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THE SCIENCE OF FOOD AND COOKING: MACROMOLECULES

Guided Inquiry Activities (Web): 1, Elements, Compounds, and Molecules; 2, Bonding; 3, Mixtures and States of Matter; 4, Water; 5, Amino Acids and Proteins; 6, Protein Structure; 7, Carbohydrates; 8, pH; 9, Fat Structure and Properties; 10, Fat Intermolecular Forces; 11, Smoking Point and Rancidity of Fats

1.1 INTRODUCTION

The process of cooking, baking, and preparing food is essentially an applied science. Anthropologists and historians venture that cooking originated when a pen holding pigs or other livestock caught fire or a piece of the day's catch of mammoth fell into the fire pit. The smell of roasted meat must have enticed early people to "try it"; the curious consumers found culinary and nutritional benefits to this new discovery. The molecular changes that occurred during cooking made the meat more digestible and the protein and carbohydrates more readily available as nutrients. Contaminating microbes were eliminated during cooking, which made the consumers more healthy and able to survive. Moreover, the food was tastier due to the heat-induced chemical reactions between the oxygen in the air and the fat, proteins, and sugar in the meat. Harnessing the knowledge of what is happening to our food at the molecular level is something that good scientists and chefs use to create new appetizing food and cooking techniques.

We are all born curious. Science and cooking are natural partners where curiosity and experimentation can lead to exhilarating and tasty new inventions. Scientific

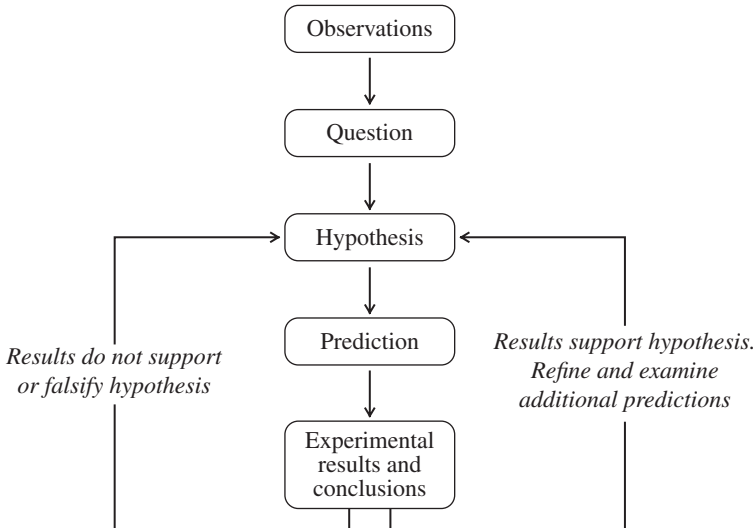


FIGURE 1.1 The scientific method. Scientists use a testable method originating from observations to generate a testable hypothesis to conduct their work. A cook or baker can also use this method to create a more interesting food.

discovery is driven by hypothesis (see Fig. 1.1 for a model of the scientific method). An observation of an event creates a question and/or a statement that explains the observation or phenomenon: the hypothesis. The hypothesis can then be tested by a series of experiments and controls that supports or falsifies the hypothesis, starting the cycle over again. For example, a scientist might observe that the growth rate of cancer cells in a petri dish slows when the cells are exposed to a sea sponge. The scientist may then hypothesize that a molecule found in the sponge binds to a protein in cancer cells. After adding the compound to a tumor, its growth slowed and the cells die. Looking at how all of the individual molecules found in the sea sponge affect the growth of cancer cells can test this hypothesis. These experiments can lead to a more advanced hypothesis, testing and eventually finding a new compound that can be used to fight cancer.

Cooking can also be a hypothesis-driven process that utilizes biology, chemistry, and physics. As you cook, you use biology, chemistry, and physics to create hypotheses in the kitchen, even if you weren't aware of being a scientist. Each time you try a recipe, you make observations. You may ask yourself questions about what you added to the concoction or how the food was baked or cooked. This creates a hypothesis or a statement/prediction that you can test through experimentation (your next attempt at the dish). A nonscientific idea is often approached as something to prove. That is different from hypothesis testing. A hypothesis is falsified rather than proven by testing. Cooking does just this; it will falsify your test rather than prove it. Tasting, smelling, and visualizing your results tell you if your hypothesis was supported or falsified. If wrong, you may create a new hypothesis that might be generated by the

time you have washed the dishes from your first experiment! Learning more of the basic science behind food and cooking will help you appreciate the world around you and become a better scientist and a better cook, baker, and consumer.

1.2 FUNDAMENTALS OF FOOD AND COOKING

Bread baking provides a great example of the importance of having a scientific understanding of cooking and baking. Take a close look at bread. Notice that it is made of large and small caves surrounded by a solid wall (Fig. 1.2).

The key to bread is making a way to trap expanding gases in the dough. Adding water to flour and sugar allows for the hydration and mixing of proteins and carbohydrates. Kneading the dough stretches a protein called gluten, which allows for an interconnected network of protein ready to trap gas that is generated by the yeast. During the proofing step of making bread, the yeast converts sugar into energy-filled molecules, ethanol, carbon dioxide gas, and other flavorful by-products. The heat applied during baking allows the water to escape as steam, which expands the bread, links the gluten protein molecules further, and traps carbon dioxide gas. While this is happening, the heat catalyzes chemical reactions between proteins and sugars, creating a beautiful brown color, a dense texture, and over 500 new aromatic compounds that waft to your nose. Clearly there is a lot of science that goes into making a loaf of bread.

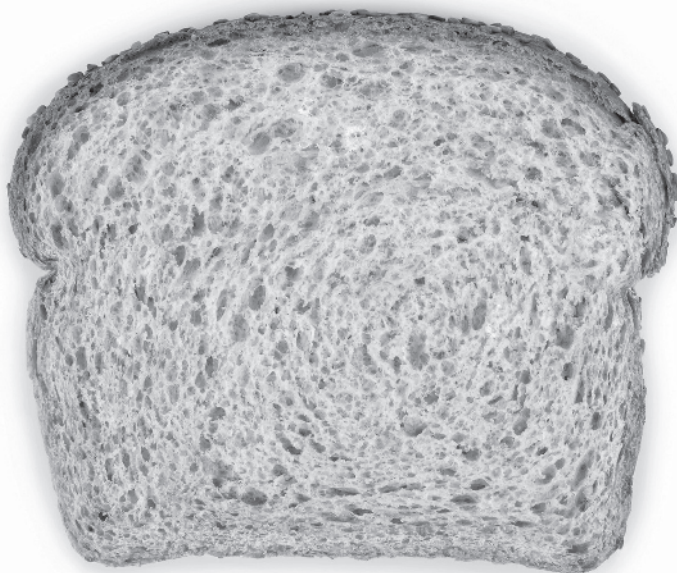


FIGURE 1.2 Structure of bread. A close look at bread demonstrates the requirement of proteins and carbohydrates needed to trap expanding gases.

Preparing food and drink is mostly a process of changing the chemical and physical nature of the food. Molecules react to form new compounds; heat changes the nature of how food molecules function and interact with each other, and physical change brings about new textures and flavors to what we eat. To gain a better appreciation for these chemical and physical processes, a fundamental understanding of the building blocks of food and cooking must first be understood. In the following two chapters we will study the basic biological principles of cooking, tasting, and smelling.

One of the most important building blocks of food is water; our bodies, food, and environment are dependent on the unique chemistry and biology of this molecule. Large biological molecules such as proteins, carbohydrates, and fats comprise the basic building blocks of food. Smaller molecules, including vitamins, salts, and organic molecules, add important components to cooking and the taste of food. Finally, the basics of plant and animal cells and cellular organization are key to understanding the nature of food and cooking processes. However, before we get into some of the science fundamentals, it is important to recognize and acknowledge the origins of and the chefs who first embraced the science behind their profession.

1.2.1 Science, Food, and Cooking

Many chefs and bakers embrace the collaboration of science and food. Historically, one means whereby science has been utilized in the kitchen is in the area of food technology—the discipline in which biology, physical sciences, and engineering are used to study the nature of foods, the causes of their deterioration, and the principles underlying food processing. This area of food science is very important in ensuring the safety and quality of food preparation, processing of raw food into packaged materials, and formulation of stable and edible food. College undergraduates can major in “food science” or attend graduate studies in this area, working for a food production company where they might look at the formulation and packaging of cereals, rice, or canned vegetables. Recently a new marriage of science and food, coined molecular gastronomy, has grown to influence popular culture that extends far beyond the historical definition of food science. A physicist at Oxford, Dr. Nicholas Kurti’s interest in food led him to meld his passion for understanding the nature of matter and cooking. In 1984 Harold McGee, an astronomer with a doctorate in literature from Yale University, wrote the first edition of the influential and comprehensive book *On Food and Cooking: The Science and Lore of the Kitchen* [1]. This fascinating book is the basis for much of the molecular gastronomy movement and describes the scientific and historic details behind most common (and even uncommon) culinary techniques. Together with cooking instructor Elizabeth Cawdry Thomas, McGee and Kurti held a scientific workshop/meeting to bring together the physical sciences with cooking in 1992 in Erice, Italy. While there were more scientists than chefs attending, with a five to one ratio, the impact of the meeting was significant. It was at Erice that the beginnings of what was then called molecular and physical gastronomy became the catalyst for an unseen growth in science and cooking. Hervé This, a chemist who studies the atomic and subatomic nature of chemistry, attended the workshop and has been a key player in the growth of molecular gastronomy. Dr. This blames a failed cheese soufflé

for sparking his interest in culinary precisions and has since transformed into a career in molecular gastronomy. Other participants of the meetings include chef Heston Blumenthal and physicist Peter Barham, who have collaborated and influenced many molecular-based recipes and projects. Finally another scientist, biochemist Shirley O. Corriher, was present at these early meetings (Box 1.1). Shirley found her love of cooking as she helped her husband run a school in Nashville in nearby Vanderbilt Medical School where she worked as a biochemist. Her influence on science and cooking includes a friendship and advisory role with Julia Child and the many informative, science approach-based cookbooks (Ms. Corriher, personal communications, June 2012). The impact on popular culture and influence on modernist cooking are immense. For 13 years, Alton Brown brought the scientific approach to culinary arts in the series *Good Eats*. Through the work of all of these scientist chefs, use of liquid nitrogen, a specialized pressure cooking called sous vide, and unique presentation and mixtures of flavors are now more commonplace and creating new options for the daring foodie.

BOX 1.1 SHIRLEY CORRIHER

Shirley Corriher has long been one of the original scientists/cooks to influence the new approach to cooking and baking. Using everyday language as a way to explain food science, Shirley has authored unique books on becoming a successful cook and baker with her books *CookWise* [2] and *BakeWise* [3]. Her influence on popular acceptance of science on cooking and baking includes a friendship with Julia Child, appearances on several of Alton Brown's *Good Eats* episodes, and her involvement in the growth of the science and cooking. Shirley earned a degree in biochemistry from Vanderbilt University where she worked in the medical school in a biomedical research laboratory while her husband ran a school for boys. She recalls her early attempt to cook for the large number of boys. Little did she know this experience would be the beginning of a new career. Shirley describes how she struggled with the eggs sticking to the pan and worrying that there would be no food for the students. Eventually she learned to heat the pan before adding the eggs. The reason was that the small micropores and crevices of the pan would fill and solidify in the pan. This sparked the connection between science and cooking for her. After a divorce Ms. Corriher and her sons were forced into a financial struggle, where they had to use a paper route as a source of income, a friend, Elizabeth Cawdry Thomas, who ran a cooking school in Berkeley, California, asked her to work for her cooking school where she learned formal French cooking while on the job. Later Shirley found herself mixing with a group of scientists and chefs who appreciated the yet to be studied mix of science and cooking. In 1992, the group including Thomas, Kurti, and Harold McGee obtained funds to bring scientists and chefs together to support workshops on nonnuclear proliferation in Erice, Sicily. Shirley was a presenter at that first meeting leading discussions on emulsifiers and sauces and continued as a participant in each of these early

workshops (Ms. Corriher, personal communications, June 2012). Corriher recalls that the term molecular gastronomy was voted on by the core group to reflect both the science and culinary aspects of the meeting. Shirley talks of a respect and friendship between herself and leading food scientist Harold McGee. Shirley recalls reading his book and called him to ask him where had he been all this time? She said, “You don’t know me, but I and many other ladies in Atlanta are going to bed with you every night!” Her books using science to explain how to become a better cook and baker are extremely popular. Her approach to trust in yourself and understanding the science of kitchen work is certainly an inspiration given by a person with a unique route to her spot in American culinary society.

1.3 THE REAL SHAPE OF FOOD: MOLECULAR BASICS

What are the fundamental units of all food and cooking processes? Atoms and molecules! All living systems (animals, microbes, and smaller life forms) are made of atoms and molecules. How these atoms and molecules are organized, interact, and react provides the building blocks and chemistry of life. It makes sense that to best understand cooking and baking at the molecular level, you must first appreciate how atoms and compounds are put together and function. Let’s start with the basics and ask, what is the difference between an atom and molecule? The answer is simple: an atom is the smallest basic building block of all matter, while molecules are made when two or more atoms are connected to one another.

An atom consists of three main components also known as subatomic particles. These subatomic particles are called protons, neutrons, and electrons. A simple description of what and where these particles are located is that protons and neutrons are found in the center or nucleus of the atom, while electrons orbit the core of the atom (Fig. 1.3). Protons are positively charged particles with an atomic mass of one atomic mass unit. Neutrons essentially also have an atomic mass of one, but do not have an electrical charge. Electrons have almost no mass and have an electrical charge of -1 .

The elements of the periodic table are arranged and defined by the number of protons present within an atom of a given element. The number of protons defines an atom, not the electrons or neutrons. A quick examination of a periodic table shows that their proton number organizes atoms: from the smallest atom, hydrogen, to the largest atom, ununoctium. As stated, the number of protons in an atom defines that atom. Any atom with six protons is a carbon; any atom with seven protons is nitrogen. Thus, if a carbon atom gains a proton, it becomes a nitrogen atom. However, if a carbon atom gains or loses an electron, it still is a carbon, but now has a charge associated with it. The total number of protons and electrons defines the charge of an atom. An atom of any element with an equal number of protons and electrons will have a net neutral charge; atoms that have gained an electron will have a negative charge, and those that have lost an electron will have a positive charge. Most of the atoms of the elements on the periodic table can gain or lose one or more electrons. The numbers of neutrons within a given type of atom can also vary. Isotopes are

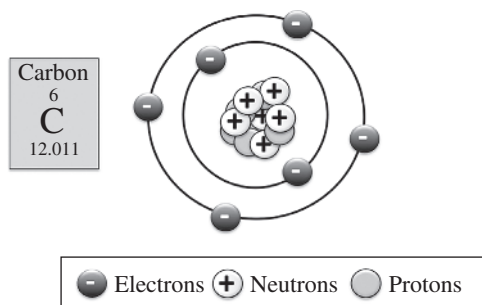


FIGURE 1.3 Atomic structure. Atoms are made of electrons in orbitals around the nucleus where protons and neutrons are found. The identity of an atom is the number of protons.

atoms that have the same number of protons but differ in the number of neutrons. Carbon 12 and carbon 13 both have six protons (thus they are carbon), but carbon 12 has six neutrons for a total atomic mass of 12, while carbon 13 has seven neutrons and when including the mass of the protons has an atomic mass of 13 (6 protons + 7 neutrons = 13 atomic mass) (Fig. 1.4).

What about a compound or a molecule? How does a molecule differ from an atom or compound? A molecule is a substance of two or more atoms connected by sharing electrons (covalent bonds). A compound is a chemical substance made of different atoms. Compounds can be made of atoms held together by ionic or covalent bonds where molecules are made only of covalently bonded atoms. Thus all molecules are compounds, but not all compounds are molecules. Molecules are often categorized further into organic (those molecules containing mostly carbon atoms) and inorganic molecules (everything else).

Most of the compounds found in living things contain carbon, hydrogen, nitrogen, or hydrogen atoms. A group of other elements, including sulfur, magnesium, and iron, make up less than 1% of the atoms in most living systems. Trace elements, such as copper, zinc, chromium, and even arsenic, although necessary for biological function, only make up a minute portion of an organism, less than 0.01% of all atoms. Due to their complexity and impact on their behavior in cooking, let's talk a little bit more about the bonds that connect atoms together.

1.3.1 Ionic and Covalent Compounds

There are two types of bonds that connect two atoms to yield a molecule or compound: ionic and covalent. Ionic bonds form between atoms that have opposite charge due to the loss or gain of electrons (Fig. 1.5). Atoms that have become charged have their own name—ions. Ionic bonds form when an ion with a positive charge (a cation) is bonded to an ion with a negative charge (an anion). The resulting molecule is called an ionic compound or a salt. This terminology is apropos because the salt that you sprinkle on your popcorn, NaCl, is an ionic compound consisting of a positively charged sodium atom or ion (Na^+) and a negatively charged chlorine atom or ion (Cl^-).

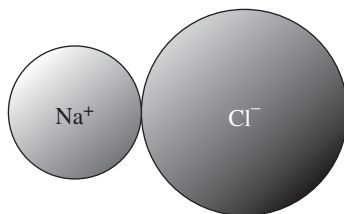


FIGURE 1.5 Ionic compound (sodium chloride). A positively charged cation (Na^+) forms an ion bond to a negatively charged anion (Cl^-) to form an ionic compound.

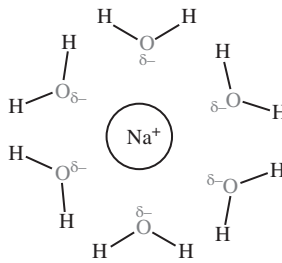
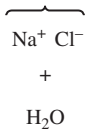
Thus compounds are divided into molecules that have a charge or those without a charge. Ionic compounds are molecules that have somehow lost or gained an electron resulting in a compound with two parts; one atom or group will be positive charged and bonded to another atom or group of atoms with a negative charge. One of the atoms in an ionic compound will have at least one metal element (Na, K, Ca, Al, etc.). Metal atoms more readily give or accept electrons transforming the atoms into charged ionic elements. The simplest ionic compounds are formed from monoatomic ions, where two ions of opposite charge act as the functional unit. A good example is table salt, or sodium chloride (NaCl). In addition to single atom ions, a group of covalently bound atoms can also possess an overall charge called polyatomic ions. Polyatomic ions are made of several atoms bonded as a group, which is charged. Potassium nitrate, commonly called saltpeter and used in curing meat, is a complex polyatomic ion with the chemical formula KNO_3 , where the potassium ion (K^+) provides the positive charge and the nitrate ion provides the negative charge (NO_3^-). Nitrate compounds have been historically used to preserve meats and fish. The nitrate dries the meat by drawing the water out of the muscle tissue leaving an inhospitable environment for bacteria to grow.

As a solid, ionic atoms are tightly held together by opposite charges in large networks called a lattice. In water, however, the attractive force between cation and anion components of the ionic compound is shielded by water and separate from one another. You can see this phenomenon with your very own eyes as you watch a teaspoon of salt dissolve in a glass of water. What is happening at the molecular level? Water is a polar covalent molecule with a positive and negative partial charge. The hydrogens have a partial positive charge, while the oxygen has a partial negative charge. Water molecules align with the charge of the ion forming a solvating shell of water (Fig. 1.6). This coating of water acts to shield the attraction between the ions, which can then separate from one another, dissolving in the water.

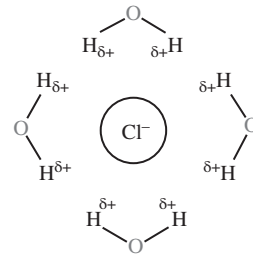
Salts are a very important aspect of foods, cooking, and taste and are often key to the demise of success of a given dish. Thus, when we refer to salts throughout the rest of this text, we will specify whether we are using the scientific definition of salt (an ionic compound made up of a cation and anion) or the common definition of salt (meaning table salt, or NaCl).

Can you have molecules that are made up of uncharged atoms? Yes, these molecules are called covalent or molecular compounds (as opposed to the ionic compounds or salts referred to earlier). In covalent compounds, sharing electrons holds atoms

Sodium chloride (i.e., table salt) is an ionic compound. It is made of two different types of atoms that are held together by a positive to negative attraction called an *ionic bond*



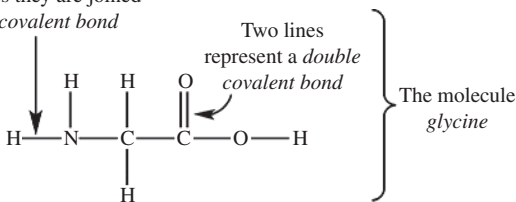
The sodium cation (Na^+) is surrounded by a cloud of water molecules that are oriented to present their *slightly negative* oxygens toward the positively charged sodium



The chloride anion (Cl^-) is surrounded by a cloud of water molecules that are oriented to present their *slightly positive* hydrogens toward the negatively charged chloride

FIGURE 1.6 Salt dissolves in water. In water, the polar nature of water surrounds and reduces the attractive force between ionic compounds dissolving each ion into the water solution.

A line between two atoms indicates they are joined by a *covalent bond*



The two electrons being *shared*. This joins the atoms together

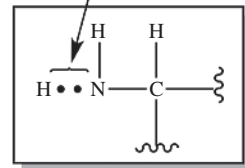


FIGURE 1.7 Covalent bonds have shared electrons. The sharing of two electrons forms a covalent bond. The straight line between atoms represents these electrons. Electrons are very tiny particles with negative charge. Every atom of each unique element has a specific number of electrons. For example, every hydrogen atom has one electron.

together; the force that ties the atoms together is called a covalent bond. The amino acid glycine is a great example of a covalent compound (Fig. 1.7). In a molecule of glycine, each nitrogen, carbon, oxygen, and hydrogen atom shares electrons with neighboring atoms forming a bond. The sharing of electrons that creates these covalent bonds has a particular order. Sharing of one set of electrons between atoms creates a single bond often shown by a single line drawn between the atoms. A double or triple bond is created when two or three pairs of electrons are shared between atoms (Fig. 1.8). Covalent compounds are made up of nonmetal atoms and are typically much more diverse (i.e., different arrangements of atoms) and larger (i.e., more atoms) than ionic compounds. The main difference between ionic and covalent compounds is that covalent compounds are not held together by charges, but atoms are bonded

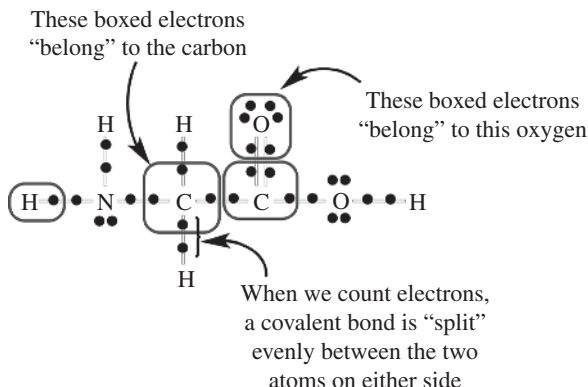


FIGURE 1.8 Counting electrons with covalent bonds. Shared electrons making a covalent bond are often drawn as pairs of dots. However most molecular structures use single lines to represent the shared pairs of electrons.

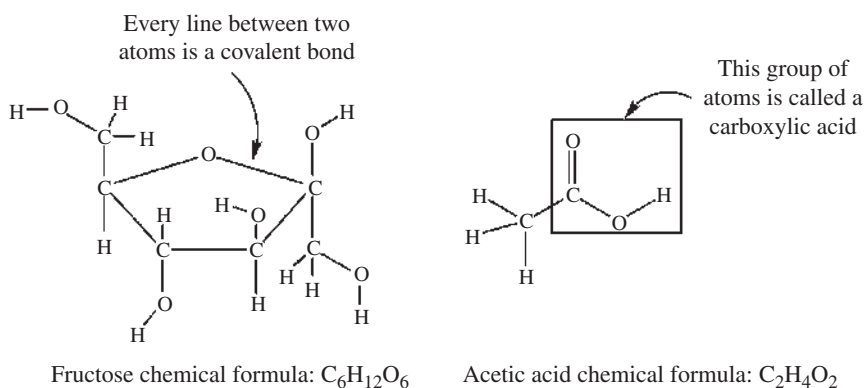


FIGURE 1.9 Structure of fructose and acetic acid. The organization, shape, and chemical nature of the bonds and atoms create very different tastes and biological roles for these simple compounds.

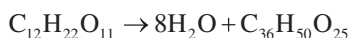
together by sharing electrons in what is called a covalent bond. Molecular compounds make up the bulk of our food and include water, sugars, fats, proteins, and most vitamins. Sugars, fat, protein, and most vitamins are covalent compounds. Given their importance in food and cooking, let's look at two detailed examples of covalent compounds, fructose, and acetic acid.

Fructose is a sweet tasting sugar found in fruit and honey, while acetic acid is responsible for the sour taste in vinegar (Fig. 1.9). Looking at its molecular structure, the six carbon atoms are bonded (shown by the lines connecting atoms) to the 12 hydrogen or six oxygen atoms. Because of its atomic components, the molecular formula of fructose is $C_6H_{12}O_6$. This molecule is relatively large and has no overall charge, and all of the atoms are nonmetals. Clearly at the molecular level, fructose is

different from table salt. One is organic made of a special arrangement of carbon, oxygen, and hydrogen, while salt is an ionic compound of sodium and chloride. Of course we all know the difference by taste and would prefer to eat a spoonful of honey over a spoonful of table salt. Interestingly, acetic acid is also made of carbon, hydrogen, and oxygen atoms. However, the arrangement and number of atoms between fructose and acetic acid are different, which give the two covalent molecules very different chemical and biological properties. Acetic acid has a carbon bonded to two oxygen atoms. One of the oxygen atoms is bonded to the carbon with a single bond, and the second has two bonds. This particular arrangement of atoms is called a carboxylic acid; we will discuss carboxylic acids in more depth later in this chapter. Notice also that one of the oxygen atoms in acetic acid has a negative charge. Don't let this confuse you! Even though acetic acid can be charged, it is not a salt or an ionic compound since its atoms are connected via covalent bonds. However, these covalent molecules do behave very differently than those covalent molecules that are uncharged. Specifically, these "charged" covalent molecules have acidic or basic properties. You have heard of acids and bases and likely have surmised that acetic acid is, in fact, an acid. Covalent molecules that are acidic or basic (and their corresponding charges) play many key roles in cooking processes. For example, charges on a covalent molecule are important to a cheese maker who is curdling milk to make cheese. When a negative charge is present on fat and protein particles in milk, the milk is a smooth, refreshing liquid. When the negative charges are removed from the fat and protein particles, protein and fat particles aggregate together, forming a semisolid curd. You will learn more about the properties and role of specific ionic and covalent molecules important in foods within the topical chapters that follow. However, in order to understand that chemistry and biology, the way food cooks, the flavors of food, and the reactions of food, we need a little more background on some basic concepts on molecules, how to draw them, and how they behave and interact with other molecules (Box 1.2).

BOX 1.2 DRAWING AND UNDERSTANDING CHEMICAL STRUCTURES

Scientists use a number of ways to represent chemical compounds. The simplest way to represent a molecule is the molecular formula. This is simply a count of each kind of atom in a molecule. The subscript describes the number of atoms in the molecule for the preceding element. While simple, it does not describe very much about the way the atoms are joined together. For example, both glucose and fructose can be described by the molecular formula $C_6H_{12}O_6$, as both a molecule of glucose and a molecule of fructose contain 6 carbons, 12 hydrogens, and 6 oxygen atoms. However, a molecular formula is often used for simple molecules to show how they react. For example, to produce caramel from table sugar ($C_{12}H_{22}O_{11}$), the applied heat results in a loss of water and a decomposition of sucrose to yield caramelen ($C_{36}H_{50}O_{25}$):



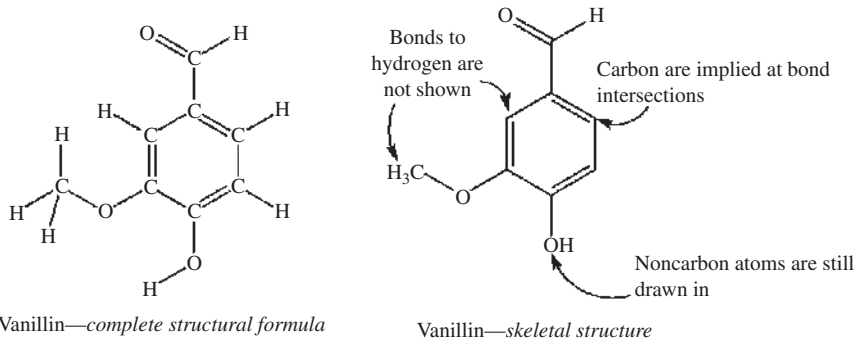


FIGURE 1.10 Structure of vanillin. On the left: structural formula of vanillin. Each atom is drawn and each bond is clearly marked—notice the single and double bonds and carbon atoms bonded to H, O, and other C atoms. On the right: Skeletal formula of vanillin. Note the implied carbons at the intersection and end of each line. Groups of atoms are explicitly drawn. Double and single bonds are drawn the same as shown in a structural formula.

A complete structural formula is used to depict the way atoms are bonded together and show every atom and every bond. Covalent bonds are illustrated as a line between atoms. For example, C—C shows that there is one (—) bond between two carbon atoms, where each bond is a pair of (i.e., two) shared electrons. Some compounds have two bonding sets of electrons, a double bond shown as =. Some molecules even have triple bonds, which involve six shared electrons (\equiv). Let's use vanillin, the molecule responsible for artificial vanilla extract odor and flavor, as an example of different bonding arrangements. The molecular formula of vanillin is $C_8H_8O_3$. Vanillin contains both single and double bonds between atoms (Fig. 1.10).

A third common way of depicting molecules with lots of carbon atoms is to draw a line structure formula, sometimes referred to as a skeletal formula. Skeletal formulas are useful in that they provide the information contained within a complete structural formula, but they are drawn in a shortcut manner. In a skeletal formula, a carbon–carbon bond is drawn without specifically showing the carbons and hydrogens, but all of the other atoms or groups of atoms are included. In these drawings, a carbon is implied at each bend and end of a line (the line represents the bond of a carbon atom); if any carbon atom doesn't have four covalent bonds, then there are hydrogens present to ensure that each carbon atom is involved in four covalent bonds.

1.3.2 Properties of Covalent Molecules

1.3.2.1 Functional Groups The structure of a molecule defines how it functions in a cell and how a food may taste or react when cooking or baking. Special groups of molecules called functional groups define the behavior of molecules. Functional groups are arrangements of atoms that have specific chemical and biochemical behavior. These groups of atoms are useful to predict and understand properties of

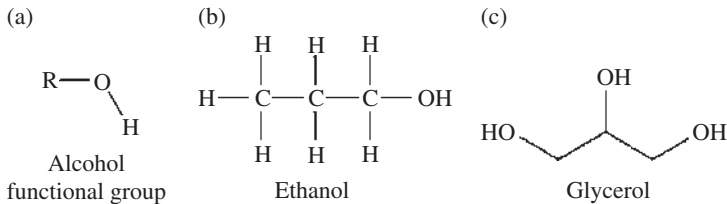


FIGURE 1.11 Alcohol functional groups. (a) The basic convention for alcohol with R as an undetermined carbon group. (b) A structural drawing of the two-carbon ethanol. (c) Glycerol without the hydrogens. At the intersection of each line is a carbon.

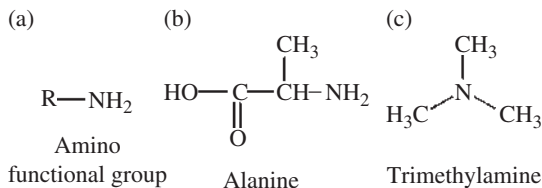


FIGURE 1.12 Amino functional groups. (a) The basic convention for amino with R as an undetermined carbon group. (b) L-Alanine, one of the common 20 amino acids used to make proteins. (c) Three CH_3 (methyl) groups bound to central nitrogen to make trimethylamine.

organic molecules and molecules important in food and cooking. Specific functional groups and examples of molecules that are important in food and cooking are shown throughout the book.

Alcohol —OH An alcohol is the simplest of all functional groups. It is an oxygen atom covalently bonded to a hydrogen atom, often designated as $-\text{OH}$ (Fig. 1.11). Sugars, like fructose, have many alcohol groups. Molecules of ethanol and glycerol both contain alcohol functional groups. The $-\text{OH}$ plays key roles in allowing these molecules to interact with and dissolve in water. You likely already know a little about or have experienced the use of fructose (honey) and ethanol in food or drinks. Glycerol is a sweet, sticky, and thick compound that is often added to bread, cookies, and cakes to keep them moist. A glycerol molecule also provides the molecular framework for fat molecules.

Amino $-\text{NH}_2$ and $-\text{NH}_3^+$ A group of atoms containing a nitrogen covalently bonded to hydrogen is called an amine or amino group (Fig. 1.12). Two or three hydrogen atoms can bond to the nitrogen, creating a neutral ($-\text{NH}_2$) or positively charged ($-\text{NH}_3^+$) group. Amino acids, which combine to make proteins, contain an amine functional group. The molecule trimethylamine provides the unique odor associated with fish.

Saltwater fish contain high amounts of trimethylamine oxide in their muscle cells to counter the high salt content in water balancing the resulting osmotic pressure in the cells of the fish.

Carboxylic Acid $-\text{COOH}$ and $-\text{COO}^-$ The tangy taste associated with a nice cool glass of lemonade or a sour citrus hard candy is provided by carboxylic acids (Fig. 1.13). This functional group consists of a carbon bound to two oxygen atoms, where one of the

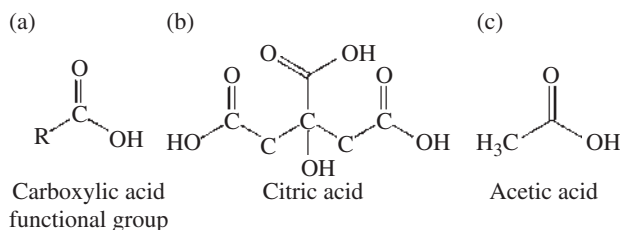


FIGURE 1.13 Carboxylic acid functional groups. (a) The basic convention for carboxylic acid with R as an undetermined carbon group. (b) The sour tasting weak acid citrate with three carboxylic groups. (c) The molecular structure of acetic acid whose household name is vinegar.

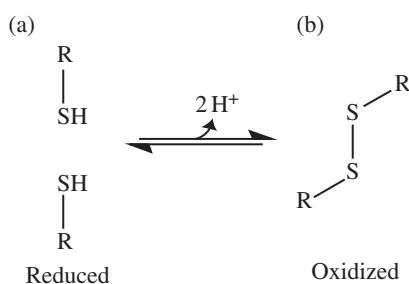


FIGURE 1.14 Thiol functional groups. (a) The basic convention for a reduced sulfhydryl with R as an undetermined carbon group. (b) The change in oxidation state of a sulfhydryl group from reduced (R—SH) to oxidized (R—S—S—R).

oxygen atoms may also be bonded to a hydrogen ion. Thus, it is designated as R—COOH or R—COO⁻. Why is the hydrogen sometimes absent? Due to oxygen's affinity for electrons and hydrogen's lack of affinity electrons, the bond between the hydrogen and oxygen in carboxyl groups is easily broken, yet the oxygen keeps the electron from the previously shared covalent bond, yielding a carboxyl group that lacks a hydrogen ion (H⁺) and maintains a negative charge (R—COO⁻). The R—COO⁻ is a weak organic acid, hence the name carboxylic acid. Carboxylic acids are found throughout food and cooking, most notably in citrus fruits (citric acid) and vinegar (acetic acid). The acid component of these foods stimulates the sour taste receptor on our tongues giving these foods a sour taste. An example is malic acid. Malic acid is an organic acid that is found in unripe fruit like green apples and gives the food a sour green apple flavor.

Sulfhydryl (Thiol) Group —SH Sulfur atoms that are contained within a molecule have a very important and diverse role in cooking and baking, depending upon its bonding partners. The amino acid cysteine has an —SH group. When sulfur is bonded to a hydrogen atom, we call the functional group a sulfhydryl or thiol group and designate it as —SH (Fig. 1.14). Most proteins found in plant and animal tissues have various amounts of cysteine and therefore sulfhydryl groups. However, the sulfur in cysteine does not have to remain bonded to a hydrogen; it can also be bonded to another sulfur atom (often found in a different cysteine amino acid) when a chemical reaction, called an oxidation/reduction reaction, occurs, resulting in the formation of a

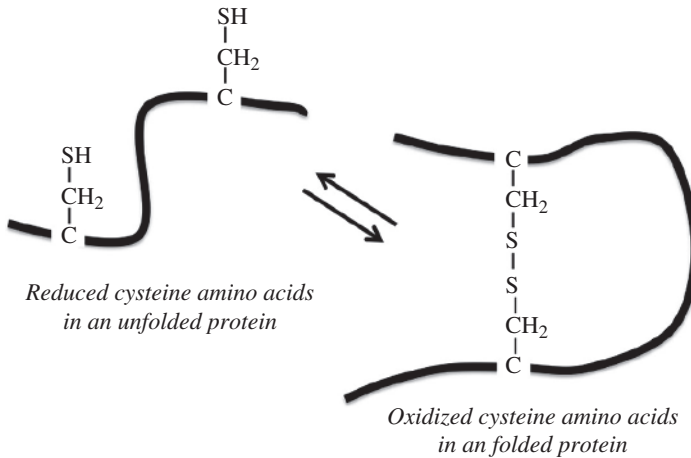


FIGURE 1.15 The important role of cysteine sulfhydryl functional groups. When proteins are folded, the sulfhydryl groups of two cysteine amino acids are involved in maintaining the shape of the protein. Loss of the bond by reduction will result in the loss or denaturation of the shape of the protein.

covalent disulfide bond ($-\text{SS}-$). Proteins often require disulfide bonds to be present to keep the protein folded in a functional, native state, and in solution (Fig. 1.15). However, because an $\text{S}-\text{S}$ bond is weaker than a $\text{C}-\text{C}$ bond, heat can break disulfide bonds. The more disulfide bonds, the more heat that is required to break them and unfold the proteins. Some compounds will change the “oxidation state” of disulfide bonds and will contribute to the denaturing of the protein. In cooking, we visualize this process of protein unfolding when we cook eggs. Eggs have several different kinds of proteins. Those found in egg whites have relatively few disulfide bonds, and low levels of heat cause the proteins to denature. You observe this when the egg whites change from clear to white and “cook” in your warm skillet. In contrast, proteins found in the egg yolk have more disulfides and require a higher temperature to unfold and “cook” these proteins. Disulfides also play an important role in baking and wheat.

1.3.3 Gluten, Fumaric Acid, and Tortillas

A handmade tortilla is a simple food made from wheat flour, water, shortening, and salt. Wheat flour has two gluten proteins that include large numbers of cysteine (sulfhydryl-containing) amino acids. Once processed, the gluten proteins link together via disulfide bonds providing an elastic, chewy texture to the tortilla. Unfortunately, machine processing of tortillas creates excess links between the proteins resulting in a rubbery, less than satisfying tortilla. The molecule fumaric acid has a carboxylic acid functional group used to overcome this problem. Fumaric acid is naturally made in tissues of plant and animals. Fumaric acid acts as a reducing agent, keeping the $-\text{SH}$ groups from forming disulfide bonds ($\text{S}-\text{S}$) and decreases the pH level of the flour dough, defeating the toughening disulfide bonds of gluten (Fig. 1.16).

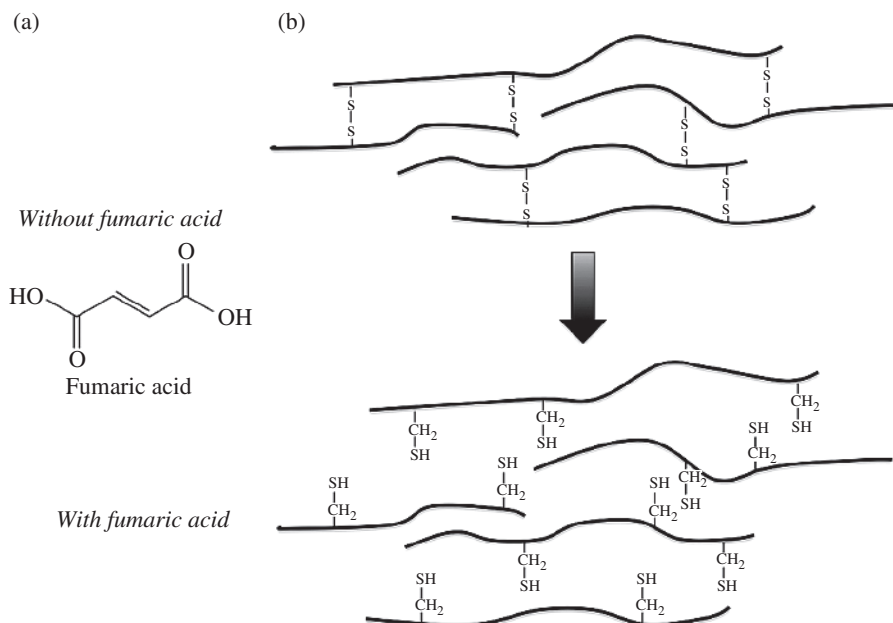


FIGURE 1.16 Soft tortillas. (a) The molecular structure of fumaric acid. (b) The impact of fumaric acid on disulfide formation in gluten found in tortillas. The addition of the acid keeps the disulfide bonds in the reduced state limiting the cross-linking of gluten for a softer chewier food.

This results in softer more machinable tortilla dough. In addition to limiting the gluten cross-linking, fumaric acid also acts as an antimicrobial agent and does not easily bind to water from the atmosphere increasing the shelf life of the food from a few days to over 2 months.

Now you know something about the individual molecular components of food molecules; however that doesn't provide the full picture of what happens when a protein clumps when eggs are cooked, when fat globules curdle together when making cheese, or when flour is added to broth to make a thick gravy. In all of these processes and many others, it is the interaction of different molecules that causes the cooking or baking process to take place.

1.3.3.1 Interaction of Food Molecules: Intermolecular Forces Forces that attract or repel two different molecules are called intermolecular forces. There are a number of different kinds of these forces, with different strengths and properties, but a key concept is that intermolecular forces are not bonds that hold atoms together. Intermolecular forces are weaker interactions that bring molecules together or keep them apart. Once you know some details about intermolecular forces, you will have a better understanding of how to make a foam or emulsion, why adding lime juice slows down the browning of avocado, and why destroying the structure of protein makes a solid in your cooked scrambled eggs.

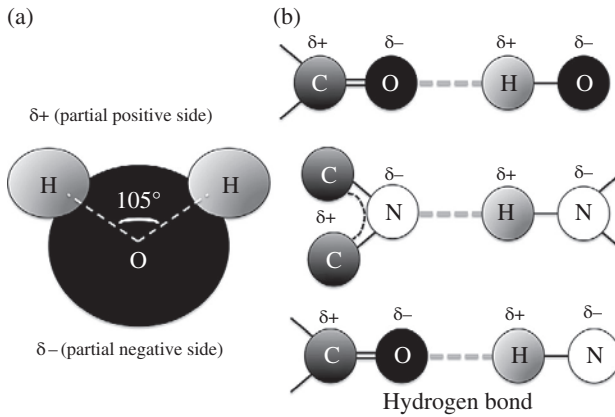


FIGURE 1.17 Hydrogen bonding. (a) The polar nature of the O—H bond creates a weak dipolar across a water molecule. (b) The electrical negative atoms N and O, when covalently bonded to the less electronegative H, results in a weak charge, which will form special weak bonds called hydrogen bonds between compounds.

Hydrogen Bonding Some atoms, like oxygen and nitrogen, have a high affinity for electrons, while other atoms, like hydrogen, have a low affinity for electrons. When atoms with differing affinities for electrons are bonded to one another, the high electron affinity atom (i.e., nitrogen or oxygen) pulls on the shared electrons more than the low electron affinity atom. Since electrons are negatively charged, the oxygen or nitrogen atoms become slightly negative, indicated by a partial charge ($\delta-$). At the same time, the hydrogen atom that has “lost” some of the shared electrons has a very weak positive charge ($\delta+$). The resulting partial positive and negative portions of the atoms can become attracted to and attract partially positive and negative atoms from nearby molecules or even within the same molecule. The resulting interaction between a partial positive component of one molecule and a partial negative component of another molecule is called a hydrogen bond (Fig. 1.17). It is called a hydrogen bond because of the involvement of hydrogen as the low electron affinity atom; the high electron affinity atom is typically nitrogen or oxygen in foods and cooking (Fig. 1.18).

Given the hydrogen bonding potential for water, as H_2O , and the presence of water in many foods and cooking processes, hydrogen bonding is a very important intermolecular interaction. Let’s look at the example of starch. Anyone who has made gravy with cornstarch has experienced the frustration of adding hot water to dried starch and the resulting blob at the bottom of the dish. As we will learn later, starch is a long polymer of glucose molecules (from hundreds to thousands of glucose molecules) resulting in tens of thousands of —OH groups (Fig. 1.18). That is a *lot* of alcohol functional groups! In fact, you may be thinking this is good because then water molecules can interact with the starch via hydrogen bonding.

As predicted, when water is added to dried starch, the water molecules form intermolecular interactions with the many alcohol groups (—OH) on starch. However, there are so many —OH functional groups on the surface of starch granules that the

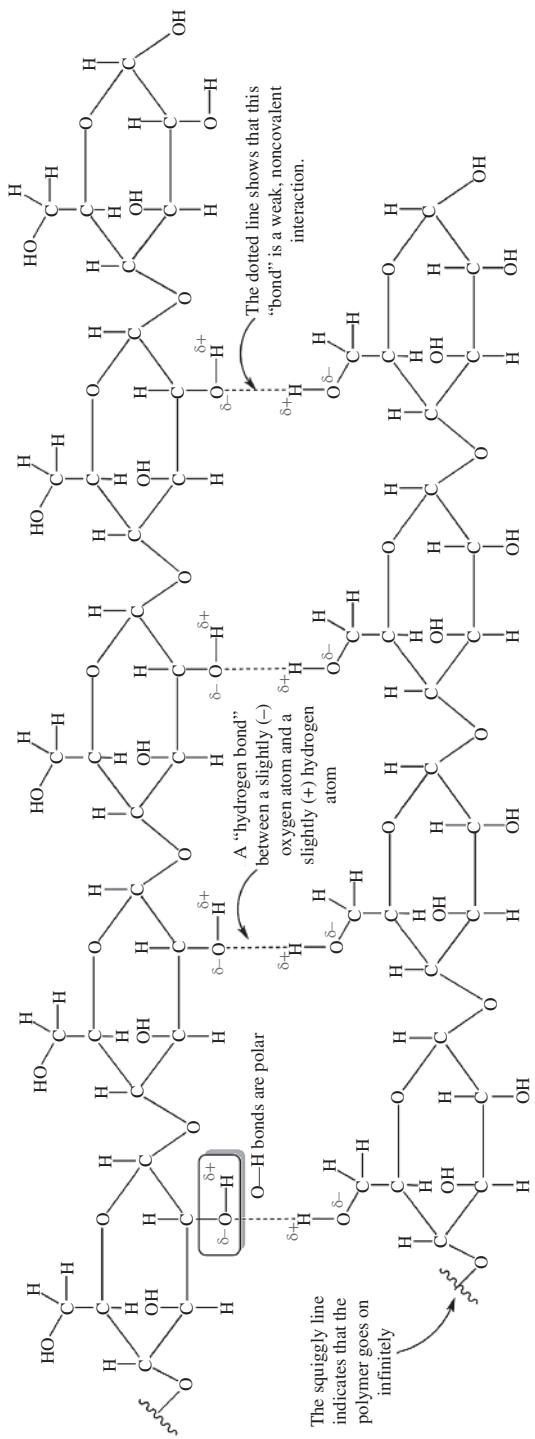


FIGURE 1.18 Hydrogen bonding in starch. Long glucose polymers of starch form tangles of hydrogen-bonded strands, which serve to thicken a gravy. Think of a tangle of yarn.

water binds too tightly to the starch, causing the starch to form an almost solid gel. Additional structural changes cause the starch to expand and eventually contract, which happens at such a high rate with warm or hot water that an impenetrable blanket of water forms over the expanding starch granule. So what is the take-home message? When making gravy, first mix your starch with cold water. The cold water slows down this process to allow a controlled and more complete hydration of the starch granules.

Electrostatic Interactions Opposites attract is a good way to think of the interaction between molecules that are charged. Molecules that have one or more charged atoms will be attracted to an oppositely charged group on another molecule. Proteins have many different kinds of functional groups, in which several have the potential to be charged, including carboxylic acids ($-\text{COO}^-$) and amines ($-\text{NH}_3^+$). Electrostatic interactions govern the behavior of the milk protein, casein. Molecules of casein have carboxylic acid groups that coat each milk fat droplet with negative charges. Because of the negative charges, the fat droplets in milk will repel one another, reducing the possibility of aggregation of the droplets and curdling of the milk. Thus the key electrostatic interaction, in this case, is repulsion or lack of an interaction, which allows the fat to remain suspended in the milk liquid.

Hydrophobic Interactions Hydrophobic interactions are forces that are of particular importance for food molecules that are in a water (aqueous) environment. Plant and animal tissues are rich in water. Animal muscle is made of nearly 70% water, while plant water content ranges from 75 to 90% of total mass. Thus, the proteins, sugars, fats, and other compounds in our bodies and plants are constantly exposed and surrounded by water molecules. Compounds that have a charge (full or partial) will interact with the water molecules via hydrogen bonding or electrostatic-like interactions; they easily dissolve and remain suspended in this water or aqueous environment. However, some molecules, like fats, have no charge and cannot hydrogen-bond or be involved in electrostatic interactions. These molecules tend to clump or aggregate together to “hide” from the water surroundings; this phenomenon is called the hydrophobic effect. Molecules (or regions of molecules) that have no charge and do not participate in hydrogen bonds are considered nonpolar; the hydrophobic interaction brings these molecules together to “avoid” interacting with water molecules. Why does this interaction take place? Consider two hydrophobic molecules (Fig. 1.19). When first placed into water, each hydrophobic molecule becomes surrounded by a shell or cage of water molecules. Why does the water form a cage? Because there are minimal favorable interactions (such as hydrogen bonding or electrostatic interactions) between the hydrophobe and the water, any water molecule that does interact organizes itself in the caged format to reduce the number of water molecules that have to interact with the hydrophobe. This allows more water molecules (in the entire solution) to remain in a disordered or random array. The scientific term for disorder or randomness is entropy. The more entropy within the system, the better. Thus, in this type of a system, entropy can be increased further through a “clumping” of all of the hydrophobic molecules together. On mixing, the hydrophobic

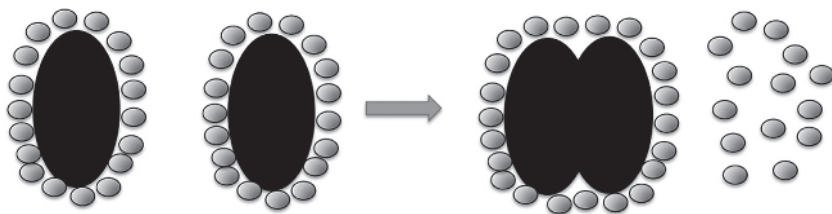


FIGURE 1.19 Hydrophobic effect is driven by entropy. Hydrophobic compounds shown in black are separate on the left. Because water (shown as small gray globes) cannot hydrogen-bond to the water-fearing compound, they are forced to form a rigid shell of water where the water hydrogen bonds to itself. If the two hydrophobic compounds come together, there is less surface area and less water needed to form the cage around the combined molecules. There is more order on the right than on the left. Entropy drives the hydrophobic molecular interaction.

molecules begin to interact with one another (via a hydrophobic interaction), thus reducing the number of water molecules that are caged around the hydrophobes. Overall then, there is more randomness or disorder within the system. Thus, the hydrophobic interaction isn't so much about an attraction of the hydrophobes (although there is a transient attractive force called a van der Waals force that can occur); it is more about the increase in disorder or entropy of the system when the hydrophobic molecules come together.

We have been using a lot of scientific terminology in our discussion to this point. It might be useful to clarify some of that terminology and summarize our discussion of intermolecular interactions here. The terms hydrophobic and nonpolar, often used interchangeably, describe molecules or components of molecules that possess only carbon and hydrogen atoms. Polar molecules or regions possess partial charges because they contain nitrogen and/or oxygen atoms. Charged molecules or regions possess full charges, because of their charged nature; they behave similarly to polar molecules. In which types of intermolecular interactions do each of these species participate? The phrase “like dissolves like” is useful here. Nonpolar molecules interact with other nonpolar molecules in hydrophobic interactions. Nonpolar molecules (like olive oil) do not interact well with water (a polar molecule); thus olive oil and water do not mix. Given that water is polar, polar molecules will interact with water via hydrogen bonding and electrostatic-like interactions and will dissolve. A good example of this is sugar. The alcohol functional groups ($-\text{OH}$) are able to hydrogen-bond and will easily dissolve in water.

1.3.4 Molecules in Motion: Water

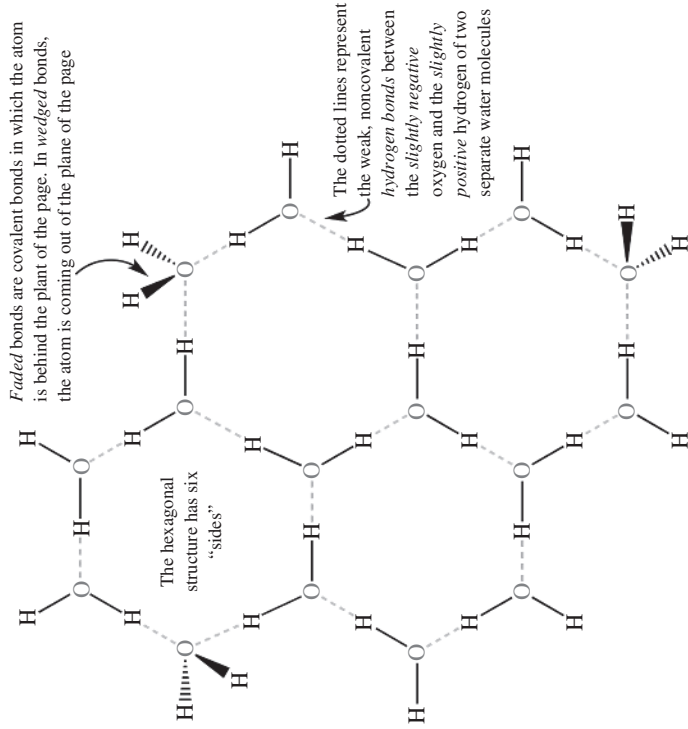
As already mentioned, water is a major component of food: a cucumber is 95% water, an avocado is 73% water, and a chicken breast is 69% water. Thus, the properties of water must be considered when thinking about food and cooking. For example, water expands when freezing, which impacts the texture of and types of foods that can be frozen and thawed without damage, and water has a high heat of vaporization and fusion, which makes water-rich foods take longer and higher

temperatures to heat and lengthens the time required to reduce the volume of a stock. These properties and their impact in the kitchen are due to the shape and chemistry of water.

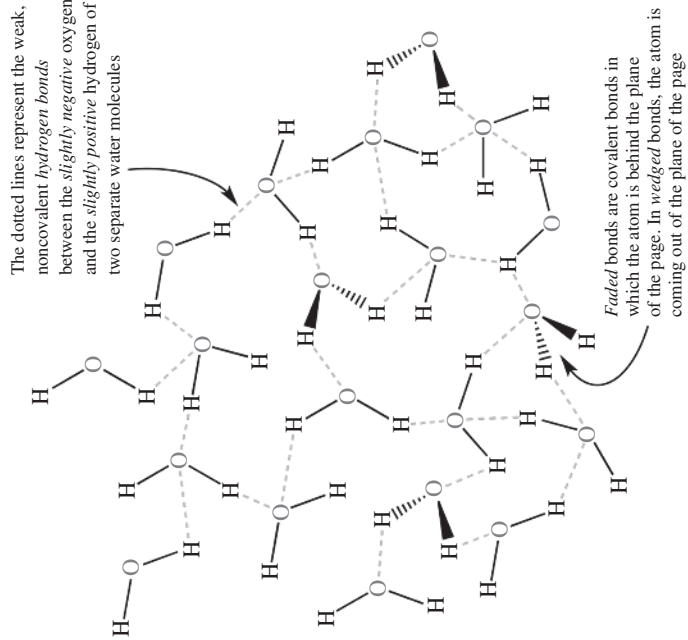
Water is composed of a single oxygen atom covalently bonded to two hydrogen atoms (H_2O). You already know about covalent bonds, so you know that each oxygen–hydrogen covalent bond consists of two shared electrons. However, the oxygen atom in water also contains two pair of electrons. These electrons (shown as a pair of “dots” or “..” in Figs. 1.7 and 1.8) cause the hydrogens to bend away from the electrons. Thus, these elements give the water molecule a bent rather than straight structure (Fig. 1.20). How does this shape impact the properties of water? You already know that the —OH bonds make every water molecule polar, where the hydrogen atoms have a partial positive and the oxygen atom has a partial negative charge. The “v” shape actually adds to the polar nature of water, as it allows other polar molecules (up to four) to more easily access and interact with water via hydrogen bonding; oxygen has a strong affinity for electrons, called electronegativity, while hydrogen does not have as high of an electronegative hold on these shared molecules. This results in an unequalled sharing of the common set of electrons between oxygen and hydrogen. The result leaves one atom (hydrogen) with a slightly positive charge from the protons in the nucleus and the oxygen with the unbounded pair of electrons on the oxygen atom with a slightly negative charge. The shape and arrangement of electrons (free and those in bonds) make water a “polar” molecule. These are not the full charges found in ions, but the charges are strong enough to attract other partial or fully charged compounds.

How do you get four hydrogen bonds from one water molecule? The partial positive charge on each hydrogen atom attracts a partial negative charge oxygen atom in a different water molecule (this makes two). The partial negative charge oxygen in the same water molecule can attract partial positive charge hydrogens in two different water molecules. Thus, each water molecule can hydrogen-bond to four different water molecules at one time! This occurs when water freezes, forming a solid lattice and hydrogen-bonded network of water molecules. Water molecules can also interact with fully charged ions. In this case, the water molecule surrounds the charged ion with the appropriate partial charge of the water molecule, forming a jacket or hydration shell, around the ion; this allows the ion to dissolve in the aqueous solution (think about dissolving a teaspoon of table salt in water). Other polar covalent molecules can hydrogen-bond and interact with ions in a similar manner. However, when other molecules are mixed into water, these “nonwater” interactions interfere with water’s ability to interact with itself. Thus dissolved particles in water depress the point at which water freezes.

Another important property of water is that, in food, some of the water is tied up in solid hydration shells (and is held rigidly in its hydrogen bonding interactions), while other water molecules are not close enough to be held in place by this water and is considered bulk or free water. Ice cream has sections of both liquid (free) and solid (rigid) water molecules. The liquid water is filled with dissolved proteins, sugars, and salts, while the solid water is frozen in the form of ice crystals. The moisture content of food is a measure of free water; it is measured in a term called water activity (a_w)



Organized, hexagonal array of hydrogen bonds connects the molecules of solid water (ice)



Disorganized array of many hydrogen bonds connects the molecules of liquid water

FIGURE 1.20 Water molecule interactions in liquid and solid form. The hydrogen bonds of water help it both form a cohesive liquid and a solid that is highly ordered and less dense than liquid water.

and provides a measure of the accessibility of water for microbes, enzymes, and chemical reactions. Dry goods like ground coffee beans, or powdered milk, and or even potato chips have a low a_w (0.2–0.08). Foods like those with low water activities have a long shelf life, as there is little or not enough water for microbe microbial survival. Fresh meat and bread have a high water activity with a_w values of 0.95–0.9765, respectively. Correspondingly, these foods have a short (or no) shelf life. Interestingly honey has a long shelf life, with a relatively moderate water activity of 0.6. In honey, which lasts a long time at room temperature, most of the water molecules are hydrogen bonded to the high concentration of sugar molecules (like fructose). This results in a water activity of 0.6 a_w which means there is not enough free or bulk water available for microbes to survive.

What do the intermolecular interactions of water have to do with cooking and foods? The state of matter of a substance is governed by the intermolecular interactions of the individual molecules. A solid has the strongest interactions. Solid water molecules, also known as ice, participate in four hydrogen bond interactions. When the ice changes state (melts or vaporizes), heat must be added to the substance to break some of the intermolecular interactions. The transition between melting and freezing or vaporization and condensation is a balance between the intermolecular forces holding the molecules together and the amount of energy required to free the molecules from these interactions. The greater the number and strength of the intermolecular forces, the more energy (heat) that is required to cause a phase change. Think of two blocks of wood covered in Velcro. The more Velcro attracting the blocks of wood, the more force you would need to use to separate these blocks. If we apply this concept to water, in its liquid form, water has enough heat from the surroundings to bend, rotate, and vibrate the bonds and molecules of water. This action is just enough to cause the hydrogen bonds between water molecules to continually form and reform, thereby preventing the most stable structure of four hydrogen bonds for each water molecule found in solid water (ice). As heat is removed from liquid water, each water molecule forms four hydrogen bonds and the water molecules form an expanded cage or lattice relative to the liquid water. Thus, ice has fewer water molecules per unit area than liquid water, causing it to be less dense than liquid water and thus float.

The expansion that occurs when water freezes to ice is problematic when freezing food. Plant and animal tissues have water inside each cell. When the water freezes and forms crystals, the expanded ice crystals often puncture the cells, causing the tissue to become mushy and expel water when thawing. Moreover, with large pieces of food, some of the water doesn't freeze because it mixes with the salt and other molecules present within the cell. This decreases the freezing point of that area of the food wherein a small portion of the food remains liquid, leading to mush. There will be more on this subject in both the meat and vegetable chapters later in the book. Freezer burn is another equally vexing problem. When frozen food is exposed to dry cold air, water molecules can directly escape from solid ice to the gas phase in a process called sublimation. The sublimation of water leaves the food dehydrated, the cells damaged, and the food more susceptible to react with oxygen in the air. The resulting dried patches of food have a different color and consistency but are safe to eat (Box 1.3).

BOX 1.3 MODERNIST COOKING: SOUS VIDE

It takes a lot of heat to turn liquid water to gaseous water (steam), again because of the strength of hydrogen bonding. Heat adds energy to the water molecules, giving them more kinetic activity until the molecules are free from all or almost all of the hydrogen bonds, allowing for escape into the gas phase (steam water). The energy required to vaporize liquid water is called the latent heat of vaporization; this is what allows foods to cook at or near 100°C (212°F) as long as there is considerable water content in the tissue. Simmering large pieces of meat in water or stock allows the cook to keep a constant temperature; the water stays near boiling point because any excess energy (heat) is being spent as water molecules escape the water phase into the vapor phase. Modernist cooks also called molecular gastronomists use a method called sous vide, French for cooking under vacuum. Imagine a fish with a large midsection and long tapering thin end. The thinner parts of the fish would reach a higher temperature earlier while cooking than would the thicker middle portion of the fish. Sous vide-style cooking allows for a precise, even temperature maintained throughout the food. This means the food is cooked to the same temperature in the core of the food without excess temperature at the surface of the food. Essentially, sous vide cooking involves placing a food item and seasoning into an airtight sealable plastic bag, removing the air, immersing the bag in a controlled water bath, and precisely heating the food to a controlled temperature (Fig. 1.21). This style of cooking allows the entire food item, regardless the shape or different size, to be



FIGURE 1.21 **Sous vide cooking.** Using a controller as shown here to maintain a narrow temperature range while circulating water, food in a bag can be cooked to a precise heat throughout the food. Photo credit Jeff Rogers.

cooked to a specific temperature. *Sous vide* is more about controlling the temperature in a water bath than removing (vacuum) the air in the bag. Today many *sous vide* cooks do not use a vacuum but instead limit air using ziplock bags. This technique results in a less dry, more consistently cooked food. Most foods are cooked in the bag to include juice or liquids. The result is a constant exposure to a less dry consistency and less oxidation in heated air conditions.

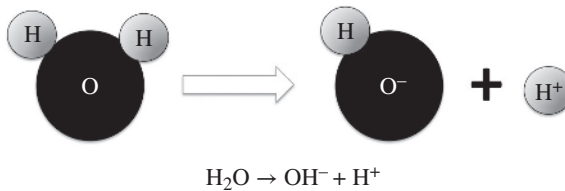


FIGURE 1.22 Dissociation of water. Will dissociate into the OH^- (hydroxyl) and H^+ (proton) but only a small amount of the water molecules will do this.

1.3.5 Acids, Bases and pH

Water has another important feature that impacts cooking. One of the hydrogen atoms of a water molecule can separate (also known as dissociate) from the rest of the atoms. This produces two new molecules that are charged, a positively charged hydrogen ion called a proton (H^+) and a hydroxide ion (OH^-) (see Fig. 1.22).

HINT! Don't confuse the hydroxide ion (OH^-) with the alcohol functional group ($-\text{OH}$). A hydroxide ion is charged and is not covalently bonded to any other atoms, while an alcohol is bonded to a carbon atom and is uncharged.

However, in pure water, only a very small fraction of the water molecules are dissociated into protons and hydroxide ions, approximately two out of every billion (10^9) molecules. However, even with this small fraction, this dissociation plays a significant role in our lives and our food.

The concentration of protons in a solution is a measure of acidity or basicity. A Danish biochemist, Søren Sørensen working at the Carlsberg Laboratories in Copenhagen, invented a scale to measure acid levels/proton concentration while he was studying proteins, enzymes, and yeast involved in making Carlsberg beer. This scale is called pH: “p” stands for *puissance* (French) or *potenz* (German), both words translating to power. Thus, pH stands for the power of hydrogen and is used to determine the acid and base content of a substance (Fig. 1.23).

The pH scale is a measure of the balance of both protons and hydroxide ions; it ranges from the most acidic ($\text{pH}=0$; 10^1 H^+ and 10^{-14} OH^- mol/l concentration) to the most basic ($\text{pH}=14$; 10^{-14} H^+ and 10^1 OH^- mol/l concentration). A pH of 7 is considered neutral and occurs when H^+ and OH^- ions are at the same concentration (neutral solutions are not acid-free, but have an equal number of protons and hydroxide ions). Substances with a pH higher than 7 have more hydroxide ions relative to protons;

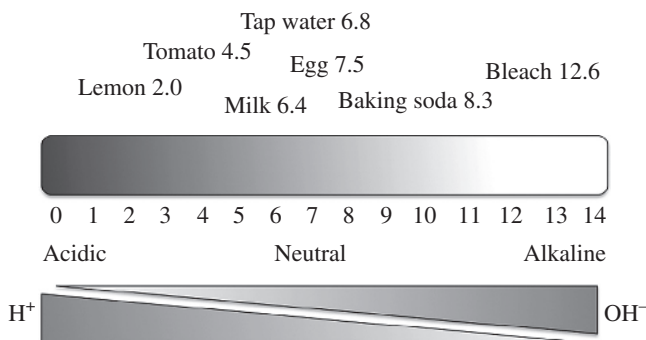


FIGURE 1.23 pH scale and foods. The pH scale from low pH (High H^+ concentration) to high pH (low concentration of H^+) and a few common food and household items.

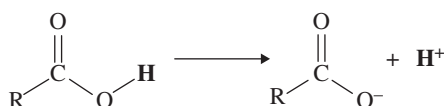


FIGURE 1.24 Weak acids. A weak acid such as vinegar containing a carboxyl functional group will weakly ionize to form a charged COO^- group and protons (hydrogen ions). Unlike a strong acid such as HCl , only a fraction of the weak organic acids will react to generate a free proton.

these solutions are considered basic or alkaline. Foods or drinks with a pH less than 7 are considered acidic and have a higher concentration of protons relative to hydroxide. Acidic foods typically range in pH from 2 to 4, while the pH of more basic foods may approach 8 or even 9; most foods are neutral to acidic. Although pure water has a neutral pH, tap water contains minerals and gases that can cause the pH to range between 6 and 8. The pH of most living cells is 7.2 and the pH of human blood ranges between 7.35 and 7.41.

While pH is a measure of how many protons and hydroxide ions are in solution, in foods, the definition of acids and bases is expanded to include consideration of pH or proton concentration, taste, and feel. Acidic food and drinks have those compounds that have a sour taste. The term *acid* is Latin for *acidus*, meaning “sour or tart.” Bacterial contamination of food reduces pH and produces vinegar making the food taste sour. The Latin term for vinegar, *acetum*, is related to the *acidus* and has been around since antiquity to describe our food and drink. A more technical scientific definition of an acid is a compound that causes an increase in proton concentration in water. The increase in proton concentration is due to release of a proton or by reducing the concentration of hydroxide ion ($\text{H}_2\text{O} \rightarrow \text{H}^+ + \text{OH}^-$). For many acidic foods and drinks, the acidity comes from the presence of weak organic acids such as citric, malic, tartaric, and acetic acids. These are considered weak acids because only a fraction of the compounds will dissociate (also called ionize) to generate a free proton (Fig. 1.24). Citric fruits include many kinds of organic acid molecules containing one, two, or even three carboxylic functional



FIGURE 1.25 Using weak acids to make ceviche. Raw shrimp is made tender and tangy by weak acids in citrus juices.

groups; each of these carboxylic groups can dissociate to generate a proton into solution increasing the acidity (by increasing the H^+ concentration). There are many examples of these weak organic acids in food. Sour hard candies are coated with two organic acids: citric and malic acids. Grapes, lemons, and limes include tartaric and citric acids. Lactic acid, another carboxylic acid containing organic weak acid that is produced by yeast, helps create a tart flavor in cheese. Ceviche is a Spanish and South American dish that contains raw or partially cooked seafood treated with carboxylic acid-containing molecules found in lemon or lime juice (Fig. 1.25). Acids from the juices provide flavor, partially break down the seafood protein that tenderizes the meat, and slow the growth of some harmful microbes. Thus, acids in foods, in addition to their role in flavor, also act as preservatives (because microbes don't survive well in acidic environments) and tenderizing and hygroscopic agents. What are hygroscopic agents? Acids help keep dry goods free flowing because many carboxylic acids have a low attraction for water (they are hydroscopic) and inclusion of the acid limits clumping of dry goods like flour, sugar, and other components due to moisture.

A basic solution is something that has a slippery feel or a bitter taste. The slippery phenomenon is due to the fact that strong bases dissolve the oils and fats naturally covering your skin creating a slippery feel. Chemically, bases add hydroxide ions to a system or have different functional groups that react with protons; in both cases, the relative number of protons is reduced within the solution, so the pH increases. The traditional description of a base as a compound that tastes bitter is somewhat misleading. Many compounds that taste bitter, like coffee, unsweetened cocoa, or beer hops have a pH greater than 7 and are basic. However, as you will learn, the bitter taste is not directly due to high pH of the food or drink, but is due to the presence of a compound (often a base) that binds to a taste receptor that signals a bitter flavor to the brain. Many plant materials have a basic or alkali pH and contain

toxins. Recognition of a bitter taste (which might stop an organism from eating the toxic plant), although an evolutionary benefit, is not necessarily an appropriate modern definition or descriptor for a base.

1.3.6 Macromolecules (Proteins, Sugars, and Fats)

You have likely read about some of the different types of food molecules, like carbohydrates, proteins, and fats, on a nutritional food label. These large biological molecules, proteins, carbohydrates (sugars), and fats are the functional units of a cell and are key components of food and drink. Each is comprised of simple starting building blocks (amino acids, simple sugars, individual fatty acids) that are chemically combined to make a larger, more complex molecule that plays numerous functions within the cell and food.

How are these large molecules made? The chemistry of assembly and disassembly of the complex molecules is perhaps surprisingly similar, even if the details of the molecules are distinct. Polymerization is a process where smaller molecules, called monomers, are chemically combined to produce a larger chain known as a polymer (Fig. 1.26). Starch, a carbohydrate polymer, consists of hundreds or thousands of individual sugar molecules that are connected to produce the final product. Chemically,

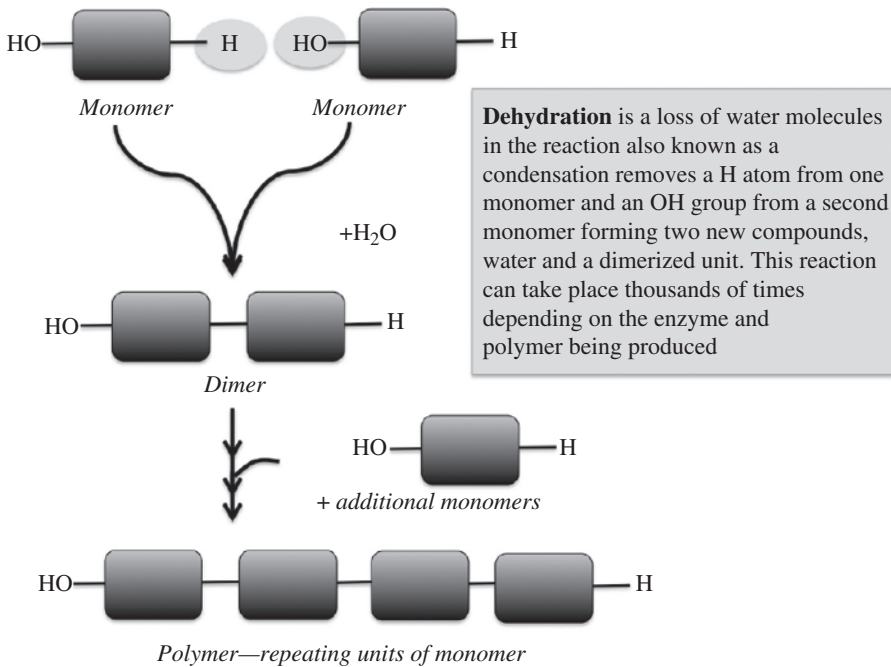


FIGURE 1.26 Growing a biological polymer. Adding individual building blocks called monomers into long strands of monomers creates polymers such as proteins, starches, or DNA molecules. Enzymes that dehydrate the monomers linking them together while generating a water molecule create most biological polymers.

two individual units are combined in a process called condensation or dehydration. In this example (Fig. 1.26), a hydrogen atom is lost from one of the units, and an —OH group is removed from another unit, allowing the two units to combine or condense together in formation of a new covalent bond, resulting in a larger linked growing polymer. The “lost” H and OH reform to generate a molecule of water as a side product. Depending on the molecule being created, this dehydration reaction can be repeated thousands of times making a larger and more complex new molecule. When discussing polymers, we often give the polymer a name that indicates how many monomeric units have been condensed together. When two monomers are linked together, the growing polymer is called a dimer; the sugars lactose, maltose, and sucrose are dimeric polymers, also known as disaccharides.

As you can imagine, polymers can also be broken down, and individual monomeric units can be chemically removed. The process of removing a monomer from a polymer is called hydrolysis; this term means breaking (lysing) bonds through the addition of water. Hydrolysis reactions happen naturally in living cells, but in cooking, the presence of acid and heat often promote hydrolysis reactions and the breakdown or degradation of complex molecules like proteins, lipids, and sugars. You will see the theme of degradation throughout the book as we describe the production and breakdown of foodstuffs.

1.3.6.1 Proteins Proteins are found in every cell of every organism, plant, animal, or microbe. They do the work of the cell, provide structural support, allow cell movement when needed, carry oxygen, and are a source of energy and flavor. While some food is considered high or low in protein content relative to the fat or sugar content found in a food, all food contains protein (Fig. 1.27).

Proteins are made of individual building blocks (monomers) called amino acids. There are 20 common amino acids that make up protein in the plant, animal, and the microbe world. Every amino acid contains the following components: an alpha



FIGURE 1.27 Protein-rich foods. Many foods are good sources of proteins including milk, cheese, meat, and fish.

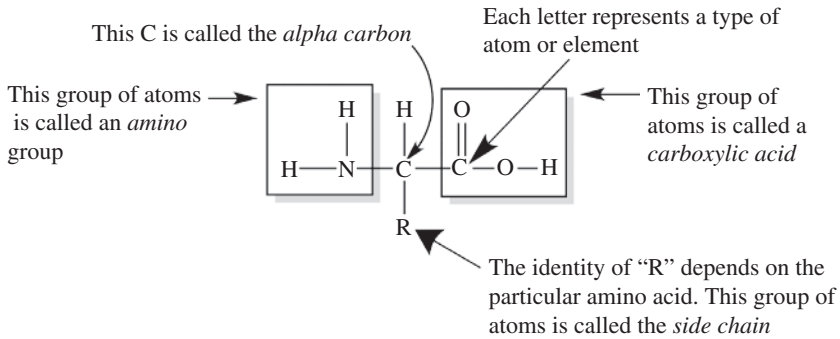


FIGURE 1.28 The anatomy of an amino acid. An amino acid has four main components; the R group is the portion unique for each of the 20 common amino acids.

TABLE 1.1 Essential Amino Acids and Some Food Sources.

Food	Missing Essential Amino Acid
Eggs, fish, meat	None
Beans	Methionine, tryptophan
Corn	Lysine, tryptophan
Wheat and rice	Lysine
Peas	Methionine
Almonds and walnuts	Lysine, tryptophan

carbon (the center carbon in the structure), an amino functional group, a carboxylic acid functional group, and another group called the side chain (Fig. 1.28). Each of the 20 different amino acids has a unique side chain group; thus it is this group (often chemically notated as an “R group”) that makes each of the 20 common amino acids different from the others. Chemically the side groups can be organized by their chemical reactivity/properties. Some are hydrophobic or nonpolar, while others are polar or charged (the term hydrophilic might be used to describe these amino acids because of the side chain interaction with water). Some amino acids can also be described as acidic or basic, while several have other unique chemical qualities. In order to make a protein, individual amino acids are linked together via a covalent bond in a dehydration/condensation reaction that involves the carboxylic group of one amino acid and the amino group of another amino acid. The resulting covalent bond between the two amino acids is called a peptide bond (Table 1.1).

The human genetic makeup codes for about 20,000–25,000 different proteins. Each of these proteins is made from combinations of the same 20 amino acids. A typical protein is between 500 and 900 amino acids in length. Humans can make some of our amino acids from scratch; however, we need to obtain nine amino acids from our diet since we cannot synthesize them and they are required to make the proteins that our cells need to support life. Proteins that are high in these nine “essential” amino acids are called high-quality proteins. Meat, fish, eggs, and dairy

products are good sources of proteins that contain these essential amino acids. Incomplete protein sources are foods that contain proteins, but the proteins present are low in one or more of the essential amino acids (this means that the essential amino acid is present or isn't present in high amounts in the protein). Rice, dry beans, potatoes, and some other plant-based foods are foods that contain proteins with a limited amount of one or more of the essential amino acids and are thus considered incomplete. Therefore, individuals with a diet that is lacking in meat, fish, and eggs must combine plant foods from a variety of cereals and grains to achieve enough of the essential amino acids in their diet.

1.3.7 Protein Structure

Once synthesized from amino acids, each protein molecule folds into a unique and special shape, a shape that is influenced by the order and number of amino acids present. How a protein folds and stays in this folded shape is based on the intermolecular forces imparted by the amino acids and their interactions of the side chains (Fig. 1.29). Many of the hydrophobic amino acids are found clumped or aggregated together on the inside of the protein structure; here, they can avoid the water that fills the cells. Positive and negative charged amino acids attract each other in electrostatic interactions or ionic bonds. Polar amino acids tend to be involved in hydrogen bonding interactions with other polar amino acids or water. The amino acid called cysteine contains sulfur in the side group. If you recall from our discussion of functional groups, two cysteines can come together in a folded protein to form a sulfur–sulfur covalent bond that is known as a disulfide bond. If the amino acids on the surface of a protein are charged, depending on the overall charge (positive or negative charge), proteins can attract other proteins of the opposite charge or repel proteins of the same charge.

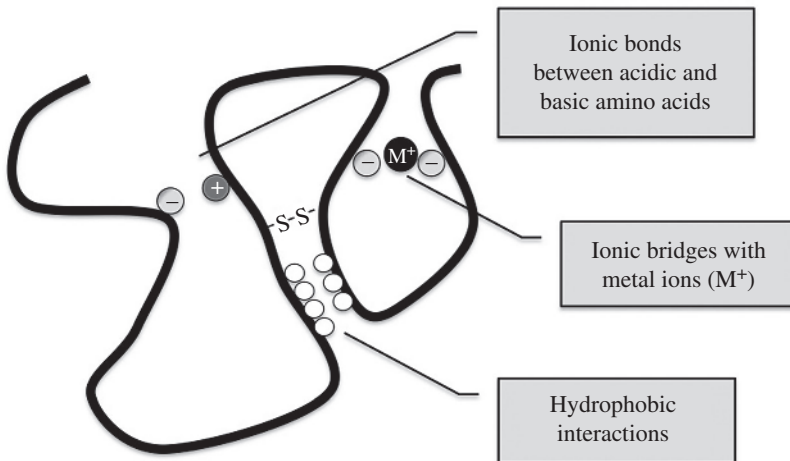


FIGURE 1.29 Forces maintaining the protein structure. The backbone of a protein (shown as a black line) is folded in its native state by the chemical interactions of the side chains.

1.3.8 Protein Denaturation

A protein folded into its functional shape is called a native folded protein. When proteins are subjected to heat, acids, or bases, the intermolecular forces holding the protein in its native structure are broken and the protein unravels; we call these proteins denatured (Fig. 1.30). Ovalbumin, one of the proteins in egg whites, in its native structure is suspended/dissolved in the water present in the egg white, so light can pass through the liquid egg white and it looks transparent or clear. Heat denatures the proteins (ovalbumin and others) in the white, causing the individual protein molecules to aggregate or clump together. As a result, the egg white solidifies, and light is reflected off the egg white, creating a solid white appearance. In contrast, the proteins in yolks denature more slowly (or require more heat to be denatured) due to differences in the amino acids and intermolecular interactions that maintain the protein structure. As an example of this diversity, let's look at the three egg proteins: ovalbumin, conalbumin, and ovomucin. Ovalbumin, the major protein component of an egg at approximately 54%, denatures at 80°C. Conalbumin has fewer intermolecular forces that hold the protein in its native structure and denatures at 63°C. By contrast, ovomucin has a larger number of cysteine amino acids, which can form disulfide bonds that stabilize the protein's native structure and denatures at a higher temperature. The thin part of an egg white has very little ovomucin; you can observe this by watching the thin egg white solidify first when frying an egg.

Acids and bases can change the charge state on the side chain groups of amino acids; a negatively charged carboxylic acid side chain might become neutral (uncharged) in the presence of an acid, while a positively charged amine might become neutral in the presence of a base. This change in charge state also leads to an unraveling or denaturation of protein molecules. As an example, the acid produced

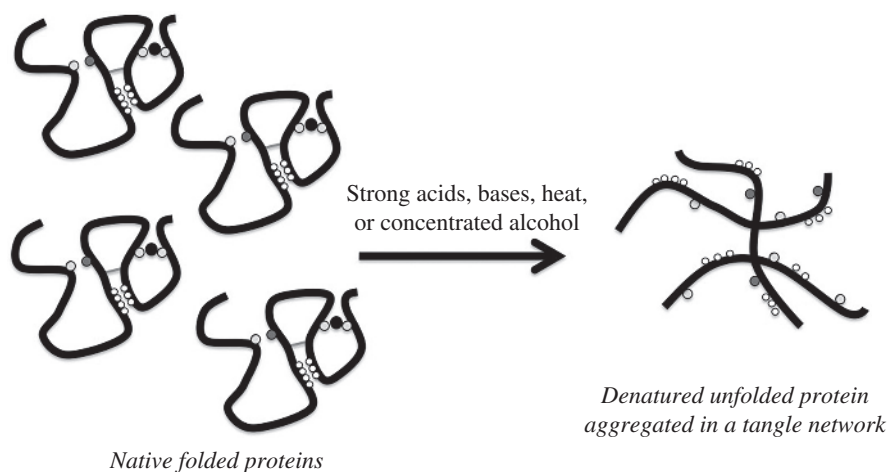


FIGURE 1.30 Denaturing protein. Extreme conditions can lead to protein unfolding causing a mesh network of insoluble protein. Cheese curds (from acid) and egg whites (from heat) are two classic examples of denaturing proteins and food.

by lactobacillus bacteria causes negatively charged milk proteins to become neutral. In turn, the milk proteins aggregate and curdle into yogurt or soft cheese.

Proteins can also denature due to agitation or stress. In the kitchen, you can agitate proteins with a whisk (this is what you do when you make meringue). The mechanical agitation of the egg white proteins introduces air into the proteins, causing the proteins to distort, stretch, and denature. The long tangles of denatured proteins then ravel together forming a cage around the air bubbles; the whites expand creating a foam.

1.3.9 Protein Function

Proteins play a diverse role in living cells. One special group of proteins called enzymes aids in chemical reactions. Enzymes reduce the energy needed for a chemical reaction, thus increasing the rate of the reaction. In other words, enzymes serve as biological catalysts. Some enzymes are involved in making new molecules needed for a growing cell, others are involved in breaking down molecules for cellular energy, and others are released from digestive organs to help break down food. Enzymes also play an important role in cooking and baking. Some enzymes chemically cut (or cleave) proteins into smaller pieces. Other enzymes chemically modify sugars or fats, converting them into new compounds with different flavors. For example, aged steaks are enhanced in flavor due, in part, to the enzymes released by dying cells that break down some of the connective tissue, which makes a tenderized meat, and generate flavorful amino acids. Aged cheese contains enzymes that chemically alter the protein, sugars, and fats in the cheese, creating a more mature and stronger tasting food. However, enzymes can also create havoc during cooking and baking. Lysozyme, an enzyme found in egg white, degrades large carbohydrate sugar polymers into much smaller sugar molecules. Thus, the presence of egg white in an egg yolk that is being used to make a custard or some pastries will result in disaster.

One complicating factor when working with enzymes in the kitchen is that enzymes are proteins. Yes, you knew that. But, for any protein to remain functional, that is, for a protein to “do its job,” the protein must retain its folded, native structural form. Heat from cooking, dehydration, the addition of lemon juice, or whisking a mixture may compromise the protein’s structure, leading to denaturation and an inactive enzyme/protein. Enzyme activity can also be slowed or reduced by storing a food at cool temperatures in the refrigerator or freezer. Thus, either chilling or cooking foods can lessen enzyme activity. This is the basis for some recent controversy over the health benefits of a raw food diet. Raw food enthusiasts advocate that cooking food denatures the enzymes needed for digestion and better health. Promoters for a raw food diet believe that we can replace the digestive enzymes naturally produced in the human body by plant enzymes if the food is eaten uncooked. However, our stomach and intestinal digestive enzymes as well as the acid content of our stomach will denature most or almost all of the proteins long before the protein from the raw food will cross the intestine, travel through our circulatory system, and get to our organs.

Another important role of proteins in cooking is their capacity to hold water. As described earlier, the native structure of most proteins keeps the hydrophobic amino

acids tucked away inside the structure where water is excluded, leaving the charged and polar amino acids on the surface of the protein free to form hydrogen bonds with water. When a protein denatures, the hydrophobic portions of the unraveled protein are exposed, driving the protein to interact with other protein molecules instead of water. Thus, native proteins help to retain water in foods, while denatured proteins allow water to be released. This phenomenon plays a critical role in food texture in meat, milk, plant products, and baked goods. Native proteins in meat allow the tissue to remain moist after cutting or grinding. However, once heated, the meat proteins denature and have fewer interactions with water. The juices leaked from a cooked steak are mostly water that is no longer retained by the myosin proteins of meat (colored with other components from the tissue). Resting a steak after cooking allows some of the water to find new interactions with proteins; thus less juice leaks out upon cutting. Later, we will see that starch plays a similar role in holding water-baked goods, keeping them moist.

It may seem like proteins are the only molecular players in food chemistry; however carbohydrates and fats play equally important roles. Let's take a look at the molecular components and cooking characteristics of carbohydrates next.

1.3.9.1 Sugars are Carbohydrates Sugar, saccharides, polysaccharides, complex carbohydrates, simple sugars, starches, pectins, fiber, and gums all refer to the same family of biomolecules called carbohydrates. Carbohydrates, as the name suggests, contain carbon, hydrogen, and oxygen atoms, often arranged in a manner in which a chain of bonded carbon atoms is each bonded to $-OH$ and $-H$ groups or a single oxygen via a double bond ($C=O$). A carbon that has a double bond to an oxygen atom is a functional group called carbonyl. Because of the presence of multiple alcohol groups on carbohydrates, carbohydrates are soluble in water; the alcohol groups are also important in making the carbohydrate sweet. The carbonyl group is key for the browning action that occurs when sugars are combined with protein, as observed when a cooked pie crust that was coated with an egg wash.

The simplest carbohydrates are the monosaccharides (Fig. 1.31). Monosaccharides are linear or single ring structures. Any monosaccharide can be described structurally by a linear or ring structure the carbonyl group has reacted with an $-OH$ from another carbon forming a ring structure. There are a multitude of monosaccharide sugars; however only a few are involved in day-to-day cooking and baking.

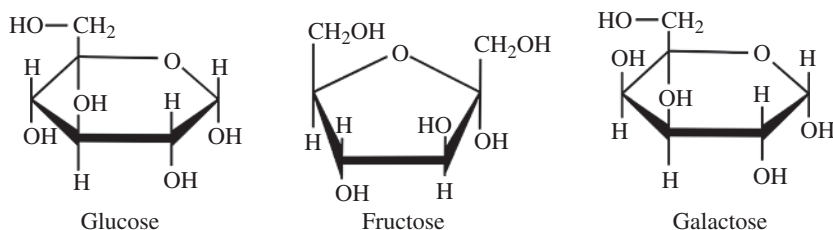


FIGURE 1.31 Common monosaccharides. Simple sugars (monosaccharides) found in food and drink.

when the oxygen atom between the monosaccharides falls below the carbon atoms. β -Glycosidic bonds happen when one of the linking carbon atoms falls above the oxygen atom in the bond. The α - or β -character of the glycosidic link is important to the function and structure of the saccharide polymer. Disaccharides cannot be used by the body in the disaccharide form for energy; thus they must be metabolized into individual monomer sugars or monosaccharide units for biological use. However, they do play an important role as key ingredients in many cooking and baking recipes. Dietary examples of disaccharides include lactose and sucrose. Joining glucose and galactose together via a β -glycosidic bond makes lactose, often called milk sugar. You will learn more about lactose in the chapters on milk, cheese, and metabolism/fermentation. Sugar beet and sugar cane plants produce sucrose, often called table sugar, as the plant cells trap energy from the sun by chemically combining carbon dioxide and water. A molecule of sucrose is formed when glucose and fructose monosaccharides are linked together in an α -glycosidic bond. If purified, there is no difference in sucrose between the two sources. Maple syrup and sorghum also contain sucrose. The conversion of sucrose into its single sugar components, glucose, and fructose, is catalyzed by enzymes secreted into human saliva. The enzyme invertase splits the indigestible sucrose into the usable fructose and glucose in the mouth. Boiling sucrose for an extended time can also hydrolyze or break apart the two simple sugars from sucrose. This process is enhanced in the presence of acids like lemon juice or tartaric acid. Inverted sugar is just sucrose that has been reduced into monomer sugars and should no longer be considered sucrose. This is a trick some winemakers use when fortifying their grapes with an additional boost of carbohydrates. Bakers sometimes use inverted sucrose (called invert syrup) because of the increased sweetness of fructose compared with sucrose.

Once you begin to link more than two sugars together, the terminology used to describe a sugar or carbohydrate may be unclear to the novice. What exactly do we mean at a molecular level when using the terms simple sugars, oligosaccharides, or complex carbohydrates? Now that you know a little more about the molecular structure of mono- and disaccharides, these terms are easily clarified by examining the number of monomer saccharides incorporated into the molecule. Both monosaccharides and disaccharides are considered “simple sugars”; these sugars are easily absorbed by the body and are readily available as an energy source or building block for other biomolecules. Carbohydrates that contain less than a hundred monosaccharide units, called oligosaccharides, are found in dried beans, peas, and lentils. These molecules are poorly digested by the human body and typically pass through your digestive system unaltered. However, once in the gut, your intestinal bacteria metabolize the oligosaccharides and produce gases. Complex carbohydrates consist of even longer chains of monosaccharide units (on the order of hundreds or thousands of the monosaccharide building blocks). The individual monosaccharide units in complex carbohydrates often participate in multiple glycosidic bonds, which gives them a structure that is much more complex than the shorter-chain carbohydrates. Moreover, like proteins, these long polymers bind tightly to water through hydrogen bonds; thus they readily absorb water. Complex carbohydrates can be placed into two major classes. Dietary or nutritionally unavailable complex carbohydrates include gums, fibers, and pectins. These complex carbs are certainly important in cooking, even

though they lack nutritional value (think about the pectin that you might add to fruit that thickens a jelly). Other complex carbohydrates are nutritionally important, such as starches. Let's look more in depth at both types of complex carbohydrate.

Starches are long polymers of glucose and serve as a source of glucose storage that naturally occurs in plants and animals. There are three main forms of starch: glycogen, amylose, and amylopectin. Glycogen is the form of starch that is used in animals as our glucose reserve; it is made and stored in the liver and red muscle tissue. Glycogen is a good example of a branched polymer; this means that approximately every 10-glucose monomer has two glucose monosaccharide units linked by a glycosidic bond. The "second" link serves as a branch point to grow another polymeric chain. The energy storage molecule in plants is called starch; it also consists of long polymers of glucose molecules that serve as energy stores of glucose in seeds and the roots of rice, corn, wheat, potatoes, beans, and cereals. Plant starch consists of two types of molecules: amylose and amylopectin. Amylose, which makes up about 20% of plant starch, consists of unbranched chains of 200–4000 glucose molecules that structurally forms a coil. The remaining 80% of most plant starches are amylopectin. Amylopectin is branched, like glycogen, but the branch points occur less frequently, approximately every 25 glucose units. In both glycogen and plant starch, each glycosidic bond that connects one glucose to another is an α -glycosidic bond. Enzymes in our saliva can break down (hydrolyze) the α -glycosidic bonds in these large complex carbohydrates so that we can use the remaining smaller pieces as an energy source. By contrast, cellulose is also a complex carbohydrate made of glucose, where the glucose molecules are linked via a β -glycosidic bond. Cellulose is used by plants to provide rigid strength in cell walls in wood and fibrous plants and has a linear, extended (noncoiled) structure, which contributes to its role as a structural protein. Furthermore, the linear arrangement of the carbohydrate allows for hydrogen bonding between different cellulose chains, thus creating a strong cross-linked fiber. Our salivary enzymes do not break down cellulose because of the β -glycosidic bonds, so cellulose is unavailable to humans as an energy source. However, cows, goats, and termites (to name a few) have symbiotic bacteria living in their gut that can break down the cellulose to yield glucose for use as an energy source; thus cows and goats can survive by eating grasses and termites thrive on wood (Fig. 1.34 and Box 1.4).

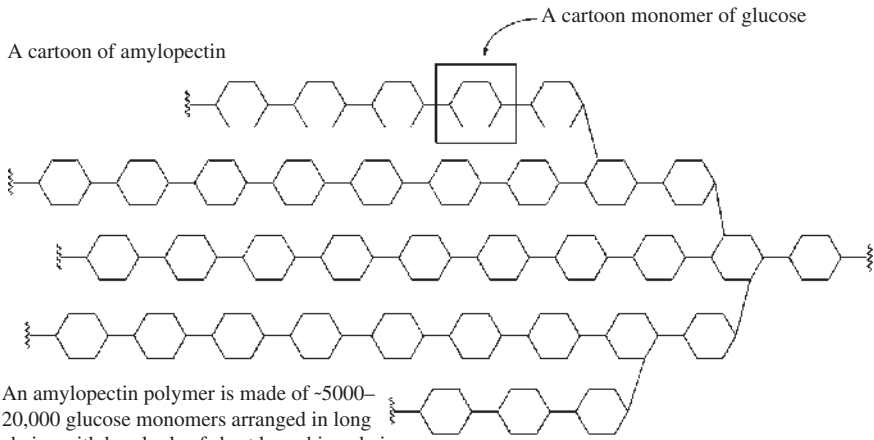
Another class complex carbohydrate is dietary fiber. Dietary fibers, also called roughage or just fiber, are poorly digested plant polymers that contain a diverse mixture of monosaccharide components, many of which are chemically modified. Fiber comes in two forms, soluble and insoluble. Fiber that readily dissolves in water is soluble. Soluble dietary fiber tightly binds water through hydrogen bonds, swells, and turns into a gel. The thick water-soluble fiber gel slows down digestion; thus foods that contain soluble fiber create a feeling of being "full." Moreover, some soluble fibers bind cholesterol and aid in carrying it through the intestinal system. Good sources of soluble fiber include oatmeal, lentils, apples, pears, celery, and carrots. Insoluble fiber does not dissolve in water and speeds digestion and transit of molecules through the digestive system. Sources of insoluble fiber include whole wheat, whole grains, bran, seeds and nuts, dark leafy vegetables, grapes, and tomatoes. Both soluble and insoluble fibers are important to food, nutrition, cooking, and flavor. Let's look at some examples.

A cartoon of amylose



A amylose polymer is made of ~1000 glucose monomers attached in one long extended chain

A cartoon of amylopectin



An amylopectin polymer is made of ~5000–20,000 glucose monomers arranged in long chains with hundreds of short branching chains

FIGURE 1.34 Plant starches. Two glucose polymers amylose and amylopectin are depicted. Amylopectin is a coiled unbranched polymer, while amylopectin is branched with a tree-like structure.

BOX 1.4 SIMPLE VERSUS COMPLEX SUGARS: WHY ARE THEY BAD FOR YOU?

Sugar or “refined sugar” has gained a reputation as being “bad” for you. Refined sugar is simply purified sucrose, fructose, or glucose that comes from sugar cane, sugar beets, or other plants such as corn. There is nothing intrinsically bad about the sugar molecule when it is present in food or used in cooking. In fact, consuming 1 g of sucrose or fructose that is added to a food in cooking will have the same effect as eating 1 g of the same sugar from fruit or other plant sources. As an example, one banana contains about the same amount of simple sugar as a prepared food that contains four tablespoons of granulated sugar per serving! However, excess consumption of sugar, like any food, results in poor health consequences. Spikes in glucose (or blood sugar) occur after you consume a supersized candy bar that contains 40 g of carbohydrates (in the form of simple sugars). These sugars are easily absorbed into the body, causing a spike in blood glucose levels from 70–100 milligram per deciliter of blood (mg/dl) to 120–200 mg/dl depending on the individual. Having chronic high blood sugar leads to a number of negative health consequences including glaucoma and nerve damage in the extremities. Why do you get a “crash” after eating a large quantity of sugar? Once glucose levels rise, the body releases a hormone called insulin from the

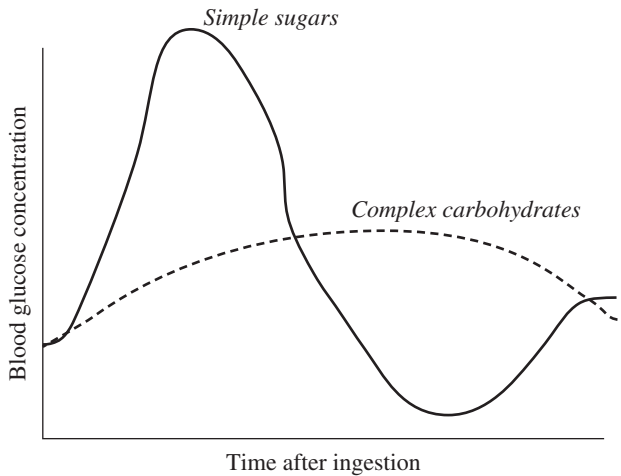


FIGURE 1.35 Simple versus complex carbohydrate. The impact on blood sugar (glucose) levels after eating simple mono- or disaccharides versus complex carbohydrates.

pancreas. Insulin allows the glucose to move from the circulatory system into the muscle tissue. The amount of insulin released is directly proportion to the levels of glucose in the blood. Thus, abnormally high amounts of sugar, due to mega candy bar consumption, cause abnormally large amounts of insulin to be secreted by the pancreas, resulting in high amounts of glucose to be transported into the muscle tissue. This phenomenon results in a serious reduction in blood sugar to a level that is much lower than a premeal level. Because the brain gets most of its energy from blood glucose, low levels of blood glucose cause you to feel tired, weak, confused, and even dizzy (Fig. 1.35). Interestingly, eating the same mass of complex carbohydrates avoids this spike and crash in blood sugar levels because the starch/glycogen polymers have to be broken down by the digestive enzymes in the gut before the individual glucose molecules can be transported from the intestine into the bloodstream. This takes time and allows for the gradual release of glucose into the circulatory system. The result is a slow, gradual increase and decline in blood sugar levels due to the modest and controlled release of insulin. The rate at which a food spikes the blood glucose level is called the glycemic index. Foods that contain high amounts of simple sugars have a high glycemic index. In contrast, complex carbohydrates including starches and fibers have a much lower glycemic index.

Because of the gel-like character that is imparted by soluble fiber in water, soluble fiber is often used as a thickening agent in cooking. Pectin, a soluble fiber found in plant cell walls, is made of the monosaccharide galacturonic acid (Fig. 1.36). An immature apple contains chemically unmodified pectin, which gives the fruit a hard rigid consistency. As the fruit ripens, enzymes modify pectin by adding methyl

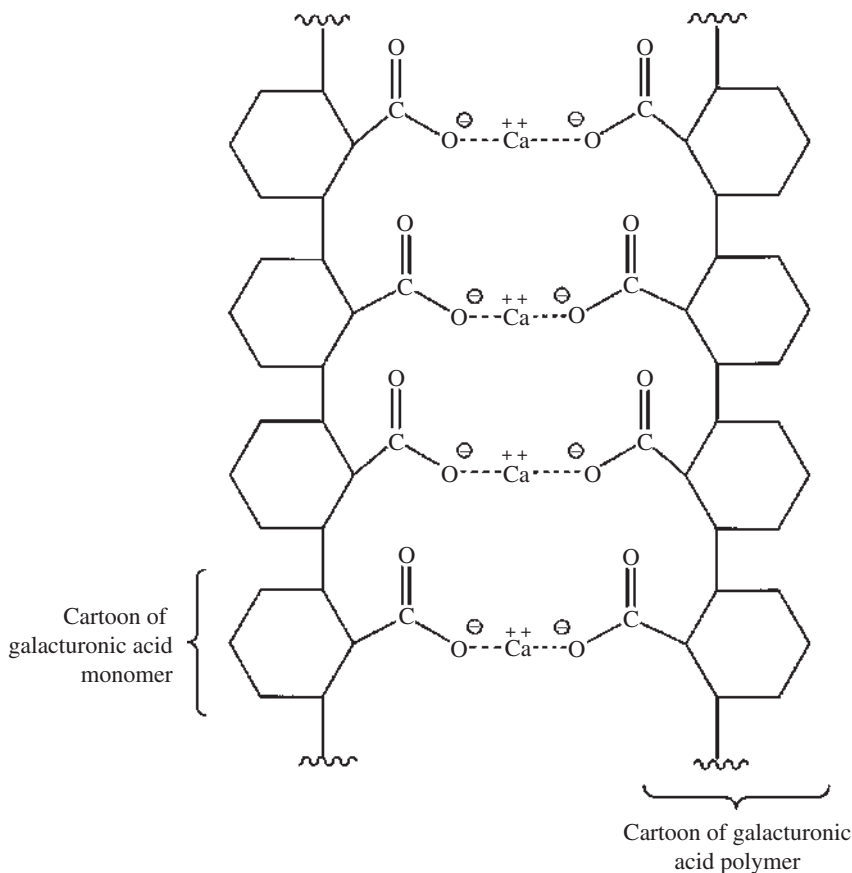


FIGURE 1.36 Pectin. A cartoon of pectin, a polymer of galacturonic acid. The positive charged calcium helps bind strands of pectin to form a gel.

groups; this causes the fruit to soften (due to the gel formation and water retention). Moreover, in cooking, a more stable gel can be formed during the preparation of applesauce or apple pie. If you have ever tried to make an apple pie with unripened apples, the resulting watery mess was due to the lack of gel-forming pectin found in the fruit. Natural (from within the fruit) or added pectin is key to form an effective gel in jellies and jams. The pectin “gel” consists of long tangles of carbohydrate polymer that is tangled together into a rigid mass that tightly retains water. A great example is the gel in jelly. In acidic conditions when citric acids are included, they interact with mono- and disaccharides to form a stable gel that swells several times its dried volume. Mature fruits provide pectin from the cell walls to form an effective gel in making jellies and jams. The gel-like nature of pectin is also used to stabilize yogurts (Fig. 1.36).

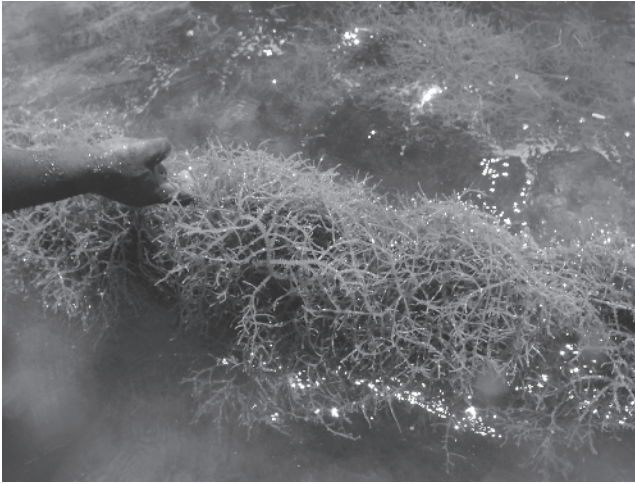


FIGURE 1.37 Red carrageenan. Red seaweed is dried and the cell wall carbohydrates are used as additives (gums) in foods. By StinaTano (own work) (CC BY-SA 3.0 (<http://creativecommons.org/licenses/by-sa/3.0>)) via Wikimedia Commons.

Onions, garlic, and lettuce contain inulin, a short polysaccharide primarily made of fructose. Inulin is a soluble dietary fiber whose use in cooking and food preparation has increased because of its ability to form viscous solutions at low concentrations. Because inulin is not digestible, there is a very low caloric value to the complex carbohydrate (1 kcal/g) and is often used as a low-calorie substitute for fat and simple sugars in cheese, frozen desserts, whipped cream dairy products, and processed meats.

Plant gums are another diverse family of complex carbohydrates that are utilized in foods and cooking. In plants, gums act as a mortar to keep plant cells glued together and are secreted into gaps in damaged plants and fruits. Like pectins, plant gums are used in the food industry for their thickening characteristics and come from a variety of sources, including the hardened sap from *Acacia* trees (gum arabic), seaweed extracts from brown seaweed (alginate) and red seaweed (carrageenan), and microorganisms (xanthan gum) (see Fig. 1.37).

What makes a gum different from a fiber? Gums are specifically defined as a hydrocolloid; this means that a gum can form a gel or solid depending on the amount of water present. How are they used in food preparation? Gums are used to improve mouthfeel, emulsify liquids, and trap or encapsulate flavor molecules. Mouthfeel is the way the food or drink feels thick or thin as it is eaten. When someone says a sauce is too thin, this is mouthfeel. The gum arabic present in a can of Mountain Dew acts as an emulsifier, helps to keep the oil in suspension, and improves mouthfeel. Some gums produce very smooth textures in processed foods and tightly hold on to water and reduce ice crystal formation during freezing/thawing. Because of these properties, gums are often added to process frozen prepared microwave meals from separating into water and solids. Agar agar is a gum used by molecular gastronomy-inspired

cooks and chefs. Agar agar (also just called agar) is an extract of algae that has been used historically for many years by microbiologists as a solid gel infused with growth compounds to culture bacteria. This use of course was influenced by cooks who had used agar in Java, as well as in other Asian countries, for centuries. Agar agar is an efficient gelling agent that readily forms a semisolid consistency, can be easily infused with flavors (or can infuse flavors), can provide a firm solid shape and mouthfeel, and can suspend or encapsulate liquids and solid food particles. Unlike other gels, once formed, agar agar will retain its solid consistency even when heated at 90°C! Some creative cooks use the gel to create unusual dishes with unique shapes and properties (Box 1.5).

BOX 1.5 THICKENERS

The ability to thicken a soup, gravy, sauce, or beverage is a critical tool for any cook. The trick to creating a successful thickened sauce, soup, or gravy is through incorporation of a complex carbohydrate and/or protein that binds water, yielding a more viscous liquid. The feeling that comes with tasting and eating a thick gravy or salad dressing is called mouthfeel. In order to understand how thickening works, you need to learn some physics about liquids. Water is considered a Newtonian fluid because there is a proportional relationship between viscosity and the force applied to the fluid. The more viscous the Newtonian fluid, the more force required to get it to flow. Gravies and other thickened foods are non-Newtonian fluids; these fluids require a larger force to start movement, but once in motion non-Newtonian fluids move with a greater ease. Most of you have experience with ketchup. What a great example of a fluid that does not easily start to move but, once flowing, flows much faster than you often desire! What does a non-Newtonian fluid have to do with mouthfeel? The stickiness and viscosity of a non-Newtonian fluid are amazingly detected by the human mouth and give foods containing these fluids a distinctive, pleasurable character. Think of a soup that seems watery versus one that has been thickened with starch or gum. The thickened soup tastes better even when the flavor of the soups is identical.

One cooking technique used to thicken a recipe is called reduction. Heating a mixture provides enough energy to the water molecules to allow them to rotate, vibrate, and escape the intermolecular forces that hold the water molecules in place. As the water “boils off,” the remaining molecules of complex carbohydrates or proteins are forced to interact with each other, increasing the viscosity of the fluid. Unfortunately, this preparation that requires high heat or long cooking times often alters the flavor and nature of the fluid in unintended ways. The starches found in flour can form pastes and gelatinize for use in gravies and stews. Thick flour pastes are difficult to form, as the starch solidifies in a low water environment. Cooks will use fats to coat and interact with the starch. Such a mixture, called a roux, is the base for pasta gravies and some thick stews.

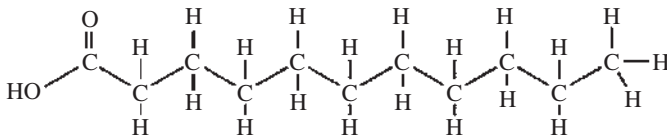
How do you decide what thickening agent to use—a protein, starch, or gum? It depends upon the flavor and final presentation of the desired food. Is the food to

be served hot or cold? Proteins coagulate upon cooling (making a solid mess), while gums and starches are more effective thickeners when cold. Starch thickeners quickly clump when reheated. If you want a clear thickened soup, some gums (like xanthan gum) can be used in a small amount to avoid clumping and cloudiness. Both starch and xanthan gums work well for more viscous preparations. pH can also impact the behavior of a thickening agent. Acidic foods cause some gums to be less effective; thus cornstarch or arrowroot starch is a better choice. Clear Jel is a chemically modified cornstarch that is specially made for baking and freezing acidic foods; it is a good choice for acid-containing fruit pies that need thickening.

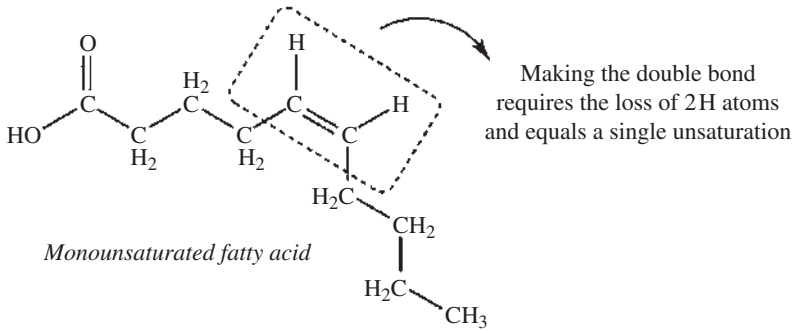
1.3.9.2 Lipids (Fats, Oils, Waxes, Phospholipids, Fatty Acids) Besides the well publicized nutritional role fats and oils play in our food, this third biological macromolecule is important in cooking and the taste of the foods we eat. Lipids are a class of molecules composed mostly of carbon and hydrogen atoms and are poorly insoluble in water but soluble in solvents like chloroform or ether. Fats, fatty acids, oils, waxes, cholesterol, membrane lipids, and other molecules all belong in the lipid family. Lipids, unlike other biological macromolecules, are not long polymers (repeating units of monomers); however many of the lipid molecules are composed of several smaller molecules bonded together to form a larger functional compound. We will look at the structure and chemical nature of several important lipids and investigate how lipids impact cooking and baking.

The simplest lipids are the fatty acids. Fatty acids are long chains of carbon atoms bonded to hydrogen atoms ending with a carboxyl group (Fig. 1.38). The carbons in fatty acids will be bonded to one, two, or three hydrogen atoms, making this a very nonpolar, water-insoluble molecule. The (COO⁻) carboxyl groups on the end gives the molecule the ability to hydrogen-bond to water or ionic bond to positive charged ions and that portion of the fatty acid is water soluble or hydrophilic. By definition, *lipids* are insoluble in water, so that means triglycerides are *insoluble* in water. To be *soluble* means that two molecules will dissolve in one another to form a homogeneous mixture. When compounds are *insoluble*, the combination forms a heterogeneous mixture. When a lipid (e.g., oil) is mixed with water, you will see boundaries form between the two *phases*—literally, the two cannot mix. Polar compounds can mix with or *dissolve/are soluble in water (hydrophilic)* to form homogeneous mixtures (i.e., sugar dissolving in water, lemon juice dissolving in water, vinegar dissolving in water). Nonpolar compounds can mix with or *dissolve/are soluble in oils (hydrophobic)* to form homogeneous mixtures (e.g., vanilla extract dissolving in oil, melted butter mixing with olive oil). Figure 1.39 highlights the differences between polar and nonpolar bonds. These facts are described by the principle *like dissolves like*.

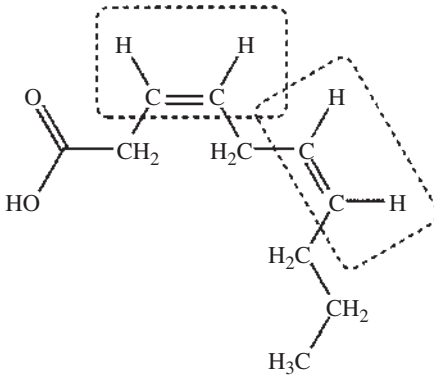
Molecules with regions that are both hydrophilic and hydrophobic are considered “amphipathic.” The amphipathic nature of fatty acids drives the hydrophilic and hydrophobic regions to align together creating globules or complicated micelles and even into sheets of lipids called membranes. Fatty acids are naturally found in plants



Saturated fatty acid



Monounsaturated fatty acid



Polyunsaturated fatty acid

FIGURE 1.38 Saturated, unsaturated, and polyunsaturated fatty acids. Free fatty acids (not bonded to a glycerol) are shown here. Note each has a polar carboxyl end and a CH_3 (methyl) end. Loss of a hydrogen (unsaturation) results in a special orientation around the double bond (a *cis* double bond).

Polar bonds	Nonpolar bonds
$\delta^- \quad \delta^+$	$\text{C} - \text{H}$
$\text{O} - \text{H}$	$\text{C} - \text{C}$
$\text{N} - \text{H}$	$\text{C} = \text{C}$
$\text{O} = \text{C}$	

FIGURE 1.39 Polar versus nonpolar bonds. The polarity of a molecule is determined by the separation of charge between its atoms. In polar molecules, most atoms are connected polar bonds. In nonpolar molecules, nonpolar bonds connect most atoms.

TABLE 1.2 Common Fatty Acids.

Common Name	Abbreviation	Typical Sources
Butyric	C4:0	Dairy fat
Capric	C10:0	Dairy fat, coconut, and palm kernel oils
Lauric	C12:0	Coconut oil, palm kernel oils
Palmitic	C16:0	Most fats and oils
Stearic	C18:0	Most fats and oils
Arachidic	C20:0	Peanut oil
Behenic	C22:0	Peanut oil
Lignoceric	C24:0	Peanut oil
Palmitoleic	C16:1 Δ^9	Marine oils, macadamia oil, most animal and vegetable oils
Oleic	C18:1 Δ^9	All fats and oils, especially olive, canola, sunflower, and safflower oils
Erucic acid	C22:1 Δ^{13}	Mustard seed and rapeseed oil
Linoleic acid	C18:2 $\Delta^{9,12}$	Most vegetable oils
Arachidonic acid	C20:4 $\Delta^{5,8,11,14}$	Animal fats, liver and egg lipids, and fish

The length of the fatty acids is indicated by the number following letter “C.” C12 is a fatty acid made of 12 carbons. The number after the semicolon (:) indicates the number of unsaturated carbon double bond(s). For example, C10:2 $\Delta^{2,4}$ is a polyunsaturated fatty acid with 10 carbons and four double bonds. The delta (Δ) symbol indicates at which carbon from the carboxyl end the double bond is located.

and animal tissues and come in a range of carbon chain lengths. Fatty acids can be very short with four carbons (butyric fatty acid) or very long with 20 or more carbon atoms in its chain. Table 1.2 gives examples of different fatty acids. Short fatty acids are often involved with flavors of butter and cheese and when heated to gases provide a flavor and smell of bread and cooked meat (Fig. 1.40).

Fatty acids whose carbon chains have single bonds to other carbons or hydrogen atoms are considered saturated. That is, the carbon has four single bonds leaving the atom “saturated” with bonds to hydrogen and carbon atoms. Fatty acids with carbon–carbon double bonds will have fewer hydrogen atoms bound to the carbons and is considered unsaturated. A fatty acid with one carbon–carbon double bond is a monounsaturated fatty acid, while fatty acids with two or more carbon double bonds are polyunsaturated. Unsaturation dramatically impacts the orientation of carbons around the carbon double bonds. The two configurations for unsaturated fatty acids are *cis* and *trans*. In a *cis* double bond orientation, the adjacent carbon atoms are close to each other leaving a kink in fatty acid chain at the unsaturation. *Trans* configuration leaves the carbon atoms on either side of the double-bonded carbons farther away (*trans*) from each other, resulting in a fatty acid with a straight chain shape. The *cis* or *trans* shape to the fatty acid can have a significant impact on the melting point and chemical reactivity (Fig. 1.41).

In the early 1900s less expensive vegetable oil was used to create margarine and shortening. The process called hydrogenation involves heating fats with high heat in the presence of nickel while bubbling hydrogen gas (H_2 (g)) through the mixture. Changing the *cis* unsaturated fats to saturated fats created an inexpensive way to make food. A by-product of hydrogenation was that some of the *cis* double bonds



FIGURE 1.40 Oil. Unsaturated and polyunsaturated fatty acids are liquid at room temperature.

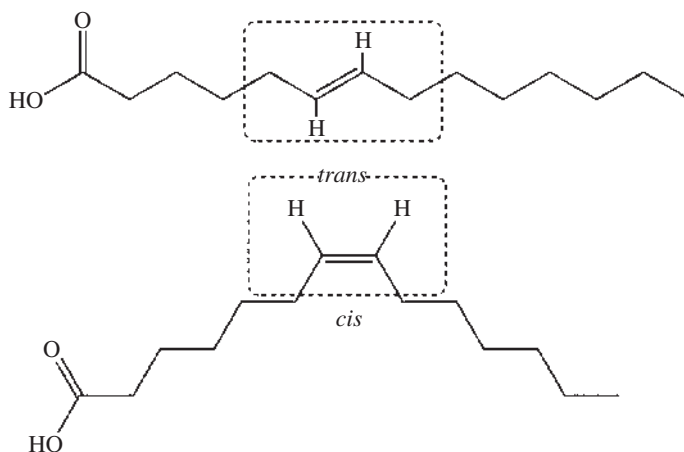


FIGURE 1.41 *Cis* and *trans* fatty acids. Loss of two hydrogens in a fatty acid chain results in the sharing of electrons forming a double bond. The arrangement of the atoms around the double results in the hydrogens being on the same (*cis*) or opposite (*trans*) side of the double bond. Note the impact of a *cis* and *trans* desaturation on the shape of the fatty acid chain.

were converted to *trans* double bonds. The unintentional creation of *trans* fatty acids during the production of margarine and shortening was initially considered a bonus effect of hydrogenation. This was because *trans* fatty acids, due to their shape, are more resistant to reaction with oxygen and are a poor food for bacteria. These *trans* fats have a much longer shelf life and less likely to become rancid (a product of

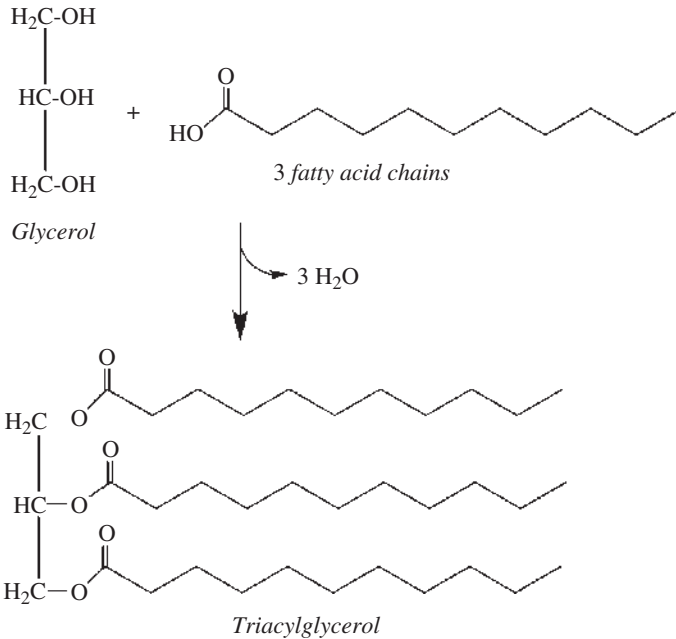


FIGURE 1.42 Glycerol and fatty acids combine to make a triglyceride. Like other polymer reactions, dehydration/condensation reactions result in the joining of two different molecules. The glycerol chain is the backbone of the fat. One, two, and three fatty acids bound to a glycerol molecule result in a mono-, di-, or triacylglycerol. More commonly known as fat.

reaction with air or bacterial degradation) and with the straight chain shape are solid at room temperature. In the 1970s margarine with these *trans* fats sold nearly twice that of butter consisting mostly of saturated fatty acids. Part of the reason for using *trans* fats in foods was to avoid the backlash against saturated fats and cardiovascular disease. Unfortunately in the 1990s a relationship between *trans* fats and heart disease was discovered. A lawsuit in 2003 against Kraft caused the food company to eliminate the use of partially hydrogenated vegetable oils in foods like Oreo cookies. In 2006 Starbucks followed suit and eliminated *trans* fats in making its baked goods. While low levels of *trans* fatty acids are found in some foods like pork, lamb, and milk, the problem with *trans* fatty acids is the higher incidence of coronary disease. *Trans* fats raise the levels of LDL that can contribute to blood flow blocking fatty deposits in arteries and can cause one type of white blood cells to change, collect cholesterol from LDL, and harden, blocking flow to the heart.

Fats and oils are essentially the same molecule, a triacylglycerol. Triacylglycerol is the major form of energy for animals and is stored in specialized fat cells called adipose cells. To create a triacylglycerol, three fatty acids are bonded to a short organic molecule called glycerol through the same dehydration reaction seen with proteins and carbohydrates (Fig. 1.42). Overall the new molecule is very hydrophobic and is nonpolar. A triglyceride is made from the combination of fatty acids and

TABLE 1.3 Smoke Point of Common Cooking Oils.

Fat	Oil Grade/Quality	Smoke Point
Vegetable shortening	Hydrogenated	360°F/180°C
Butter	Unsalted	350°F/175°C
Clarified butter	Removed sugars, water, and protein	450°F/230°C
Canola oil	Refined	400°F/205°C
Corn oil	Refined	450°F/230°C
Olive oil	Extra virgin	350–410°F/177–210°C
Sesame oil	Refined	350–410°F/175–210°C
Peanut oil	Refined	450°F/230°C
Safflower	Refined	510°F/265°C

glycerol; it has the basic structure shown in Figure 1.42 and Table 1.3. Fatty acids can be from 4 to 35 carbons long, but 14–20 carbon fatty acids are most common in food. When fatty acids and glycerol combine, bonds are broken and formed in a chemical reaction to produce a triglyceride and three molecules of water. In that process, a new group of atoms is formed called an *ester*. The properties of a given triglyceride depend upon the chemical structure of the three fatty acids it contains, and the properties of a lipid depend upon the particular mixture of triglycerides it contains.

A fat is a triacylglycerol that is solid at room temperature and found in fats in meat and milk. Oil is a triacylglycerol with fatty acid chains usually from plants and is liquid at room temperature. Essentially, the only difference between fat and oil is the length and number of double bonds on the fatty acids. However, these are significant differences both chemically and for cooking.

Melting of solid fat or oil like butter is a change in states of matter. Melting butter takes place when heat is applied, and the state of matter moves from solid to liquid. Fat molecules will stack and interact with each other with weak but numerous bonds. The more contact between fats, the more bonds can be formed and the more stable the fat will be in a solid state. Heat supplies enough energy to shift, move, and vibrate the molecules far enough apart from each other that they feel very little attraction. Now the fat molecules behave like a liquid and, with weak interactions attracting each other, are free to move. The melting point is the temperature at which molecules shift from a solid configuration to a liquid state. Fats that melt at a higher melting point require more heat to melt than a fat with a low melting point. The reason for this is the number of contacts between fats. Saturated fats pack very efficiently, densely packed with lots of interactions. Longer fatty acid chain results in more interactions between fatty acid chains. Thus it takes more energy to separate longer fatty acid chains than shorter fatty acid chains. *Cis* unsaturated fatty acids create the kinked fatty acid shape discussed earlier, keeping the fatty acid carbon chains from efficiently packing, reducing the heat needed to separate and melt a solid fat. On the other hand, *trans* fatty acids have a shape similar to saturated fatty acids and pack like the saturated fats. A simple approach is to remember that the longer the fatty acid chain, the higher the melting point and the more *cis* unsaturated double bonds, the lower the melting point.

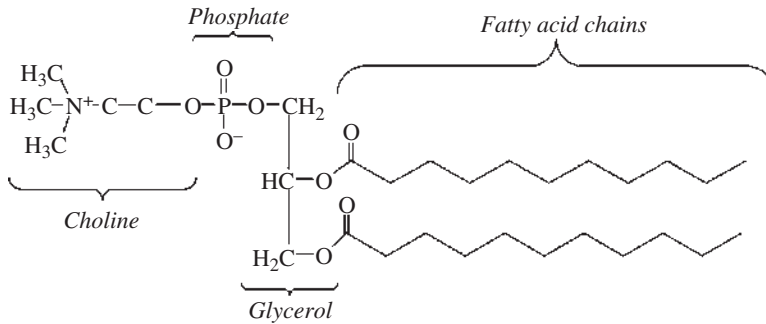


FIGURE 1.43 Phospholipid. A phospholipid similar to a diacylglycerol has a very different function and includes a polar head group (charged compound) linked to the glycerol backbone via a phosphate group.

Another lipid important in biology and cooking is the phospholipid. Like the triacylglycerol, phospholipids have a glycerol backbone, but, instead of three fatty acids, phospholipids contain two fatty acid chains. The third —OH of glycerol is bonded to a range of phosphate-containing molecules. The phosphate group is called the polar head group of the phospholipid. These molecules are now polar with the fatty acids creating a hydrophobic region, and the phosphate-containing portion usually is charged and hydrophilic. Phospholipids make up the major component of cell membranes—which surround the cell containing the contents of the cell. Phospholipid membranes are tough and form into globules in milk fat to provide a durable enclosure for the fatty acids and triacylglycerol. Lecithin, formally called phosphatidylcholine (Fig. 1.43), is a special phospholipid with a choline head group. Lecithin is found in high amounts in soybean and egg yolk and is used for cooking. The nonstick cooking spray PAM is primarily lecithin and water and utilized for its oil-like properties. A quick search of your pantry and refrigerator will find lecithin in a number of items including salad dressing, chocolate, and a number of interesting molecular gastronomy-inspired dishes and preparations. A curious dessert is liquid popcorn with caramel froth. Popcorn, sugar, and water are used with syrup and dry lecithin to create a two-phase drink where lecithin plays a role in keeping caramel cohesive.

Fats provide special flavors and characteristics to foods. The lubricating properties of lipids create a slippery smooth mouthfeel to foods and make some foods seem moist. Fats are often reported to tenderize food. Think of the difference between a lean and marbled steak. The cut marbled with fat is easier to chew and more tender. In baking, fat acts as a shortening agent. That is, fat coats some of the proteins and starches in flour, limiting the network and keeping a crust together. Adding fat (shortening) to a pie crust recipe creates a softer smaller crumb with thin layers of pie crust rather than a solid thick sheet of baked dough (Fig. 1.44). Short-chain fatty acids have a special flavor, creating a complex flavor to several foods. Microorganisms used to make some cheeses create sharp cheese flavors and some of the odors of cheeses. When cooked at high heats, fats of meat will change chemically to volatile



FIGURE 1.44 Role of shortening on pastry crust. The Greek pastry, baklava. Notice the sheets of flaky crust due to the addition of shortening. Caused by fat blocking or shortening the gluten interactions.

molecules that impart the flavor and smell of meat. Raw meat has little aroma and a very simple, blood-like taste. Phospholipids and fatty acids in meat react with oxygen to form smaller molecules called aldehydes, unsaturated alcohols, ketones, and lactones. Each provides a single note of flavor and smell of cooked meat. Certain fats like molecules derived from plants called terpenoids provide strong flavors to cooked foods. Examples include cinnamon, cloves, and mint.

Cooking with fats and oils provide a unique challenge. Heating fats and oils can create a smelly, smoky mess that leaves food tasting bitter. Fats will melt into oils when warmed but do not boil. Before the fat can reach the boiling point, it smokes and breaks down. The breakdown of fat at high temperatures is due to several factors. At high temperatures, oxygen in the air will oxidize the double bonds of unsaturated fatty acids creating a rancid and smelly product. Impurities in the oil including sugars, water, and proteins will burn in the oil, producing dark colors and off-tasting molecules. Free fatty acids are naturally present in fats and oils in very small amounts, but the amount of free fatty acids increases as the fats/oils are heated. The smoke point of oil is the temperature at which overheating causes a fat to give off smoke. At this point the fat decomposes where the fatty acids are released from glycerol and form into longer polymers that are very unpleasing to taste. The released glycerol further reacts with oxygen and heat to form acrolein and water. Acrolein is a toxic compound that irritates soft tissues. The fatty acid component and purity of oil influence the smoke point, and choosing the right oil or fat is critical to avoid ruining your food. More saturated fats decompose quickly, and butter, made mostly of saturated fatty acids, will smoke much more quickly than canola oil, which is a mixture of mono- and polyunsaturated fats. Safflower oil (12% monounsaturated and 75% polyunsaturated) has one of the highest smoke points. Impurities also decrease the temperature at which oil will smoke. Butter is a mixture of fats, water, proteins, and lactose. The latter components readily burn and are the reason why

sautéing with butter leads to a mess. Professional chefs will separate the fat from protein and water (clarified butter) to sauté food. To sauté in a higher temperature, use a vegetable oil-like canola or saffron oil.

Olive oil poses a special challenge when cooking. There are several grades of olive oil, each depending on the way the oil is extracted and stored. One way of making olive oil is to simply squeeze or press the fruit. The resulting oil is separated from large solids by filtering or centrifugation. This is cold-pressed oil. Sometimes hot water is then added and the oil extracted from the remaining paste to recover more oil. Another method involves dissolving the ground olive in a solvent to extract the oil. To be called a “virgin” olive oil, no chemical purification can be used in its production. Extra virgin olive oil is free of acids found in some species of olives and retains a good flavor. This olive oil is often used to add to foods for its flavor and not cooking. Refined olive oil is the extra virgin olive oil that does not qualify for the extra virgin status and has been chemically treated to remove impurities. Some oils, simply labeled “olive oil,” are a blend of refined and virgin olive oil and will have some of the flavors but will contain less of the impurities. Unrefined olive oil has a very low smoke point with a mix of impurities (320°F/160°C). Extra virgin olive oil has a slightly higher smoke point of 185°C/365°F, while processed purified, refined olive oil without the particles and acids from the olive paste will have a much higher smoke point of 450°F/232°C and serves as a good cooking medium.

1.3.9.3 Emulsions Proteins, lipids, and complex carbohydrates can each be used to prepare a critical technique for food and cooking called an emulsion. Emulsions are evenly mixed (homogeneous) dispersions of two components that repel each other. Examples of food emulsions include sauces, dressings, or mayonnaises. In chemical terms, the two phases are immiscible. A common culinary emulsion is a mixture of oil and water. If there is more water than oil, the emulsion is called oil-in-water emulsion, and if there is more oil than water, the emulsion is a water-in-oil emulsion. Mayonnaise is an oil-in-water emulsion, while butter is a water-in-oil emulsion. Either way, the basic concept of cooking with an emulsion is to create small enough droplets or fragments of the oil or water to be evenly dispersed through the mixture. Small droplets are created by a physical force called sheering is most commonly performed using blenders, whisking, or food processors. Industrial kitchens use fine-gauge strainers and force the fluids to create an emulsion. Consider shaking a mixture of oil and water. Shake or mix hard enough and the tiny spheres of oil will seemingly mix within the water. However, the two phases quickly separate from each other. That is the challenge of making an emulsion, keeping the solutions mixed.

Emulsifiers are food additive compounds that help create emulsions from separating back into two distinct layers. For oil-in-water emulsions, an emulsifier must have both a water-loving and water-fearing (oil-loving) region. Emulsifiers surround oil droplets with the hydrophobic portion of the molecule and align the hydrophobic region of the molecule to face the water. A second additive called a stabilizer is also often used in making emulsions. Stabilizers help keep the small droplets prepared in

the emulsion from reuniting into a larger mass and finally fully separating into two layers. Some molecules can act as both an emulsifier and a stabilizer. Common ingredients used for emulsifiers and stabilizers are egg yolks. The key compound in egg yolks used as an emulsifier is the phospholipid lecithin. The fatty acid component of the lipid buries itself into the oil droplets with the charged choline head group facing outward where it can interact with water by hydrogen bonds. This coats the newly formed oil droplet with a negative charged compound that allows the droplet to stabilize interactions with water and will avoid other oil droplets. Sugars that have been modified by adding short fatty acids are often used. The base sugar-fat compound used as emulsifiers is called sorbate. The carbon chain fatty acid interacts with the lipid, while the carbohydrate end of the molecule interacts with water. Polysorbate 80 is an emulsifier used in ice creams to keep the fats separated and ice cream smooth and slows down the “liquefaction” or appearance. Some proteins also serve as effective emulsifiers. Casein, one of the main proteins found in milk, coats the globules of fat in a similar way as lecithin coats oil droplets. The hydrophobic portions of casein interact nicely with the oil, and the charged component of the protein faces water to hydrogen bond, keeping the droplet intact.

Once the emulsion is formed, even in the presence of emulsifiers, the mixture is doomed and will eventually coalesce and form into distinct layers creating a watery, runny, and oily sauce. Complex carbohydrates like starches and gums and proteins interact and bind to emulsifiers and are often used as emulsion stabilizers and thicken the solution as well. The key job of a stabilizer is to help keep the droplets of oil or water apart so they cannot collect to form larger droplets where oil and water will eventually separate into two different phases. Starches and gums from tomatoes are released during preparation and act as stabilizers in pastes and ketchup. Dried ground mustard seed contains a considerable amount of gum carbohydrates, which serve well as stabilizers in hollandaise sauce. Agar and carrageenans are used as stabilizers of emulsions in prepared food. A quick examination of Velveeta processed cheese will find alginate and whey proteins—both used to emulsify and stabilize the cheese. Thickening the emulsification limits the diffusion or movement of the oil or water droplets so they cannot come together.

In making a good emulsion (sauce, mayonnaise, etc.), Harold McGee, the influential author of *On Food and Cooking* [1], writes that “the cook has made one of three mistakes: he has added the liquid to be dispersed too quickly to the continuous liquid, or added too much of the dispersed liquid, or allowed the sauce to get either too hot or too cold.” Key rules to making an effective emulsion are to start with the largest volume liquid (oil or water) in the bowl or mixer first. Add the lesser liquid to the greater liquid and add slowly to allow the droplets to form and become surrounded by the emulsifier. Keep the proportions correct; the larger phase should be three times that of the dispersed liquid. Ensure there is enough emulsifier for the dispersed liquid. If there isn’t enough emulsifier, the droplets will not be covered. High temperatures can cause proteins to fully denature, and emulsifiers and stabilizers will stop working and begin to curdle. At colder temperatures the oils will begin to solidify. Commercial mayonnaise is refrigerated and remains stable because more polyunsaturated oils are used that remain fluid at lower temperatures.

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