2 Energy-Yielding Macronutrients

As you have learned, there are three energy-yielding macronutrients: carbohydrates, proteins, and lipids. The energy contained in these molecules is found in the electrons that are shared in the covalent bonds that link the atoms. Our individual cells (in a process called Cellular Respiration, documented in a later chapter) deconstruct these molecules, and use the energized electrons to generate the ATP needed to keep our cells alive. This chapter goes more in depth about these major dietary components that are so critical to life.

Sections:
- 2.1 Carbohydrates
- 2.2 Proteins
- 2.3 Lipids

2.1 Carbohydrates

Carbohydrates have become surprisingly divisive. Some people swear by them, others swear against them. But it is important to understand that carbohydrates are a diverse group of compounds that have a multitude of effects in the body. Thus, trying to make blanket statements about carbohydrates is probably not a good idea.

Carbohydrates are named because they are hydrated (as in water, H$_2$O) carbon. Below is the formula showing how carbon dioxide (CO$_2$) and water (H$_2$O) are used to make carbohydrates (CH$_2$O)$_n$ and oxygen (O$_2$). The “n” after the carbohydrate in the formula indicates that the chemical formula is repeated an unknown number of times, but that for every carbon and oxygen, there will always be two hydrogens. Putting it another way: a carbohydrate always contains carbon, hydrogen, and oxygen atoms in a ratio of 1:2:1.

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow (\text{CH}_2\text{O})_n + \text{O}_2
\]

Carbohydrates are produced by plants through a process known as photosynthesis. In this process, plants use the energy from photons of light to synthesize carbohydrates. The formula for this reaction looks like this:

Carbon Dioxide + water $\rightarrow$ Carbohydrate (Glucose) and Oxygen

\[
6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Light} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2
\]
Light (sunlight) in the reaction above is the energy that will ultimately be stored in the glucose molecule (C₆H₁₂O₆). This will be the energy available for use when a human being consumes a glucose molecule! There are many different types of carbohydrates as shown in the figure below. One way that carbohydrates can be classified is into simple carbohydrates, complex carbohydrates, and sugar alcohols. As the names imply, complex carbohydrates contain more sugar units, while simple carbohydrates contain either 1 or 2 sugars. In the next sections, you will learn more about the different forms of carbohydrates.

Subsections:
- 2.11 Simple Carbohydrates
- 2.12 Alternative Sweeteners
- 2.13 Oligosaccharides
- 2.14 Polysaccharides

No References
2.11 Simple Carbohydrates

As shown in the figure below, simple carbohydrates can be further divided into monosaccharides and disaccharides. Mono- means one, thus monosaccharides contain one sugar. Di- means two, thus disaccharides contain 2 sugar units.

**Monosaccharides**

While there are many organic compounds that qualify as monosaccharides, there are only three that are found in the foods we eat. These three monosaccharides are: glucose, fructose and galactose. Notice that all are 6-carbon sugars (hexoses). However, fructose has a five member ring, while glucose and galactose have 6 member rings. Also notice that the only structural difference between glucose and galactose is the position of the alcohol (OH) group that is shown in red.
Despite these differences in structure, glucose, galactose, and fructose have the same chemical formula ($C_6H_{12}O_6$). Molecules with a common chemical formula, yet different chemical structures, are called **isomers**. These three monosaccharides are additionally characterized by the following:

**Glucose** - Product of photosynthesis, major source of energy in our bodies
**Fructose** - Commonly found in fruits and used commercially in many beverages
**Galactose** - Not normally found in nature alone, normally found in the disaccharide lactose (also known as milk sugar)

### Required Web Link

**Not familiar with ring structures? See how glucose forms a ring.**

### Disaccharides

Disaccharides are produced from 2 monosaccharides. The commonly occurring disaccharides are:

**Maltose** (glucose + glucose, aka malt sugar) - seldom found in foods, present in alcoholic beverages and barley
**Sucrose** (glucose + fructose, aka table sugar) - only made by plants.
**Lactose** (galactose + glucose, aka milk sugar) - primary milk sugar

The different disaccharides and the monosaccharides components are illustrated in Figure 2.113.
Each of these disaccharides contains glucose and all the reactions are dehydra-
tion reactions (a reaction that creates a link between two molecules through the loss of a molecule of water). You might hear the term glycosidic bond used to identify the bonds between monosaccharides. A glycoside is a sugar, so glycosidic is referring to a sugar bond. Interestingly, lactose has a unique glycosidic bond. People require special enzyme, lactase, to break this bond, and the absence of lactase activity leads to lactose intolerance.

High-Fructose Corn Syrup

Food manufacturers are always searching for cheaper ways to produce their food. One method that has been popular is the use of high-fructose corn syrup as an alternative to sucrose. High-fructose corn syrup contains either 42 or 55% fructose, which is similar to sucrose. Nevertheless, because an increase in high-fructose corn syrup consumption (see figure below) has coincided with the increase in obesity in the U.S., there is a lot of controversy surrounding its use.
Opponents claim that high-fructose corn syrup is contributing to the rise in obesity rates. As a result, some manufactures have started releasing products made with natural sugar. You can read about this trend in the following New York Times article in the link below. Also, manufacturers tried to rebrand high-fructose corn syrup as corn sugar to get around the negative perception of the name. But the FDA rejected the Corn Refiners Association request to change the name officially to corn sugar as described in the second link. The last link is a video made by the American Chemical Society that gives some background on how HFCS is produced and how it compares to sucrose.

Required Web Links
Sugar is back on labels, this time as a selling point
No new name for high-fructose corn syrup
(Video): Sugar vs. High Fructose Corn Syrup - What's the Difference? (2:41)

References & Links

Links
Sugar is back on labels, this time as a selling point - [http://www.nytimes.com/2009/03/21/dining/21sugar.html?_r=1&ref=nutrition](http://www.nytimes.com/2009/03/21/dining/21sugar.html?_r=1&ref=nutrition)

No new name for high-fructose corn syrup - [http://well.blogs.nytimes.com/2012/05/31/no-new-name-for-high-fructose-corn-syrup/?_r=0](http://well.blogs.nytimes.com/2012/05/31/no-new-name-for-high-fructose-corn-syrup/?_r=0)

**Video**
Sugar vs. High Fructose Corn Syrup – What’s the Difference? - [https://www.youtube.com/watch?v=fXMvregmU1g](https://www.youtube.com/watch?v=fXMvregmU1g)

---

### 2.12 Sugar Alcohols (Polyols, Sugar Replacers)

Sugar(s) can provide a lot of calories and contribute to tooth decay. Thus there are many other compounds that are used as alternatives to sugar that have been developed or discovered. We will first consider sugar alcohols and then the alternative sweeteners in subsequent sections.

Below you can see the structure of three common sugar alcohols: xylitol, sorbitol, and mannitol.

![Figure 2.121 Structure of three commonly used sugar alcohols: xylitol, sorbitol, and mannitol](image)

Xylitol  
Sorbitol  
Mannitol

Figure 2.121 Structure of three commonly used sugar alcohols: xylitol, sorbitol, and mannitol

Remember that alcohol subgroups are (OH), and you can see many of them in these structures.

Sugar alcohols are also known as "sugar replacers", because some in the public might get confused by the name sugar alcohol. Some might think a sugar alcohol is a sweet alcoholic beverage. Another name for them is nutritive sweeteners, which indicates that they do provide calories. Sugar alcohols are nearly as sweet as sucrose but only provide approximately half the calories as shown below. The name polyols also seems to be increasingly used to describe these compounds.
Table 2.121 Relative sweetness of monosaccharides, disaccharides, and sugar alcohols

<table>
<thead>
<tr>
<th>Sweetener</th>
<th>Relative Sweetness</th>
<th>Energy (kcal/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactose</td>
<td>0.2</td>
<td>4*</td>
</tr>
<tr>
<td>Maltose</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>Glucose</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>Sucrose</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>Fructose</td>
<td>1.2-1.8</td>
<td>4</td>
</tr>
<tr>
<td>Erythritol</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Isomalt</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Lactitol</td>
<td>0.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Differs based on a person’s lactase activity

Sugars are fermented by bacteria on the surfaces of teeth. This results in a decreased pH (higher acidity) that leads to tooth decay and, potentially, cavity formation (a process officially known as dental caries). The major advantage of sugar alcohols over sugars is that sugar alcohols are not fermented by bacteria on the tooth surface. There is a nice picture of this process in the link below as well as a video explaining the process of tooth decay.

Required Web Links

Sugar and Dental Caries
Video: Tooth Decay (1:06)

References & Links

Link
Sugar and Dental Caries - http://www.asu.edu/courses/css335/caries.htm

Video
Tooth Decay - http://www.youtube.com/watch?v=_olv59bTL4
2.13 Alternative Sweeteners

**Alternative sweeteners** are simply alternatives to sucrose and other mono- and disaccharides that provide sweetness. Many have been developed to provide zero-calorie or low calorie sweetening for foods and drinks.

Because many of these provide little to no calories, these sweeteners are also referred to as non-nutritive sweeteners (FDA is using high-intensity sweeteners to describe these products). Aspartame does provide calories, but because it is far sweeter than sugar, the small amount used does not contribute meaningful calories to a person’s diet. Until the FDA allowed the use of the term **stevia**, this collection of sweeteners was commonly referred to as artificial sweeteners, because they were synthetically or artificially produced. However, with stevia, the descriptor artificial can no longer be used to describe these sweeteners. More recently, Luo Han Guo (monk fruit) extracts have also been allowed to be used as another high-intensity sweetener that is not synthesized or artificially produced. The table in the link below summarizes the characteristics of the FDA approved high-intensity sweeteners.

<table>
<thead>
<tr>
<th>Required Web Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDA High-Intensity Sweeteners</td>
</tr>
</tbody>
</table>

**Saccharin**

**Saccharin** is the oldest of the artificial sweeteners. Saccharin was linked to bladder cancer in rats in the late 70’s, but subsequent research did not establish the link in humans. While saccharin might not present as a significant health hazard, you do not want to use it in cooking or baking because it develops a bitter taste.

![Figure 2.131 Structure of saccharin](image)
Cyclamate

Cyclamate (sodium cyclamate) is a artificial sweetener that was discovered in 1937. It was banned by the FDA in 1969, primarily due to its questionable safety. Cyclamate is about 30 times sweeter than sucrose, and is often used in combination with other artificial sweeteners. Cyclamate is approved for use in over 80 countries, including those in the European Union and Canada.

Aspartame

Aspartame is made up of 2 amino acids (phenylalanine and aspartate) and a methyl (CH₃) group. Aspartame is marketed under the product name NutraSweet®. The compound is broken down during digestion into the individual amino acids. This is why it provides 4 kcal/g, just like protein⁴. Because it can be broken down to phenylalanine, products that contain aspartame contain the following message: "Phenylketonurics: Contains phenylalanine." Phenylketonuria (PKU) will be covered in greater detail in section 2.25. When heated, aspartame breaks down and loses its sweet flavor¹.

![Figure 2.132 Structure of aspartame](image)

Neotame

Neotame is like aspartame version 2.0. Neotame is structurally identical to aspartame except that it contains an additional side group (bottom of figure below, which is flipped backwards to make it easier to compare their structures). While this looks like a minor difference, it has profound effects on the properties of neotame. Neotame is much sweeter than aspartame and is heat-stable. It can still be broken down to phenylalanine, but such small amounts are used that it is not a concern for those with PKU¹,⁴.
Advantame
The newest, sweetest alternative sweetener approved by the FDA in 2014 is **advantame**. It is heat-stable and does not have a trade name yet\(^3\). Notice it also has a similar structure to aspartame and neotame. Like Neotame, it can be broken down to phenylalanine, but such small amounts are used that it is not a concern for those with PKU. However, it has a much higher acceptable daily intake than Neotame\(^4\), meaning there is less concern about adverse effects from consuming too much.
Acesulfame-Potassium (K)
Acesulfame-potassium (K) is not digested or absorbed, therefore it provides no energy or potassium to the body\(^1\). It is a heat-stable alternative sweetener.

![Figure 2.135 Structure of acesulfame-potassium (K)\(^9\)](image)

Sucralose
Sucralose is structurally identical to sucrose except that 3 of the alcohol groups (OH) are replaced by chlorine molecules (Cl). This small change causes sucralose to not be digested and as such is excreted in feces\(^1,4\). It is a heat-stable alternative sweetener.

![Figure 2.136 Structure of sucralose\(^10\)](image)

Stevia
Stevia is a heat-stable alternative sweetener derived from a South American shrub, with the leaves being the sweet part. The components responsible for this sweet taste are a group of compounds known as **steviol glycosides**. The structure of steviol is shown in Figure 2.137.
The term glycoside means that there are sugar molecules bonded to steviol. The two predominant steviol glycosides are stevioside and rebaudioside A. The structure of these two steviol glycosides are very similar\textsuperscript{13}. The structure of stevioside is shown below as an example.

The common name for a sweetener containing primarily rebaudioside A is rebiana\textsuperscript{13}. Stevia sweeteners have been marketed as natural alternative sweeteners, something that has been stopped by lawsuits as described in the following link.

**Required Web Link**

[What is natural and who decides?](#)
Luo Han Guo Extracts

Luo Han Guo (aka Siraitia grosvenrii Swingle, monk fruit) extracts are a newer, natural heat-stable alternative sweetener option derived from a native Chinese fruit. These extracts are sweet because of the mogrosides that they contain. The structure of a mogroside is shown below.

![Figure 2.139 Structure of a mogroside](image)

References & Links
2. [http://www.fda.gov/AboutFDA/Transparency/Basics/ucm214865.htm](http://www.fda.gov/AboutFDA/Transparency/Basics/ucm214865.htm)
3. [http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm](http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm)

Links
FDA High-Intensity sweeteners - [http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm](http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm)
2.14 Oligosaccharides

Within the category of complex carbohydrates, there are oligosaccharides and polysaccharides. Oligosaccharides (oligo means few) are composed of 3-10 sugar units and polysaccharides contain greater than 10 sugar units.

![Diagram of Carbohydrates]

Raffinose and stachyose are the most common oligosaccharides. They are found in legumes, onions, broccoli, cabbage, and whole wheat\(^1\). The link below shows the raffinose and stachyose content of some plant foods.

**Required Web Link**
Raffinose and stachyose content of selected plant foods
The structures of the two oligosaccharides are shown below.

![Structure of raffinose](image1)

**Figure 2.142 Structure of raffinose**

![Structure of stachyose](image2)

**Figure 2.143 Structure of stachyose**

Our digestive system lacks the enzymes necessary to digest the unique glycosidic bonds found in oligosaccharides. As a result, the oligosaccharides are not digested in the small intestine and reach the colon where they are fermented by the bacteria there. Gas (methane, CH₄) is produced as a byproduct of this bacteria fermentation that can lead to flatulence. To combat this problem, Beano® is a popular product that contains an enzyme (alpha-galactosidase) to break down oligosaccharides, thereby preventing them from being used to produce gas. The video link below describes how Beano® works.

**Required Web Link**
[Video] Beano’s University of Gas: Lesson 2


References & Links

Videos
Raffinose and stachyose content of foods -
http://books.google.com/books?id=LTGFV2NOySYC&pg=PA374&lpg=PA374&dq=raffinose+and+stachyose+content+of+vegetables&source=bl&ots=X4Dr7jWmwL&sig=CJFvhAIysSZCP2SOy_MqhfoVYQQ&hl=en&ei=TSRITdTdTfLNHOgA
fB2MX_BQ&sa=X&oi=book_result&ct=result&resnum=6&ved=0CD0Q6AEwBQ#v=onepage&q=raffinose%20and%2
0stachyose%20content%20of%20vegetables&f=false

2.15 Polysaccharides

Poly means "many" and thus polysaccharides are made up of many monosaccharides (>10). There are 3 main classes of polysaccharides: starch, glycogen, and most fibers. The following sections will describe the structural similarities and differences between the 3 classes of polysaccharides that are divided in the figure below.
Subsections:
- 2.151 Starch
- 2.152 Glycogen
- 2.153 Fiber

2.151 Starch

Starch is the storage form of glucose in plants. There are two forms of starch (shown in the figures below): amylose and amylopectin. Structurally they differ in that amylose is a linear polysaccharide (Figure 2.1511), whereas amylopectin is branched (Figure 2.1512).

Figure 2.1511 Structure of amylose

Figure 2.1512 Structure of amylopectin

Amylopectin is more common than amylose (4:1 ratio on average) in starch\(^1,2\). Some starchy foods include grains, root crops, tubers, and legumes.

References & Links
2.152 Glycogen

**Glycogen** is similar to starch in that it is a storage form of glucose. Glycogen, however, is the carbohydrate storage form in animals, rather than plants. It is even more highly branched than amylopectin, as shown below.

![Figure 2.1521 Structure of glycogen](image)

The advantage of glycogen's highly branched structure is that the multiple ends (shown in red above) are where enzymes start to cleave off glucose molecules. As a result, with many ends available, it can provide glucose much more quickly to the body than if it was a linear molecule like amylose with only two ends. Although glycogen is characteristically found in muscle tissue (meats), we consume almost no glycogen, because it is rapidly broken down by enzymes in animals after slaughter¹.

**References & Links**

2.153 Fiber

The simplest definition of **fiber** is indigestible matter. Indigestible means that it survives digestion in the small intestine and reaches the large intestine.

There are 3 major fiber classifications¹:

**Dietary Fiber** - non-digestible carbohydrates and lignin that are intrinsic and intact in plants
**Functional Fiber** - isolated, non-digestible carbohydrates that have beneficial physiological effects in humans

**Total Fiber** - dietary fiber + functional fiber

The differences between dietary and functional fiber are compared in the table below:

<table>
<thead>
<tr>
<th>Dietary Fiber</th>
<th>Functional Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact in plants</td>
<td>Isolated, extracted, or synthesized</td>
</tr>
<tr>
<td>Carbohydrates + lignins</td>
<td>Only carbohydrates</td>
</tr>
<tr>
<td>Only from plants</td>
<td>From plants or animals</td>
</tr>
<tr>
<td>No proven benefit</td>
<td>Must prove benefit</td>
</tr>
</tbody>
</table>

Dietary fiber is always intact in plants, whereas functional fiber can be isolated, extracted or synthesized. Functional fiber is only carbohydrates, while dietary fiber also includes lignins. Functional fiber can be from plants or animals, while dietary fiber is only from plants. Functional fiber must be proven to have a physiological benefit, while dietary fiber does not. The reason behind the non-digestibility of fiber is the unique glycosidic bonds that link the individual monosaccharide units; the glycosidic bonds in fiber cannot be broken by our digestive enzymes.

Fiber can be classified by its physical properties. In the past, fibers were commonly referred to as **soluble** and **insoluble**. This classification distinguished whether the fiber was soluble in water. However, this classification is being phased out in the nutrition community. Instead, most fibers that would have been classified as insoluble fiber are now referred to as **non-fermentable** and/or **non-viscous** and soluble fiber as **fermentable**, and/or **viscous** because these better describe the fiber's characteristics. Fermentable refers to whether the bacteria in the colon can ferment or degrade the fiber into short chain fatty acids and gas. Viscous refers to the capacity of certain fibers to form a thick gel-like consistency.

The following table lists some of the common types of fiber and provides a brief description about each.
Table 2.1532 Common types of non-fermentable, non-viscous (insoluble) fiber

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>Main component of plant cell walls</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>Surround cellulose in plant cell walls</td>
</tr>
<tr>
<td>Lignin</td>
<td>Non-carbohydrate found within “woody” plant cell walls</td>
</tr>
</tbody>
</table>

Table 2.1533 Common types of fermentable, viscous (soluble) fiber

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemicellulose</td>
<td>Surround cellulose in plant cell walls</td>
</tr>
<tr>
<td>Pectin</td>
<td>Found in cell walls and intracellular tissues of fruits and berries</td>
</tr>
<tr>
<td>Beta-glucans</td>
<td>Found in cereal brans</td>
</tr>
<tr>
<td>Gums</td>
<td>Viscous, usually isolated from seeds</td>
</tr>
</tbody>
</table>

The following table gives the percentage of total dietary fiber in 5 foods.

Table 2.1534 Total dietary fiber (as percent of sample weight)

<table>
<thead>
<tr>
<th>Food</th>
<th>Total Dietary Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal, all bran</td>
<td>30.1</td>
</tr>
<tr>
<td>Blueberries, fresh</td>
<td>2.7</td>
</tr>
<tr>
<td>Broccoli, fresh, cooked</td>
<td>3.5</td>
</tr>
<tr>
<td>Pork and beans, canned</td>
<td>4.4</td>
</tr>
<tr>
<td>Almonds, with skin</td>
<td>8.8</td>
</tr>
</tbody>
</table>
The table below shows the amount of non-fermentable, non-viscous fiber in these same five foods.

Table 2.1535 Non-viscous fiber (as percent of sample weight)³

<table>
<thead>
<tr>
<th>Food</th>
<th>Hemicellulose</th>
<th>Cellulose</th>
<th>Pectin</th>
<th>Lignin</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal, all bran</td>
<td>15.3</td>
<td>7.5</td>
<td>0.9</td>
<td>4.3</td>
<td>28.0</td>
</tr>
<tr>
<td>Blueberries, fresh</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td>0.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Broccoli, fresh, cooked</td>
<td>0.9</td>
<td>1.2</td>
<td>0.7</td>
<td>0.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Pork and beans, canned</td>
<td>0.9</td>
<td>1.6</td>
<td>0.3</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Almonds, with skin</td>
<td>1.8</td>
<td>3.3</td>
<td>1.6</td>
<td>1.9</td>
<td>8.6</td>
</tr>
</tbody>
</table>

The table below shows the amount of fermentable, viscous fiber in these same five foods.

Table 2.1536 Viscous Fiber (as percent of sample weight)³

<table>
<thead>
<tr>
<th>Food</th>
<th>Hemicellulose</th>
<th>Pectin</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal, all bran</td>
<td>2.0</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Blueberries, fresh</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Broccoli, fresh, cooked</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Pork and beans, canned</td>
<td>1.1</td>
<td>0.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Almonds, with skin</td>
<td>0.2</td>
<td>tr</td>
<td>0.2</td>
</tr>
</tbody>
</table>

tr = trace amounts

Foods that are good sources of non-fermentable, non-viscous fiber include whole wheat, whole grain cereals, broccoli, and other vegetables. This type of fiber is believed to decrease the risk of constipation and colon cancer, because it increases stool bulk and reduces transit time⁴. This reduced transit time theoretically means shorter exposure to consumed carcinogens in the intestine, and thus lower cancer risk.

Fermentable, viscous fiber can be found in oats, rice, psyllium seeds, soy, and some fruits. This type of fiber is believed to decrease blood cholesterol and sugar levels, thus also lowering the risk of heart disease and diabetes, respectively⁴. Its viscous nature slows the absorption of glucose preventing blood glucose from spiking after consuming carbohydrates. It lowers blood cholesterol levels primarily by binding bile acids, which are made from cholesterol, and causing them to be excreted. As such, more cholesterol is used to synthesize new bile acids.
2.2 Proteins

Proteins are another major macronutrient that, like carbohydrates, are made up of small repeating units. But instead of sugars, proteins are made up of amino acids. In the following sections, you will learn more about how proteins are synthesized and why they are important in the body.

Subsections:
- 2.21 Amino Acids
- 2.22 Protein Synthesis
- 2.23 Protein Structure
- 2.24 Protein Functions
- 2.25 Types of Amino Acids
- 2.26 Amino Acid Structures
- 2.27 Protein Quality
- 2.28 Protein-Energy Malnutrition

2.21 Amino Acids

Similar to carbohydrates, proteins contain carbon (C), hydrogen (H), and oxygen (O). However, unlike carbohydrates (and lipids) proteins also contain nitrogen (N). Proteins are made up of smaller units called amino acids. This name, amino acid, signifies that each contains an amino (NH$_2$) and carboxylic acid (COOH) groups. The only structural difference in the 20 amino acids is the side group represented by the R below.
To illustrate the differences in the side group we will consider glycine and alanine, the two simplest amino acids. For glycine, the R group is hydrogen (H), while in alanine the R group is a methyl (CH₃). The structures of these two amino acids are shown below.

Individual amino acids are joined together using a peptide bond (green) and is shown in the figure below. You might note that the formation of a peptide bond is a dehydration reaction (a reaction that creates a link between two molecules through the loss of a molecule of water). This is the same basic reaction that links monosaccharides into more complex carbohydrates.
In addition to dipeptides, amino acids can also come together to form **tripeptides** (three amino acids), **oligopeptides** (3-10 amino acids), and **polypeptides** (10 or more amino acids). A polypeptide is a chain of amino acids as shown below.

**References & Links**
2.22 Protein Synthesis

Protein synthesis is a process critical to life. It is a cellular-based process that makes the proteins that are necessary to keeping each of our cells alive and functional. The process of protein synthesis (making protein) is not as simple as stringing together amino acids to form a polypeptide. As shown below, this is a fairly involved process. DNA contains the genetic code that is used as a template to create mRNA in a process known as transcription. The mRNA then moves out of the nucleus into the cytoplasm where it serves as the template for the process of translation, where tRNAs bring in individual amino acids that are bonded together to form a polypeptide.

![Diagram of the process of creating a polypeptide](image)

Figure 2.221 The process of creating a polypeptide

Tiny, intracellular structures, known as ribosomes, assist with translation. After translation, the polypeptide can be folded or gain structure as shown below and will be discussed in the next subsection (Protein Structure).
These videos do an excellent job of showing and explaining how protein synthesis occurs.

**Required Web Links**

**Video: Transcription (1:49)**

**Video: Translation (2:05)**

**References & Links**


**Videos**

Transcription - [http://www.youtube.com/watch?v=5MfSYnItYvg](http://www.youtube.com/watch?v=5MfSYnItYvg)

Translation - [http://www.youtube.com/watch?v=8dsTvBaUMvw](http://www.youtube.com/watch?v=8dsTvBaUMvw)
2.23 Protein Structure

There are four levels of protein structure. **Primary structure** is the linear polypeptide chain. **Secondary structure** occurs when hydrogen bonding between amino acids in the same polypeptide chain causes the formation of structures such as **beta-pleated sheets** and **alpha-helices**. **Tertiary structure**, a three-dimensional folding of the polypeptide chain, occurs as a result of an attraction between different amino acids of the polypeptide chain and interactions between the different secondary structures. Finally, certain proteins contain **quaternary structure** where multiple polypeptide chains are bonded together to form a larger molecule. **Hemoglobin**, the protein that binds oxygen in our red blood cells, is an example of a protein with quaternary structure. The figure below illustrates the different levels of protein structure.

![Figure 2.231 Different Protein Structures](image)

Figure 2.231 Different Protein Structures
This video does a nice job of illustrating and explaining the different protein structures.

<table>
<thead>
<tr>
<th>Required Web Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video: Protein Structure (0:52)</td>
</tr>
</tbody>
</table>

References & Links

Video
Protein Structure - http://www.youtube.com/watch?v=lijQ3a8yUYQ

2.24 Protein Functions

There are various functions of proteins in the body that are described below.

Structural
Proteins, such as collagen, serve as the scaffolding of the body, and thus are important for the structure of tissues.

Figure 2.241 Triple-helix structure of collagen

Enzymes
We will discuss a number of enzymes throughout this class, and the vast majority are proteins. An enzyme catalyzes (enhances the rate) of a chemical reaction. The key part of an enzyme is its "active site". The active site is where a compound to be acted on, known as a substrate, enters. Enzymes are specific for their substrates; they do not catalyze reactions on any random compounds floating by. You might have heard the "lock and key" analogy used for enzymes and substrates, respectively.
After the substrate enters the active site and binds, the enzyme slightly changes shape (conformation). The enzyme then catalyzes a reaction that, in the example below, splits the substrate into two parts. The products of this reaction are released and the enzyme returns to its native or original shape. It is then ready to catalyze another reaction. The figure and video below nicely illustrate the function of an enzyme.

![Figure 2.242 The function of enzymes](image)

Enzymes’ names commonly end in -ase, and many are named for their substrate. For example, the enzyme amylase cleaves bonds found in amylase and amylopectin.

**Hormones**

Many hormones are proteins. A **hormone** is a compound that is produced in one tissue, released into circulation, then has an effect on a different organ. Most hormones are produced from several organs, collectively known as endocrine organs. Insulin is an example of a hormone that is a protein.

![Required Web Link](Required Web Link)

**Video: Hormones (1:02)**

**Fluid Balance**

Proteins help to maintain the balance between fluids in the plasma and the interstitial fluid. Interstitial fluid is the fluid that surrounds cells. Interstitial fluid and plasma (fluid part of blood) are the two components of extracellular fluid, or the fluid outside of cells. The following figure illustrates the exchange of fluid between interstitial fluid and plasma.
Acid-Base Balance
Proteins serve as buffers, meaning that they help to prevent the pH of the body from getting too high or too low.

Transport
Transport proteins move molecules through circulation or across cell membranes. One example is hemoglobin that transports oxygen through the body. We will see a number of other examples as we move through class.

Immune Function
Antibodies are proteins that recognize antigens (foreign substances that generate antibody or inflammatory response) and bind to and inactivate them. Antibodies are important in our ability to ward off disease.

Other Functions
Proteins can also serve as neurotransmitters and can be used for energy by forming glucose through gluconeogenesis.

References & Links
2.25 Types of Amino Acids

There are 20 amino acids our body uses to synthesize proteins. These amino acids can be classified as essential, non-essential, or conditionally essential. The table below shows how the 20 amino acids are classified.

Table 2.251 Essential, conditionally essential, and nonessential amino acids

<table>
<thead>
<tr>
<th>Essential</th>
<th>Conditionally Essential</th>
<th>Non-essential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>Arginine</td>
<td>Alanine</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>Cysteine</td>
<td>Asparagine</td>
</tr>
<tr>
<td>Leucine</td>
<td>Glutamine</td>
<td>Aspartic Acid or Aspartate</td>
</tr>
<tr>
<td>Lysine</td>
<td>Glycine</td>
<td>Glutamic Acid or Glutamate</td>
</tr>
<tr>
<td>Methionine</td>
<td>Proline</td>
<td>Serine</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>Tyrosine</td>
<td></td>
</tr>
<tr>
<td>Threonine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tryptophan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The body cannot synthesize nine amino acids. Thus, it is essential that these are consumed in the diet. As a result, these amino acids are known as essential amino acids, or indispensable amino acids. As an example of how amino acids were determined to be essential, Dr. William C. Rose at the University of Illinois discovered that threonine was essential by feeding different diets to graduate students at the university as described in the following link.

Required Web Link
Discovery of Threonine by William C. Rose

Non-essential, or dispensable, amino acids can be made in our body, so we do not need to consume them. Conditionally essential amino acids become essential for individuals in certain situations. An example of a condition when an amino acid becomes essential is the disease phenylketonuria (PKU). Individuals with PKU have a mutation in the enzyme phenylalanine hydroxylase, which normally adds an alcohol group (OH) to the amino acid phenylalanine to form tyrosine as shown below.
Figure 2.251 Phenylketonuria (PKU) results from a mutation in the enzyme phenylalanine hydroxylase.\textsuperscript{2,3}

Since tyrosine cannot be synthesized by people with PKU, it becomes essential for them. Thus, tyrosine is a conditionally essential amino acid. Individuals with PKU have to eat a very low protein diet and avoid the alternative sweetener aspartame, because it can be broken down to phenylalanine. If individuals with PKU consume too much phenylalanine, phenylalanine and its metabolites, can build up and cause brain damage and severe mental retardation. The drug Kuvan was approved for use with PKU patients in 2007 who have low phenylalanine hydroxylase activity levels. You can learn more about this drug using the link below.

**Required Web Link**
Kuvan

**References & Links**
2. [https://en.wikipedia.org/wiki/Phenylalanine#/media/File:L-Phenylalanine.png](https://en.wikipedia.org/wiki/Phenylalanine#/media/File:L-Phenylalanine.png)

**Links**
Discovery of Threonine by William C. Rose - [http://www.jbc.org/content/277/37/e25.full](http://www.jbc.org/content/277/37/e25.full)
2.26 Amino Acid Structures

It is a good idea to have a general idea of the structure of the different amino acids and to be able to recognize them as amino acids. You are not expected to memorize these structures. Often, I’ll say the name of particular amino acids, and many students aren’t aware that it’s an amino acid. For example, around Thanksgiving, many of us have heard about tryptophan associated with turkey, but how many people know that tryptophan is actual a single amino acid?

Structurally, all amino acids have nearly the same base structure. They are all composed of an $\alpha$-carbon, an amino group, a carboxyl group, and a side chain.

![Basic structure for all amino acids](image.png)

Figure 2.261 Basic structure for all amino acids

Each amino acid differs only by its side chain, as show in Figure 2.262 (on the next page). Notice how the only difference between each amino acid is in its side chain (highlighted in pink.)

You may hear someone talk about the branched-chain amino acids (BCAAs), which are a common nutritional supplement. While their effect on athletic performance is in question, BCAAs provide several metabolic and physiologic roles. Metabolically, BCAAs promote protein synthesis and turnover, signaling pathways, and metabolism of glucose. Additionally, the oxidation of BCAAs may increase fatty acid oxidation and play a role in obesity. Physiologically, BCAAs take on roles in the immune system and in brain function. Of the 20 amino acids found in the human body, only isoleucine, leucine, and valine are classified as BCAAs.
Figure 2.262 Amino acid structures for the 20 amino acids found in the human body

References & Links
2.27 Protein Quality

Proteins can be classified as either complete or incomplete. **Complete proteins** provide adequate amounts of all nine essential amino acids. Animal proteins such as meat, fish, milk, and eggs are good examples of complete proteins. **Incomplete proteins** do not contain adequate amounts of one or more of the essential amino acids. For example, if a protein doesn't provide enough of the essential amino acid leucine it would be considered incomplete. Leucine would be referred to as the limiting amino acid, because there is not enough of it for the protein to be complete. Most plant foods are incomplete proteins, with a few exceptions such as soy. The table below shows the limiting amino acids in some plant foods.

Table 2.27.1 Limiting amino acids in some common plant foods

<table>
<thead>
<tr>
<th>Food</th>
<th>Limiting Amino Acid(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bean and Most Legumes</td>
<td>Methionine, Tryptophan</td>
</tr>
<tr>
<td>Tree Nuts and Seeds</td>
<td>Methionine, Lysine</td>
</tr>
<tr>
<td>Grains</td>
<td>Lysine</td>
</tr>
<tr>
<td>Vegetables</td>
<td>Methionine, Lysine</td>
</tr>
</tbody>
</table>

**Complementary Proteins**

Even though most plant foods do not contain complete proteins, it does not mean that they should be sworn off as protein sources. It is possible to pair foods containing incomplete proteins with different limiting amino acids to provide adequate amounts of the essential amino acids. These two proteins are called complementary proteins, because they supply the amino acid(s) missing in the other protein. A simple analogy would be that of a 4 piece puzzle. If one person has 2 pieces of a puzzle, and another person has 2 remaining pieces, neither of them have a complete puzzle. But when they are combined, the two individuals create a complete puzzle.

Figure 2.27.1 Complementary proteins are kind of like puzzle pieces
Two examples of complementary proteins are shown below.

Peanut Butter and Jelly Sandwich

Red Beans and Rice

Figure 2.272 Two complementary protein examples²,³

It should be noted that complementary proteins do not need to be consumed at the same time or meal. It is currently recommended that essential amino acids be met on a daily basis, meaning that if a grain is consumed at one meal, a legume could be consumed at a later meal, and the proteins would still complement one another⁴.

**Measures of Protein Quality**

How do you know the quality of the protein in the foods you consume? The **protein quality** of most foods has been determined by one of the methods below.

**Biological Value (BV)** - (grams of nitrogen retained / grams of nitrogen absorbed) x 100

**Protein Efficiency Ratio (PER)** - (grams of weight gained / grams of protein consumed)
This method is commonly performed in growing rats.

**Chemical or Amino Acid Score (AAS)** - (Test food limiting essential amino acid (mg/g protein) / needs of same essential amino acid (mg/g protein))

**Protein Digestibility Corrected Amino Acid Score (PDCAAS)** - (Amino Acid Score x Digestibility)
This is the most widely used method and was preferred by the Food and Agriculture Organization and World Health Organization (WHO) until recently⁵,⁶.
The following table shows the protein quality measures for some common foods.

Table 2.272 Measures of protein quality

<table>
<thead>
<tr>
<th>Protein</th>
<th>PER</th>
<th>Digestibility</th>
<th>AAS (%)</th>
<th>PDCAAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egg</td>
<td>3.8</td>
<td>98</td>
<td>121</td>
<td>100*</td>
</tr>
<tr>
<td>Milk</td>
<td>3.1</td>
<td>95</td>
<td>127</td>
<td>100*</td>
</tr>
<tr>
<td>Beef</td>
<td>2.9</td>
<td>98</td>
<td>94</td>
<td>92</td>
</tr>
<tr>
<td>Soy</td>
<td>2.1</td>
<td>95</td>
<td>96</td>
<td>91</td>
</tr>
<tr>
<td>Wheat</td>
<td>1.5</td>
<td>91</td>
<td>47</td>
<td>42</td>
</tr>
</tbody>
</table>

*PDCAAS scores are truncated (cut off) at 100. These egg and milk scores are actually 118 and 121 respectively.

The Food and Agricultural Organization (FAO) recently recommended that PDCAAS be replaced with a new measure of protein quality, the **Digestible Indispensable Amino Acid Score (DIAAS)**. “DIAAS is defined as: DIAAS % = 100 x [(mg of digestible dietary indispensable amino acid in 1 g of the dietary protein) / (mg of the same dietary indispensable amino acid in 1g of the reference protein)].” Ideal digestibility should be utilized to determine the digestibility in DIAAS; ideally in humans, but if not possible in growing pigs or rats.

The main differences between DIAAS and PDCAAS are:

1. DIAAS take into account individual amino acids digestibility rather than protein digestibility.
2. Its focus on ileal instead of fecal (total) digestibility.
3. Has 3 different reference patterns (different age groups, 0-6 months, 6 months - 3 years, 3-10 years old) instead of a single pattern
4. DIAAS scores will not be truncated

**How do I find out the protein quality of what I'm eating and identify complementary proteins?**

Nutrition Data is a useful resource for determining protein quality and identifying complementary proteins. To use the site, go to [www.nutritiondata.com](http://www.nutritiondata.com), type in the name of the food you would like to know about in the search bar and hit 'Enter'. When you have selected your food from the list of possibilities, you will be given information about this food. Included in this information is the Protein Quality section. This will give you an amino acid score and a figure that illustrates which amino acid(s) is limiting. If your food is an incomplete protein, you can click "Find foods with a complementary profile". This will take you to a list of dietary...
choices that will provide complementary proteins for your food. You can read more about this option in the link below.

**Required Web Link**

*Nutrition Data: Protein Quality*

**References & Links**

2. [http://upload.wikimedia.org/wikipedia/commons/a/a6/PBJ.jpg](http://upload.wikimedia.org/wikipedia/commons/a/a6/PBJ.jpg)

**Links**


### 2.28 Protein-Energy Malnutrition

Protein deficiency rarely occurs alone. Instead it is often coupled with insufficient energy intake. As a result, the condition is called protein-energy malnutrition (PEM). This condition is not common in the U.S., but is more prevalent in less developed countries. *Kwashiorkor* and *marasmus* are the two forms of protein energy malnutrition. They differ in the severity of energy deficiency as shown in the figure below.
Kwashiorkor is a Ghanaian word that means "the disease that the first child gets when the new child comes". The characteristic symptom of kwashiorkor is a swollen abdomen. Energy intake could be adequate, but protein consumption is too low.

The video below does a nice job showing the symptoms of the condition.

Required Web Link
Video: Kwashiorkor (1:17)
Marasmus means "to waste away" or "dying away", and thus occurs in individuals who have severely limited energy intakes.

![Two individuals suffering from marasmus](image)

Figure 2.283 Two individuals suffering from marasmus

The video below shows individuals suffering from this condition.

**Required Web Link**

**Video: Marasmus (2:24)**

**References & Links**


**Videos**

Kwashiorkor - [http://www.youtube.com/watch?v=eTU3iPWAWXg](http://www.youtube.com/watch?v=eTU3iPWAWXg)

Marasmus - [https://www.youtube.com/watch?v=LDCi3eda4WM](https://www.youtube.com/watch?v=LDCi3eda4WM)

### 2.3 Lipids

Lipids, commonly referred to as fats, have a poor reputation among some people, in that "fat free" is often synonymous with healthy. We do need to consume certain fats and we should try to incorporate some fats into our diets for their health benefits. However, consumption of certain fats is also associated with greater risk of developing chronic disease(s). In this section, we will dive deeper into fats and why they do not need to be feared altogether.
Subsections:
- 2.31 How does fat differ from lipids?
- 2.32 Fatty Acids
- 2.33 Fatty Acid Naming & Food Sources
- 2.34 Essential Fatty Acids
- 2.35 Triglycerides
- 2.36 Phospholipids
- 2.37 Sterols

2.31 How Does Fat Differ from Lipids?

The answer you receive from this question will depend on who you ask, so it is important to have an understanding of lipids and fats from a chemical and nutritional perspective.

To a chemist, lipids consist of:
- Triglycerides
- Fatty Acids
- Phospholipids
- Sterols

These compounds are grouped together because of their structural and physical property similarities. For instance, all lipids have hydrophobic (water-fearing) properties. Chemists further separate lipids into fats and oils based on their physical properties at room temperature:

Fats are solid at room temperature
Oils are liquid at room temperature

From a nutritional perspective, the definition of lipids is the same. The definition of a fat differs, however, because nutrition-oriented people define fats based on their caloric contribution rather than whether they are solid at room temperature. Thus, from a nutrition perspective:

Fats are triglycerides, fatty acids, and phospholipids that provide 9 kcal/g.

The other difference is that from a caloric perspective, an oil is a fat. For example, let's consider olive oil. Clearly, it is an oil according to a chemist definition, but from a caloric standpoint it is a fat because it provides 9 kcal/g.
The following sections will discuss the different lipid classes introduced above in detail.

No References

2.32 Fatty Acids

Fatty acids are lipids themselves, and they are also components of triglycerides and phospholipids. Like carbohydrates, fatty acids are made up of carbon (C), hydrogen (H), and oxygen (O).

On one end of a fatty acid is a methyl group (CH$_3$) that is known as the methyl or omega end. On the opposite end of a fatty acid is a carboxylic acid (COOH). This end is known as the acid or alpha end. The figure below shows the structure of fatty acids.

![Figure 2.321 Structure of a saturated fatty acid](image)

There are a number of fatty acids in nature that we consume that differ from one another in three ways:

1. Carbon chain length (i.e. 6 carbons, 18 carbons)
2. Saturation/unsaturation
3. Double bond configuration (cis, trans)

1. Carbon Chain Length

Fatty acids differ in their carbon chain length (number of carbons in the fatty acid). Most fatty acids contain somewhere between 4-24 carbons, with even numbers (i.e. 8, 18) of carbons occurring more frequently than odd numbers (i.e. 9, 19). Fatty acids are classified as short-chain fatty acids, medium-chain fatty acids, and long-chain fatty acids based on their carbon chain length using the criteria shown in the table below.
Table 2.3.21 Fatty acid classification

<table>
<thead>
<tr>
<th>Classification</th>
<th># of carbons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-Chain Fatty Acid</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>Medium-Chain Fatty Acid</td>
<td>6-10</td>
</tr>
<tr>
<td>Long-Chain Fatty Acid</td>
<td>≥12</td>
</tr>
</tbody>
</table>

Carbon chain length also impacts the physical properties of the fatty acid. As the number of carbons in a fatty acid chain increases, so does the melting point. Shorter chain fatty acids are more likely to be liquid, while longer chain fatty acids are more likely to be solid at room temperature (20-25°C, 68-77°F).

2. Saturation/Unsaturation

A saturated fatty acid is one that contains the maximum number of hydrogens possible, and no carbon-carbon double bonds. Carbon normally has four bonds to it. Thus, a saturated fatty acid has hydrogens at every position except carbon-carbon single bonds and carbon-oxygen bonds on the acid end.

Unsaturation means the fatty acid doesn't contain the maximum number of hydrogens on each of its carbons. Instead, unsaturated fatty acids contain a carbon-carbon double bond and only 1 hydrogen off each carbon. The simplest example of unsaturation is a monounsaturated fatty acid. Mono means one, so these are fatty acids with one degree of unsaturation, or one double bond.

Any fatty acid that has two or more double bonds is considered a polyunsaturated fatty acid. As you may remember from the polysaccharide section, poly means many. A simple example of a polyunsaturated fatty acid is linoleic acid (shown below).
3. Double Bond Configuration (Shape)

Double bonds in unsaturated fatty acids are in one of two structural orientations: cis or trans. In a trans orientation, the hydrogens on the carbons involved in the double bond are opposite one another. In the cis orientation, the hydrogens are on the same side of the bond. Steric hindrance in the cis orientation causes the chain to take on a more bent shape.
Most natural unsaturated fatty acids are in the cis conformation. As can be seen in Figure 2.327, the cis fatty acids have a more of kinked shape, which means they do not pack together as well as the saturated or trans fatty acids. As a result, the melting point is much lower for cis fatty acids compared to trans and saturated fatty acids.

There are some naturally occurring trans fatty acids, such as conjugated linoleic acid (CLA), in dairy products. However, for the most part, trans fatty acids in our diets are not natural; instead, they have been produced synthetically. The primary source of trans fatty acids in our food supply is partially hydrogenated vegetable oil. The 'hydrogenated' means that the oil has gone through the process of hydrogenation. Hydrogenation, like the name implies, is the addition of hydrogen. If an unsaturated fatty acid is completely hydrogenated it would be converted to a saturated fatty acid as shown in Figure 3.324.
However, complete hydrogenation isn’t/wasn’t always desirable, thus partially hydrogenated vegetable oil became widely used. To visualize the difference in the amount of hydrogenation consider the difference between tub margarine and stick margarine.

Stick margarine is more fully hydrogenated giving it a more solid texture. This is one of the two reasons to hydrogenate, to get a more solid texture. The second reason is that it makes it more shelf-stable, because the double bond(s) of unsaturated fatty acids are susceptible to oxidation, which causes them to become rancid.

Partial hydrogenation causes the conversion of cis to trans fatty acids along with the formation of some saturated fatty acids. Originally, it was thought that trans fatty acids would be a better alternative to saturated fat (think margarine vs. butter). However, it turns out that trans fat is actually worse than saturated fat in altering biomarkers associated with cardiovascular disease. Trans fat increases LDL and decreases HDL levels, while saturated fat increased LDL without altering HDL levels. But this does not mean that butter is a better choice than margarine as described in the first link. The FDA revoked Generally Recognized as Safe (GRAS) status of partially hydrogenated vegetable oil as described in the second link, and is requiring its use to be phased out by 2018. After that point, permission will need to be requested to use them in foods.

**Required Web Links**

[Butter vs. Margarine: Which is better for my heart?](#)

[FDA to Limit Trans Fats in Foods](#)
References & Links

Links

2.33 Fatty Acid Naming & Food Sources

We will look at two naming systems used for fatty acids:

1. Omega nomenclature
2. Common names

Omega Nomenclature
For omega nomenclature, you need to know 3 things:

1. Number of carbons in the fatty acid
2. Number of double bonds
3. Number of carbons from the methyl end (aka Omega end) to the first carbon in the double bond closest to the methyl end

We will again consider the same fatty acid.

Figure 2.331 Omega Nomenclature
1. Number of carbons in the fatty acid = 18
2. Number of double bonds = 1 (between carbons 9 & 10)
3. Number of carbons from the methyl (aka omega) end to the first carbon in the double bond closest to the methyl end = 9

Instead of an omega prefix as seen in the figure, the prefix n- (i.e. n-9) is also commonly used. Therefore, the fatty acid in Figure 2.331 would be named 18:1 n-9.

If naming a saturated fatty acid, then the omega nomenclature is not added to the end of the name. If it is an 18-carbon saturated fatty acid, then it would be named 18:0.

**Common Names**
The common names of fatty acids are something that, for the most part, have to be learned/memorized. The common name of the fatty acid we have been naming in this section is oleic acid.

![Oleic acid](image)

Figure 2.332 Oleic acid

However, it can also be called oleate. The only difference is that it has been ionized to form a salt (shown below; there is now a charge on the red oxygen atom). This is what the -ate ending indicates and the two names are used interchangeably.
The table below gives the common names and food sources of some common fatty acids.

Table 2.331 Common names of fatty acids

<table>
<thead>
<tr>
<th>Omega Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:0</td>
<td>Butyric Acid</td>
</tr>
<tr>
<td>12:0</td>
<td>Lauric Acid</td>
</tr>
<tr>
<td>14:0</td>
<td>Myristic Acid</td>
</tr>
<tr>
<td>16:0</td>
<td>Palmitic acid</td>
</tr>
<tr>
<td>18:0</td>
<td>Stearic Acid</td>
</tr>
<tr>
<td>20:0</td>
<td>Arachidic Acid</td>
</tr>
<tr>
<td>24:0</td>
<td>Lignoceric Acid</td>
</tr>
<tr>
<td>18:1 (n-9)</td>
<td>Oleic Acid</td>
</tr>
<tr>
<td>18:2 (n-6)</td>
<td>Linoleic Acid</td>
</tr>
<tr>
<td>18:3 (n-3)</td>
<td>Alpha-linolenic Acid</td>
</tr>
<tr>
<td>20:4 (n-6)</td>
<td>Arachidonic Acid</td>
</tr>
<tr>
<td>20:5 (n-3)</td>
<td>Eicosapentanoic Acid</td>
</tr>
<tr>
<td>22:6 (n-3)</td>
<td>Docosahexanoic Acid</td>
</tr>
</tbody>
</table>

The NutritionData link below can help you identify foods that are high in a specific fatty acid.

**Required Web Link**

NutritionData: Fatty Acids
Food Sources of Fatty Acids

After going through this wide array of fatty acids, you may be wondering where they are found in nature. The figure below shows the fatty acid composition of certain oils and oil-based foods. As you can see, most foods contain a mixture of fatty acids. Stick margarine is the only product in the figure that contains an appreciable amount of trans fatty acids. Corn, walnut, and soybean are rich sources of n-6 polyunsaturated fatty acids (a.k.a. omega-6 fatty acids), while flax seed is fairly unique among plants in that it is a good source of n-3 polyunsaturated fatty acids (a.k.a. omega-3 fatty acids). Canola and olive oil are rich sources of monounsaturated fatty acids. Lard, palm oil, butter and coconut oil all contain a significant amount of saturated fatty acids.

![Fatty acid composition of foods and oils](image)

References & Links

3. [www.nutritiondata.com](http://www.nutritiondata.com)

Links

2.34 Essential Fatty Acids & Eicosanoids

The two essential fatty acids are:

1. **linoleic acid** (omega-6 fatty acid)
2. **alpha-linolenic** (omega-3 fatty acid)

These fatty acids are essential because we cannot synthesize them. This is because we do not have an enzyme capable of adding a double bond (desaturating) beyond the omega-9 carbon counting from the alpha end (the omega-6 and 3 positions). The structures of the two essential fatty acids are shown below.

![Linoleic acid](Image1)

![Alpha-linolenic acid](Image2)

However, we do possess enzymes that can take the essential fatty acids, elongate them (add two carbons to them), and then further desaturate them (add double bonds) to other omega-6 and omega-3 fatty acids. Thus, there are 2 families of fatty acids that the majority of polyunsaturated fatty acids fit into as shown below.

![Eicosanoids](Image3)

The same enzymes are used for both omega-6 and omega-3 fatty acids. However, we cannot convert omega-3 fatty acids to omega-6 fatty acids, or omega-6 fatty acids to omega-3 fatty acids. Among these families, the omega-3 fatty acid, eicosapentaenoic acid (EPA), and the omega-6 fatty acids, dihomo-gamma-linolenic acid (DGLA) and arachidonic acid (AA), are used to form compounds known as **eicosanoids**. These 20 carbon fatty acid derivatives are biologically active in the body (like hormones, but they act locally in the tissue they are produced).
There are four classes of eicosanoids:

- Prostaglandins (PG)
- Prostacyclins (PC)
- Thromboxanes (TX)
- Leukotrienes (LT)

The difference in the effects and outcomes of omega-6 and omega-3 fatty acid intake is primarily a result of the eicosanoids produced from them. Omega-6 fatty acid derived eicosanoids are more inflammatory than omega-3 fatty acid derived eicosanoids. As a result, omega-3 fatty acids are considered anti-inflammatory because replacing the more inflammatory omega-6 fatty acid derived eicosanoids with omega-3 fatty acid derived eicosanoids will decrease inflammation.

You have probably heard that you should get more omega-3s in your diet, and in general polyunsaturated fatty acids are considered healthy. However, since omega-3 fatty acids are competing for the same enzymes as omega-6 fatty acids, and because the omega-6 fatty acids are more inflammatory, consuming too many omega-6s is probably more detrimental than helpful. As a result, many people talk about the omega-3:6 fatty acid ratio in peoples' diets. For most Americans, the ratio is believed to be too high, at almost 10-20 times more omega-6 fatty acids than omega-3 fatty acids\(^1\). The table below shows good food sources of some selected omega-3 and omega-6 fatty acids.

<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Good Food Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linoleic Acid (LA, n-6)</td>
<td>Safflower Oil, Corn Oil, Sunflower Oil</td>
</tr>
<tr>
<td>Arachidonic Acid (AA, n-6)</td>
<td>Eggs, Meat</td>
</tr>
<tr>
<td>Alpha-Linolenic Acid (ALA, n-3)</td>
<td>Walnuts, Flaxseed (linseed), Canola (rapeseed), and Soybean Oils</td>
</tr>
<tr>
<td>Eicosapentaenoic Acid (EPA, n-3)</td>
<td>Fatty Fish &amp; Fish Oils</td>
</tr>
<tr>
<td>Docosahexanoic Acid (DHA, n-3)</td>
<td>Fatty Fish &amp; Fish Oils</td>
</tr>
</tbody>
</table>
Essential Fatty Acid Deficiency

Essential fatty acid deficiency is rare and unlikely to occur, but the symptoms include:

- Growth retardation
- Reproductive problems
- Skin lesions
- Neurological and visual problems

References & Links

Links
Fish Oil Claims Not Supported by Research - http://well.blogs.nytimes.com/2015/03/30/fish-oil-claims-not-supported-by-research/

2.35 Triglycerides

*Triglycerides* are the most common lipid in our bodies and in the foods we consume. Fatty acids are not typically found free in nature, instead they are found in triglycerides. Breaking down the name triglyceride tells a lot about their structure. "Tri" refers to the three fatty acids, "glyceride" refers to the *glycerol* backbone that the three fatty acids are bonded to. Thus, a *monoglyceride* contains one fatty acid, a *diglyceride* contains two fatty acids. Triglycerides perform the following functions in our bodies:

- Provide energy
- Primary form of energy storage in the body
- Insulate and protect
- Aid in the absorption and transport of fat-soluble vitamins.
A triglyceride is formed by three fatty acids being bonded to glycerol as shown below.

When a fatty acid is added to the glycerol backbone, this process is called **esterification**. This process is so named, because it forms an **ester bond** between each fatty acid and the glycerol. Three molecules of water are also formed during this process as shown below.

A stereospecific numbering (sn) system is used to number the three fatty acids in a triglyceride sn-1, sn-2, and sn-3 respectively. A triglyceride can also be simply represented as a polar (hydrophilic) head, with 3 nonpolar (hydrophobic) tails, as shown in Figure 2.353.
The three fatty acids in a triglyceride can be the same or can each be a different fatty acid. A triglyceride containing different fatty acids is known as a **mixed triglyceride**. An example of a mixed triglyceride is shown below.
2.36 Phospholipids

Phospholipids are similar in structure to triglycerides, with the only difference being a phosphate group and nitrogen-containing compound in the place of a fatty acid.

The best-known phospholipid is phosphatidylcholine (a.k.a. lecithin). As you can see in the structure below, it contains a choline off of the phosphate group.

However, you will not normally find phospholipids arranged like a triglyceride, with the 3 tails opposite of the glycerol head. This is because the phosphate/nitrogen tail of the phospholipid is polar. Thus, the structure will look like those in Figures 2.363 & 2.364.
Figure 2.363 Structure of phosphatidylcholine (lecithin)$^2$

Figure 2.364 Structure of phosphatidylcholine (lecithin)$^3$

Similar to triglycerides, phospholipids are also represented as a hydrophilic head with two hydrophobic tails as shown below.

Figure 2.365 Schematic of a phospholipid

**Phospholipid Functions**

Because its structure allows it to be at the interface of water-lipid environments, there are two main functions of phospholipids:

1. Key Component of the Cell's Lipid Bilayer
2. Emulsification
Number 1 in the figure below is a cell's lipid bilayer, while 2 is a micelle that is formed by phospholipids to assist in **emulsification**.

![Figure 2.366, 1 - lipid bilayer, 2 - micelle](image)

**1. Key Component of Cells' Lipid Bilayers**

Phospholipids are an important component of the lipid bilayers of cells. A cross section of a lipid bilayer is shown below. The hydrophilic heads are on the outside and inside of the cell; the hydrophobic tails are in the interior of the cell membrane.

![Figure 2.367 Phospholipids in a lipid bilayer](image)

Figure 2.367 Phospholipids in a lipid bilayer. The blue represents the watery environment on both sides of the membrane, while the dark green represents the hydrophobic environment in between the membranes.
2. Emulsification
As emulsifiers, phospholipids help hydrophobic substances mix in a watery environment. It does this by forming a micelle as shown below. The hydrophobic substance is trapped on the interior of the micelle away from the aqueous environment.

As a result, it can take a hydrophobic liquid (oil) and allow it to mix with hydrophilic liquid (water).

In a practical sense, the micelle is an ideal transportable particle for our blood stream. Since our blood is an aqueous solution, transport of nonpolar (hydrophobic) substances, like fat, cholesterol and fat-soluble vitamins (like vitamin D), can be a problem. The solution: micelles can function like tiny delivery trucks, transporting nonpolar substances through our circulatory system to our cells as they are needed.
Figure 2.369 How an emulsion can allow the dispersion of a hydrophobic substance (II) into a hydrophilic environment (I) as shown in D

Foods rich in phosphatidylcholine include: egg yolks, liver, soybeans, wheat germ, and peanuts. Egg yolks serve as an emulsifier in a variety of recipes. However, your body can make all the phospholipids that it needs, so they do not need to be consumed (not essential).

References & Links
The last category of lipids are the **sterols**. Their structure is quite different from the other lipids because sterols are made up of a number of carbon rings. The generic structure of a sterol is shown below.

![Generic structure of a sterol](image1.png)

Figure 2.371 Generic structure of a sterol

The primary sterol that we consume is **cholesterol**. The structure of cholesterol is shown below.

![The carbon ring structure of cholesterol](image2.png)

Figure 2.372 The carbon ring structure of cholesterol

Cholesterol is frequently found in foods as a cholesterol ester, meaning that there is a fatty acid attached to it. The structure of a cholesterol ester is shown below.

![Structure of a cholesterol ester](image3.png)

Figure 2.373 Structure of a cholesterol ester
All sterols have a similar structure to cholesterol. Cholesterol is only found in foods of animal origin. If consumers were more knowledgeable, intentionally misleading practices, such as labeling a banana “cholesterol free”, would not be as widespread as they currently are today.

**Function**

Although cholesterol has acquired the status of a nutritional "villain", it is a vital component of cell membranes, and is used to produce vitamin D, hormones, and bile acids. However, we do not need to consume any cholesterol from our diets (not essential) because our bodies have the ability to synthesize the required amounts. The figure below gives you an idea of the cholesterol content of a variety of foods.

![Cholesterol Content of Foods](http://en.wikipedia.org/wiki/File:Cholesterol.svg)

**Figure 2.374** The cholesterol content (mg) of foods

There is neither bad nor good cholesterol, despite these descriptions being commonly used for LDL and HDL, respectively. Cholesterol is cholesterol. HDL and LDL contain cholesterol but are actually lipoproteins that will be described later in chapter 4.

**References & Links**