**Metabolisms**

**Introduction**

All living organisms need energy to survive and reproduce. Organisms like us use energy all the time, like when we walk, study, and even when we are asleep. Our bodies use energy for many purposes, like growing, transporting molecules, and even keeping us warm. Eventually, this energy is lost as heat, and because heat energy cannot be recycled, cells need to have a constant supply of energy so they can continue to grow and stay alive.

We know that we eat food to get energy. In fact, we can measure the amount of energy that food will give us in the form of calories. But what processes allow us to extract energy from our food? How does our food get its energy? In this chapter, we will discuss how our bodies convert food into energy through cellular respiration, how other organisms convert food into energy through fermentation, energy molecules used by cells, and how organisms can produce their own food from the sun.

**Energy Molecules**

All organisms have a **metabolism**, which is defined as the set of chemical processes that the organism performs to survive. Metabolism has two main components: **catabolism**, the breaking down of organic molecules for energy and resources, and **anabolism**, using energy and resources to build new organic molecules.

Energy Molecules Key Terms

**metabolism:** The set of chemical processes that an organism performs to survive

**Catabolism:** The breaking down of organic molecules like glucose for energy and resources

**Anabolism:** Using energy and resources from catabolism to build new organic molecules

**ATP:** The primary energy currency of a cell that stores energy in a phosphate group

**nadh:** A molecule that carries large amounts of energy in the form of electrons

Many cells get their energy by eating food molecules. Food molecules store energy in chemical bonds between atoms. One of the most important food molecules is glucose. Cells catabolize glucose by breaking its chemical bonds and extracting energy from them. Our cells can use this extracted energy to create energy carrier molecules like **ATP** (Adenosine triphosphate) or **NADH** (nicotinamide adenine dinucleotide (NAD) + hydrogen (H)) that they can use to fuel cellular processes.

ATP is composed of the nucleotide adenosine linked to three phosphate groups. Like food, ATP stores energy in the form of chemical bonds between atoms. When a cell needs to use energy from ATP, it breaks off one of the phosphate groups, releasing energy and producing a molecule of ADP (Adenosine diphosphate) and a phosphate group (Pi). Cells can also perform the reverse reaction and take energy to turn ADP and a phosphate group into ATP.

ADP + Pi + energy ↔ ATP

 NADH and FADH2 are other energy carrier molecules found in cells. Like ATP, NADH and FADH2 store chemical energy in bonds between atoms. However, unlike ATP, both NADH and FADH2 store their energy as electrons rather than a phosphate group. NADH and FADH2 also store more energy than a molecule of ATP. When NADH or FADH are oxidized, or lose electrons, they also lose a hydrogen atom, or two in the case of FADH2. The oxidation of NADH produces NAD+, a hydrogen atom, electrons, and energy.

NAD+ + H+ + 2 e- ↔ NADH

FAD + 2H+ + e- ↔ FADH2

NADH stores more energy than FADH2, which stores more energy than ATP. A molecule of NADH could convert a molecule of ADP and Pi into a molecule of ATP. However, a molecule of ATP would not have enough energy to convert a molecule of NAD+ and a H+ into a molecule of NADH. When a reaction has energy leftover, that energy is released into the environment as heat.

**Cellular Respiration**

**Cellular respiration** is how organisms break down food into resources and energy. As cells break down their food particles, they take the released energy to create energy carrying molecules like ATP and NADH. All organisms undergo cellular respiration because all organisms need energy to survive. Cellular respiration occurs in three main steps: glycolysis, the Krebs cycle (also known as the TCA cycle or the citric acid cycle), and the electron transport chain. A summary of cellular respiration is shown below.

Cellular Respiration Key Terms

**Cellular respiration:** The processes by which cells break food molecules down into energy

**glycolysis:** The first step of cellular respiration, in which food molecules are catabolized to pyruvate molecules and a small amount of energy

**krebs cycle:** The second step of cellular respiration, also called the TCA cycle or the Citric Acid Cycle, in which pyruvate molecules are used to produce energy carrier molecules like NADH

**oxidative phosphorylation:** The final step of cellular respiration, in which the majority of the ATP molecules from cellular respiration are produced

**chemiosmosis:** The movement of ions across a membrane following a gradient

**electron transport chain:** A protein system that uses energized electrons to pump protons through a membrane

**terminal electron acceptor:** A molecule used to accept spent electrons at the end of cellular respiration

**atp synthase:** A protein system that uses protons to create ATP

C6H12O6 + 6O2 ⟶ 6 CO2 +6 H2O + energy

The first step of cellular respiration is **glycolysis**. Glycolysis occurs in the cytoplasm. As soon as a cell uptakes a molecule of glucose, it uses an ATP molecule to convert the glucose to glucose-6-phosphate. This allows the cell to maintain a gradient of glucose into the cell (because there is no glucose in the cell), and it also kick-starts glycolysis. The glucose-6-phosphate molecule is eventually converted into a molecule of fructose 1,6-bisphosphate in a reaction that consumes another ATP molecule. The cell continues breaking down the fructose 1,6-bisphosphate into two molecules of pyruvate. During glycolysis, 2 ATP are consumed, and 4 ATP are produced. Additionally, 2 NADH are produced by high-energy electrons for a total yield of 2 ATP molecules and 2 NADH molecules produced. The pyruvate molecules continue to the Krebs cycle.

Before the **Krebs cycle** can begin, the pyruvate molecules are moved into the mitochondria, organelles that perform cellular respiration. In the mitochondria, the three-carbon pyruvate molecules are converted into a two-carbon acetyl group, which binds to a carrier molecule known as CoA (coenzyme A). This product is known as acetyl-CoA. Acetyl-CoA’s primary function is to deliver the acetyl group to the next part of respiration, the Krebs cycle. The third carbon atom from pyruvate reacts with oxygen molecules to form carbon dioxide (CO2) which is released as a waste product. It is important to note that the Krebs cycle is an aerobic process, which means that it will not work in the absence of oxygen.

In the Krebs cycle, acetyl-CoA reacts with a 4-carbon molecule known as oxaloacetate, producing a 6-carbon molecule known as citric acid. This is also why the Krebs cycle is known as the citric acid cycle. The citric acid molecule undergoes a series of reactions that release energy, which the cell captures in the energy carrier molecules NADH, ATP, and FADH2. These reactions also produce carbon dioxide, which is released as a waste product. In the last step of the Krebs cycle, oxaloacetate, the molecule that began the Krebs cycle, is regenerated. The Krebs cycle repeats twice per glucose molecule because one molecule of glucose is split into two molecules of pyruvate.

After the second turn of the Krebs cycle, the cell has produced 4 ATP, 10 NADH, and 2 FADH2. Remember that 2 of the ATP molecules and 2 of the NADH molecules were produced earlier, during glycolysis.

*A simplified diagram of the Krebs cycle.*

The final stage of aerobic cellular respiration is known as **oxidative phosphorylation**. There are two stages of oxidative phosphorylation: the etc (electron transport chain), and **chemiosmosis**. During the etc, electrons from NADH and FADH2 are used to produce ATP.

Recall that the mitochondria is composed of an inner and outer membrane. The **electron transport chain** occurs on the inner membrane layer of the mitochondria. In the electron chain transport, electrons from NADH and FAD2 are used to create ATP. These electrons are passed through several protein complexes and lose energy in each step. These proteins pump protons (hydrogen ions, H+) across the inner mitochondrial membrane, and establish a chemical and electrical gradient across the membrane. The chemical gradient is established because there are more protons on the inside of the membrane than the outside. The electrical gradient is established because the protons are positively charged. The electron transport chain is also an aerobic process. In humans, once electrons can no longer pump protons, oxygen acts as a **terminal electron acceptor** to remove the spent electrons from the system. Other organisms may use different terminal electron acceptors; however, they are not as efficient as oxygen.

These protons power an enzyme (a biological catalyst) known as **ATP Synthase**, which is responsible for the synthesis of ATP molecules. ATP synthase is shaped like a motor and is embedded in the mitochondrial membrane. Imagine you have compressed a slinky. When you release the tension on the slinky, you could slinky expands.

You could use this expansion of the slinky to do work, like pushing a tube of chapstick.  Similarly, work can be performed as protons flow along the gradient, out of the inner mitochondrial membrane space. As the protons flow through the membrane, they turn the “motor” of the ATP synthase protein using mechanical energy. This motor turns a series of two rotors, which ends in a second motor. At this second motor, ADP molecules and Pi molecules are bound together, producing an ATP molecule. Using protons to do work in this way is known as proton motive force. Proton motive force is used in many other systems, like to turn bacterial flagella.

*An ATP synthase molecule. Protons flow through the membrane along a gradient, which causes the protein to turn. As the protein turns, it creates ATP.*

 36 total ATP molecules are produced during aerobic cellular respiration per glucose molecule. Glycolysis produces 2 ATP molecules, and Krebs cycle produces 2 more ATP molecules. The electrons from the NADH and FADH2 molecules produced during the Krebs cycle can produce 32 additional ATP molecules.

**Fermentation**

If cells are able, they will undergo aerobic respiration because it produces more ATP molecules per molecule of glucose consumed. Because aerobic respiration uses oxygen as the terminal electron acceptor, cells sometimes cannot supply enough energy with aerobic respiration to meet their energy needs, for example during a hard workout or in a low-oxygen environment. Under these conditions, organisms will also undergo anaerobic respiration, which uses other molecules as the terminal electron acceptors, such as sulfur (S) or nitrate ions (NO3-) to help fulfill their energy needs.

Fermentation key terms

**fermentation:** Alternate pathways for breaking down food molecules without using oxygen

In the absence of oxygen, the Krebs cycle is inactivated, and the electron transport chain will not occur. Instead, a process known as fermentation occurs. Different organisms produce different end products for fermentation, so we will not discuss all these pathways, but we will discuss the main two products. In humans, fermentation produces lactic acid, and in yeast, fermentation produces ethanol.

Some prokaryotes prefer to grow in oxygen-poor conditions and have different terminal electron acceptors than oxygen. By doing so, these organisms can grow in environments that are hostile to other prokaryotes. For example, methanogens use carbon dioxide as a terminal electron acceptor and release methane as their waste product. Methanogens can be found in the stomachs of animals like cows. Other species of bacteria use sulfur as a terminal electron acceptor and produce hydrogen sulfide (H2S) as a waste product.

**Fermentation** begins at the end of glycolysis. Instead of providing its electrons to the etc, NADH donates its electrons to organic molecules such as pyruvate, allowing glycolysis to continue to produce ATP by maintaining a supply of NAD+.

In lactic acid fermenters, for example, humans, NADH transfers its electrons directly to the pyruvate produced at the end of glycolysis, producing a molecule of lactate. In humans, lactic acid is transported to the liver through the bloodstream, where it is converted back into pyruvate. It will eventually be processed normally when oxygen levels recover.

2 Pyruvate + 2 NADH → 2 Lactate + 2 NAD+

 Another common type of fermentation is ethanol fermentation (alcohol fermentation). In this type of fermentation, pyruvate is converted into acetaldehyde and carbon dioxide. NADH donates its electrons to the acetaldehyde, producing ethanol.

2 Pyruvate → 2 Acetaldehyde + 2 CO2

2 Acetaldehyde + 2 NADH → 2 Ethanol

**Photosynthesis**

Excepting some niche deep-sea bacteria, all life is reliant on the sun for energy. In a process called **photosynthesis**, organisms convert light energy into chemical energy, producing sugars to use in respiration. Organisms that can do this are called **autotrophs**: they can convert inorganic materials, like carbon dioxide, into something usable by life. A summarized equation of photosynthesis is shown below.

Photosynthesis key terms

**photosynthesis:** A process for producing carbon molecules from CO2 and light

**autotrophs:** Organisms that can produce their own food molecules

**light-dependent reactions:** The photosynthetic reactions that use light to produce energy molecules for use in the light-independent reactions

**light-independent reactions:** Also known as the Calvin cycle, using energy molecules from the light-dependent reactions and CO2 to create carbon molecules usable by the cell

**carbon fixation:** Converting CO2 into a form usable by cells, such as glucose

**rubisco:** The most abundant enzyme on Earth; responsible for carbon fixation

6 CO2 + 6 H2O + Energy → C6H12O6 + 6 O2

 It is important to note that there are two types of photosynthesis: oxygenic photosynthesis and anoxygenic photosynthesis. The formula for oxygenic photosynthesis is shown above. Organisms that perform oxygenic photosynthesis transfer electrons from water (H2O) to carbon dioxide, and water is released as a waste product. Oxygenic photosynthesis is more common than anoxygenic photosynthesis, and can be found in plants, alga, and cyanobacteria. Anoxygenic photosynthetic organisms use electron donors other than water, like green sulfur bacteria, which use hydrogen sulfide (H2S) as their electron donor. A general formula for anoxygenic photosynthesis is shown below. Note that A could be any electron donor.

CO2 + 2 H2A + Energy → CH2O + 2 A + H2O

 Photosynthesis occurs in organelles called chloroplasts. The innermost portion of the chloroplast is known as the grana, which is a stack of disc-shaped membranes. Individual membranes are called thylakoids. In photosynthesis, light energy is absorbed by pigment molecules, like chlorophyll, found on thylakoid membranes. Photosynthesis is divided into two parts: light-dependent reactions, and light-independent reactions.

To start the **light-dependent reactions**, photons (light particles) hit the pigment particles, and energize electrons found in the pigment molecule. These pigments pass the energized electrons to proteins embedded in the thylakoid membrane. These proteins pump hydrogen ions through the thylakoid membrane to an interior space called the thylakoid lumen. ATP synthase proteins are also found on the thylakoid membrane, and ATP is produced for use later in photosynthesis as the protons leave the membrane. NADPH, an energy carrier molecule similar to NADH, is also produced during the light-dependent reactions. These energy molecules are used to fuel the next step of photosynthesis, the dark reaction (also known as the Calvin cycle).

 However, for this to occur, electrons that are taken from the pigment particles must be replaced. In oxygenic photosynthesis, these replacement electrons come from water. This process releases oxygen as a waste product into the atmosphere.

 During the **light-independent reactions**, energy molecules produced during the light-dependent reactions are consumed, and carbon dioxide is **fixed** (turned into a usable form, like a sugar). During the first step of the light-independent reactions, carbon fixation, an enzyme called **Rubisco** (Ribulose-1, 5-bisphosphate carboxylase oxygenase) attaches a molecule of CO2 to a 5-carbon molecule known as RuBP (Ribulose bisphosphate). This produces a very unstable molecule, that immediately degrades into two 3-carbon molecules.

 During the next step of the light-independent reactions, ATP and NADPH convert 6 molecules of the 3-carbon intermediate into another 3-carbon molecule known as G3P (glyceraldehyde 3-phosphate). This consumes a total of 6 ATP molecules and 6 NADPH molecules, one of each per molecule of G3P produced. The ADP and NADP+ molecules return to the light-dependent reactions to be reenergized.

 Five of these G3P molecules are recycled into molecules of RuBP, in a series of reactions that consume 3 additional ATP molecules. The remaining molecule of G3P exits the Calvin cycle, and is sent to the cytoplasm, where it is used by the cell to create other essential compounds. Because G3P is a 3-carbon molecule and the Calvin cycle only adds a 1-carbon CO2 molecule per cycle, it takes 3 turns of the Calvin cycle to produce one G3P molecule. However, because one turn of the Calvin cycle only produces two 3-carbon G3P molecules, the Calvin cycle must “turn” 3 times to make six G3P molecules.

**Wrapping up**

 Metabolic processes like respiration and photosynthesis are constantly occurring in every organism. These processes provide the energy we need to function daily. We now know how our bodies produce energy molecules, like ATP, from food, and how plants convert energy from the sun into food. It is important to understand these processes because they are the foundation for all life. In this chapter, we looked at energy molecules, cellular respiration, fermentation, and photosynthesis. Now that you have read this chapter, you are prepared for further studies into these topics. You are also ready for related topics that we will discuss in following chapters.

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