15.1: Glycolysis

Learning Outcomes

- List the three stages of cellular respiration.
- Explain the purpose of glycolysis.
- Describe the use and formation of ATP during glycolysis.
- Name the products of glycolysis.
- Distinguish between aerobic and anaerobic.

How do you slice a molecule of glucose in half? With sharp knives? Not really. But you lyse it with enzymes during a process named glycolysis. Glucose is sliced right in half from a 6-carbon molecule to two 3-carbon molecules. This is the first step and an extremely important part of cellular respiration. It happens all the time, both with and without oxygen. And in the process, transfers some energy to ATP.

Glycolysis: A Universal and Ancient Pathway for Making ATP

When was the last time you enjoyed yogurt on your breakfast cereal, or had a tetanus shot? These experiences may appear unconnected, but both relate to bacteria which do not use oxygen to make ATP. In fact, tetanus bacteria cannot survive if oxygen is present. However, *Lactobacillus acidophilus* (bacteria which make yogurt) and *Clostridium tetani* (bacteria which cause tetanus or lockjaw) share with nearly all organisms the first stage of cellular respiration, **glycolysis** (see figure below). Because glycolysis is universal, whereas aerobic (oxygen-requiring) cellular respiration is not, most biologists consider it to be the most fundamental and primitive pathway for making ATP.

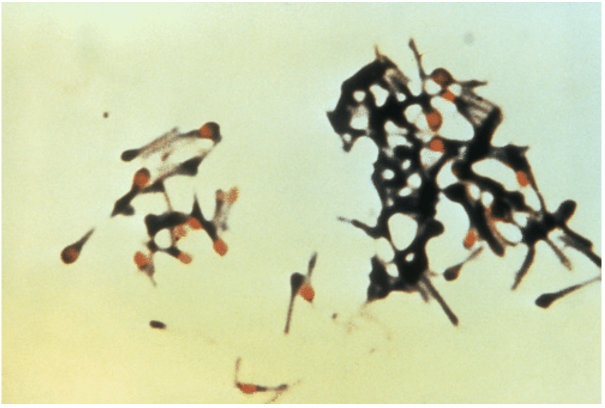

Figure 15.1.1: Clostridium tetani *bacteria are obligate anaerobes, which cannot grow in the presence of oxygen and use a variation of glycolysis to make ATP. Because they can grow in deep puncture wounds and secrete a toxin, which can cause muscle spasms, seizures, and death, most people receive tetanus vaccinations at least every ten years throughout life.*

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \tag{15.1.1}$$

Like photosynthesis, the process represented by this equation is actually many small, individual chemical reactions. We will divide the reactions of cellular respiration into three stages: glycolysis, the **Krebs Cycle** (also known as the citric acid cycle), and the **electron transport chain** (see figure below). In this concept, Stage 1, glycolysis, the oldest and most widespread pathway for making ATP, is discussed. Before diving into the details, we must not that this first stage of cellular respiration is unique among the three stages: it does not require oxygen, and it does not take place in the mitochondrion. The chemical reactions of glycolysis occur without oxygen in the cytosol of the cell (see figure below).

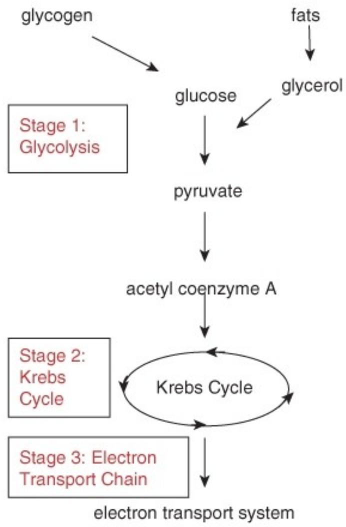

Figure 15.1.2: The many steps in the process of aerobic cellular respiration can be divided into three stages. The first stage, glycolysis, produces ATP without oxygen. Because this part of the cellular respiration pathway is universal, biologists consider it the oldest segment. Note that **glycogen** and fats can also enter the glycolysis pathway. The second stage is the Krebs Cycle, and the third stage is the electron transport chain. It is during the third stage that chemiosmosis produces numerous ATP molecules.

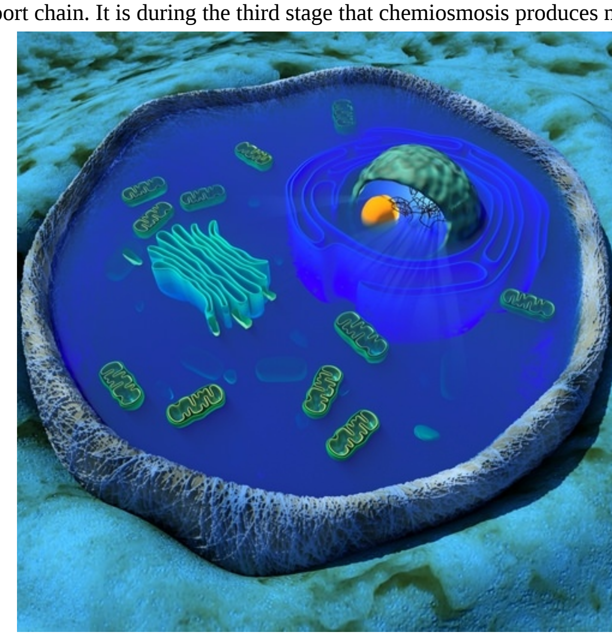

Figure 15.1.3: Glycolysis, unlike the latter two stages of cellular respiration, takes place without oxygen in the cytosol (blue) of the cell. For many organisms, aerobic respiration continues with the Krebs Cycle and the electron transport chain in the mitochondria (green). To enter the mitochondria, glucose must first be lysed into smaller molecules.

The name for Stage 1 clearly indicates what happens during that stage: *glyco-* refers to glucose, and *-lysis* means "splitting". In glycolysis, within the cytosol of the cell, a minimum of eight different enzymes break apart glucose into two 3-carbon molecules. The energy released in breaking those bonds is transferred to carrier molecules, ATP and NADH. **NADH** temporarily holds small amounts of energy which can be used to later build ATP. The 3-carbon product of glycolysis is **pyruvate**, or pyruvic acid (see figure below). (The sole difference between them is actually a sole hydrogen atom. Pyruvic acid: $\mathrm{CH_3COCOOH}$, pyruvate: $\mathrm{CH_3COCOO^-}$). Overall, glycolysis can be represented as:

$$\mathrm{C_6H_{12}O_6} + 2\mathrm{NAD^+} + 2\mathrm{P_i} + 2\mathrm{ADP} \rightarrow 2 \text{ pyruvate } + 2\mathrm{NADH} + 2\mathrm{ATP} \tag{15.1.2}$$

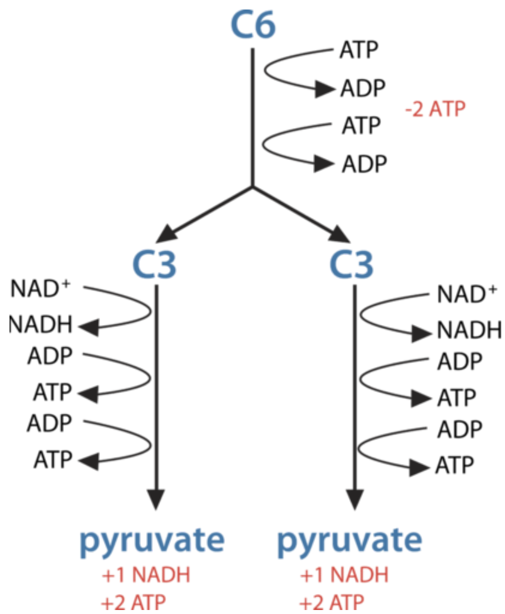

Figure 15.1.4: In glycolysis, glucose (C6) is split into two 3-carbon (C3) pyruvate molecules. This releases energy, which is transferred to ATP. How many ATP molecules are made during this stage of cellular respiration?

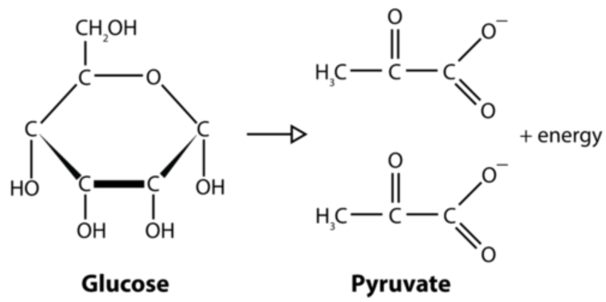

Figure 15.1.5: Glycolysis breaks the 6-carbon molecule glucose into two 3-carbon pyruvate molecules, releasing some of the chemical energy which had been stored in glucose.

However, even this equation is deceiving. Just the splitting of glucose requires many steps, each transferring or capturing small amounts of energy. Individual steps appear in the figure below. Studying the pathway in detail reveals that cells must "spend" or "invest" two ATP in order to begin the process of breaking glucose apart. Note that the phosphates produced by breaking apart ATP join with glucose, making it unstable and more likely to break apart. Later steps harness the energy released when glucose splits, and use it to build "hot hydrogens" (NAD^+ is reduced to NADH) and ATP (ADP + $P_i \rightarrow$ ATP). If you count the ATP produced, you will find a net yield of two ATP per glucose (4 produced $-$ 2 spent). Remember to double the second set of reactions to account for the two 3-carbon molecules which follow that pathway! The "hot hydrogens" can power other metabolic pathways, or in many organisms, provide energy for further ATP synthesis.

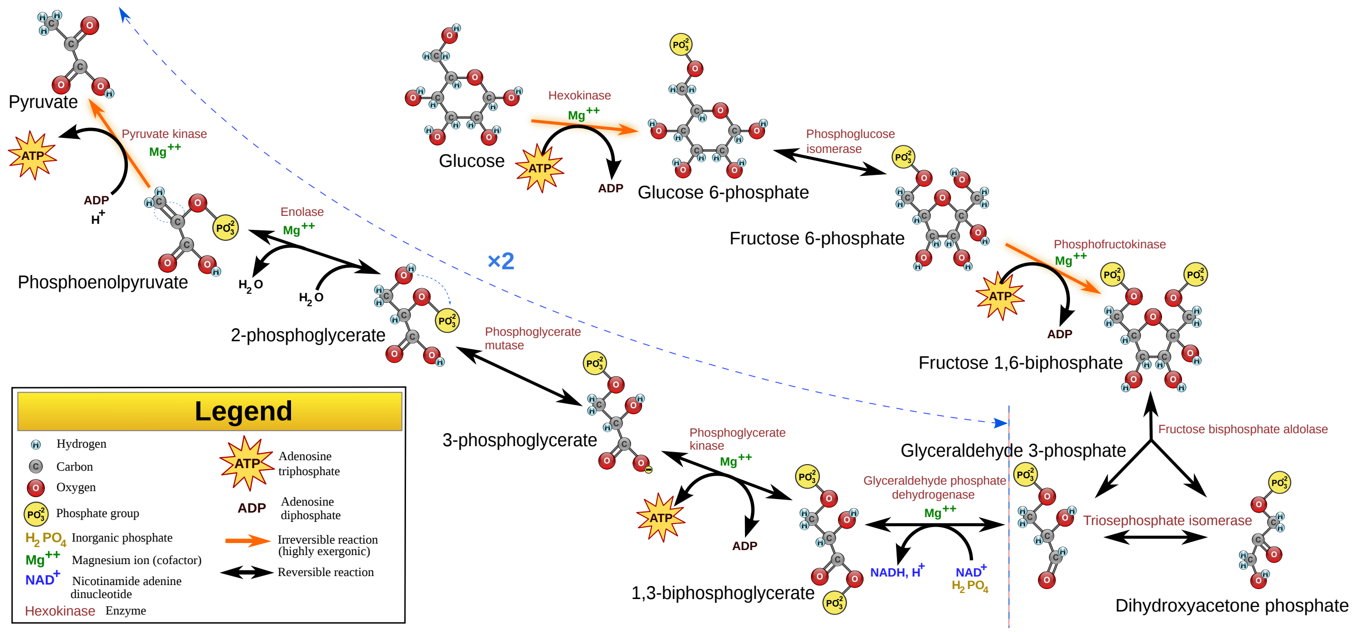

Figure 15.1.6*: Glycolysis pathway. from Wikipedia (CCBY-SA 3.0; YassineMrabet).*

To summarize: In the cytosol of the cell, glycolysis transfers some of the chemical energy stored in one molecule of glucose to two molecules of ATP and two NADH. This makes (some of) the energy in glucose, a universal fuel molecule for cells, available to use in cellular work - moving organelles, transporting molecules across membranes, or building large organic molecules.

Although glycolysis is universal, pathways leading away from glycolysis vary among species depending on the availability of oxygen. If oxygen is unavailable, pyruvate may be converted to lactic acid or ethanol and carbon dioxide in order to regenerate NAD^+, called anaerobic respiration. **Anaerobic respiration** is also called **fermentation**, which will be discussed in another concept.

If oxygen is present, pyruvate enters the mitochondria for further breakdown, releasing far more energy and producing many additional molecules of ATP in the latter two stages of **aerobic respiration** - the Krebs Cycle and electron transport chain.

Supplemental Resources

- Glycolysis: http://johnkyrk.com/glycolysis.html

Contributors and Attributions

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