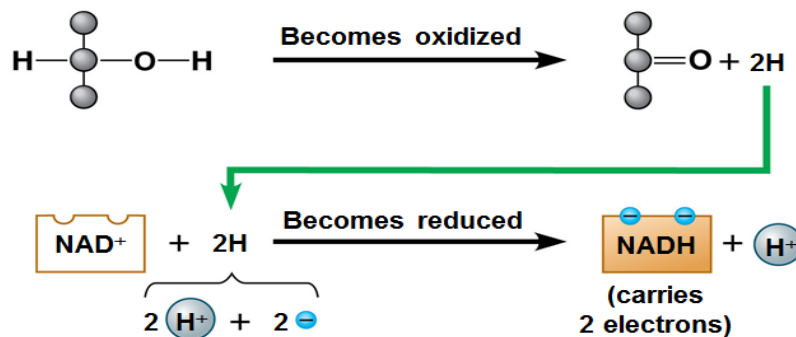
1. The average adult human needs about 2,200 kcal of energy per day.
  - a. About 75% of these calories are used to maintain a healthy body.
  - b. The remaining 25% is used to power physical activities.
2. **calorie**- amount of energy needed to raise the temperature of one gram of water by one degree Celsius
3. A **kilocalorie (kcal)** is the quantity of energy required to raise the temperature of 1 kilogram (kg) of water by  $1^\circ C$ ; it is the same as a food **Calorie**, and used to measure the nutritional values indicated on food labels.

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

1. The energy necessary for life is contained in the arrangement of electrons in chemical bonds in organic molecules.
2. An important question is how do cells extract this energy?
3. When the carbon-hydrogen bonds of glucose are broken, electrons are transferred to oxygen.
  - a. Oxygen has a strong tendency to attract electrons.
  - b. An electron loses potential energy when it “falls” to oxygen.
4. Energy can be released from glucose by simply burning it.
5. The energy is dissipated as heat and light and is not available to living organisms.
6. On the other hand, cellular respiration is the controlled breakdown of organic molecules.
7. Energy is gradually released in small amounts, captured by a biological system, and stored in ATP.
8. The movement of electrons from one molecule to another is type of reaction
  - a. the loss of electrons from one substance is called **oxidation**; a molecule is oxidized when it loses one or more electrons
  - b. the addition of electrons to another substance is called **reduction**; reduced when it gains one or more electrons
  - c. LEO the lion goes GER – mnemonic way to memorize that loss of electrons is oxidation and gain of electrons is reduction.



9. A cellular respiration equation is helpful to show the changes in hydrogen atom distribution. (Remember the hydrogen atom has one electron)
10. Glucose loses its hydrogen atoms and becomes oxidized to  $\text{CO}_2$ .
11. Oxygen gains hydrogen atoms and becomes reduced to  $\text{H}_2\text{O}$ .
12. Enzymes are necessary to oxidize glucose and other foods.
13.  $\text{NAD}^+$  is an important enzyme in oxidizing glucose, accepts electrons, and becomes reduced to  $\text{NADH}$ .



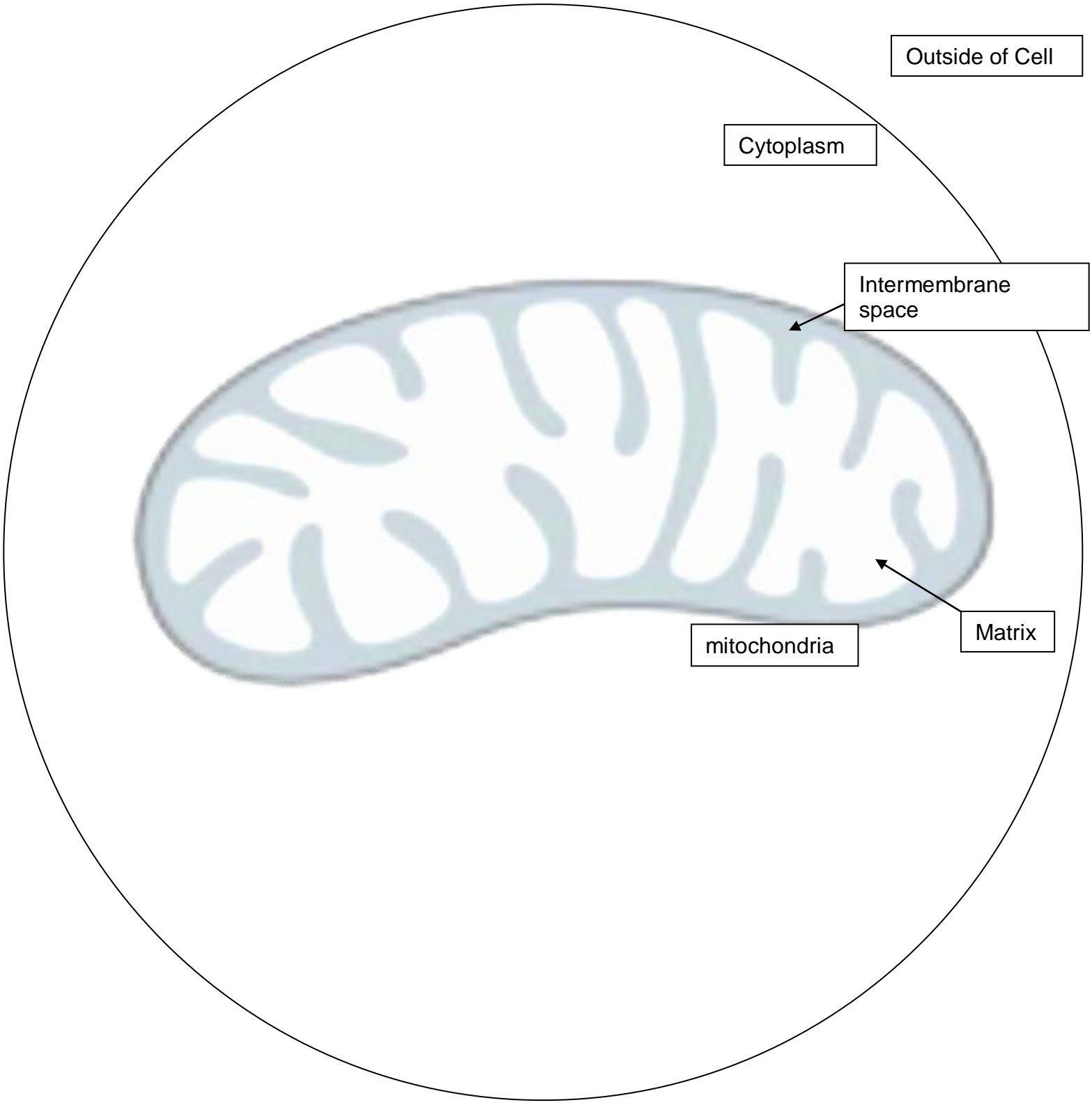
14. There are other electron “carrier” molecules that function like  $\text{NAD}^+$ .
  - a. They form a staircase where the electrons pass from one to the next down the staircase.
  - b. These electron carriers collectively are called the **electron transport chain**.
  - c. As electrons are transported down the chain, ATP is generated.

### \*\*\*Stages of Cellular Respiration\*\*\*

6.6 Overview: Cellular respiration occurs in four main stages

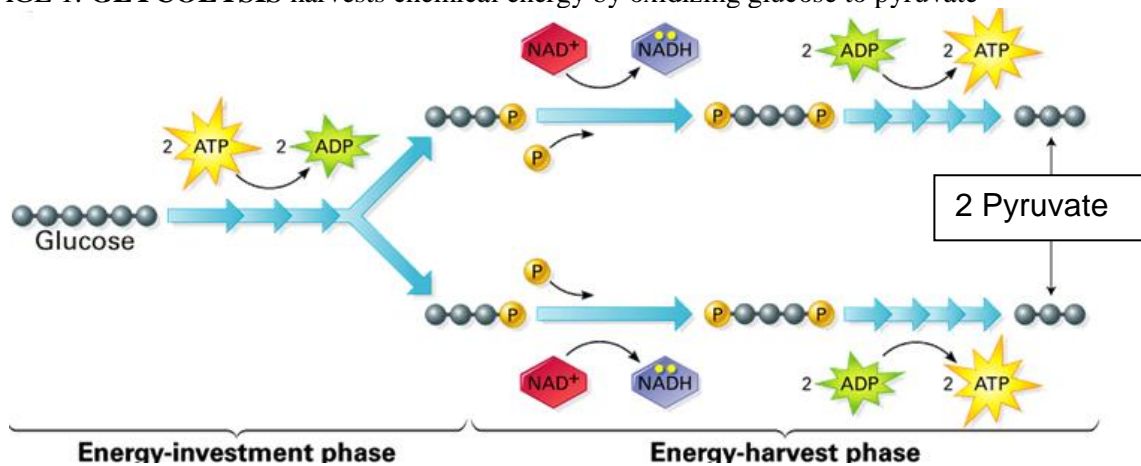
1. Cellular respiration consists of a sequence of steps that can be divided into four stages.
  - a. Stage 1 – Glycolysis
  - b. Stage 2 – Pyruvate oxidation / ‘cut and groom’/ transition
  - c. Stage 3 - Citric acid cycle or Krebs’ Cycle
  - d. Stage 4 – Oxidative phosphorylation (Electron Transport Chain & Chemiosmosis)
2. Stage 1: Glycolysis
  - a. occurs in the cytoplasm & begins cellular respiration
  - b. breaks down glucose into two molecules of a three-carbon compound called pyruvate.
  - c. **Anaerobic** process that does not require oxygen
3. Stage 2: Pyruvate Oxidation/ ‘cut and groom’/ Transition
  - a. Carboxyl group removed from pyruvate, Two-carbon compound is oxidized, & Co-enzyme A binds to molecules

**Cell Respiration in 4 Stages**



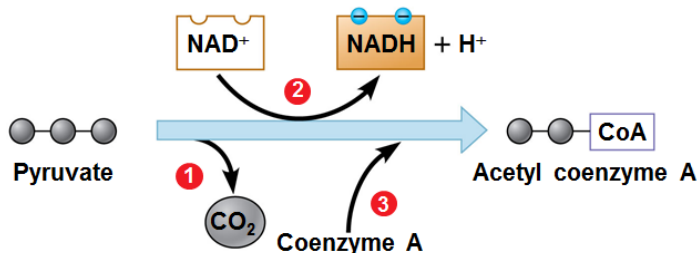
4. Stage 3: The Citric Acid Cycle / Krebs's Cycle (aerobic)
  - a. takes place in matrix of the mitochondria, oxidizes pyruvate to a two-carbon compound, & supplies the third stage with electrons.
5. Stage 4: Oxidative phosphorylation (aerobic)
  - a. involves electrons carried by NADH and FADH<sub>2</sub> & shuttles these electrons to the Electron Transport Chain (ETC) embedded in the inner mitochondrial membrane (cristae),
  - b. involves chemiosmosis (movement of protons through ATP synthase), and generates ATP.

6.7 STAGE 1: **GLYCOLYSIS** harvests chemical energy by oxidizing glucose to pyruvate



1. In **glycolysis**,
  - a. a single molecule of glucose is enzymatically cut in half through a series of steps
  - b. two molecules of pyruvate are produced
  - c. two molecules of NAD<sup>+</sup> are reduced to two molecules of NADH
  - d. a net of two molecules of ATP is produced
2. 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.
3. The steps of glycolysis can be grouped into two main phases.
  - a. In steps 1–4, the *energy investment* phase
    - i. 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.
  - b. In steps 5–9, the *energy payoff*,
    - i. two NADH molecules are produced for each initial glucose molecule
    - ii. four ATP molecules are generated when 2-three carbon pyruvate molecules are formed.

6.8 STAGE 2: **PYRUVATE OXIDATION** occurs prior to the citric acid cycle (**CUT & GROOM**)

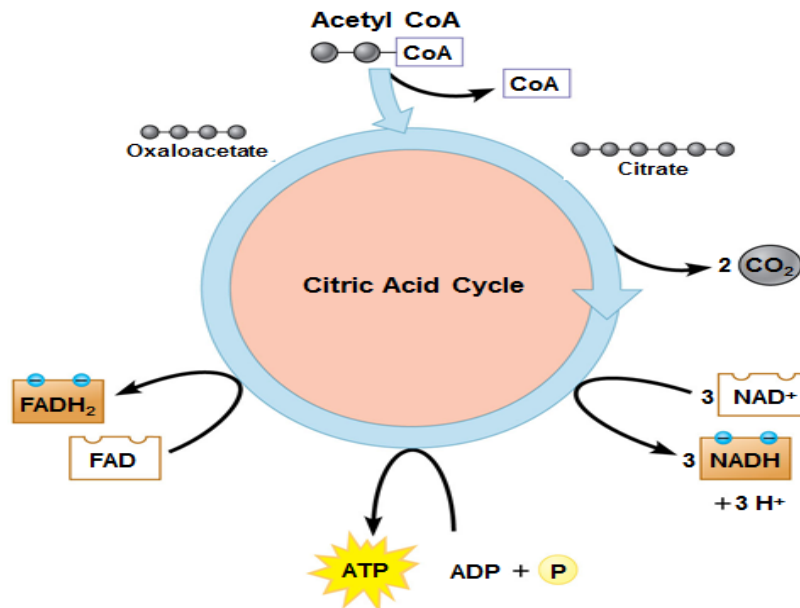


1. The pyruvate formed in glycolysis is transported from the cytoplasm into a mitochondrion matrix
2. Pyruvate does not enter the citric acid cycle, but undergoes some chemical grooming in which

- a. a carboxyl group is removed and given off as  $\text{CO}_2$
- b. the two-carbon compound remaining is oxidized while a molecule of  $\text{NAD}^+$  is reduced to  $\text{NADH}$
- c. 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.

#### 6.9 STAGE 3: The **CITRIC ACID CYCLE (KREBS CYCLE)**

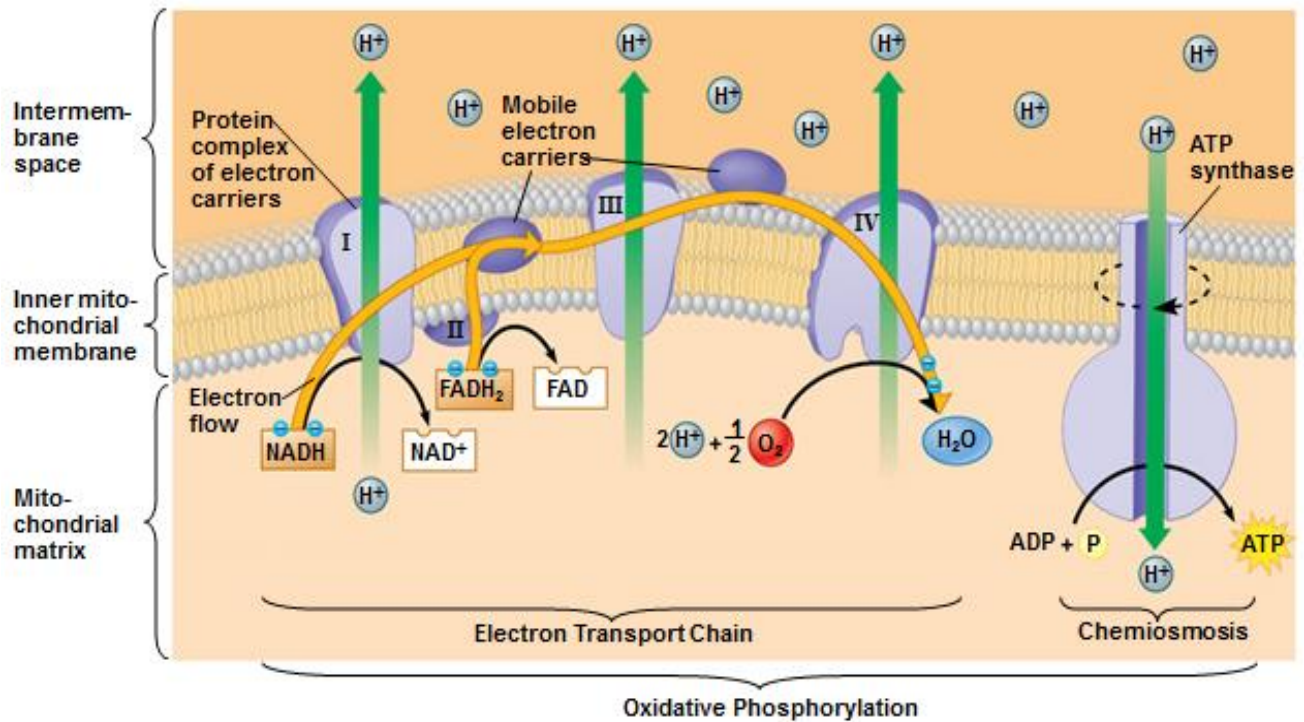
1. The citric acid cycle is also called the Krebs cycle (after the German-British researcher Hans Krebs); it completes the oxidation of organic molecules, and generates many  $\text{NADH}$  and  $\text{FADH}_2$  molecules.
2. During the citric acid cycle
  - a. the two-carbon group of acetyl CoA is added to a four-carbon compound, forming citrate
  - b. citrate is degraded back to the four-carbon compound
  - c. two  $\text{CO}_2$  are released
  - d. 1 ATP, 3  $\text{NADH}$ , and 1  $\text{FADH}_2$  are produced.
3. Remember that the citric acid cycle processes two molecules of acetyl CoA for each initial glucose molecule.
4. Thus, after two turns of the citric acid cycle, the overall yield per glucose molecule is  $2 \text{ ATP} + 6 \text{ NADH} + 2 \text{ FADH}_2 + 4 \text{ CO}_2$



#### 6.10 STAGE 4: **OXIDATIVE PHOSPHORYLATION** where most ATP's are produced

1. Oxidative (meaning oxygen is required) phosphorylation involves electron transport and chemiosmosis
2. Electrons from  $\text{NADH}$  and  $\text{FADH}_2$  travel down the electron transport chain to  $\text{O}_2$ .
3. Oxygen picks up  $\text{H}^+$  & electrons 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 (yes, it is passive) back across the inner membrane through **ATP synthase** complexes, driving the synthesis of ATP.



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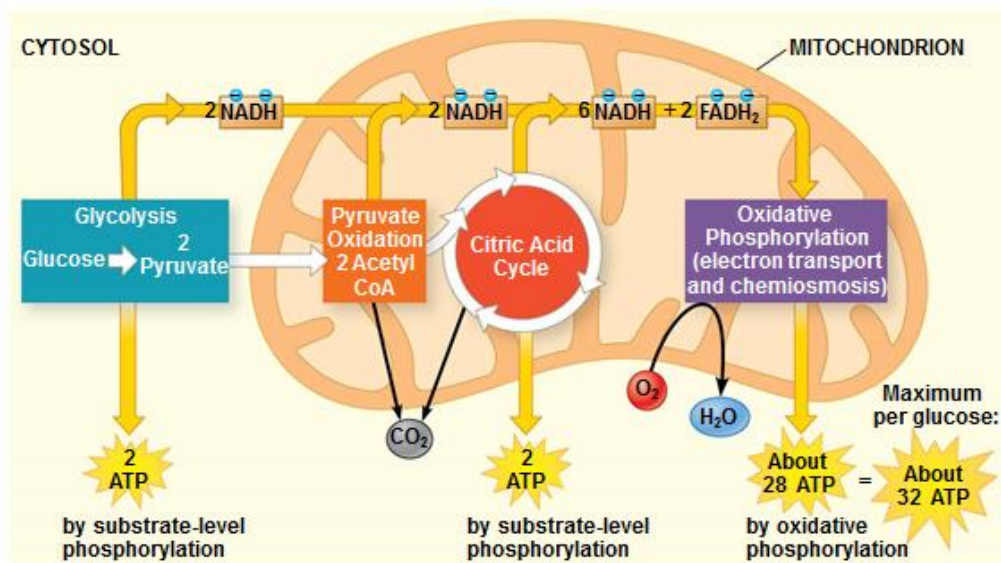
#### 6.11 Interrupting cellular respiration can have both harmful and beneficial effects

- Three categories of cellular poisons obstruct the process of oxidative phosphorylation. These poisons
  - block the electron transport chain (for example, rotenone, cyanide, and carbon monoxide), inhibit ATP synthase (for example, the antibiotic oligomycin), or
  - 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

- Recall that the energy payoff of cellular respiration involves glycolysis, cut & groom of pyruvate, the citric acid cycle, and oxidative phosphorylation.
- The total yield is about 32 ATP molecules per glucose molecule.
- In addition, water and  $CO_2$  are produced.

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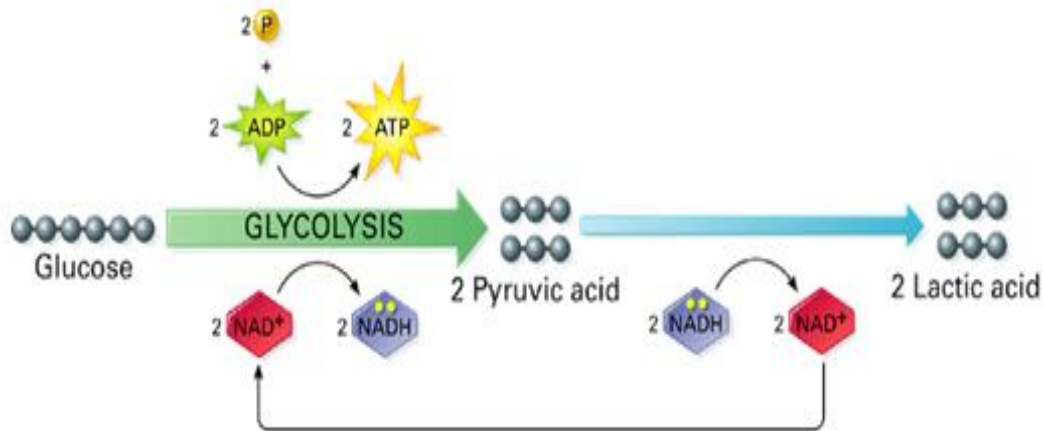


## Fermentation: Anaerobic Harvesting of Energy

6.13 Fermentation enables cells to produce ATP without oxygen

1. Fermentation is a way of harvesting chemical energy that does not require oxygen.
  - a. takes advantage of glycolysis with an additional step produces two ATP molecules per glucose
  - b. oxidizes NADH back to NAD<sup>+</sup> so glycolysis can continue again
2. The trick of fermentation is to provide an anaerobic path for recycling NADH back to NAD<sup>+</sup>.
3. Your muscle cells and certain bacteria can oxidize NADH through **lactic acid fermentation**
  - a. NADH is oxidized to NAD<sup>+</sup>
  - b. pyruvate is reduced to lactate.
4. Lactate is carried by the blood to the liver, where it is converted back to pyruvate and oxidized in the mitochondria of liver cells.
5. The dairy industry uses lactic acid fermentation by bacteria to make cheese and yogurt.
6. Other types of microbial fermentation turns soybeans into soy sauce and cabbage into sauerkraut.

### Lactic Acid Fermentation

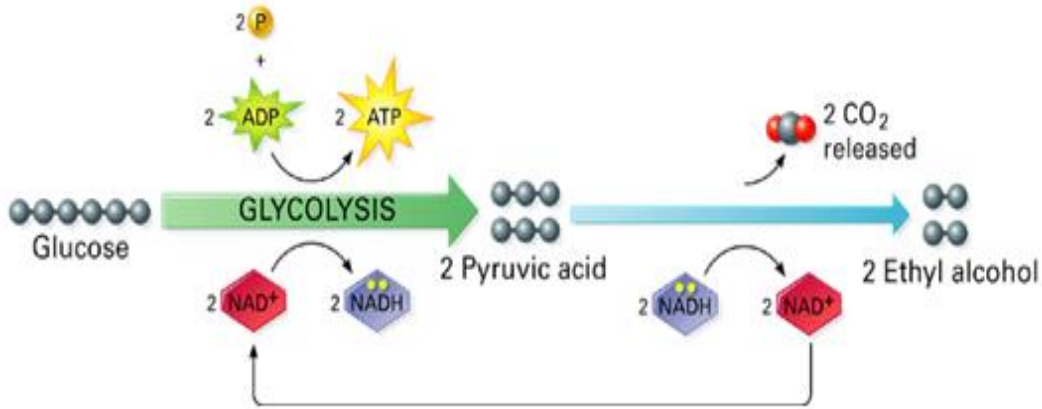


7. The baking and winemaking industries have used **alcohol fermentation** for thousands of years.



- In this process **yeasts** (single-celled fungi) oxidize NADH back to NAD<sup>+</sup> and convert pyruvate to CO<sub>2</sub> and ethanol.
- Obligate anaerobes** are poisoned by oxygen, requiring anaerobic conditions, and live in stagnant ponds and deep soils.

### Alcoholic Fermentation

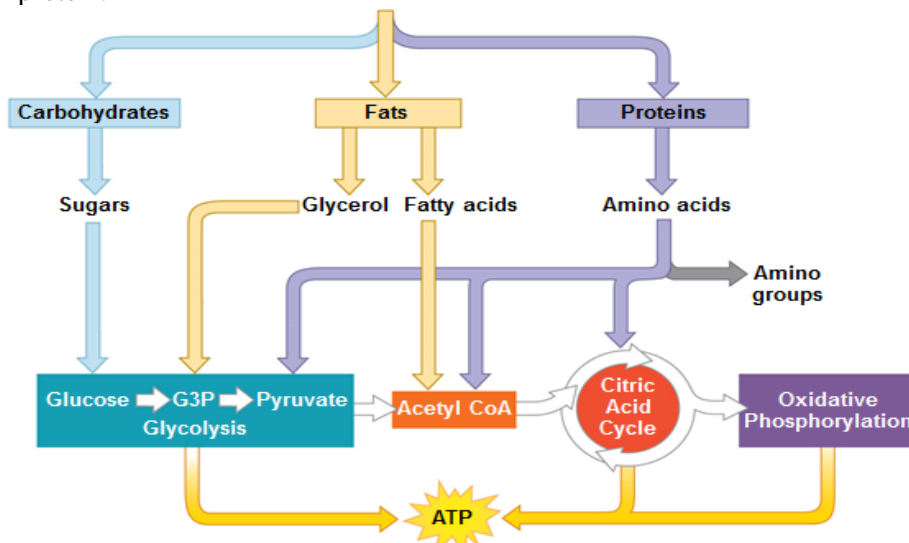


- Facultative anaerobes** include yeasts and many bacteria and can make ATP by fermentation or oxidative phosphorylation.

### Connections Between Metabolic Pathways

6.15 Cells use many kinds of organic molecules as fuel for cellular respiration (see online Interactive Metabolic Pathway Map)

- Although glucose is considered to be the primary source of sugar for respiration and fermentation, ATP is generated using other carbohydrates, fats, and proteins.
- Fats make excellent cellular fuel because they
  - contain 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.



6.16 Food molecules provide raw materials for biosynthesis

- Cells use intermediates from cellular respiration for the biosynthesis of other organic molecules.
- Metabolic pathways are often regulated by feedback inhibition in which an accumulation of product suppresses the process that produces the product.

## Chapter 6: How Cells Harvest Chemical Energy

### Word Parts

**aero-** = air

**an-** = not

**chemi-** = chemical

**de-** = without;

**-hydro** = water

**glyco-** = sweet;

**-lysis** = split

### Vocabulary

1. **cellular respiration**- The aerobic harvesting of energy from food molecules; the energy-releasing chemical breakdown of food molecules, such as glucose, and the storage of potential energy in a form that cells can use to perform work; involves glycolysis, the citric acid cycle, and oxidative phosphorylation (the electron transport chain and chemiosmosis).

2. **kilocalories (kcal)**- A quantity of heat equal to 1,000 calories. Used to measure the energy content of food, it is usually called a "Calorie."

3. **redox reaction**- Short for reduction-oxidation reaction; a chemical reaction in which electrons are lost from one substance (oxidation) and added to another (reduction).

4. **oxidation**- The loss of electrons from a substance involved in a redox reaction; always accompanies reduction.

5. **reduction**- The gain of electrons by a substance involved in a redox reaction; always accompanies oxidation.

6. **NAD(+)** -Nicotinamide adenine dinucleotide; a coenzyme that can accept electrons during the redox reactions of cellular metabolism. The plus sign indicates that the molecule is oxidized and ready to pick up hydrogens; the reduced form of NADH has gained 2 electrons and a proton (H<sup>+</sup>)

7. **electron transport chain**- A series of electron carrier molecules that shuttle electrons during the redox reactions that release energy used to make ATP; located in the inner membrane of mitochondria, the thylakoid membranes of chloroplasts, and the plasma membranes of prokaryotes.

8. **glycolysis**- The multistep chemical breakdown of a molecule of glucose into two molecules of pyruvate & 2 ATP's; the first stage of cellular respiration in all organisms; occurs in the cytoplasmic fluid.

9. **citric acid cycle (Krebs Cycle)**- the process of oxidizing acetyl CoA (derived from pyruvate) to carbon dioxide. The cycle occurs in the matrix of mitochondria and supplies NADH and FADH<sub>2</sub> molecules that carry energy to the electron transport chains.

10. **oxidative phosphorylation**- The production of ATP using energy derived from the redox reactions of an electron transport chain; the fourth major stage of cellular respiration. Process consists of two parts: electron transport chain and chemiosmosis.

11. **chemiosmosis**- Energy-coupling mechanism that uses the energy of hydrogen ion (H<sup>+</sup>) gradients across membranes to drive cellular work, such as the phosphorylation of ADP into ATP (usable cell energy)

12. **substrate-level phosphorylation**- The formation of ATP by an enzyme directly transferring a phosphate group to ADP from an organic molecule (for example, one of the intermediates in glycolysis or the citric acid cycle).

13. **acetyl CoA**- The entry 2 carbon-compound for the citric acid cycle in cellular respiration; formed from a fragment of pyruvate attached to a coenzyme.

14. **ATP synthase**- A cluster of several membrane proteins that function in chemiosmosis with adjacent electron transport chains, using the energy of a hydrogen ion concentration gradient to make ATP.

15. **lactic acid fermentation**- Glycolysis followed by the reduction of pyruvate to lactate, regenerating NAD<sup>+</sup>.

16. **alcohol fermentation**- Glycolysis followed by the reduction of pyruvate to ethyl alcohol, regenerating NAD<sup>+</sup> and releasing carbon dioxide.