

An Overview of Metabolic Pathways

Slide 2 If you were asked to define life, how would you do it? Would your definition include concepts such as heredity or growth, or specific structures such as the cell membrane? Or, perhaps, it might incorporate aspects of evolution. While all of these ideas may help to define life, it would be impossible to present a complete picture of life without discussing one fundamental concept – energy. Organisms differ from their non-living environment because they are able to capture *and* process energy in a controlled manner. Because they are able to process energy in a controlled way, cells and organisms can maintain complex, yet stable, internal environments.

Organisms capture energy in a variety of ways – some, such as plants and other photosynthetic organisms, gain all of their energy from the sun. Some organisms, like humans, eat other organisms to gain energy. Yet other organisms, such as some prokaryotes, even ‘eat’ reduced inorganic molecules such as hydrogen sulfide. All organisms, however, process the energy that they capture through chemical reactions that take place in cells. The sum total of the biochemical reactions in an organism, and thus the energy processing that an organism performs, is called metabolism.

Slide 4 As you learned in a previous lesson, metabolic pathways occur in a series of steps. In this way, transfers of energy occur in small, carefully controlled steps, and organisms are able to more efficiently process energy. Each step in any metabolic pathway is catalyzed by a specific enzyme. As an example, take glycolysis. During glycolysis, glucose is partially oxidized to two molecules of pyruvate, in the process releasing energy that is used in the formation of ATP and $\text{NADH} + \text{H}^+$. This entire process occurs in ten distinct steps, each step catalyzed by a different and specific enzyme.

Slide 5 In our discussions of metabolism, we will focus on the metabolic pathways of cellular respiration and photosynthesis. As we discuss these pathways, take a moment to look at the big picture, and you should see a surprising number of similarities between these two metabolic processes. First, consider how carbon moves through the pathways of photosynthesis and respiration. In photosynthesis, carbon in the form of carbon dioxide is captured and reduced to form carbohydrates. This process requires energy, because carbon dioxide is being reduced. Where does the energy come from? The energy for photosynthesis is supplied by sunlight.

Respiration is quite the opposite of photosynthesis. In respiration, the six-carbon sugar glucose is oxidized to six molecules of carbon dioxide, in the process releasing its energy. Where does the energy go? During respiration, the energy that was stored in glucose is transferred to the chemical bonds of other molecules, perhaps most importantly ATP, which serves the immediate energetic needs of the cell.

So as you learn about the metabolic pathways of photosynthesis and respiration over the next several lessons, it may be useful to follow the flow of energy through these

pathways, almost like following the proverbial bouncing ball. Energy flows into the pathways in some form – in photosynthesis the initial energy comes from light, in respiration it comes from the chemical bonds of glucose. During each process, that energy is transferred between different chemical compounds, or into different forms. Energy also flows out of the pathways – in photosynthesis it leaves as energy stored in the chemical bonds of carbohydrates, in respiration it leaves as the chemical bond energy of ATP.

Slide 6 A second feature you will note in both photosynthesis and respiration is that each process has at least one cyclic metabolic pathway. In photosynthesis, there is the Calvin-Benson cycle, also known as the ‘dark reactions.’ In respiration, there is the citric acid cycle, also known as the Krebs or TCA cycle. The metabolic cycles of photosynthesis and respiration follow a very similar pattern. First, there is a fixation step, where a specific type of carbon molecule is fixed, or bound, by a receptor molecule. Second, there are a series of steps that involve transferring energy to or from the fixed carbon. In other words, carbon is either oxidized or reduced. In the Calvin-Benson cycle, fixed carbon dioxide is reduced into carbohydrate, which may leave the cycle. In respiration, fixed carbon is oxidized into carbon dioxide, which then leaves the cycle. Lastly, there is a regeneration step which serves to regenerate the original acceptor molecule, so that the cycle can continue.

Slide 7 A third feature that both respiration and photosynthesis share is a process called oxidative phosphorylation. Oxidative phosphorylation is an important way of producing ATP for the cell. As you can see from the illustrations on this slide, this process involves a sequence of oxidation-reduction reactions occurring in membrane-bound protein complexes. This sequence is often referred to as an electron transport chain.

In electron transport chains, high energy electrons enter the chain from a donor molecule. The donor molecule is thus oxidized, while the molecule that receives electrons is reduced. Electrons are then passed to a second carrier molecule in a second oxidation-reduction reaction. In the process the first carrier is oxidized, and the second carrier is reduced. The electrons are likewise passed to a third carrier, to a fourth, and eventually to a final electron acceptor. As electrons move through this chain of reactions, they lose a little bit of energy each time they are transferred from one carrier to another. In addition, protons often move with the electrons to keep the charge balance of the electron carriers. At some points, the energy given off by the electrons is used to move protons completely across the membrane in one direction, resulting in a proton gradient, or a higher concentration of protons on one side of the membrane.

The proton gradient resulting from electron transport represents a store of potential energy. Since protons cannot pass directly back through the membrane on their own, their energy is similar to the potential energy of water stored behind a dam.

While protons can’t move directly back through the lipid bilayer of the membrane, they are able to flow across the membrane and back down their concentration gradient by

moving through a large membrane-bound protein complex called ATP Synthase. When protons flow through ATP Synthase complexes, their movement causes part of the complex to rotate. This rotational energy is then used to synthesize molecules of ATP, which can then be used by the cell.

Again, it may help to think about the transfers of energy that occur during oxidative phosphorylation to understand this process. First, high energy electrons enter the electron transport chain. Their energy is transferred into the potential energy of a proton gradient through a series of oxidation-reduction reactions. The potential energy of the proton gradient is then transferred to the kinetic energy of ATP Synthase when protons flow down their concentration gradient through this protein complex, causing part of it to rotate. Finally, the kinetic energy of the rotating ATP synthase is transferred into the potential energy of the bonds of ATP. Now can you follow that bouncing ball?

Slide 8 While we've spent a fair amount of time now talking about the importance of metabolism in terms of energy, you should note that metabolism is significant to organisms for other reasons, as well. Metabolism is also the way in which essential molecules are synthesized for cells. You may recall from the first section of this course that there are twelve chemical compounds, called the twelve key intermediates, that are used to synthesize virtually all of the molecules that cells and organisms need to survive, grow, and reproduce.

These twelve key intermediates play important roles in the metabolic pathways of photosynthesis and respiration. For example, oxaloacetate, one of the twelve key intermediates, is the acceptor molecule for the Citric acid cycle of respiration. Triose phosphate, another of the twelve key intermediates, is the carbohydrate that is produced by the Calvin-Benson cycle of photosynthesis. Since the twelve key intermediates play important roles in both photosynthesis and respiration, it should not be too surprising that these pathways are linked to other metabolic pathways of the cell, such as the anabolic pathways that cells use to build macromolecules like proteins, nucleic acids, and lipids.

Consider, too, that such anabolic pathways can run in reverse as catabolic pathways. Because of this, all types of macromolecules – proteins, lipids, nucleic acids, and carbohydrates – can be produced by or can feed into the pathways of photosynthesis and respiration at various points.