BIOL 300 – Foundations of Biology
Summer 2017 – Telleen
Lecture Outline

Energy Conversion: Photosynthesis, Cellular Respiration, and Fermentation

Photosynthesis

I. An Overview of Photosynthesis

A. Life is powered by light from the sun. Energy from light is harvested by plants, algae, and some bacteria in a process called **photosynthesis**. However, only about 1% of the total light energy is actually used. The other 99% is instead reflected and generates heat.

B. Photosynthesis occurs in the plasma membrane of bacteria, inside algal cells, and in the leaves (and other green parts) of plants.

C. Our focus will be on plants, in which photosynthesis occurs in organelles called **chloroplasts**.

D. There are three stages of photosynthesis:
   1. Capturing energy from sunlight
   2. Using the energy to make ATP and **NADPH** (an electron carrier like NADH)
   3. Using ATP and NADPH to fix CO_2 from the air to form carbohydrates

D. 1 and 2 take place in the presence of light (since this is where light energy is captured and initially used). These are called the **light-dependent reactions**.

E. 3 (basically the process of organic molecules from CO_2) is called the **Calvin Cycle** (or **light-independent reactions**). They are still indirectly dependent on light (since they are using the ATP and NADPH from stages 1 and 2), but they can take place while there is no light as long as there are available ATP and NADPH.

F. Photosynthesis can be summarized by the following equation:

$$\mathbf{6CO_2 + 12\ H_2O + light \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2}$$

carbon dioxide water glucose water oxygen

G. Chloroplast structure
   1. Chloroplasts are located inside certain plant cells and are responsible for the green color of most plants. Under a microscope, it becomes clear that the green color is localized to the chloroplasts
   2. Chloroplasts are surrounded by an outer membrane, but they also have an inner membrane. The inside cavity is called the **stroma**.
   3. Within the stroma are more internal membranes organized into flattened sacks called **thylakoids**. They often form columns called **grana** (singular = granum).
   4. Embedded in the thylakoid membranes are complexes of **chlorophyll** (the primary light absorbing pigment) and proteins called **photosystems**.
   5. The light dependent reactions take place in the thylakoid membranes, while the Calvin Cycle/light-independent/dark reactions take place in the stroma

In summary: Photosynthesis uses energy from the sun to build organic molecules out of CO_2 in the air. Plants perform photosynthesis in specialized organelles called chloroplasts.

II. Harvesting Light Energy

A. Physics tells us that light is actually tiny packets of energy called **photons**
B. Sunlight contains photons of many different energy levels. We can only see some of them (this is called visible light for obvious reasons). We can only see those wavelengths that are absorbed by pigments in our eyes called retinal. Chlorophyll, the main photosynthetic pigment absorbs mostly red and blue light (and reflects green light, which is why plants look green). X rays and ultraviolet (UV) light carry lots of energy, while others, like radiowaves, carry very little. The amount of energy depends on the wavelength of the photons (less energy = bigger wavelength). The full range of different wavelengths of photons is called the electromagnetic spectrum.
C. **Pigments** are molecules that absorb light energy (such as retinal in eyes and chlorophyll in plants, though there are many others).
D. There are actually two different types of chlorophyll, called chlorophyll a and chlorophyll b, which absorb slightly different wavelengths of light. Other pigments called **carotenoids** also absorb some light in photosynthesis.

III. Organization of Photosystems and the Light-Dependent Reactions

A. The light-dependent reactions always occur on membranes in protein-pigment complexes called **photosystems**.
B. The light-dependent reactions take place in five stages: (see text for diagram)

1. **Capturing light –** a photon of light (of the appropriate wavelength) is absorbed by a pigment molecule. Then the excitation energy is passed around from one pigment molecule to another.
2. **Exciting an electron –** the excitation energy is finally moved to a chlorophyll a molecule, called the **reaction center**. The excitation energy causes the reaction center to become oxidized (lose and electron) and reduce another molecule (an electron acceptor). The reaction center replaces the lost electron by stealing one from a water molecule (resulting in oxygen as a by-product).
3. **Electron transport –** The excited electron is shuttled through a series of carrier molecules in the membrane (in a manner similar to cellular respiration), called the **electron transport system**. The energy from the electron is removed in small amounts at each step and used to pump protons (again, very similar to cellular respiration).
4. **Making ATP –** the proton concentration gradient built using the energy from the electron is then used make ATP by **chemiosmosis**. This ATP will be used in the Calvin Cycle to make carbohydrates.
5. **Making NADPH –** The electrons leave the electron transport system to another photosystem where they are reenergized by another photon (similar to steps 1+2). The excited electron is then shuttled to another electron transport system. This time the energy is used to make a molecule called **NADPH**, which is critical for the Calvin Cycle, instead of ATP.

C. There are two different photosystems in plants and algae. Photosystem II absorbs the initial photon and produces the energy to make ATP, while photosystem I absorbs the second photon for re-excitation and provides the energy to make NADPH.

D. Overall, the light-dependent reactions produce ATP and NADPH, which are needed to build organic molecules, and produce O_2 as a by-product as they strip electrons (and protons) from water.

IV. The Calvin Cycle: Building New Molecules

A. The Calvin Cycle is the process of making organic molecules from CO2. The raw materials for this are provided by the light-dependent reactions:

1. Energy – in the form of ATP, to drive endergonic reactions
2. Reducing power – in the form of NADPH, to provide hydrogen (protons) and the energetic electrons needed to bind them to carbon atoms

B. We often refer to this process as 'fixing' carbon because the carbon is being converted from a gas into part of an organic molecule. Each turn of the Calvin Cycle fixes one carbon, so the cycle must turn 6 times to get one glucose molecule.

C. The Calvin Cycle begins when a carbon from CO2 is added to a five-carbon molecule called RuBP (ribulose-1,6-bisphosphate). This step is catalyzed by an enzyme called Rubisco (which stand for RuBP carboxylase/oxygenase). Rubsico is the most abundant protein in chloroplasts and is thought to be the most abundant protein on Earth! The resulting six-carbon molecule is unstable and immediately splits into two 3-carbon molecules.

D. Next, a series of reactions uses energy from ATP and hydrogens (and electrons) from NADPH to reduce the three-carbon molecules. These newly reduced molecules can then be combined to form glucose (or used to make other organic molecules). However, most of the reduced three-carbon molecules (and some of the ATP) are actually used to regenerate the five-carbon starting material (RuBP) so the cycle can repeat.

E. The Calvin Cycle is sometimes called C3 photosynthesis, but there are a few different variations on it:

1. Some plants have trouble carrying out C3 photosynthesis in hot conditions. As temperature increases, these plants must close the openings on there leaves (called stomata) to conserve water, but this prevents CO2 and O2 from entering and leaving. This leads to a loss of CO2 and a build up of O2. Under these conditions, rubisco doesn't work properly and incorporates O2 instead of CO2 (in a process called photorespiration). Some plants (such as sugarcane and grasses) use C4 photosynthesis to get around this. They initially fix carbon into a four-carbon molecule (oxaloacetate), which is then moved to different cells where it can be broken down into CO2 which can finally be incorporated into the Calvin Cycle.
2. Another strategy to decrease photorespiration, called crassulacean acid metabolism (CAM), is used by many succulent plants such as cacti. It is similar to C4 photosynthesis but the initial fixation into a four-carbon molecule and the release of CO2 entering the Calvin Cycle are still located in the same cell and are instead separated temporally (they occur at different times of day).

Cellular Respiration

I. Cellular Respiration: An Overview

A. **Cellular respiration** is the process of breaking down and oxidizing organic molecules to make **ATP**.

B. As I've mentioned before, all energy in living systems originally comes from the sun via photosynthesis. We'll talk about that next time; for now we'll focus on the process of breaking down the organic molecules generated by photosynthesis that are common to most organisms.

C. There are two basic types of cellular respiration:

1. **Aerobic respiration** requires oxygen to form ATP as electrons are harvested, transferred along an electron transport chain, and finally donated to oxygen gas. Most eukaryotes get their energy this way.
2. **Anaerobic respiration** does not require oxygen, but does not yield as much ATP. We'll return to this later.

D. The overall equation for cellular respiration is essentially the same as burning wood: Carbohydrates and Oxygen are converted into Carbon Dioxide, Water, and Energy (either ATP or heat):

$$\mathbf{C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy (heat or ATP)}}$$

E. There are two stages of cellular respiration

1. **Glycolysis** partially breaks down sugars and uses the energy to make ATP. This occurs in the cytoplasm and does not require oxygen. In fact, this ancient process is thought to be over 2 billion years old and evolved prior to oxygen in the atmosphere.
2. **Oxidation** only occurs in mitochondria and includes the **Kreb's Cycle** and **electron transport chain**. It is produces a lot more ATP than glycolysis, but it requires oxygen.

II. Glycolyis

A. **Glycolysis** is a series of sequential biochemical reactions (called a biochemical pathway) and uses 10 enzyme-catalyzed reactions to convert a six-carbon sugar (**glucose**) into two three-carbon sugars (**pyruvate**) and ATP.

B. Glycolysis is said to use coupled reactions because the breaking of bonds is coupled with the formation of ATP (from ADP). That is, the energy released from the bond breaking is used to make ATP. The phosphates (P_i) are provided by the molecules being broken down and transferred to the ADP. This process is called **substrate-level phosphorylation**.

C. This process also uses electron carrier molecules called **NAD**$^+$ (which can carry a proton and an electron as **NADH**). These harvested electrons can be extracted during oxidation.

D. Glycolysis doesn't make very many ATP, but it is the only way to get energy from food without oxygen. In fact, glycolysis uses up two ATP!

E. Glycolysis is one of the earliest of all biochemical processes to evolve. All known cells can perform glycolysis. Even though it isn't efficient, it forms the basis of all metabolism so it has remained important. New reactions have been added (like oxidation!), but this is a good example of how evolution builds on what is already there.

F. There are 10 basic steps of glycolysis. You should understand the basic idea, but I won't expect you to know the names of the molecules (except glucose, pyruvate, NAD(H), and ATP). See your text for helpful diagrams:
   1. Phosphorylation of glucose by ATP to produce Glucose-6-phosphate
   2. Rearrangement of the molecule to produce Fructose-6-phosphate
   3. Another phosphorylation by ATP to produce Fructose-1,6-bisphosphate

   4/5. Fructose-1,6-bisphosphate is cleaved to produce two Glyceraldehyde 3-phosphate (G3P)

   6. Oxidation followed by phosphorylation of G3P produces two NADH and two 1,3-bisphosphoglycerate (BPG)
   7. Removal of a high energy phosphate from each BPG produces two ATP and two 3-phosphoglycerate (3PG) molecules
   8. Phosphates are moved from 3PG to produce 2-phosphoglycerate (2PG)
   9. Water is removed from each 2PG to produce phophoenolpyruvate (PEP)
   10. The high energy phosphates are removed from PEP producing two ATP and two pyruvate molecules.

G. Note that at step 4 the process is doubled because there are two G3P molecules produced from a single fructose-1,6-bisphosphate.

H. Thus, the entire process uses up two ATP, but produces 4 ATP and 2 NADH. This is a net gain of two ATP and two NADH.

III. Anaerobic Respiration

A. In the presence of oxygen, eukaryotic organisms uses aerobic respiration, which occurs in two stages, the second of which (Oxidation) requires oxygen (to be reduced by the electrons carried by NADH). Respiration that does not require oxygen is called **anaerobic respiration**.

B. Some organisms can still carry out oxidation reactions by using molecules other than oxygen as their final electron receptors. Examples of this are **Methanogens**, archaea that live in various extreme conditions and use CO_2 as their final electron receptor (producing methane (CH_4)), and **Sulfur bacteria**, which use sulfate (SO_4) as an electron receptor producing hydrogen sulfide (H_2S).

C. What about happens to pyruvate if there is no oxidation? This ends up in a process called **fermentation**. Recall that NAD^+ is reduced during glycolysis to form NADH. If there is no way to get more NAD^+, glycolysis will stop! So the electrons that would be destined for oxidation reactions in aerobic cells, must get put somewhere to regenerate NAD^+. Any process that adds the extracted electrons to an organic molecule is called **fermentation**.

D. There are two basic types of fermentation that are common. One method is to simply add the electrons back to pyruvate to form lactate. This is what happens when you muscles get sore/burn from strenuous exercise. If your cells don't get enough oxygen, they still can do glycolysis to produce energy, but they build up lactic acid (lactate).

E. Yeast (single celled fungi) have a different fermentation method. They convert pyruvate into another molecule by removing a carbon (as CO_2). Then they add back the electrons to produce ethyl alcohol (or ethanol). Yeast only ferment in the absence of oxygen. This is the same process that is used to make beer, wine, and spirits!

F. There are other types of fermentation, but we won't talk about them.

IV. Oxidation, the Kreb's Cycle, and Electron Transport

A. The first step in oxidation is the conversion/oxidation of pyruvate into **acetyl-CoA** (Coenzyme A), which can then be further oxidized in the **Kreb's Cycle**

B. As CO_2 and an electron are removed from pyruvate, the remaining two carbons are added to a carrier molecule called Coenzyme A, forming acetyl-CoA. Acetyl-CoA is used in the metabolism of proteins, lipids, sugars, and ATP.

C. If a cell needs ATP, the acetyl-CoA is fed into the Kreb's Cycle, where it is further oxidized to make ATP.

D. NAD^+ carries electrons by harvesting hydrogen atoms (both the proton and electron) from energy rich molecules and shuttling them to other acceptor molecules

E. The **Kreb's Cycle** is the major oxidation pathway and occurs only in mitochondria. It is named after the man who discovered it (after next time think about how it is distinct from the Calvin Cycle in photosynthesis!). There are 3 basic stages

   1. Acetyl-CoA joins the cycle and adds it's two carbons to a four-carbon molecule to make a six-carbon molecule (citrate).
   2. Two carbons are removed (as CO_2), their electrons are donated to NAD^+ (making NADH), and a four-carbon molecule is left. An ATP is also produced.
   3. More electrons are extracted forming $FADH_2$ and additional NADH, which regenerates the original four-carbon starting material so the cycle can start again. (FADH is an electron carrier like NAD^+).

F. **Glucose is entirely consumed in this process**: First, it is broken down into pyruvate in glycolysis (producing 2 ATP and 2 NADH). Then each pyruvate is cleaved to produce Acetyl-CoA (losing one carbon as CO_2 but collecting an electron in NADH), which feeds into the Kreb's Cycle. The Kreb's Cycle releases the final two Carbons from each pyruvate and harvests the useful electrons (one ATP, three NADH, and one $FADH_2$). **So the net result of the break down of glucose is 6 CO_2 and its energy preserved as 4 ATP, 10 NADH, and 2 $FADH_2$.**

G. Electron Transport Chain

   1. **The electron transport chain** uses the protons and electrons from the reduced forms of NADH and $FADH_2$. The protons/electrons are transferred to a series of membrane associated molecules (collectively called the **electron transport chain**). All of this occurs in the inner mitochondrial membrane.
   2. A proteins carrier receives the electrons, which are passed on to a mobile carrier, and then to a second protein complex. These protein

complexes act as proton pumps which use the electrons to pump protons into the intermembrane space (generating a proton gradient!)

3. The electrons are eventually transferred to a third protein complex which uses 4 electrons to reduce 2 oxygen atoms forming two H_2O molecules (from O_2, 2 H^+, and 4 e^-).
4. As we'll see this process is fairly similar to electron transport in photosynthesis. But the work still isn't finished. We get all the ATP from the H^+ concentration gradients generated by electron transport…

H. Chemiosmosis

1. Aerobic respiration takes place in the mitochondria. The Kreb's Cycle takes place within the **matrix**, while electron transport occurs in the inner mitochondrial membrane. Electron transport generates a high H^+ concentration in the innermembrane space between the inner and outer mitochondrial membranes
2. In addition to the electron transport complexes, there are also proteins in the inner membrane called **ATP Synthase**. As the name implies, they synthesize ATP using **chemiosmosis** (like we discussed last week!). ATP synthase are the coupled channels that allow protons to diffuse back into the matrix while harvesting some of the energy of the concentration gradient to make ATP (from ADP and P_i).
3. A total of **32 ATP are made from chemiosmosis** for each glucose molecule oxidized. So the total yield of ATP from one glucose molecule is:

-2 (input) + 4 (glycolysis) + 2 (Kreb's Cycle) + 32 (Chemiosmosis) = 36 ATP

V. Other Sources of Energy

A. We have been discussing how cells can get energy from sugar molecules, but what about other organic molecules? For example, fats are used to store energy. How do cells utilize that energy?

B. It turns out that all biochemical reactions within cells are connected into a large series of biochemical pathways.

C. Cells can convert amino acids to sugars, sugars to lipids, lipids to acetyl-CoA, nucleotides to amino acids, and so on

D. Thus, the entire metabolism of cells is connected and almost every molecule can be converted from one form to another. Cells can break down almost anything (including proteins and DNA) for energy.