Lesson 24: Chemistry in the Body, aka, Biochemistry

Lesson Objectives:

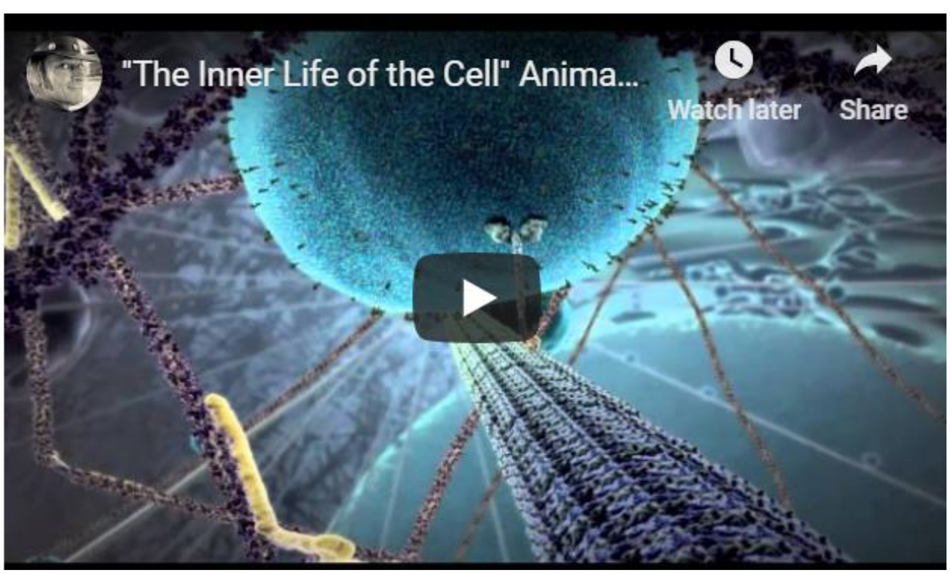
- Students will identify the functions of the four primary biological macromolecules.

Getting Curious

Welcome to your final chemistry lesson! All of the chemistry you have learned thus far has implications that go far beyond simply chemistry. For example, the union of biology and chemistry is an important field known as biochemistry that profoundly affects medicine and scientific research on new drugs. In this lesson, we will cover the very basics of biochemistry, so you can get a small idea of the important uses of chemistry in today's world.

Start off by watching this video of how biological macromolecules behave inside a cell:

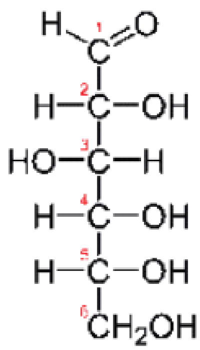
Everything you saw in that video is a scientist's and artist's best interpretation of the biochemical processes that occur inside the cell. Keep working through this lesson to learn more about the biochemistry of the participating molecules!



Carbohydrate Structure

Carbohydrates are a class of organic compounds in which each carbon in the chain is bonded to an oxygen atom, either through a single bond to an OH group or through a double bond, making a carbonyl. The name comes from the fact that the chemical formula for a carbohydrate can be written in the form $C_n(H_2O)_n$, where n is some integer. However, carbohydrates are not actually "hydrates of carbon." No water molecules are actually present, and each oxygen in the formula is bonded to at least one carbon atom.

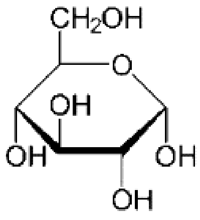
One of the most important carbohydrates is glucose, shown in the picture below.



https://commons.wikimedia.org/wiki/File:D-glucose-chain-2D-Fischer.png

Structure of glucose, a typical carbohydrate.

When dissolved in water, most of the glucose molecules are not actually present in the form represented in the picture above. Instead, one of the oxygen atoms near the end of the chain becomes bonded to the carbonyl carbon, and a subsequent transfer of hydrogen results in the cyclic structure shown in the picture below.



http://commons.wikimedia.org/wiki/File:Alpha-D-Glucopyranose.svg

Cyclic structure of glucose.

Because six-membered rings are particularly stable, the oxygen atom used to form the ring will generally be on a carbon atom that is five away from the carbonyl. If such a situation is not possible, five-membered rings can also be formed. Rings of other sizes are generally less favorable than the open-chain form and will not be present in large amounts.

Dietary Consumption and Digestion of Carbohydrates

There are several dietary sources of carbohydrates. Starch is found in many vegetables (especially potatoes) and baked goods. Sucrose (table sugar) is included as part of many prepared foods. Lactose is found in milk products, and maltose is present in some vegetables.

A small amount of starch digestion will occur in the mouth, but the bulk of this process occurs in the small intestine. Amylase, an enzyme produced in the pancreas and released into the interior of the small intestine, breaks complex carbohydrates like starch into disaccharides and trisaccharides. These molecules are then cleaved into their corresponding monosaccharides by specific enzymes located in the interior wall of the small intestine.

Disaccharide	Enzyme	Products
sucrose	sucrase	glucose + fructose
lactose	lactase	glucose + galactose
maltose	maltase	glucose + glucose

Many people have very low levels of the lactase enzyme. As a result, lactose (found in most dairy products) accumulates in the small intestine, since it cannot be fully digested. This can result in bloating, cramps, abdominal distress, and nausea. Reduction or elimination of lactose in the diet is the most effective treatment.

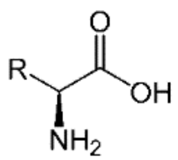
Cellular Utilization of Carbohydrates

What happens after complex carbohydrates have been broken down into simple monosaccharides? When energy is needed, glucose is broken down further via a multi-step process called **glycolysis**, which means “splitting of glucose.” All common monosaccharides can be converted by the body to glucose or to some other intermediate along the glycolytic pathway. The key “splitting” reaction occurs when the enzyme aldolase splits fructose-1, 6-disphosphate into two three-carbon compounds. These two compounds then interconvert and form two molecules of pyruvate, the end-product of the glycolytic pathway.

Pyruvate then enters an intracellular organelle called the mitochondrion (plural: mitochondria). Through a complex series of processes including two separate pathways, the cell uses O_2 and pyruvate to form, among other things, a molecule known as ATP. This compound is essential for many biochemical reactions as well as for processes such as muscle contraction and movement of materials across cell membranes.

Amino Acids

Amino acids are a class of molecules that contain both the carboxylic acid and amine functional groups. Amino acids are key building blocks in biological systems. The most common biologically relevant amino acids have the generic structure shown in the picture below, in which a central carbon atom is connected to an NH_2 group, a CO_2H group, and a variable R group.

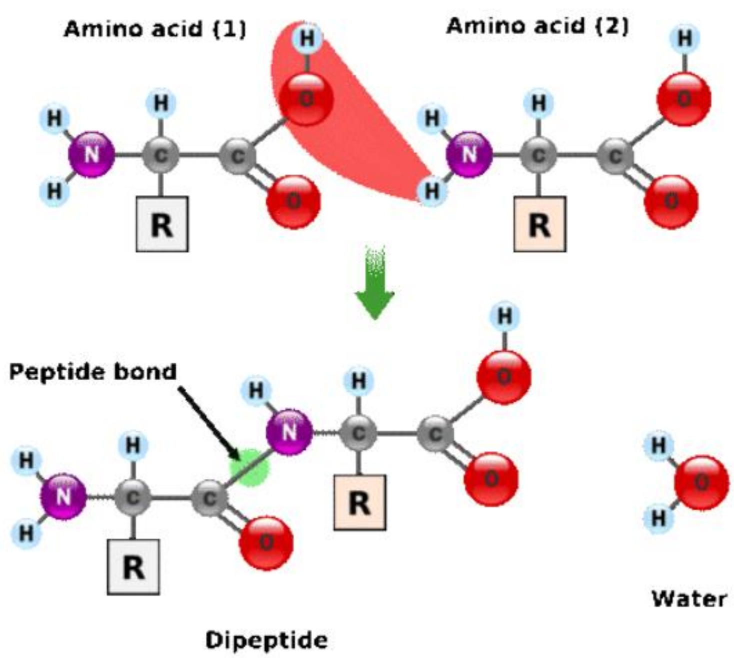


http://commons.wikimedia.org/wiki/File:L-Aminos%C3%A4ure_Rest.svg

Generic amino acid.

The only difference between one amino acid and another is the structure of the R group. In the simplest amino acid, glycine, the R group is just a hydrogen atom. However, other common amino acids may involve alcohols, amines, carboxylic acids, or aromatic rings.

Many amino acids can be linked together to form a long chain known as a **protein**. These linkages are formed when the carboxylic acid of one amino acid reacts with the amine of another to produce an amide.



https://commons.wikimedia.org/wiki/File:Peptidformationball.svg

Peptide bond in protein.

In the context of proteins, the newly formed bond between the carboxyl carbon and the amine nitrogen is referred to as an amide bond or a peptide bond.

Protein Structure

The structural features of complete proteins can be broken down into four levels, referred to as primary, secondary, tertiary, and quaternary structures. These levels are illustrated in the picture below.

http://commons.wikimedia.org/wiki/File:Main_protein_structure_levels_en.svg

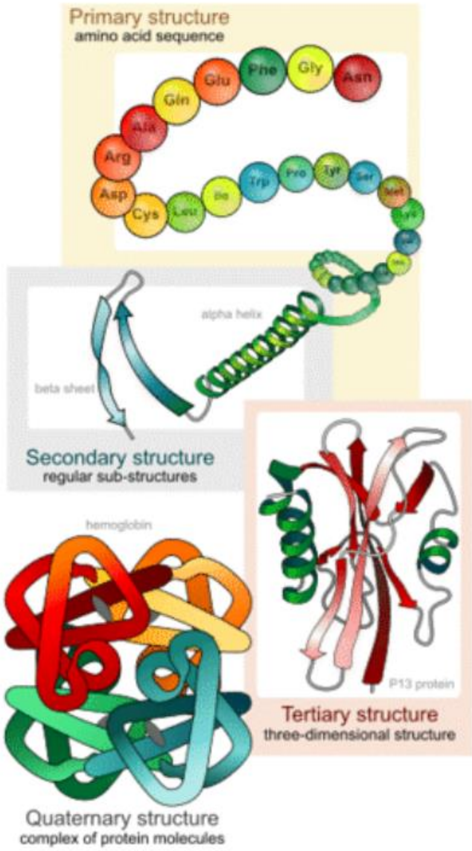
Hierarchy of protein structure.

The **primary structure** of a protein is simply the sequence of amino acids from which it is constructed. By convention, this sequence is written starting with the N-terminal amino acid, which has a free $–NH_2$ group, and ending with the C-terminal amino acid, which has a free carboxylic acid.

The **secondary structure** of a protein refers to local coiling or folding. This aspect of the structure applies only to a section of the protein, not the entire structure. The two basic forms of secondary structure are the **alpha helix** and the **beta sheet**. Because they have to do with the ways that multiple amides pack together, one or both of these substructures show up in most long protein strands. The appearance of alpha helices and beta sheets can be predicted fairly well (by computers) from the primary sequence of amino acids.

Tertiary structure refers to the overall three-dimensional shape of an entire protein chain. Because of the ways that proteins can fold in on themselves, tertiary structure often involves interactions between amino acids that are very far apart in the primary sequence. Ultimately, this is also dependent on the primary sequence of the protein, but because of these long-range interactions, predicting tertiary structures from sequences of amino acids is still very difficult.

Quaternary structure refers only to proteins in which more than one chain of amino acids interact to form a single functional structure. If a protein consists of only a single chain, it does not have any quaternary structure. The separate subunits in such a protein are held together by ionic bonds and various types of intermolecular forces, especially hydrogen bonds. They are not covalently bonded to one another, so the individual chains can be separated and studied individually. These subunits can also be recombined to form the original protein.



http://commons.wikimedia.org/wiki/File:Succinate_Dehydrogenase.jpg

Structure of succinate dehydrogenase.

In the picture above, we see the quaternary structure of an enzyme called succinate dehydrogenase. Four different peptide chains, each drawn in a different color, combine to form the fully functional protein. Again, the four chains are not covalently bound to one another, but they are held together by various other attractive forces. A number of alpha helix groups can also be seen in this structure, especially in the orange and blue subunits.

Protein Functions

Proteins play a variety of important roles in biochemical systems. Some of the most common protein functions are listed below:

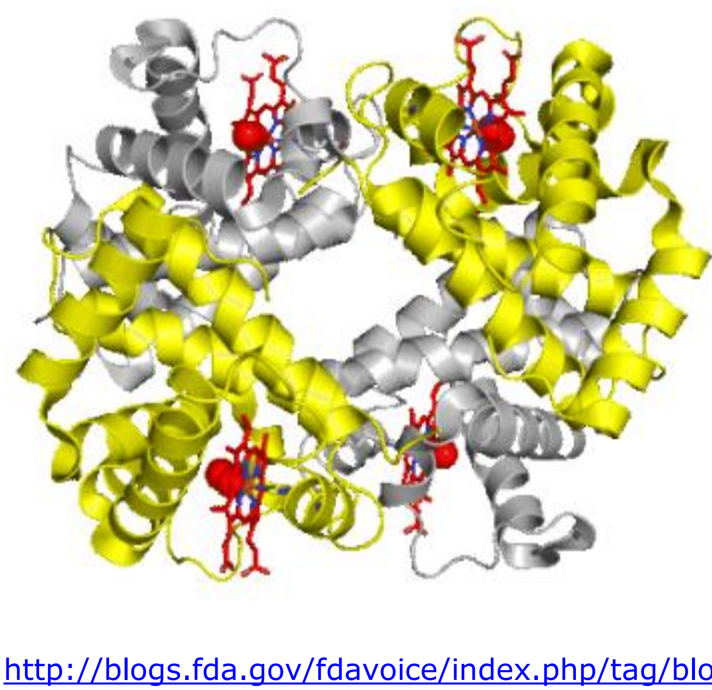
1. Structural – Support for tissues is provided by structural proteins. For example, collagen is a structural protein that provides a matrix in which bones can develop. Calcium phosphate deposited on a collagen scaffold provides the basis for forming strong bones.
2. Enzymes – Enzymes are used to catalyze biochemical reactions. We will look more at this class of proteins in the following section.
3. Hormones – Hormones are molecular signals that help regulate a number of biochemical processes. Single amino acids and short protein chains are very common types of hormones. For example, insulin is a protein

hormone that regulates the amount of glucose present in the bloodstream.

4. Antibodies – These proteins recognize and combine with harmful materials, including both toxic chemicals and invasive microorganisms (such as bacteria and viruses). When an antibody binds to its target, it is tagged for destruction. This tag is recognized by white blood cells, which complete the process. Some antibodies also partially or completely deactivate their targets while waiting for further help from white blood cells.
5. Transport – Some proteins bind to specific materials and carry them around the body through the bloodstream to a place where they are currently needed. For example, transferrin shuttles iron in and out of cells. Hemoglobin is an extremely important protein that binds to molecular oxygen and carries it throughout the body. We will discuss hemoglobin further in its own section.
6. Storage – The body does not like to get rid of materials that it might find useful later. Storage proteins such as albumin preserve amino acids until they are needed.

Hemoglobin

Hemoglobin is a large iron-containing protein that binds to oxygen molecules and transports them around the body. There are four subunits (separate chains) in the hemoglobin complex – two alpha subunits and two beta subunits. Each subunit contains one iron ion. Its oxidation state changes back and forth between +2 and +3, depending on whether it is bound to oxygen.



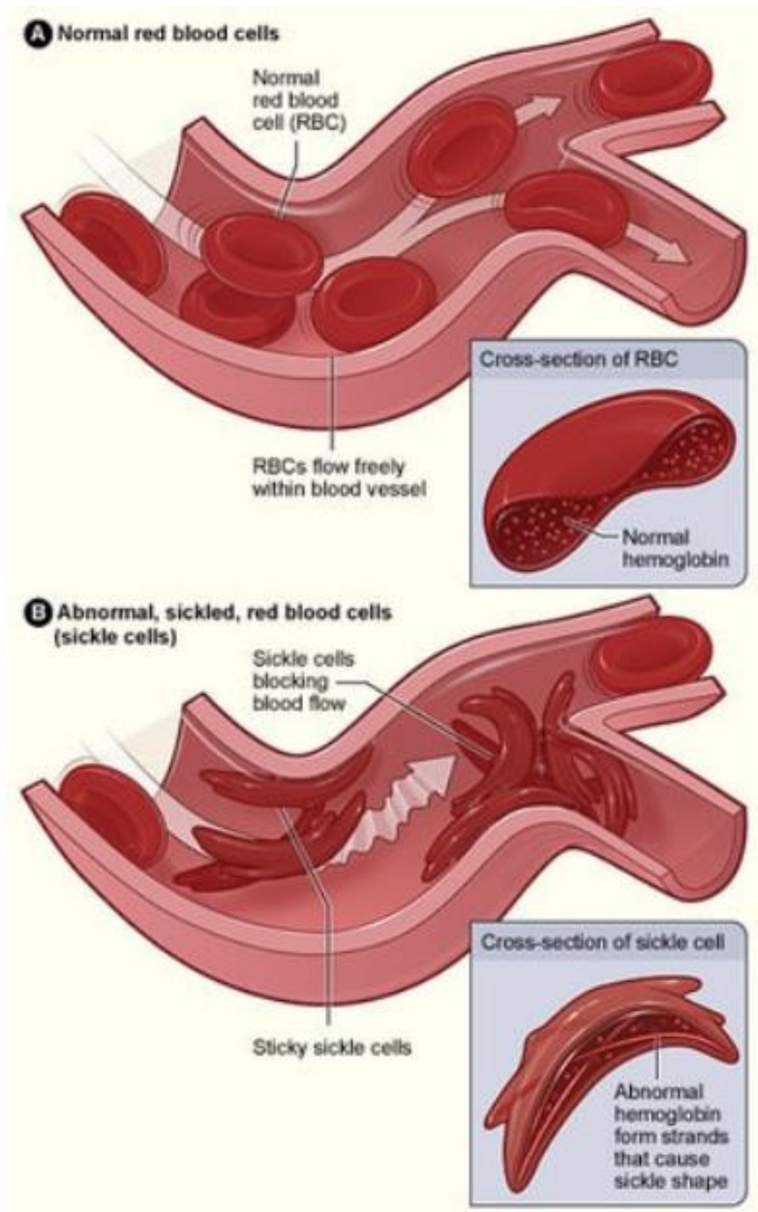
http://blogs.fda.gov/fdavoice/index.php/tag/blood-substitutes/

Hemoglobin molecule.

The yellow subunits are identical in structure, as are the gray subunits. A smaller organic structure called a porphyrin ring is attached to each protein subunit and contains the iron ion used to bind oxygen.

When the oxygen binds to the iron, the three-dimensional shape of the molecule changes. Upon release of the oxygen to the cells, the shape changes back.

Some individuals have a specific mutation in the primary sequence of their hemoglobin molecules that causes them to aggregate, resulting in a deformation of their red blood cells. This abnormality is genetic in nature. A person may inherit the gene from one parent and have sickle cell trait (only some of the hemoglobin is hemoglobin S), which is usually not life-threatening. Inheriting the gene from both parents will result in sickle cell disease, which is a very serious condition.



https://commons.wikimedia.org/wiki/File:Sickle_cell_01.jpg

Sickling in red cells due to presence of hemoglobin S.

Questions: Copy and paste question 1 in the Submit Box at the bottom of this page, and answer the questions **before** going any further in the lesson:

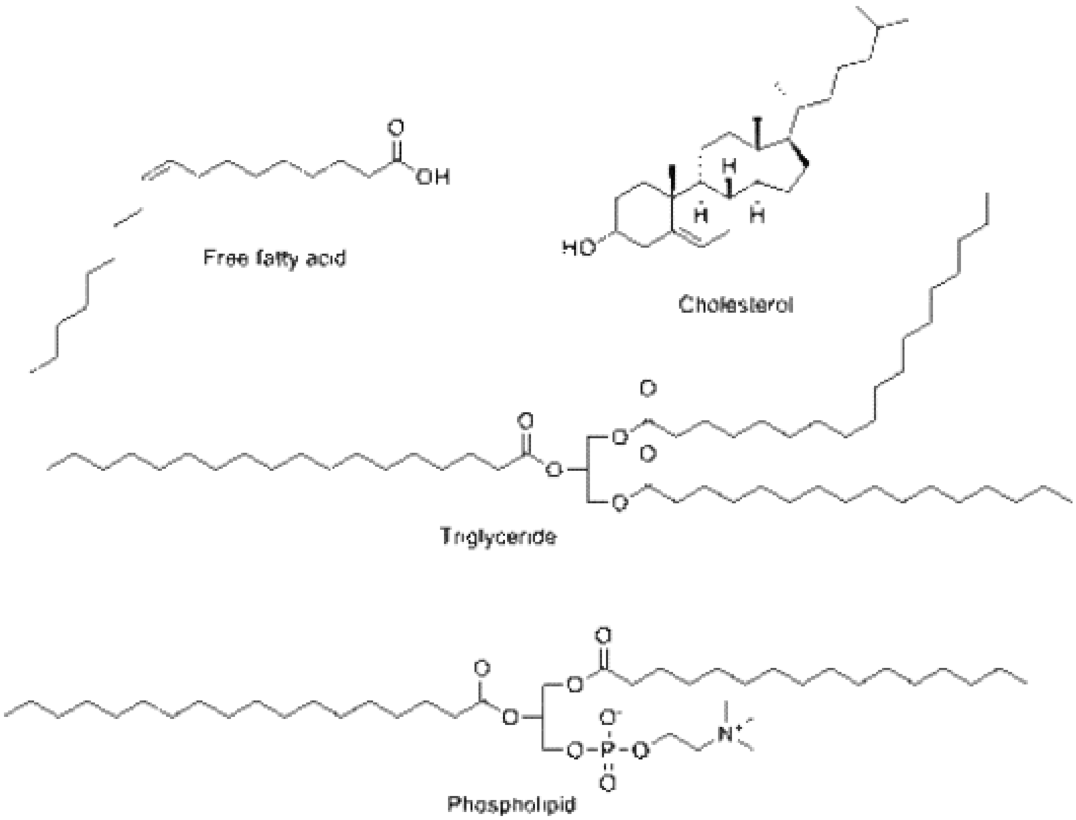
Draw a diagram showing how two amino acids form a peptide bond. Upload the picture with your lesson.

Classes of Lipids

In the lesson on carbohydrates, we saw that monosaccharides all have a similar structure, but with slight variations. Many monosaccharides can then be linked together to form long polysaccharide chains. Similarly, amino acids all share some of the same structural features, and linking many amino acids together results in the formation of proteins. In contrast, lipids constitute a much broader class of compounds. A **lipid** is a biological molecule that is soluble in nonpolar solvents. This also means that lipids are generally not very soluble in polar solvents, such as water. Because of this characteristic, lipids in the body generally cluster together in order to minimize contact with water, and transportation of lipid molecules throughout the body requires that they be reversibly attached to various transport proteins. A lipid bonded to a protein is referred to as a **lipoprotein**.

In the picture below, we see the structures of some common classes of lipids. Free fatty acids are carboxylic acids that contain long hydrocarbon chains. Saturated fatty acids are alkanes with a single carboxylic acid, whereas unsaturated fatty acids contain one or more C-C double bonds. Another common structure is a phospholipid, in which two of the alcohols in glycerol form esters with fatty acids, and the third is connected to a very polar phosphorus-containing group.

Cholesterol is also considered to be a lipid, even though its structure is very different from the ones we have discussed so far. Cholesterol belongs to a broader class of lipids called **steroids**, all of which possess the same four-ring hydrocarbon core. Other common steroids include cortisol, testosterone, and estrogen.



http://commons.wikimedia.org/wiki/File:Common_lipids.png

Classes of lipids.

In addition to the categories of lipids listed above, various vitamins are also classified as lipids, including vitamins A, D, E, and K. You may sometimes hear these referred to as "fat-soluble" vitamins, because they are nonpolar structures that are more soluble in other lipids than in water.

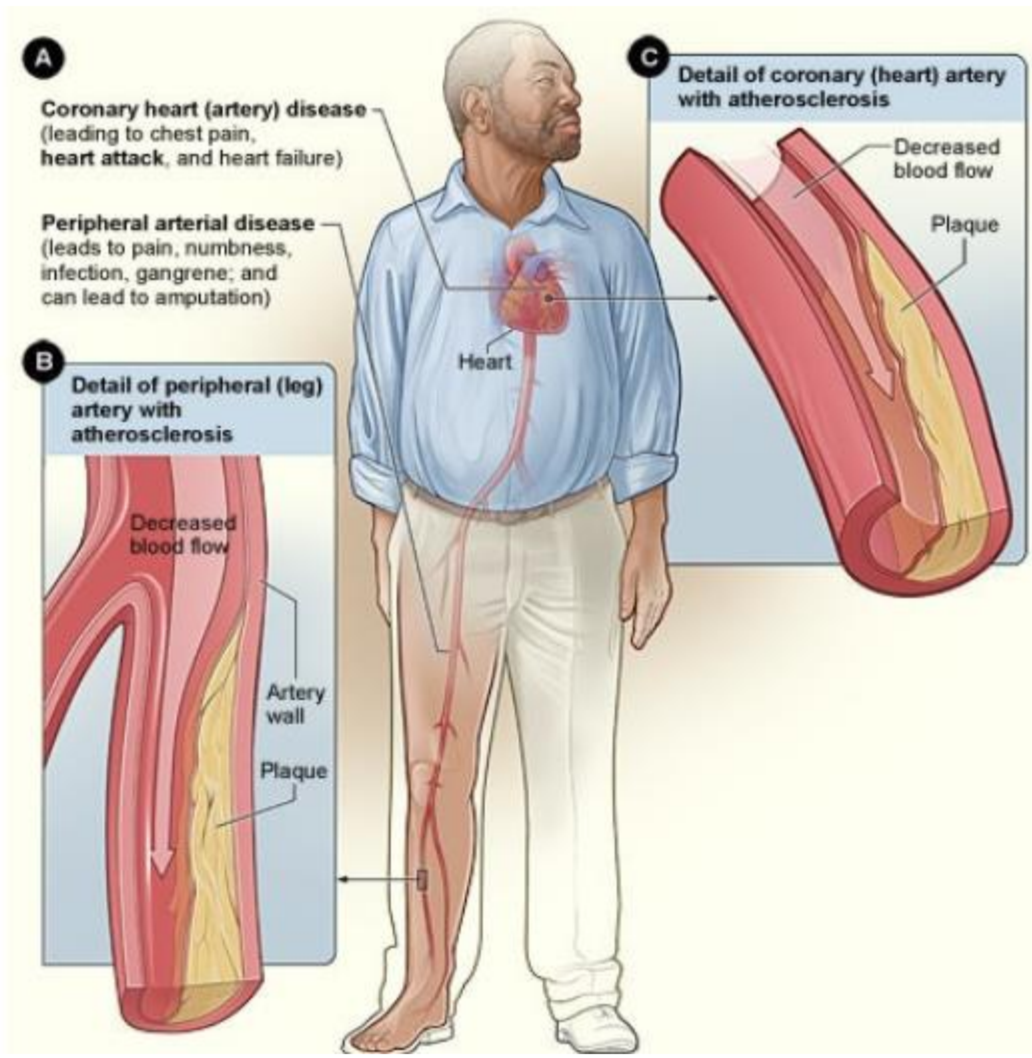
Functions of Lipids

Lipids play several important roles in the body. Triglycerides are stored in fat cells until the body needs to break them down for chemical energy. These stored triglycerides also help insulate the body against extreme temperatures and cushion organs against physical jostling. Phospholipids and cholesterol are important constituents of the cell membrane. These compounds provide structural integrity to the cell wall, since they are not water-soluble. Other steroids are used as chemical messengers in the body, and the fat-soluble vitamins serve a variety of other functions.

Cholesterol and Heart Disease

Because of the link between high levels of cholesterol and heart disease, it is commonly seen by the general public as a "bad" molecule. However, cholesterol plays a vital role in the body, as both a structural component of cell membranes and a metabolic precursor to various steroid hormones. Only about 30% of the cholesterol in our bodies comes from our diet; the rest is synthesized in the liver, intestines, adrenal glands, and reproductive organs. The same acetyl CoA molecule that provides biochemical energy can also be used by the body to synthesize cholesterol. There are approximately twenty-two steps involved in the formation of cholesterol from acetyl CoA.

Cholesterol has been implicated in heart disease for decades. Atherosclerosis is a disorder of the arteries in which cholesterol and other materials are deposited on the interior of the arterial wall. These deposits lead to the formation of plaques that can restrict or even block the flow of blood through these blood vessels. A decrease in the flow of blood can lead to high blood pressure and a lowered oxygen supply to the heart muscle. A complete blockage of blood flow to parts of the heart (a heart attack) can cause significant damage due to oxygen deprivation, in some cases leading to death.



http://commons.wikimedia.org/wiki/File:Smoking_and_Atherosclerosis.jpg

Plaque formation in artery leading to narrowing of artery.

The growth of plaques in the arteries is facilitated by a high level of low-density lipoproteins (LDL), which transport cholesterol from the liver to various parts of the body. The opposite process, moving cholesterol back to the liver, is carried out by high-density lipoproteins (HDL). Once back in the liver, the cholesterol can be converted to bile acids, which are either excreted or used in the digestion of dietary lipids.

When you get your cholesterol tested, they are measuring not only the total amount of cholesterol in the blood, but also whether it is being transported by LDL or HDL. All of these values are important for assessing the likelihood of a heart attack. Total cholesterol gives an idea of the overall cholesterol load in the body. The LDL cholesterol (sometimes referred to as “bad” cholesterol) is more likely to be incorporated into a cell or a plaque, so it is important that these levels below. Conversely, since cholesterol being carried by HDL (“good” cholesterol) is being transported away from the rest of the body and into the liver for disposal, higher HDL levels are generally considered beneficial.

High levels of cholesterol in the blood can be treated by medications. The statins (a class of cholesterol-lowering drugs) inhibit the production of cholesterol. One enzyme in the twenty-two step process is rate-limiting – this enzyme catalyzes the slowest reaction in the sequence. Blockage of cholesterol synthesis at this step is currently the most effective way of decreasing cholesterol formation in the body.

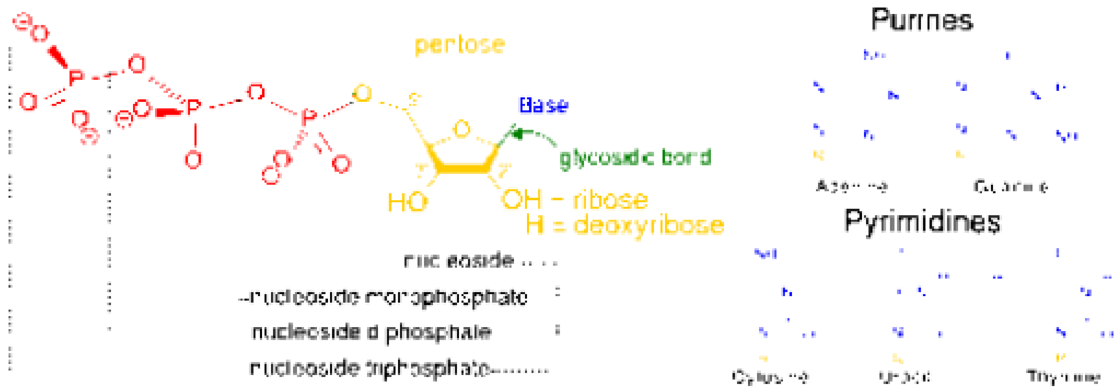
Classes of Nucleic Acids

The final type of biomolecules that we will be looking at are the nucleic acids. Like carbohydrates and proteins, nucleic acids are complex polymers of a few simple building blocks. Nucleic acids provide the molecular blueprints for all proteins produced in living systems. We will explore the process by which this information is translated into functional structures later in this lesson. First, we will look at the structures of nucleic acids.

Nucleotides

The subunits from which nucleic acids are generated are referred to as **nucleotides**. A nucleotide consists of a pentose molecule connected to a nitrogen-containing base and one or more phosphate groups. Biological systems make use of two different pentoses for the construction of nucleic acids: ribose and deoxyribose. Long polymers of ribose-derived nucleotides are referred to as ribonucleic acids (**RNA**), and polymers of deoxyribose nucleotides are referred to as deoxyribonucleic acids (**DNA**).

In a given strand of DNA or RNA, the only difference between each subunit is the choice of base. The five common bases are shown in the picture below. Based on the number of rings, they are classified as either purines or pyrimidines.



http://commons.wikimedia.org/wiki/File:Nucleotides_1.svg

Nucleotide structures.

In general, DNA does not make use of the uracil base, and RNA does not contain thymine. As a result, each strand of a nucleic acid will use only four of these bases.

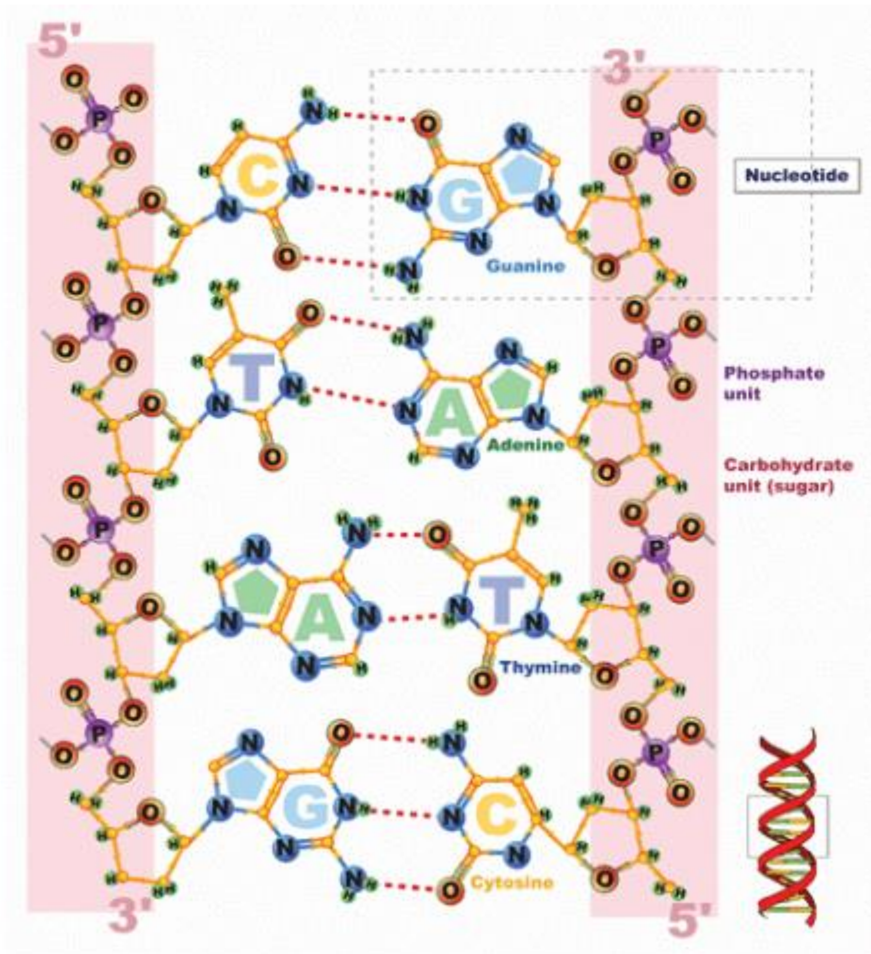
DNA

Individual nucleotides can be linked together through their phosphate groups to form nucleic acid polymers. Once constructed, DNA generally exists as two strands that are linked together by hydrogen bonds, producing a double-helical structure (see the picture below).

http://commons.wikimedia.org/wiki/File:DNA_double_helix_vertikal.PNG

DNA structure.

In order for the structure in the picture above to form, the bases that line up across from each other must be complementary to one another. Based on their structures, adenine will make favorable hydrogen bonding interactions with thymine, and vice versa. Guanine and cytosine form another complementary pair. Mismatched bases will form unfavorable interactions in the center of the helix.



CK-12 Foundation

Base pairing in DNA.

If we know the sequence of one strand in a DNA double helix, we can predict the sequence of the opposite strand based on the required pairings. This is why we describe DNA strands as being complementary to each other.

Grading Rubric:

***Note:** Your grade will be calculated by the sum of the points earned for each question. Points are earned according to the chart below.

To get a 10: A total score of 10 upon the first submission or after the first revision.

To get a 9: A total score of 9 after the first revision.

To get an 8: A total score of 8 after the first revision.

To get a 7: A total score of 7 after the first revision.

To get a 6: A total score of 6 after the first revision.

To get a 5: Any score lower than a 6; Plagiarism – purposeful or mistaken, which will lower your final grade for the course (So, be very careful when posting your work!); lack of effort, disrespect, or attitude. Lesson requirements have not been met.

Stop and Think (Total content points possible = 1 point	Answer is clearly written and accurate. Answer is based on the lesson content. **1 point**	Answer is clearly written and accurate. Answer is based on the lesson content. Answer may have 1 factual error. **.5 point**	Answer is not accurate or is based on less content. **0 points**
Short Answer (Total content points possible = 3)	Answer is clearly written and accurate. Answer is based on lesson content. **1 point each**	Answer is clearly written and but may have 1 factual omission or error. **.5 point each**	Answer is not written. There several factua omissions. **0 points each**
Apply Your Knowledge Total points possible 1 point	Answer is clearly written and accurate. **1 point**	Answer is clearly written and accurate. May have 1 factual omission or error. **.5 point**	Answer is not written. There several factua or omissions. **0 points**
Expand Your Knowledge total points possible = 3 points	Answer is clearly written and accurate. Summary covers all required points. Sources are cited. **3 points**	Answer is clearly written and accurate. Summary covers all required points. May have up to 2 factual errors or omissions. Sources are cited.	Answer is not written. There more than 2 fa errors or omis or sources are cites. **0 points**

		1.5 points	
Closure Total points possible 2 points	Answer is clearly written and accurate. Sources are cited. **2 points**	Answer is clearly written and but may have 1 factual omission or error. Sources are cited. **1 point**	Answer is not clearly written. There are several factual omissions or sources are not cited. **0 points**

Assignment:

Stop and Think (Questions 1)

Copy and paste the Stop and Think Question found throughout the lesson content and answer them in the submit Box below. Stop and Think questions should be based on the lesson content. You will not do outside research for these questions.

Short Answer

2. Identify the four primary biological macromolecules.

3. Explain the following aspects of protein structure in your own words:

a. primary

b. secondary

c. tertiary

d. quaternary

4. Identify 5 functions of proteins. Which would you argue is one of the more important functions? Why?

Apply Your Knowledge:
5. Explain what scientists mean when they say DNA strands are “complementary,” on a molecular level.

Expand Your Knowledge:

6. Choose an article that interests you from one of the following science news sites. This article should be related to chemistry, but not necessarily biochemistry.

* https://www.chemistryworld.com/

* https://www.bbc.com/news/science_and_environment

* https://www.nationalgeographic.com/

* https://www.npr.org/sections/science/

* https://www.scientificamerican.com/

* https://www.theguardian.com/science

You may choose an article from a different source but if you choose to do so *you must get your teacher's approval of the article before continuing on this part of the lesson.*

After reading your article, write a summary of the article. Your summary must answer the following questions, but should be written in prose form (do **not** submit a list of numbered questions).

- Why did you choose this article?
- What chemistry phenomenon does this article demonstrate?
- What is newsworthy about the science discussed in this article?
- Can you identify a hypothesis in this article?
- If so, how did scientists test this hypothesis?
- What conclusion did scientists come to based upon their experiments and data?
- Were you surprised by what this article said? Why or why not?
- Connect this article to at least two chemistry concepts you learned in this course, using them to explain what you read about.

Closure:

7. Go back to the video at the beginning of this lesson. Can you find any structures that look like carbohydrates, proteins, lipids, or nucleic acids like you learned about in this video? Take at least two screenshots of structures you suspect may be these molecules, and explain why you decided these structures are what they are. Upload these pictures and explanation with your lesson.