

# A Review of General Chemistry

ELECTRONS, BONDS, AND MOLECULAR PROPERTIES

## DID YOU EVER WONDER... what causes lightning?

**B**elieve it or not, the answer to this question is still the subject of debate (that's right... scientists have not yet figured out everything, contrary to popular belief). There are various theories that attempt to explain what causes the buildup of electric charge in clouds. One thing is clear, though—lightning involves a flow of electrons. By studying the nature of electrons and how electrons flow, it is possible to control where lightning will strike. A tall building can be protected by installing a lightning rod (a tall metal column at the top of the building) that attracts any nearby lightning bolt, thereby preventing a direct strike on the building itself. The lightning rod on the top of the Empire State Building is struck over a hundred times each year.

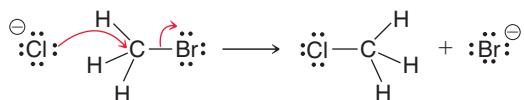
Just as scientists have discovered how to direct electrons in a bolt of lightning, chemists have also discovered how to direct electrons in chemical reactions. We will soon see that although organic chemistry is literally defined as the study of compounds containing carbon atoms, its true essence is actually the study of electrons, not atoms. Rather than thinking of reactions in terms of the motion of atoms, we

*continued >*

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must recognize that *reactions occur as a result of the motion of electrons*. For example, in the following reaction the curved arrows represent the motion, or flow, of electrons. This flow of electrons causes the chemical change shown:

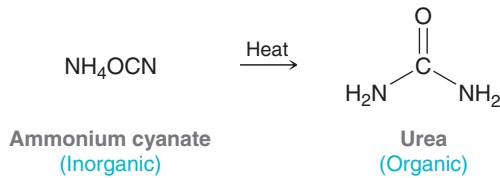


Throughout this course, we will learn how, when, and why electrons flow during reactions. We will learn about the barriers that prevent electrons from flowing, and we will learn how to overcome those barriers. In short, we will study the behavioral patterns of electrons, enabling us to predict, and even control, the outcomes of chemical reactions.

This chapter reviews some relevant concepts from your general chemistry course that should be familiar to you. Specifically, we will focus on the central role of electrons in forming bonds and influencing molecular properties.

## 1.1 Introduction to Organic Chemistry

In the early nineteenth century, scientists classified all known compounds into two categories: *organic compounds* were derived from living organisms (plants and animals), while *inorganic compounds* were derived from nonliving sources (minerals and gases). This distinction was fueled by the observation that organic compounds seemed to possess different properties than inorganic compounds. Organic compounds were often difficult to isolate and purify, and upon heating, they decomposed more readily than inorganic compounds. To explain these curious observations, many scientists subscribed to a belief that compounds obtained from living sources possessed a special “vital force” that inorganic compounds lacked. This notion, called vitalism, stipulated that it should be impossible to convert inorganic compounds into organic compounds without the introduction of an outside vital force. Vitalism was dealt a serious blow in 1828 when German chemist Friedrich Wöhler demonstrated the conversion of ammonium cyanate (a known inorganic salt) into urea, a known organic compound found in urine:



Over the decades that followed, other examples were found, and the concept of vitalism was gradually rejected. The downfall of vitalism shattered the original distinction between organic and inorganic compounds, and a new definition emerged. Specifically, organic compounds became defined as those compounds containing carbon atoms, while inorganic compounds generally were defined as those compounds lacking carbon atoms.

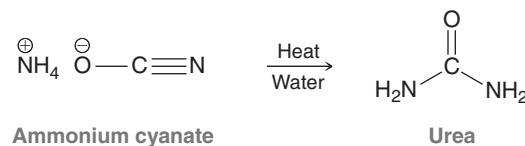
Organic chemistry occupies a central role in the world around us, as we are surrounded by organic compounds. The food that we eat and the clothes that we wear are comprised of organic compounds. Our ability to smell odors or see colors results from the behavior of organic compounds. Pharmaceuticals, pesticides, paints, adhesives, and plastics are all made



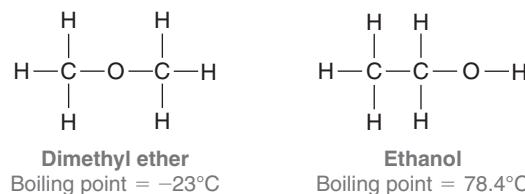
from organic compounds. In fact, our bodies are constructed mostly from organic compounds (DNA, RNA, proteins, etc.) whose behavior and function are determined by the guiding principles of organic chemistry. The responses of our bodies to pharmaceuticals are the results of reactions guided by the principles of organic chemistry. A deep understanding of those principles enables the design of new drugs that fight disease and improve the overall quality of life and longevity. Accordingly, it is not surprising that organic chemistry is required knowledge for anyone entering the health professions.

## 1.2 The Structural Theory of Matter

In the mid-nineteenth century three individuals, working independently, laid the conceptual foundations for the structural theory of matter. August Kekulé, Archibald Scott Couper, and Alexander M. Butlerov each suggested that substances are defined by a specific arrangement of atoms. As an example, consider the structures of ammonium cyanate and urea from Wöhler's experiment:



These compounds have the same molecular formula ( $\text{CH}_4\text{N}_2\text{O}$ ), yet they differ from each other in the way the atoms are connected—that is, they differ in their **constitution**. As a result, they are called **constitutional isomers**. Constitutional isomers have different physical properties and different names. Consider the following two compounds:



These compounds have the same molecular formula ( $\text{C}_2\text{H}_6\text{O}$ ) but different constitution, so they are constitutional isomers. The first compound is a colorless gas used as an aerosol spray propellant, while the second compound is a clear liquid, commonly referred to as “alcohol,” found in alcoholic beverages.

According to the structural theory of matter, each element will generally form a predictable number of bonds. The term **valence** describes the number of bonds usually formed by each element. For example, carbon generally forms four bonds and is therefore said to be **tetravalent**. Nitrogen generally forms three bonds and is therefore **trivalent**. Oxygen forms two bonds and is **divalent**, while hydrogen and the halogens form one bond and are **monovalent** (Figure 1.1).

<i>Tetravalent</i>	<i>Trivalent</i>	<i>Divalent</i>	<i>Monovalent</i>
$\begin{array}{c}   \\ -\text{C}- \\   \end{array}$ Carbon generally forms <b>four</b> bonds.	$\begin{array}{c}   \\ -\text{N}- \\   \end{array}$ Nitrogen generally forms <b>three</b> bonds.	$\begin{array}{c}   \\ -\text{O}- \\   \end{array}$ Oxygen generally forms <b>two</b> bonds.	$\begin{array}{c} \text{H} & \text{X} \\ — & — \\ \text{where X} & = \text{F, Cl, Br, or I} \end{array}$ Hydrogen and halogens generally form <b>one</b> bond.

**FIGURE 1.1**

Valencies of some common elements encountered in organic chemistry.

# SKILLBUILDER



## 1.1 DETERMINING THE CONSTITUTION OF SMALL MOLECULES



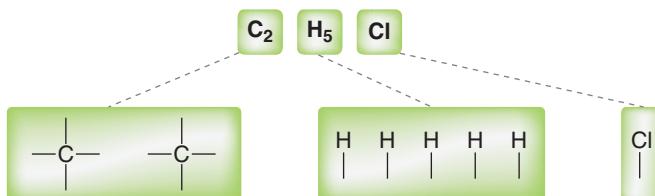
### LEARN the skill

There is only one compound that has molecular formula  $C_2H_5Cl$ . Determine the constitution of this compound.



### SOLUTION

The molecular formula indicates which atoms are present in the compound. In this example, the compound contains two carbon atoms, five hydrogen atoms, and one chlorine atom. Begin by determining the valency of each atom that is present in the compound. Each carbon atom is expected to be tetravalent, while the chlorine and hydrogen atoms are all expected to be monovalent:



#### STEP 1

Determine the valency of each atom in the compound.

#### STEP 2

Determine how the atoms are connected—atoms with the highest valency should be placed at the center and monovalent atoms should be placed at the periphery.



### PRACTICE the skill

**1.1** Determine the constitution of the compounds with the following molecular formulas:

- (a)  $CH_4O$
- (b)  $CH_3Cl$
- (c)  $C_2H_6$
- (d)  $CH_5N$
- (e)  $C_2F_6$
- (f)  $C_2H_5Br$
- (g)  $C_3H_8$



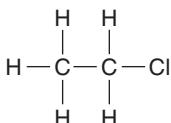
### APPLY the skill

**1.2** Draw two constitutional isomers that have molecular formula  $C_3H_7Cl$ .

**1.3** Draw three constitutional isomers that have molecular formula  $C_3H_8O$ .

**1.4** Draw all constitutional isomers that have molecular formula  $C_4H_{10}O$ .

→ need more PRACTICE? Try Problems 1.34, 1.46, 1.47, 1.54



## 1.3 Electrons, Bonds, and Lewis Structures

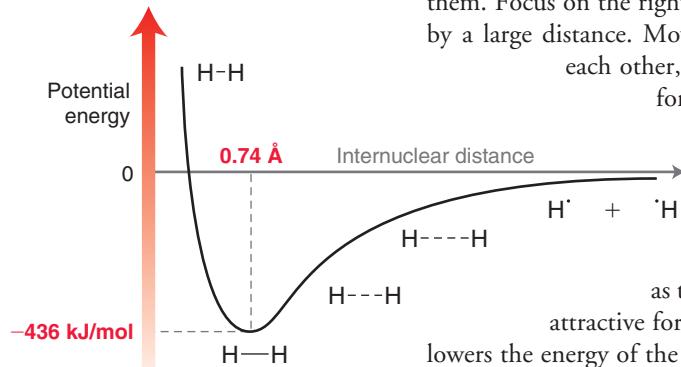
### What Are Bonds?

As mentioned, atoms are connected to each other by bonds. That is, bonds are the “glue” that hold atoms together. But what is this mysterious glue and how does it work? In order to answer this question, we must focus our attention on electrons.

The existence of the electron was first proposed in 1874 by George Johnstone Stoney (National University of Ireland), who attempted to explain electrochemistry by suggesting the existence of a particle bearing a unit of charge. Stoney coined the term *electron* to describe this particle. In 1897, J. J. Thomson (Cambridge University) demonstrated evidence supporting the existence of Stoney’s mysterious electron and is credited with discovering the electron. In 1916,



Gilbert Lewis (University of California, Berkeley) defined a **covalent bond** as the result of *two atoms sharing a pair of electrons*. As a simple example, consider the formation of a bond between two hydrogen atoms:



**FIGURE 1.2**

An energy diagram showing the total energy as a function of the internuclear distance between two hydrogen atoms.

Each hydrogen atom has one electron. When these electrons are shared to form a bond, there is a decrease in energy, indicated by the negative value of  $\Delta H$ . The energy diagram in Figure 1.2 plots the total energy of the two hydrogen atoms as a function of the distance between them. Focus on the right side of the diagram, which represents the hydrogen atoms separated by a large distance. Moving toward the left on the diagram, the hydrogen atoms approach each other, and there are several forces that must be taken into account: (1) the force of repulsion between the two negatively charged electrons, (2) the force of repulsion between the two positively charged nuclei, and (3) the forces of attraction between the positively charged nuclei and the negatively charged electrons. As the hydrogen atoms get closer to each other, all of these forces get stronger. Under these circumstances, the electrons are capable of moving in such a way so as to minimize the repulsive forces between them while maximizing their attractive forces with the nuclei. This provides for a net force of attraction, which lowers the energy of the system. As the hydrogen atoms move still closer together, the energy continues to be lowered until the nuclei achieve a separation (internuclear distance) of 0.74 angstroms ( $\text{\AA}$ ). At that point, the force of repulsion between the nuclei begins to overwhelm the forces of attraction, causing the energy of the system to increase. The lowest point on the curve represents the most stable state. This state determines both the bond length (0.74  $\text{\AA}$ ) and the bond strength (436 kJ/mol).

### Drawing the Lewis Structure of an Atom

Armed with the idea that a bond represents a pair of shared electrons, Lewis then devised a method for drawing structures. In his drawings, called **Lewis structures**, the electrons take center stage. We will begin by drawing individual atoms, and then we will draw Lewis structures for small molecules. First, we must review a few simple features of atomic structure:

- The nucleus of an atom is comprised of protons and neutrons. Each proton has a charge of +1, and each neutron is electrically neutral.
- For a neutral atom, the number of protons is balanced by an equal number of electrons, which have a charge of -1 and exist in shells. The first shell, which is closest to the nucleus, can contain two electrons, and the second shell can contain up to eight electrons.
- The electrons in the outermost shell of an atom are called the **valence electrons**. The number of valence electrons in an atom is identified by its group number in the periodic table (Figure 1.3).

The Lewis dot structure of an individual atom indicates the number of valence electrons, which are placed as dots around the periodic symbol of the atom (C for carbon, O for oxygen, etc.). The placement of these dots is illustrated in the following SkillBuilder.

1A	2A								8A
H	Be								He
Li	Mg								
Na									
K	Ca								
Rb	Sr								
Cs	Ba								
Transition Metal Elements									
		B	C	N	O	F	Ne		
		Al	Si	P	S	Cl	Ar		
		Ga	Ge	As	Se	Br	Kr		
		In	Sn	Sb	Te	I	Xe		
		Tl	Pb	Bi	Po	At	Rn		

**FIGURE 1.3**

A periodic table showing group numbers.

# SKILLBUILDER



## 1.2 DRAWING THE LEWIS DOT STRUCTURE OF AN ATOM



### LEARN the skill



Draw the Lewis dot structure of (a) a boron atom and (b) a nitrogen atom.

#### SOLUTION

##### STEP 1

Determine the number of valence electrons.

##### STEP 2

Place one valence electron by itself on each side of the atom.

##### STEP 3

If the atom has more than four valence electrons, the remaining electrons are paired with the electrons already drawn.



### PRACTICE the skill

**1.5** Draw a Lewis dot structure for each of the following atoms:

- (a) Carbon      (b) Oxygen      (c) Fluorine      (d) Hydrogen
- (e) Bromine      (f) Sulfur      (g) Chlorine      (h) Iodine



### APPLY the skill

**1.6** Compare the Lewis dot structure of nitrogen and phosphorus and explain why you might expect these two atoms to exhibit similar bonding properties.

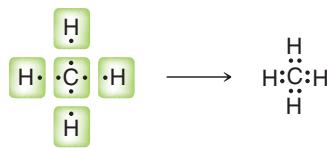
**1.7** Name one element that you would expect to exhibit bonding properties similar to boron. Explain.

**1.8** Draw a Lewis structure of a carbon atom that is missing one valence electron (and therefore bears a positive charge). Which second-row element does this carbon atom resemble in terms of the number of valence electrons?

**1.9** Draw a Lewis structure of a carbon atom that has one extra valence electron (and therefore bears a negative charge). Which second-row element does this carbon atom resemble in terms of the number of valence electrons?

### Drawing the Lewis Structure of a Small Molecule

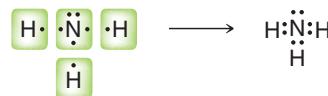
The Lewis dot structures of individual atoms are combined to produce Lewis dot structures of small molecules. These drawings are constructed based on the observation that atoms tend to bond in such a way so as to achieve the electron configuration of a noble gas. For example, hydrogen will form one bond to achieve the electron configuration of helium (two valence electrons), while second-row elements (C, N, O, and F) will form the necessary number of bonds so as to achieve the electron configuration of Neon (eight valence electrons).



This observation, called the **octet rule**, explains why carbon is tetravalent. As just shown, it can achieve an octet of electrons by using each of its four valence electrons to form a bond. The octet rule also explains why nitrogen is trivalent.

Specifically, it has five valence electrons and requires three bonds in order to achieve an octet of electrons. Notice that the nitrogen contains one pair of unshared, or nonbonding electrons, called a **lone pair**.

In the next chapter, we will discuss the octet rule in more detail; in particular, we will explore when it can be violated and when it cannot be violated. For now, let's practice drawing Lewis structures.



## SKILLBUILDER



### 1.3 DRAWING THE LEWIS STRUCTURE OF A SMALL MOLECULE



#### LEARN the skill



##### STEP 1

Draw all individual atoms.

##### STEP 2

Connect atoms that form more than one bond.

##### STEP 3

Connect the hydrogen atoms.

##### STEP 4

Pair any unpaired electrons so that each atom achieves an octet.



#### PRACTICE the skill

**1.10** Draw a Lewis structure for each of the following compounds:

(a)  $\text{C}_2\text{H}_6$       (b)  $\text{C}_2\text{H}_4$       (c)  $\text{C}_2\text{H}_2$

(d)  $\text{C}_3\text{H}_8$       (e)  $\text{C}_3\text{H}_6$       (f)  $\text{CH}_3\text{OH}$



#### APPLY the skill

**1.11** Borane ( $\text{BH}_3$ ) is very unstable and quite reactive. Draw a Lewis structure of borane and explain the source of the instability.

**1.12** There are four constitutional isomers with molecular formula  $\text{C}_3\text{H}_9\text{N}$ . Draw a Lewis structure for each isomer and determine the number of lone pairs on the nitrogen atom in each case.

→ need more PRACTICE? Try Problems 1.35, 1.38, 1.42

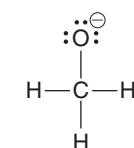
## 1.4 Identifying Formal Charges

A **formal charge** is associated with any atom that does not exhibit the appropriate number of valence electrons. When such an atom is present in a Lewis structure, the formal charge must be drawn. Identifying a formal charge requires two discrete tasks:

1. Determine the appropriate number of valence electrons for an atom.
2. Determine whether the atom exhibits the appropriate number of electrons.

The first task can be accomplished by inspecting the periodic table. As mentioned earlier, the group number indicates the appropriate number of valence electrons for each atom. For example, carbon is in group 4A and therefore has four valence electrons. Oxygen is in group 6A and has six valence electrons.

After identifying the appropriate number of electrons for each atom in a Lewis structure, the next task is to determine if any of the atoms in the Lewis structure exhibit an unexpected number of electrons. For example, consider this structure:



## SKILLBUILDER

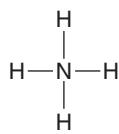


### 1.4 CALCULATING FORMAL CHARGE



#### LEARN the skill

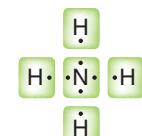
Consider the nitrogen atom in the structure below and determine if it has a formal charge:



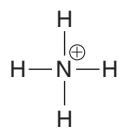
#### SOLUTION

We begin by determining the appropriate number of valence electrons for a nitrogen atom. Nitrogen is in group 5A of the periodic table, and it should therefore have five valence electrons.

Next, we count how many valence electrons are exhibited by the nitrogen atom in this particular example:

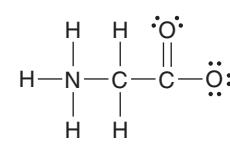
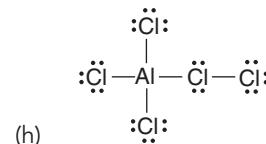
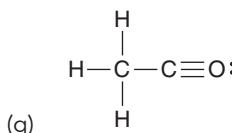
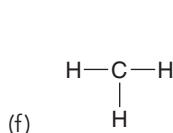
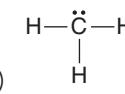
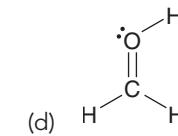
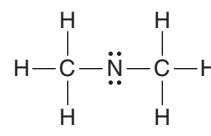
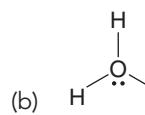
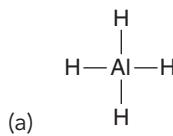


In this case, the nitrogen atom exhibits only four valence electrons. It is missing one electron, so it must bear a positive formal charge, which is shown like this:



#### STEP 3

Assign a formal charge.


**PRACTICE the skill** 1.13 Identify any formal charges in the structures below:

**APPLY the skill**

1.14 Draw a Lewis structure for each of the following ions; in each case, indicate which atom possesses the formal charge:



→ need more PRACTICE? Try Problem 1.41

## 1.5 Induction and Polar Covalent Bonds

Chemists classify bonds into three categories: (1) covalent, (2) polar covalent, and (3) ionic. These categories emerge from the electronegativity values of the atoms sharing a bond. **Electronegativity** is a measure of the ability of an atom to attract electrons. Table 1.1 gives the electronegativity values for elements commonly encountered in organic chemistry.

TABLE 1.1 ELECTRONEGATIVITY VALUES OF SOME COMMON ELEMENTS

Increasing electronegativity						
H 2.1						
Li	Be	B	C	N	O	F
1.0	1.5	2.0	2.5	3.0	3.5	4.0
Na	Mg	Al	Si	P	S	Cl
0.9	1.2	1.5	1.8	2.1	2.5	3.0
K						Br
0.8						2.8

Increasing electronegativity

When two atoms form a bond, there is one critical question that allows us to classify the bond: What is the difference in the electronegativity values of the two atoms? Below are some rough guidelines:

If the difference in electronegativity is less than 0.5, the electrons are considered to be equally shared between the two atoms, resulting in a covalent bond. Examples include C—C and C—H:



The C—C bond is clearly covalent, because there is no difference in electronegativity between the two atoms forming the bond. Even a C—H bond is considered to be covalent, because the difference in electronegativity between C and H is less than 0.5.

If the difference in electronegativity is between 0.5 and 1.7, the electrons are not shared equally between the atoms, resulting in a **polar covalent bond**. For example, consider a bond between carbon and oxygen (C—O). Oxygen is significantly more electronegative (3.5) than carbon (2.5), and therefore oxygen will more strongly attract the electrons of the bond.

The withdrawal of electrons toward oxygen is called **induction**, which is often indicated with an arrow like this:



Induction causes the formation of partial positive and partial negative charges, symbolized by the Greek symbol delta ( $\delta$ ). The partial charges that result from induction will be very important in upcoming chapters.



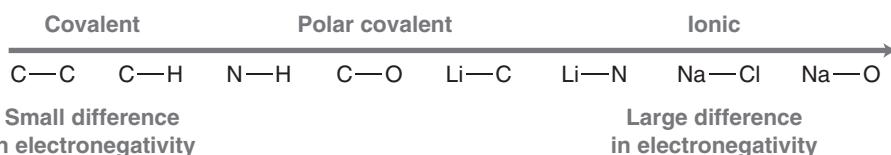
*If the difference in electronegativity is greater than 1.7,* the electrons are not shared at all. For example, consider the bond between sodium and oxygen in sodium hydroxide (NaOH):



The difference in electronegativity between O and Na is so great that both electrons of the bond are possessed solely by the oxygen atom, rendering the oxygen negatively charged and the sodium positively charged. The bond between the oxygen and sodium, called an **ionic bond**, is the result of the force of attraction between the two oppositely charged ions.

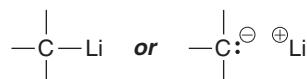
The cutoff numbers (0.5 and 1.7) should be thought of as rough guidelines. Rather than viewing them as absolute, we must view the various types of bonds as belonging to a spectrum without clear cutoffs (Figure 1.4).

**FIGURE 1.4**  
The nature of various bonds commonly encountered in organic chemistry.



This spectrum has two extremes: covalent bonds on the left and ionic bonds on the right. Between these two extremes are the polar covalent bonds. Some bonds fit clearly into one category, such as C—C bonds (covalent), C—O bonds (polar covalent), or Na—O bonds (ionic).

However, there are many cases that are not so clear-cut. For example, a C—Li bond has a difference in electronegativity of 1.5, and this bond is often drawn either as polar covalent or as ionic. Both drawings are acceptable.



Another reason to avoid absolute cutoff numbers when comparing electronegativity values is that the electronegativity values shown above are obtained via a method developed by Linus Pauling. However, there are at least seven other methods for calculating electronegativity values, each of which provides slightly different values. Strict adherence to the Pauling scale would suggest that C—Br and C—I bonds are covalent, but these bonds will be treated as polar covalent throughout this course.

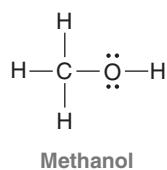
## SKILLBUILDER



### 1.5 LOCATING PARTIAL CHARGES RESULTING FROM INDUCTION

#### LEARN the skill

Consider the structure of methanol. Identify all polar covalent bonds and show any partial charges that result from inductive effects.



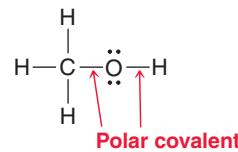


### SOLUTION

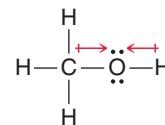
First identify all polar covalent bonds. The C—H bonds are considered to be covalent because the electronegativity values for C and H are fairly close. It is true that carbon is more electronegative than hydrogen, and therefore, there is a small inductive effect for each C—H bond. However, we will generally consider this effect to be negligible for C—H bonds.

The C—O bond and the O—H bond are both polar covalent bonds:

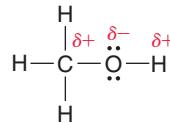
**STEP 1**  
Identify all polar covalent bonds.



**STEP 2**  
Determine the direction of each dipole.

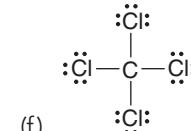
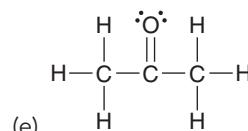
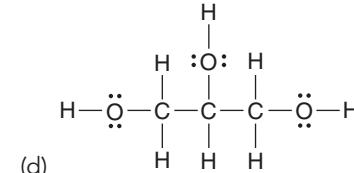
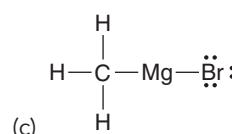
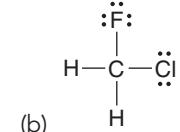
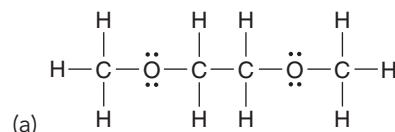


**STEP 3**  
Indicate the location of partial charges.



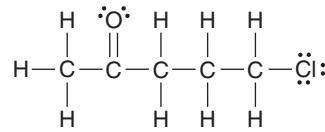
These inductive effects dictate the locations of the partial charges:

**PRACTICE the skill** **1.15** For each of the following compounds, identify any polar covalent bonds by drawing  $\delta+$  and  $\delta-$  symbols in the appropriate locations.



**APPLY the skill**

**1.16** The regions of  $\delta+$  in a compound are the regions most likely to be attacked by an anion, such as hydroxide ( $\text{HO}^-$ ). In the compound below, identify the two carbon atoms that are most likely to be attacked by a hydroxide ion:

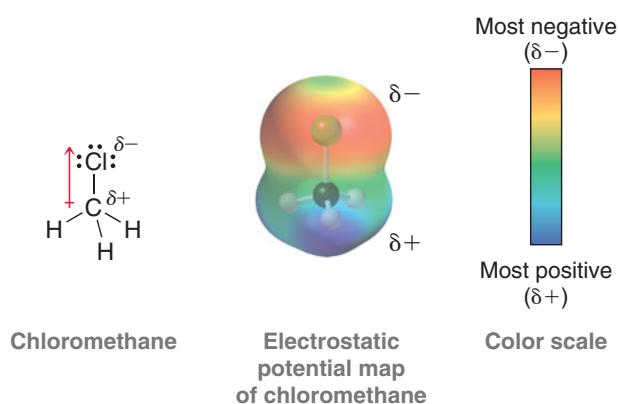


→ need more **PRACTICE?** Try Problems 1.36, 1.37, 1.48, 1.57

## PRACTICALLY SPEAKING ))

### Electrostatic Potential Maps

Partial charges can be visualized with three-dimensional, rainbow-like images called **electrostatic potential maps**. As an example, consider the electrostatic potential map of chloromethane.



In the image, a color scale is used to represent areas of  $\delta-$  and  $\delta+$ . As indicated, red represents a region that is  $\delta-$ ,

while blue represents a region that is  $\delta+$ . In reality, electrostatic potential maps are rarely used by practicing organic chemists when they communicate with each other; however, these illustrations can often be helpful to students who are learning organic chemistry. Electrostatic potential maps are generated by performing a series of calculations. Specifically, an imaginary point positive charge is positioned at various locations, and for each location, we calculate the potential energy associated with the attraction between the point positive charge and the surrounding electrons. A large attraction indicates a position of  $\delta-$ , while a small attraction indicates a position of  $\delta+$ . The results are then illustrated using colors, as shown.

A comparison of any two electrostatic potential maps is only valid if both maps were prepared using the same color scale. Throughout this book, care has been taken to use the same color scale whenever two maps are directly compared to each other. However, it will not be useful to compare two maps from different pages of this book (or any other book), as the exact color scales are likely to be different.

## 1.6 Atomic Orbitals

### Quantum Mechanics

By the 1920s, vitalism had been discarded. Chemists were aware of constitutional isomerism and had developed the structural theory of matter. The electron had been discovered and identified as the source of bonding, and Lewis structures were used to keep track of shared and unshared electrons. But the understanding of electrons was about to change dramatically.

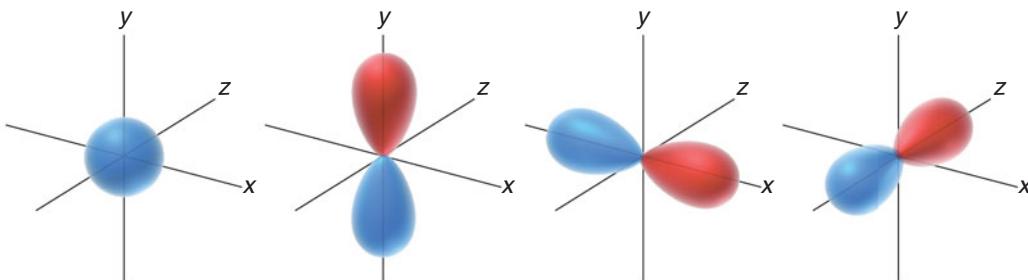
In 1924, French physicist Louis de Broglie suggested that electrons, heretofore considered as particles, also exhibited wavelike properties. Based on this assertion, a new theory of matter was born. In 1926, Erwin Schrödinger, Werner Heisenberg, and Paul Dirac independently proposed a mathematical description of the electron that incorporated its wavelike properties. This new theory, called *wave mechanics*, or **quantum mechanics**, radically changed the way we viewed the nature of matter and laid the foundation for our current understanding of electrons and bonds.

Quantum mechanics is deeply rooted in mathematics and represents an entire subject by itself. The mathematics involved is beyond the scope of our course, and we will not discuss it here. However, in order to understand the nature of electrons, it is critical to understand a few simple highlights from quantum mechanics:

- An equation is constructed to describe the total energy of a hydrogen atom (i.e., one proton plus one electron). This equation, called the **wave equation**, takes into account the wavelike behavior of an electron that is in the electric field of a proton.
- The wave equation is then solved to give a series of solutions called **wavefunctions**. The Greek symbol psi ( $\psi$ ) is used to denote each wavefunction ( $\psi_1$ ,  $\psi_2$ ,  $\psi_3$ , etc.). Each of these wavefunctions corresponds to an allowed energy level for the electron. This result is incredibly important because it suggests that an electron, when contained in an atom, can only exist at discrete energy levels ( $\psi_1$ ,  $\psi_2$ ,  $\psi_3$ , etc.). In other words, the energy of the electron is *quantized*.



- Each wavefunction is a function of spatial location. It provides information that allows us to assign a numerical value for each location in three-dimensional space relative to the nucleus. The square of that value ( $\psi^2$  for any particular location) has a special meaning. It indicates the probability of finding the electron in that location. Therefore, a three-dimensional plot of  $\psi^2$  will generate an image of an atomic orbital (Figure 1.5).



**FIGURE 1.5**  
Illustrations of an *s* orbital and three *p* orbitals.

### Electron Density and Atomic Orbitals

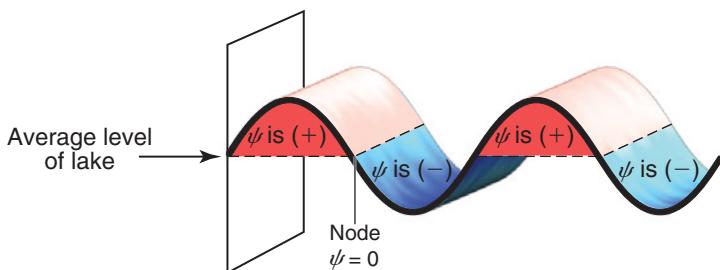
An *orbital* is a region of space that can be occupied by an electron. But care must be taken when trying to visualize this. There is a statement from the previous section that must be clarified because it is potentially misleading: “ $\psi^2$  represents the probability of finding an electron in a particular location.” This statement seems to treat an electron as if it were a particle flying around within a specific region of space. But remember that an electron is not purely a particle—it has wavelike properties as well. Therefore, we must construct a mental image that captures both of these properties. That is not easy to do, but the following analogy might help. We will treat an occupied orbital as if it is a cloud—similar to a cloud in the sky. No analogy is perfect, and there are certainly features of clouds that are very different from orbitals. However, focusing on some of these differences between electron clouds (occupied orbitals) and real clouds makes it possible to construct a better mental model of an electron in an orbital:

- Clouds in the sky can come in any shape or size. However, electron clouds only come in a small number of shapes and sizes (as defined by the orbitals).
- A cloud in the sky is comprised of billions of individual water molecules. An electron cloud is not comprised of billions of particles. We must think of an electron cloud as a single entity, even though it can be thicker in some places and thinner in other places. This concept is critical and will be used extensively throughout the course in explaining reactions.
- A cloud in the sky has edges, and it is possible to define a region of space that contains 100% of the cloud. In contrast, an electron cloud does not have defined edges. We frequently use the term **electron density**, which is associated with the probability of finding an electron in a particular region of space. The “shape” of an orbital refers to a region of space that contains 90 – 95% of the electron density. Beyond this region, the remaining 5 – 10 % of the electron density tapers off but never ends. In fact, if we want to consider the region of space that contains 100% of the electron density, we must consider the entire universe.

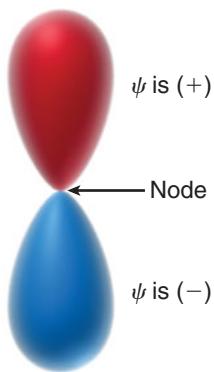
In summary, we must think of an orbital as a region of space that can be occupied by electron density. An occupied orbital must be treated as a *cloud of electron density*. This region of space is called an **atomic orbital** (AO), because it is a region of space defined with respect to the nucleus of a single atom. Examples of atomic orbitals are the *s*, *p*, *d*, and *f* orbitals that were discussed in your general chemistry textbook.

### Phases of Atomic Orbitals

Our discussion of electrons and orbitals has been based on the premise that electrons have wavelike properties. As a result, it will be necessary to explore some of the characteristics of simple waves in order to understand some of the characteristics of orbitals.

**FIGURE 1.6**

Phases of a wave moving across the surface of a lake.

**FIGURE 1.7**

The phases of a  $p$  orbital.

Consider a wave that moves across the surface of a lake (Figure 1.6). The wavefunction ( $\psi$ ) mathematically describes the wave, and the value of the wavefunction is dependent on location. Locations above the average level of the lake have a positive value for  $\psi$  (indicated in red), and locations below the average level of the lake have a negative value for  $\psi$  (indicated in blue). Locations where the value of  $\psi$  is zero are called **nodes**.

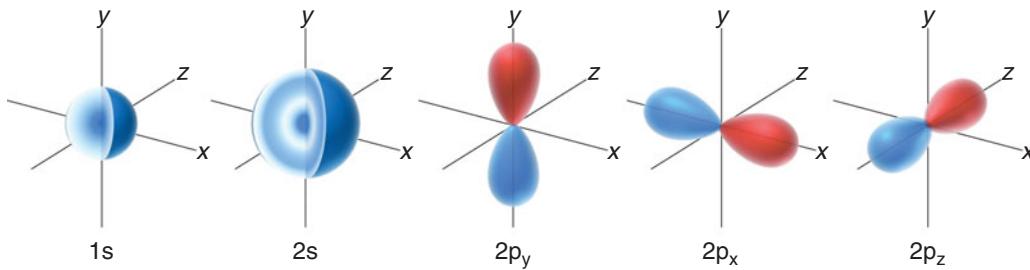
Similarly, orbitals can have regions where the value of  $\psi$  is positive, negative, or zero. For example, consider a  $p$  orbital (Figure 1.7). Notice that the  $p$  orbital has two lobes: the top lobe is a region of space where the values of  $\psi$  are positive, while the bottom lobe is a region where the values of  $\psi$  are negative. Between the two lobes is a location where  $\psi = 0$ . This location represents a node.

Be careful not to confuse the sign of  $\psi$  (+ or -) with electrical charge. A positive value for  $\psi$  does not imply a positive charge. The value of  $\psi$  (+ or -) is a mathematical convention that refers to the *phase* of the wave (just like in the lake). Although  $\psi$  can have positive or negative values, nevertheless  $\psi^2$  (which describes the electron density as a function of location) will always be a positive number. At a node, where  $\psi = 0$ , the electron density ( $\psi^2$ ) will also be zero. This means that there is no electron density located at a node.

From this point forward, we will draw the lobes of an orbital with colors (red and blue) to indicate the phase of  $\psi$  for each region of space.

### Filling Atomic Orbitals with Electrons

The energy of an electron depends on the type of orbital that it occupies. Most of the organic compounds that we will encounter will be composed of first- and second-row elements (H, C, N, and O). These elements utilize the  $1s$  orbital, the  $2s$  orbital, and the three  $2p$  orbitals. Our discussions will therefore focus primarily on these orbitals (Figure 1.8). Electrons are lowest in energy when they occupy a  $1s$  orbital, because the  $1s$  orbital is closest to the nucleus and it has no nodes (the more nodes that an orbital has, the greater its energy). The  $2s$  orbital has one node and is farther away from the nucleus; it is therefore higher in energy than the  $1s$  orbital. After the  $2s$  orbital, there are three  $2p$  orbitals that are all equivalent in energy to one another. Orbitals with the same energy level are called **degenerate orbitals**.

**FIGURE 1.8**

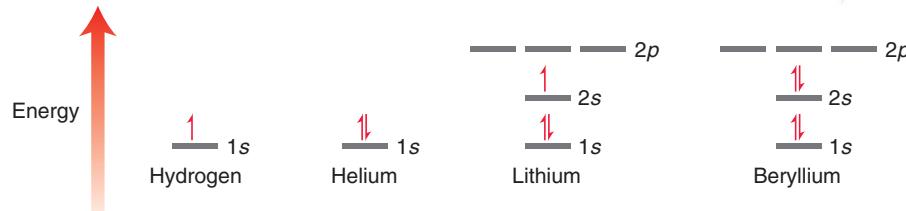
Illustrations of  $s$  orbitals and three  $p$  orbitals.

As we move across the periodic table, starting with hydrogen, each element has one more electron than the element before it (Figure 1.9). The order in which the orbitals are filled by electrons is determined by just three simple principles:

1. The **Aufbau principle**. The lowest-energy orbital is filled first.
2. The **Pauli exclusion principle**. Each orbital can accommodate a maximum of two electrons that have opposite spin. To understand what “spin” means, we can imagine an



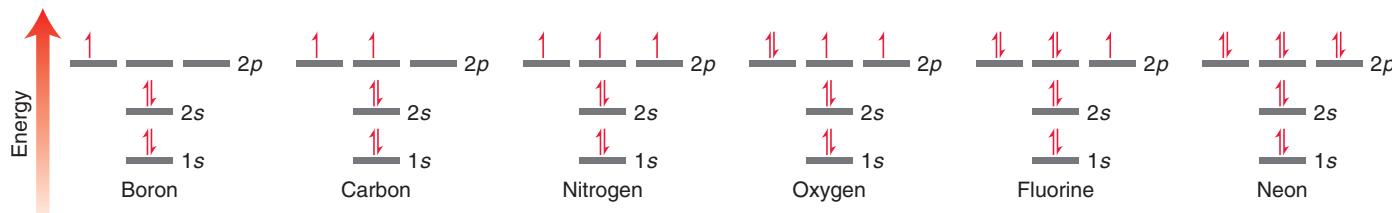
**FIGURE 1.9**  
Energy diagrams showing the electron configurations for H, He, Li, and Be.



electron spinning in space (although this is an oversimplified explanation of the term “spin”). For reasons that are beyond the scope of this course, electrons only have two possible spin states (designated by  $\downarrow$  or  $\uparrow$ ). In order for the orbital to accommodate two electrons, the electrons must have opposite spin states.

3. **Hund’s Rule.** When dealing with degenerate orbitals, such as  $p$  orbitals, one electron is placed in each degenerate orbital first, before electrons are paired up.

The application of the first two principles can be seen in the electron configurations shown in Figure 1.9 (H, He, Li, and Be). The application of the third principle can be seen in the electron configurations for the remaining second-row elements (Figure 1.10).



**FIGURE 1.10**  
Energy diagrams showing the electron configurations for B, C, N, O, F, and Ne.

## SKILLBUILDER



### 1.6 IDENTIFYING ELECTRON CONFIGURATIONS



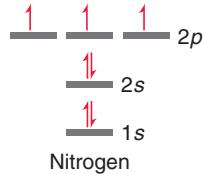
#### LEARN the skill

Identify the electron configuration of a nitrogen atom.

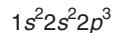


#### SOLUTION

The electron configuration indicates which atomic orbitals are occupied by electrons. Nitrogen has a total of seven electrons. These electrons occupy atomic orbitals of increasing energy, with two electrons being placed in each orbital:



Two electrons occupy the 1s orbital, two electrons occupy the 2s orbital, and three electrons occupy the 2p orbitals. This is summarized using the following notation:



#### PRACTICE the skill 1.17 Determine the electron configuration for each of the following atoms:

- Carbon
- Oxygen
- Boron
- Fluorine
- Sodium
- Aluminum

**APPLY the skill**

**1.18** Determine the electron configuration for each of the following ions:

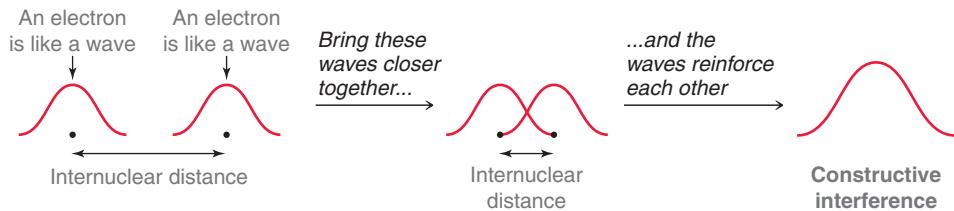
- (a) A carbon atom with a negative charge
- (c) A nitrogen atom with a positive charge
- (b) A carbon atom with a positive charge
- (d) An oxygen atom with a negative charge

-----> need more **PRACTICE?** Try Problem 1.44

## 1.7 Valence Bond Theory

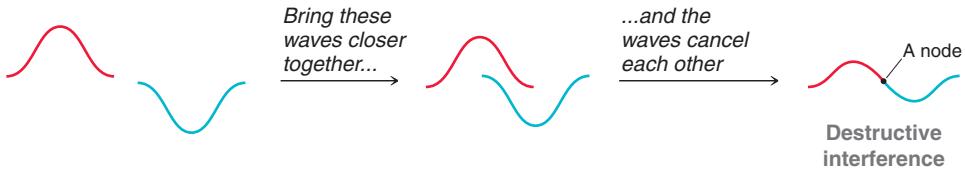
With the understanding that electrons occupy regions of space called orbitals, we can now turn our attention to a deeper understanding of covalent bonds. Specifically, a covalent bond is formed from the overlap of atomic orbitals. There are two commonly used theories for describing the nature of atomic orbital overlap: valence bond theory and molecular orbital (MO) theory. The valence bond approach is more simplistic in its treatment of bonds, and therefore we will begin our discussion with valence bond theory.

If we are going to treat electrons as waves, then we must quickly review what happens when two waves interact with each other. Two waves that approach each other can interfere in one of two possible ways—constructively or destructively. Similarly, when atomic orbitals overlap, they can interfere either constructively (Figure 1.11) or destructively (Figure 1.12).



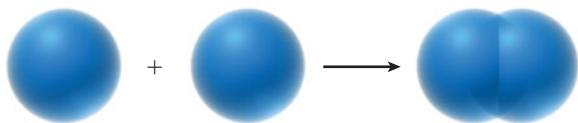
**FIGURE 1.11**  
Constructive interference resulting from the interaction of two electrons.

**Constructive interference** produces a wave with larger amplitude. In contrast, **destructive interference** results in waves canceling each other, which produces a node (Figure 1.12).

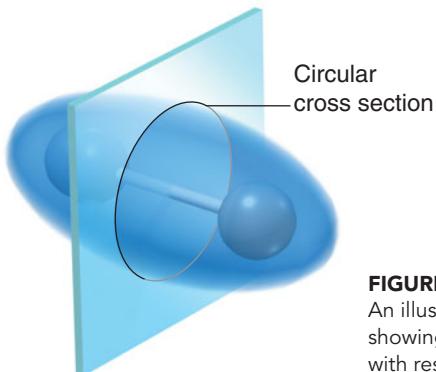


**FIGURE 1.12**  
Destructive interference resulting from the interaction of two electrons.

According to **valence bond theory**, a bond is simply the sharing of electron density between two atoms as a result of the constructive interference of their atomic orbitals. Consider, for example, the bond that is formed between the two hydrogen atoms in molecular hydrogen ( $\text{H}_2$ ). This bond is formed from the overlap of the  $1s$  orbitals of each hydrogen atom (Figure 1.13). The electron density of this bond is primarily located on the bond axis (the line that can be drawn between the two hydrogen atoms). This type of bond is called a **sigma ( $\sigma$ ) bond** and is characterized by circular symmetry with respect to the bond axis. To visualize what this means, imagine a plane that is drawn perpendicular to the bond axis. This plane will carve out a circle (Figure 1.14). This is the defining feature of  $\sigma$  bonds and will be true of all purely single bonds. Therefore, *all single bonds are  $\sigma$  bonds*.



**FIGURE 1.13**  
The overlap of the  $1s$  atomic orbitals of two hydrogen atoms, forming molecular hydrogen ( $\text{H}_2$ ).



**FIGURE 1.14**  
An illustration of a sigma bond, showing the circular symmetry with respect to the bond axis.



## 1.8 Molecular Orbital Theory

In most situations, valence bond theory will be sufficient for our purposes. However, there will be cases in the upcoming chapters where valence bond theory will be inadequate to describe the observations. In such cases, we will utilize molecular orbital theory, a more sophisticated approach to viewing the nature of bonds.

Much like valence bond theory, **molecular orbital (MO) theory** also describes a bond in terms of the constructive interference between two overlapping atomic orbitals. However, MO theory goes one step further and uses mathematics as a tool to explore the consequences of atomic orbital overlap. The mathematical method is called the **linear combination of atomic orbitals (LCAO)**. According to this theory, atomic orbitals are mathematically combined to produce new orbitals, called **molecular orbitals**.

It is important to understand the distinction between atomic orbitals and molecular orbitals. Both types of orbitals are used to accommodate electrons, but an atomic orbital is a region of space associated with an individual atom, while a molecular orbital is associated with an entire molecule.

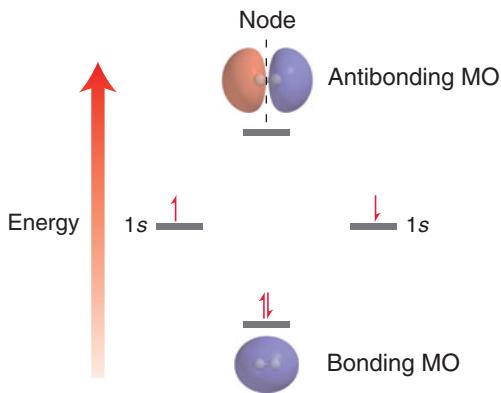
That is, the molecule is considered to be a single entity held together by many electron clouds, some of which can actually span the entire length of the molecule. These molecular orbitals are filled with electrons in a particular order in much the same way that atomic orbitals are filled. Specifically, electrons first occupy the lowest energy orbitals, with a maximum of two electrons per orbital. In order to visualize what it means for an orbital to be associated with an entire molecule, we will explore two molecules: molecular hydrogen ( $H_2$ ) and bromomethane ( $CH_3Br$ ).

Consider the bond formed between the two hydrogen atoms in molecular hydrogen. This bond is the result of the overlap of two atomic orbitals ( $s$  orbitals), each of which is occupied by one electron. According to MO theory, when two atomic orbitals overlap, they cease to exist. Instead, they are replaced by two molecular orbitals, each of which is associated with the entire molecule (Figure 1.15).

In the energy diagram shown in Figure 1.15, the individual atomic orbitals are represented on the right and left, with each atomic orbital having one electron.

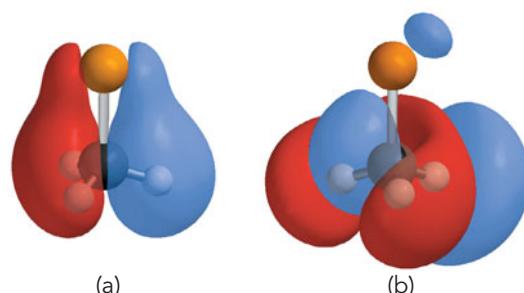
These atomic orbitals are combined mathematically (using the LCAO method) to produce two molecular orbitals. The lower energy molecular orbital, or **bonding MO**, is the result of constructive interference of the original two atomic orbitals. The higher energy molecular orbital, or **antibonding MO**, is the result of destructive interference. Notice that the antibonding MO has one node, which explains why it is higher in energy. Both electrons occupy the bonding MO in order to achieve a lower energy state. This lowering in energy is the essence of the bond. For an  $H-H$  bond, the lowering in energy is equivalent to 436 kJ/mol. This energy corresponds with the bond strength of an  $H-H$  bond (as shown in Figure 1.2).

Now let's consider a molecule such as  $CH_3Br$ , which contains more than just one bond. Valence bond theory continues to view each bond separately, with each bond being formed from two overlapping atomic orbitals. In contrast, MO theory treats the bonding electrons as being associated with the entire molecule. The molecule has many molecular orbitals, each of which can be occupied by two electrons. Figure 1.16 illustrates two of the many molecular orbitals of  $CH_3Br$ . Each of the two images in Figure 1.16 represents a molecular orbital capable of accommodating up to two electrons. In each molecular orbital, red and blue regions indicate the different phases, as described in Section 1.6. As we saw with molecular hydrogen,



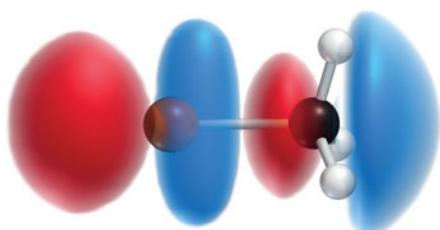
**FIGURE 1.15**

An energy diagram showing the relative energy levels of bonding and antibonding molecular orbitals.



**FIGURE 1.16**

(a) A low-energy molecular orbital of  $CH_3Br$ .  
 (b) A high-energy molecular orbital of  $CH_3Br$ .



**FIGURE 1.17**  
The LUMO of  $\text{CH}_3\text{Br}$ .

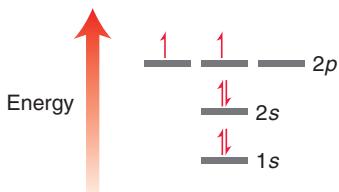
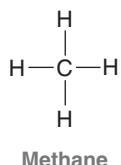
not all molecular orbitals will be occupied. The bonding electrons will occupy the lower energy molecular orbitals (such as the one shown in Figure 1.16a), while the higher energy molecular orbitals (as in Figure 1.16b) remain unoccupied. For every molecule, two of its molecular orbitals will be of particular interest: (1) the highest energy orbital from among the occupied orbitals is called the **highest occupied molecular orbital**, or **HOMO**, and (2) the lowest energy orbital from among the unoccupied orbitals is called the **lowest unoccupied molecular orbital**, or **LUMO**. For example, in Chapter 7, we will explore a reaction in which  $\text{CH}_3\text{Br}$  is attacked by a hydroxide ion ( $\text{HO}^-$ ). In order for this process to occur, the hydroxide ion must transfer its electron density into the lowest energy, empty molecular orbital, or LUMO, of  $\text{CH}_3\text{Br}$  (Figure 1.17). The nature of the LUMO (i.e., number of nodes, location of nodes, etc.) will be useful in explaining the preferred direction from which the hydroxide ion will attack.

We will use MO theory several times in the chapters that follow. Most notably, in Chapter 17, we will investigate the structure of compounds containing several double bonds. For those compounds, valence bond theory will be inadequate, and MO theory will provide a more meaningful understanding of the bonding structure. Throughout this textbook, we will continue to develop both valence bond theory and MO theory.

## 1.9 Hybridized Atomic Orbitals

### Methane and $sp^3$ Hybridization

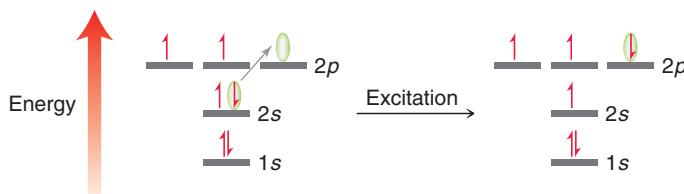
Let us now apply valence bond theory to the bonds in methane:



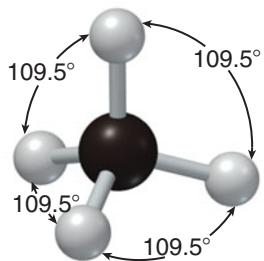
**FIGURE 1.18**  
An energy diagram showing the electron configuration of carbon.

Recall the electron configuration of carbon (Figure 1.18). This electron configuration cannot satisfactorily describe the bonding structure of methane ( $\text{CH}_4$ ), in which the carbon atom has four separate C—H bonds, because the electron configuration shows only two atomic orbitals capable of forming bonds (each of these orbitals has one unpaired electron). This would imply that the carbon atom will form only two bonds, but we know that it forms four bonds. We can solve this problem by imagining an excited state of carbon (Figure 1.19): a state in which a 2s electron has been promoted to a higher energy 2p orbital. Now the carbon atom has four atomic orbitals capable of forming bonds, but there is yet another problem here. The geometry of the 2s and three 2p orbitals does not satisfactorily explain the observed three-dimensional geometry of methane (Figure 1.20). All bond angles are  $109.5^\circ$ , and the four bonds point away from each other in a perfect tetrahedron. This geometry cannot be explained by an excited state of carbon because the s orbital and the three p orbitals do not occupy a tetrahedral geometry. The p orbitals are separated from each other by only  $90^\circ$  (as seen in Figure 1.5) rather than  $109.5^\circ$ .

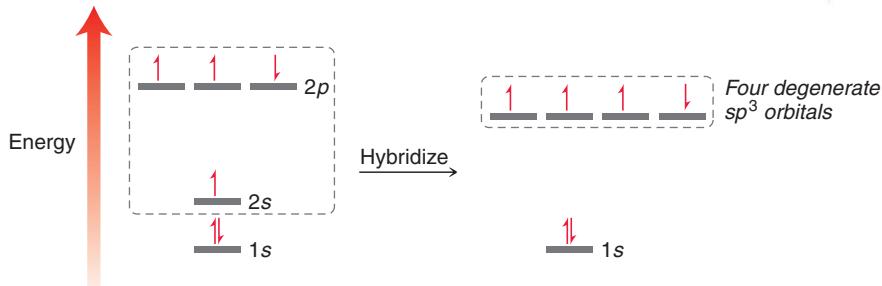
This problem was solved in 1931 by Linus Pauling, who suggested that the electronic configuration of the carbon atom in methane does not necessarily have to be the same as the electronic configuration of a free carbon atom. Specifically, Pauling mathematically averaged, or *hybridized*, the 2s orbital and the three 2p orbitals, giving four degenerate **hybridized atomic orbitals** (Figure 1.21). The hybridization process in Figure 1.21 does not represent a real physical process that the orbitals undergo. Rather, it is a mathematical procedure that is used to arrive



**FIGURE 1.19**  
An energy diagram showing the electronic excitation of an electron in a carbon atom.

**FIGURE 1.20**

The tetrahedral geometry of methane. All bond angles are 109.5°.

**FIGURE 1.21**

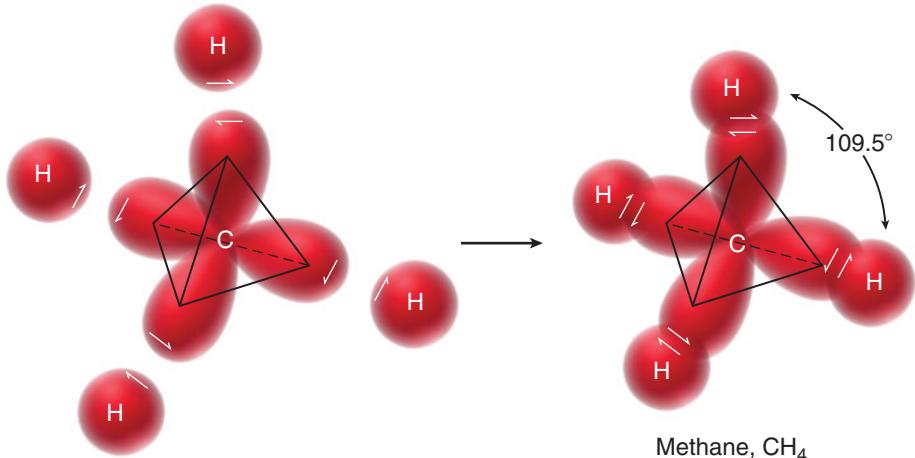
An energy diagram showing four degenerate hybridized atomic orbitals.

at a satisfactory description of the observed bonding. This procedure gives us four orbitals that were produced by averaging one *s* orbital and three *p* orbitals, and therefore we refer to these atomic orbitals as ***sp*<sup>3</sup>-hybridized orbitals**. Figure 1.22 shows an *sp*<sup>3</sup>-hybridized orbital. If we use these hybridized atomic orbitals to describe the bonding of methane, we can successfully explain the observed geometry of the bonds. The four *sp*<sup>3</sup>-hybridized orbitals are equivalent in energy (degenerate) and will therefore position themselves as far apart from each other as possible, achieving a tetrahedral geometry. Also notice that hybridized atomic orbitals are unsymmetrical. That is, hybridized atomic orbitals have a larger front lobe (shown in red in Figure 1.22) and a smaller back lobe (shown in blue). The larger front lobe enables hybridized atomic orbitals to be more efficient than *p* orbitals in their ability to form bonds.

**FIGURE 1.22**

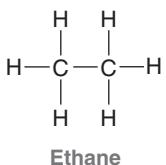
An illustration of an *sp*<sup>3</sup>-hybridized atomic orbital.

Using valence bond theory, each of the four bonds in methane is represented by the overlap between an *sp*<sup>3</sup>-hybridized atomic orbital from the carbon atom and an *s* orbital from a hydrogen atom (Figure 1.23). For purposes of clarity the back lobes (blue) have been omitted from the images in Figure 1.23.

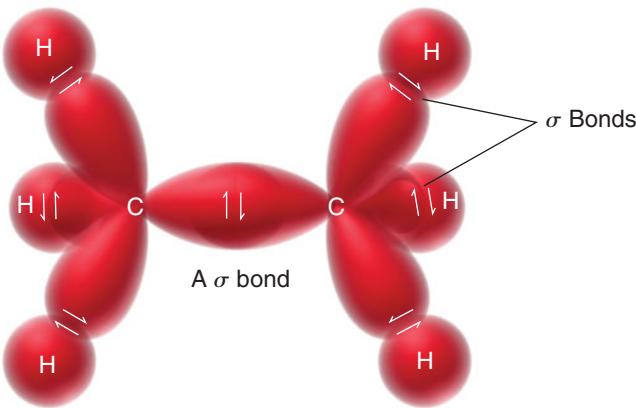
**FIGURE 1.23**

A tetrahedral carbon atom using each of its four *sp*<sup>3</sup>-hybridized orbitals to form a bond.

The bonding in ethane is treated in much the same way:



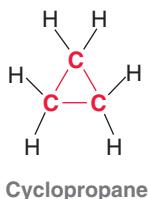
All bonds in this compound are single bonds, and therefore they are all  $\sigma$  bonds. Using the valence bond approach, each of the bonds in ethane can be treated individually and is represented by the overlap of atomic orbitals (Figure 1.24).



**FIGURE 1.24**  
A valence bond picture of the bonding in ethane.

### CONCEPTUAL CHECKPOINT

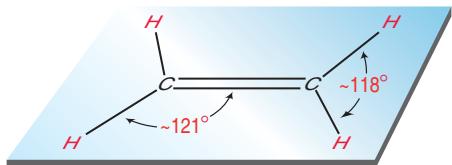
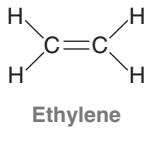
- 1.19** Cyclopropane is a compound in which the carbon atoms form a three-membered ring:



Each of the carbon atoms in cyclopropane is  $sp^3$  hybridized. Cyclopropane is more reactive than other cyclic compounds (four-membered rings, five-membered rings, etc.). Analyze the bond angles in cyclopropane and explain why cyclopropane is so reactive.

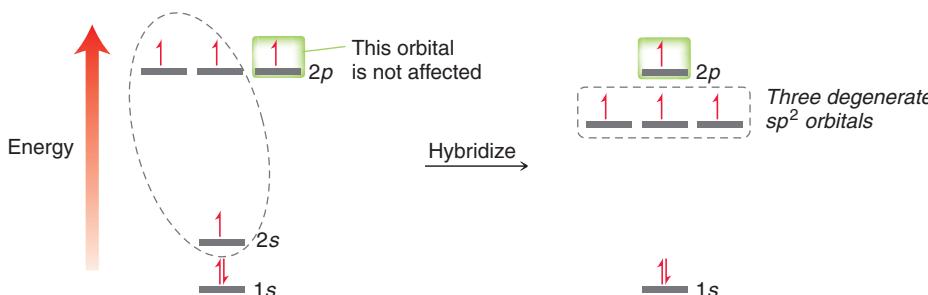
### Double Bonds and $sp^2$ Hybridization

Now let's consider the structure of a compound bearing a double bond. The simplest example is ethylene:



**FIGURE 1.25**  
All six atoms of ethylene are in one plane.

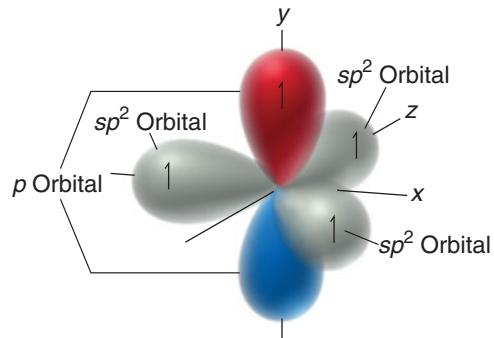
Ethylene exhibits a planar geometry (Figure 1.25). A satisfactory model for explaining this geometry can be achieved by the mathematical maneuver of hybridizing the  $s$  and  $p$  orbitals of the carbon atom to obtain hybridized atomic orbitals. When we did this procedure before to explain the bonding in methane, we hybridized the  $s$  orbital and all three  $p$  orbitals to produce four equivalent  $sp^3$ -hybridized orbitals. However, in the case of ethylene, each carbon atom only needs to form bonds with three atoms, not four. Therefore, each carbon atom only needs three hybridized orbitals. So in this case we will mathematically average the  $s$  orbital with only two of the three  $p$  orbitals (Figure 1.26). The remaining  $p$  orbital will remain unaffected by our mathematical procedure.



**FIGURE 1.26**  
An energy diagram showing three degenerate  $sp^2$ -hybridized atomic orbitals.



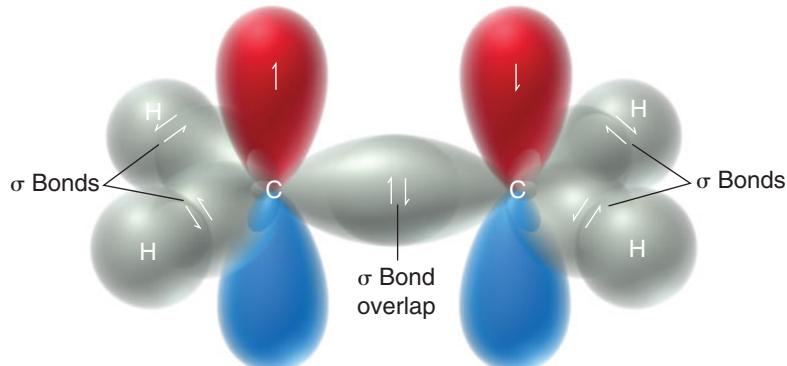
The result of this mathematical operation is a carbon atom with one  $p$  orbital and three  $sp^2$ -hybridized orbitals (Figure 1.27). In Figure 1.27 the  $p$  orbital is shown in red and blue, and the hybridized orbitals are shown in gray (for clarity, only the front lobe of each hybridized orbital is shown). They are called  $sp^2$ -hybridized orbitals to indicate that they were obtained by averaging one  $s$  orbital and two  $p$  orbitals. As shown in Figure 1.27, each of the carbon atoms in ethylene is  $sp^2$  hybridized, and we can use this hybridization state to explain the bonding structure of ethylene.



**FIGURE 1.27**

An illustration of an  $sp^2$ -hybridized carbon atom.

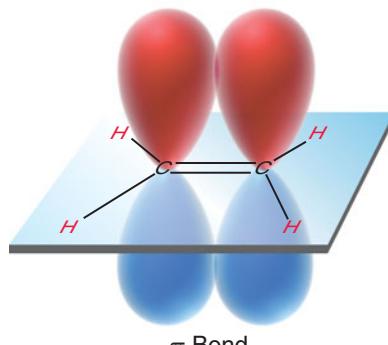
Each carbon atom in ethylene has three  $sp^2$ -hybridized orbitals available to form  $\sigma$  bonds (Figure 1.28). One  $\sigma$  bond forms between the two carbon atoms, and then each carbon atom also forms a  $\sigma$  bond with each of its neighboring hydrogen atoms.



**FIGURE 1.28**

An illustration of the  $\sigma$  bonds in ethylene.

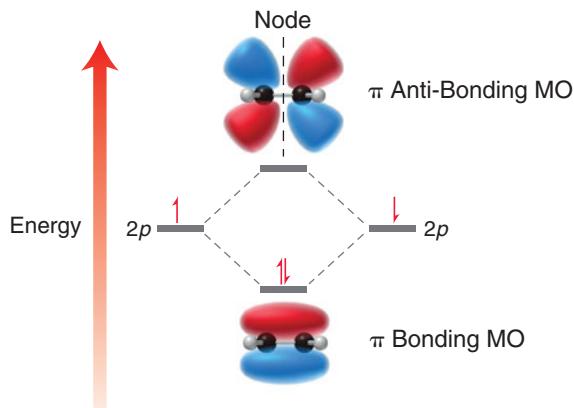
In addition, each carbon atom has one  $p$  orbital (shown in Figure 1.28 with blue and red lobes). These  $p$  orbitals actually overlap with each other as well, which is a separate bonding interaction called a **pi ( $\pi$ ) bond** (Figure 1.29). Do not be confused by the nature of this type of bond. It is true that the  $\pi$  overlap occurs in two places—above the plane of the molecule (in red) and below the plane (in blue). Nevertheless, these two regions of overlap represent only one interaction called a  $\pi$  bond.



**FIGURE 1.29**

An illustration of the  $\pi$  bond in ethylene.

The picture of the  $\pi$  bond in Figure 1.29 is based on the valence bond approach (the  $p$  orbitals are simply drawn overlapping each other). Molecular orbital theory provides a fairly similar image of a  $\pi$  bond. Compare Figure 1.29 with the bonding MO in Figure 1.30.

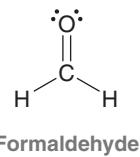
**FIGURE 1.30**

An energy diagram showing images of bonding and antibonding MOs in ethylene.

To summarize, we have seen that the carbon atoms of ethylene are connected via a  $\sigma$  bond and a  $\pi$  bond. The  $\sigma$  bond results from the overlap of  $sp^2$ -hybridized atomic orbitals, while the  $\pi$  bond results from the overlap of  $p$  orbitals. These two separate bonding interactions ( $\sigma$  and  $\pi$ ) comprise the double bond of ethylene.

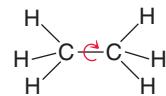
### CONCEPTUAL CHECKPOINT

- 1.20** Consider the structure of formaldehyde:



- (a) Identify the type of bonds that form the  $\text{C}\equiv\text{O}$  double bond.
- (b) Identify the atomic orbitals that form each  $\text{C}-\text{H}$  bond.
- (c) What type of atomic orbitals do the lone pairs occupy?

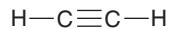
- 1.21** Sigma bonds experience free rotation at room temperature:



In contrast,  $\pi$  bonds do not experience free rotation. Explain. (Hint: Compare Figures 1.24 and 1.29, focusing on the orbitals used in forming a  $\sigma$  bond and the orbitals used in forming a  $\pi$  bond. In each case, what happens to the orbital overlap during bond rotation?)

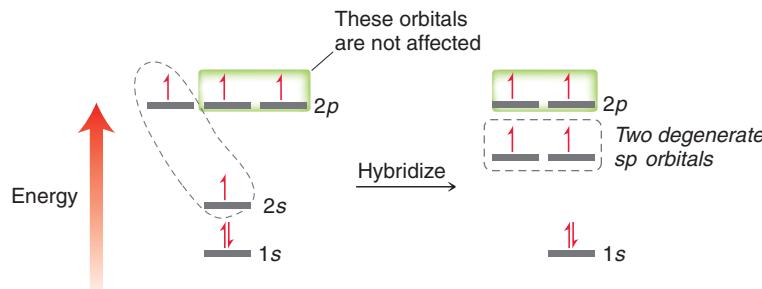
### Triple Bonds and $sp$ Hybridization

Now let's consider the bonding structure of a compound bearing a triple bond, such as acetylene:



Acetylene

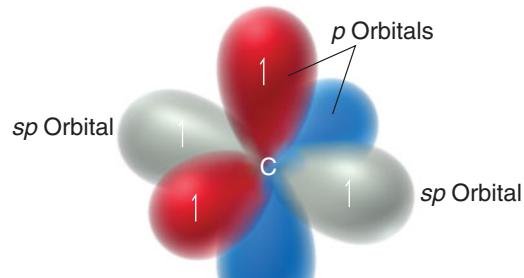
A triple bond is formed by  $sp$ -hybridized carbon atoms. To achieve  **$sp$  hybridization**, one  $s$  orbital is mathematically averaged with only one  $p$  orbital (Figure 1.31). This leaves two  $p$  orbitals

**FIGURE 1.31**

An energy diagram showing two degenerate  $sp$ -hybridized atomic orbitals.



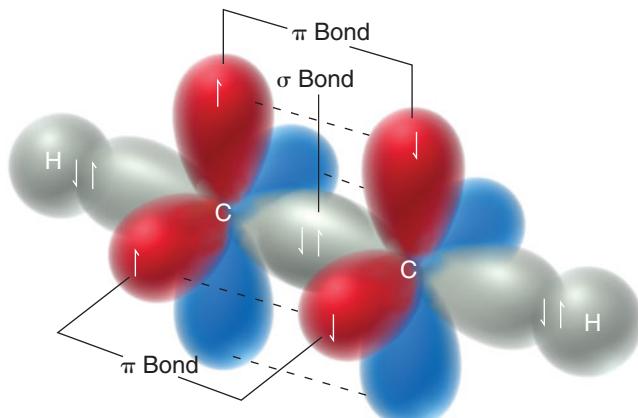
als unaffected by the mathematical operation. As a result, an *sp*-hybridized carbon atom has two *sp* orbitals and two *p* orbitals (Figure 1.32).



**FIGURE 1.32**

An illustration of an *sp*-hybridized carbon atom. The *sp*-hybridized orbitals are shown in gray.

The two *sp*-hybridized orbitals are available to form  $\sigma$  bonds (one on either side), and the two *p* orbitals are available to form  $\pi$  bonds, giving the bonding structure for acetylene shown in Figure 1.33. A triple bond between two carbon atoms is therefore the result of three separate bonding interactions: one  $\sigma$  bond and two  $\pi$  bonds. The  $\sigma$  bond results from the overlap of *sp* orbitals, while each of the two  $\pi$  bonds result from overlapping *p* orbitals. As shown in Figure 1.33, the geometry of the triple bond is linear.



**FIGURE 1.33**

An illustration of the  $\sigma$  bonds and  $\pi$  bonds in acetylene.

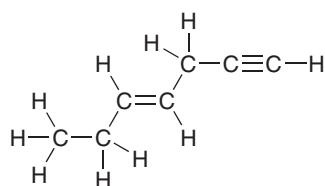
## SKILLBUILDER

### 1.7 IDENTIFYING HYBRIDIZATION STATES



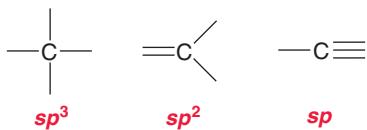
#### LEARN the skill

Identify the hybridization state of each carbon atom in the following compound:



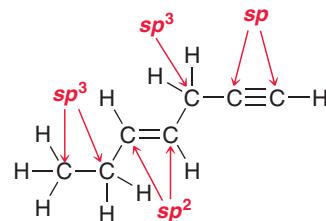

**SOLUTION**

To determine the hybridization state of an uncharged carbon atom, simply count the number of  $\sigma$  bonds and  $\pi$  bonds:



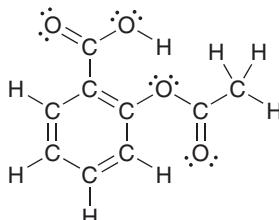
A carbon atom with four single bonds (four  $\sigma$  bonds) will be  $\text{sp}^3$  hybridized. A carbon atom with three  $\sigma$  bonds and one  $\pi$  bond will be  $\text{sp}^2$  hybridized. A carbon atom with two  $\sigma$  bonds and two  $\pi$  bonds will be  $\text{sp}$  hybridized. Carbon atoms bearing a positive or negative charge will be discussed in more detail in the upcoming chapter.

Using the simple scheme above, the hybridization state of most carbon atoms can be determined instantly:

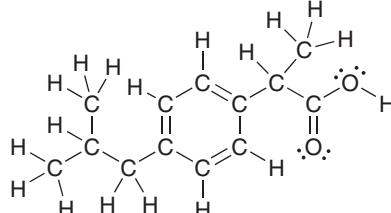


**PRACTICE the skill**

- 1.22** Below are the structures of two common over-the-counter pain relievers. Determine the hybridization state of each carbon atom in these compounds:



(a)

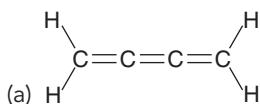
Acetylsalicylic acid  
(aspirin)

(b)

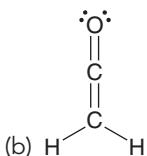
Ibuprofen  
(Advil or Motrin)

**APPLY the skill**

- 1.23** Determine the hybridization state of each carbon atom in the following compounds:



(a)



(b)

→ need more **PRACTICE?** Try Problems 1.55, 1.56, 1.58

### Bond Strength and Bond Length

The information we have seen in this section allows us to compare single bonds, double bonds, and triple bonds. A single bond has only one bonding interaction (a  $\sigma$  bond), a double bond has two bonding interactions (one  $\sigma$  bond and one  $\pi$  bond), and a triple bond has three bonding interactions (one  $\sigma$  bond and two  $\pi$  bonds). Therefore, it is not surprising that a triple bond is stronger than a double bond, which in turn is stronger than a single bond. Compare the strengths and lengths of the C—C bonds in ethane, ethylene, and acetylene (Table 1.2).



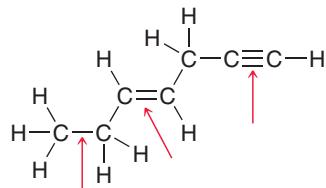
**TABLE 1.2 COMPARISON OF BOND LENGTHS AND BOND ENERGIES FOR ETHANE, ETHYLENE, AND ACETYLENE**

	ETHANE	ETHYLENE	ACETYLENE
Structure			
C—C bond length	1.54 Å	1.34 Å	1.20 Å
Bond energy	368 kJ/mol	632 kJ/mol	820 kJ/mol



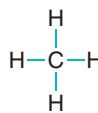
### CONCEPTUAL CHECKPOINT

- 1.24 Rank the indicated bonds in terms of increasing bond length:



## 1.10 VSEPR Theory: Predicting Geometry

In order to predict the geometry of a small compound, we focus on the central atom and count the number of  $\sigma$  bonds and lone pairs. The total ( $\sigma$  bonds plus lone pairs) is called the **steric number**. Figure 1.34 gives several examples in which the steric number is 4 in each case.



# of  $\sigma$  bonds = 4  
# of lone pairs = 0

Steric number = 4



# of  $\sigma$  bonds = 3  
# of lone pairs = 1

Steric number = 4

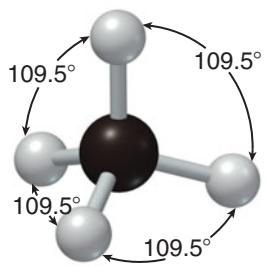


# of  $\sigma$  bonds = 2  
# of lone pairs = 2

Steric number = 4

**FIGURE 1.34**  
Calculation of the steric number for methane, ammonia, and water.

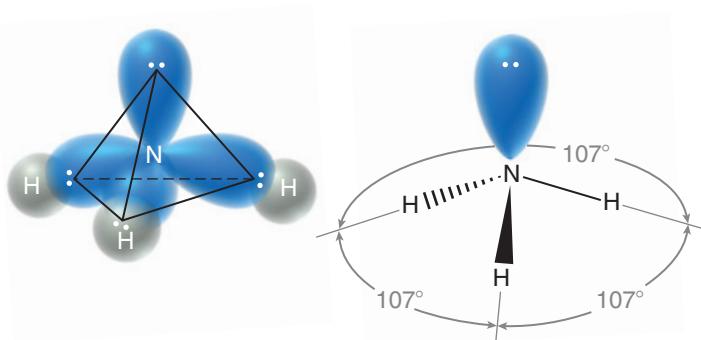
The steric number indicates the number of electron pairs (bonding and nonbonding) that are repelling each other. The repulsion causes the electron pairs to arrange themselves in three-dimensional space so as to achieve maximal distance from each other. As a result, the geometry of the central atom will be determined by the steric number. This principle is called the **valence shell electron pair repulsion (VSEPR)** theory. Let's take a closer look at the geometry of each of the compounds above.



**FIGURE 1.35**  
The tetrahedral geometry of methane.

### Geometries Resulting from $sp^3$ Hybridization

In all of the previous examples, there are four pairs of electrons (steric number 4). In order for an atom to accommodate four electron pairs, it must use four orbitals and is therefore  $sp^3$ -hybridized. Recall that the geometry of methane is **tetrahedral** (Figure 1.35). In fact, any  $sp^3$ -hybridized atom will have four  $sp^3$ -hybridized orbitals arranged in a shape approximating a tetrahedron. This is true for the nitrogen atom in ammonia as well (Figure 1.36). The nitrogen atom is using four orbitals and is therefore  $sp^3$  hybridized. As a result, its orbitals are arranged in a tetrahedron (shown on the left in Figure 1.36). However, there is one important difference between ammonia and methane. In the case of ammonia, one of the four orbitals is housing a nonbonding pair of electrons (a lone pair). This lone pair repels the other bonds more strongly, causing bond angles to be smaller than 109.5°. Bond angles for ammonia have been determined to be 107°.

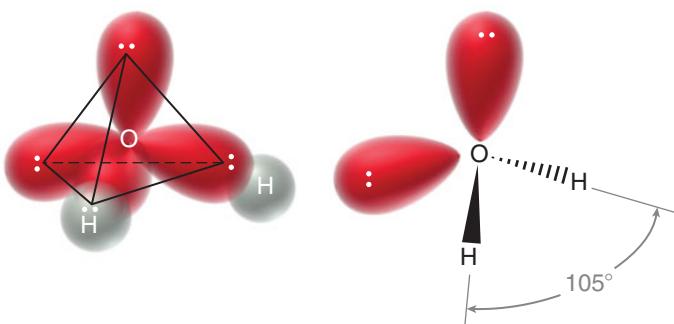


**FIGURE 1.36**  
The orbitals of ammonia are arranged in a tetrahedral geometry.



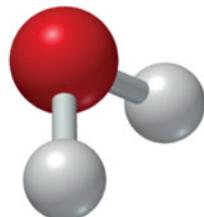
**FIGURE 1.37**  
The geometry of ammonia is trigonal pyramidal.

The term “geometry” does not refer to the arrangement of electron pairs. Rather, it refers to the arrangement of atoms. When we show only the positions of the atoms (ignoring the lone pairs), ammonia appears as in Figure 1.37. This geometry is called **trigonal pyramidal** (Figure 1.37). “Trigonal” indicates the nitrogen atom is connected to three other atoms, and “pyramidal” indicates the compound is shaped like a pyramid, with the nitrogen atom sitting at the top of the pyramid.



**FIGURE 1.38**  
The orbitals of  $\text{H}_2\text{O}$  are arranged in a tetrahedral geometry.

Another example of  $sp^3$  hybridization is water ( $\text{H}_2\text{O}$ ). The oxygen atom has a steric number of 4, and it therefore requires the use of four orbitals. As a result, it must be  $sp^3$  hybridized, with its four orbitals in a tetrahedral arrangement (Figure 1.38). Once again, lone pairs repel each other more strongly than bonds, causing the bond angle between the two O—H bonds to be even smaller than the bond angles in ammonia. The bond angle of water has been determined to be 105°. In order to describe the geometry, we ignore the lone pairs and focus only on the arrangement of atoms, which gives a **bent** geometry in this case (Figure 1.39). In summary,

**FIGURE 1.39**

The geometry of water is bent.

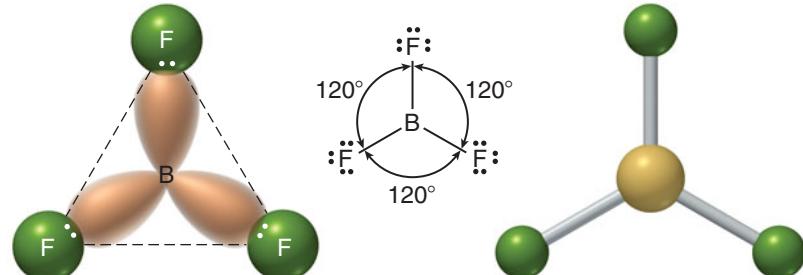
there are only three different types of geometry arising from  $sp^3$  hybridization: tetrahedral, trigonal pyramidal, and bent. In all cases, the electrons were arranged in a tetrahedron, but the lone pairs were ignored when describing geometry. Table 1.3 summarizes this information.

**TABLE 1.3 GEOMETRIES RESULTING FROM  $sp^3$  HYBRIDIZATION**

EXAMPLE	STERIC NUMBER	HYBRIDIZATION	ARRANGEMENT OF ELECTRON PAIRS	ARRANGEMENT OF ATOMS (GEOMETRY)
CH <sub>4</sub>	4	$sp^3$	Tetrahedral	Tetrahedral
NH <sub>3</sub>	4	$sp^3$	Tetrahedral	Trigonal pyramidal
H <sub>2</sub> O	4	$sp^3$	Tetrahedral	Bent

### Geometries Resulting from $sp^2$ Hybridization

When the central atom of a small compound has a steric number of 3, it will be  $sp^2$  hybridized. As an example, consider the structure of BF<sub>3</sub>. Boron has three valence electrons, each of which is used to form a bond. The result is three bonds and no lone pairs, giving a steric number of 3. The central boron atom therefore requires three orbitals, rather than four, and must be  $sp^2$  hybridized. Recall that  $sp^2$ -hybridized orbitals achieve maximal separation in a **trigonal planar** arrangement (Figure 1.40): “trigonal” because the boron is connected to three other atoms and “planar” because all atoms are found in the same plane (as opposed to trigonal pyramidal).

**FIGURE 1.40**

The geometry of BF<sub>3</sub> is trigonal planar.

As another example, consider the nitrogen atom of an imine:



An imine

#### LOOKING AHEAD

We will explore imines in more detail in Chapter 20.

To determine the geometry of the nitrogen atom, we first consider the steric number, which is not affected by the presence of the  $\pi$  bond. Why not? Recall that a  $\pi$  bond results from the overlap of  $p$  orbitals. The steric number of an atom is meant to indicate how many hybridized orbitals are necessary ( $p$  orbitals are not included in this count). The steric number in this case is 3 (Figure 1.41). As a result, the nitrogen atom must be  $sp^2$  hybridized. The  $sp^2$  hybridization state is always characterized by a trigonal planar arrangement of electron pairs, but when describing geometry, we focus only on the atoms (ignoring any lone pairs). The geometry of this nitrogen atom is therefore bent.

**FIGURE 1.41**

The steric number of the nitrogen atom of an imine.



## Geometry Resulting from *sp* Hybridization

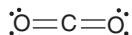
When the central atom of a small compound has a steric number of 2, the central atom will be *sp* hybridized. As an example, consider the structure of  $\text{BeH}_2$ . Beryllium has two valence electrons, each of which is used to form a bond. The result is two bonds and no lone pairs, giving a steric number of 2. The central beryllium atom therefore requires only two orbitals and must be *sp* hybridized. Recall that *sp*-hybridized orbitals achieve maximal separation when they are **linear** (Figure 1.42).



**FIGURE 1.42**

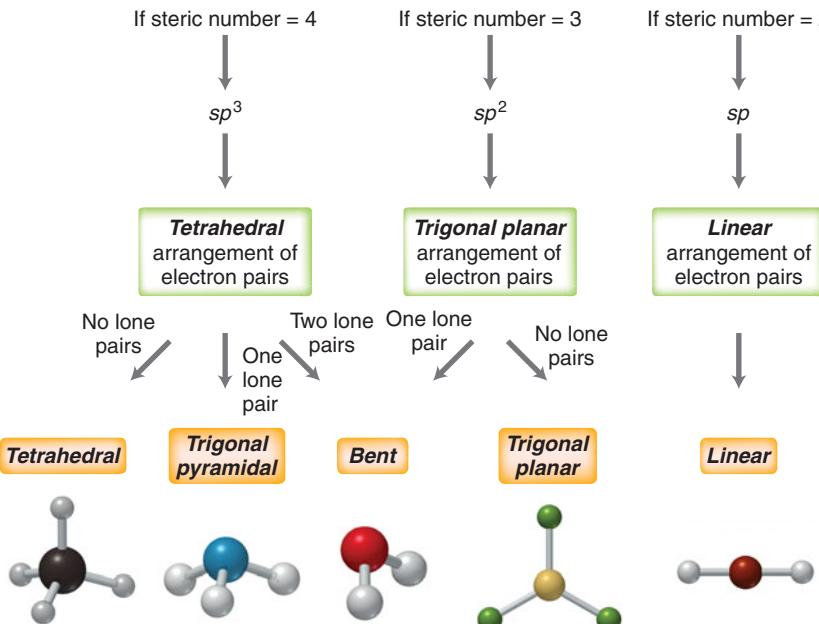
The geometry of  $\text{BeH}_2$  is linear.

As another example of *sp* hybridization, consider the structure of  $\text{CO}_2$ :



Once again, the  $\pi$  bonds do *not* impact the calculation of the steric number, so the steric number is 2. The carbon atom must be *sp* hybridized and is therefore linear.

As summarized in Figure 1.43, the three hybridization states give rise to five common geometries.



**FIGURE 1.43**

A decision tree for determining geometry.

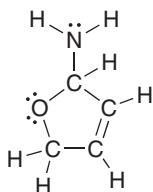
## SKILLBUILDER

### 1.8 PREDICTING GEOMETRY



#### LEARN the skill

Predict the geometry for all atoms (except hydrogens) in the compound below:





## SOLUTION

For each atom, the following three steps are followed:

### STEP 1

Determine the steric number.

### STEP 2

Determine the hybridization state and electronic arrangement.

### STEP 3

Ignore lone pairs and describe the resulting geometry.

1. Determine the steric number by counting the number of lone pairs and  $\sigma$  bonds.

2. Use the steric number to determine the hybridization state and electronic arrangement:

- If the steric number is 4, then the atom will be  $sp^3$  hybridized, and the electronic arrangement will be tetrahedral.
- If the steric number is 3, then the atom will be  $sp^2$  hybridized, and the electronic arrangement will be trigonal planar.
- If the steric number is 2, then the atom will be  $sp$  hybridized, and the electronic arrangement will be linear.

3. Ignore any lone pairs and describe the geometry only in terms of the arrangement of atoms:

1) Steric number =  $3 + 1 = 4$   
2)  $4 = sp^3$  = electronically tetrahedral  
3) Arrangement of atoms = trigonal pyramidal

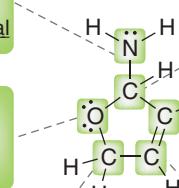
1) Steric number =  $2 + 2 = 4$   
2)  $4 = sp^3$  = electronically tetrahedral  
3) Arrangement of atoms = bent

1) Steric number =  $4 + 0 = 4$   
2)  $4 = sp^3$  = electronically tetrahedral  
3) Arrangement of atoms = tetrahedral

1) Steric number =  $4 + 0 = 4$   
2)  $4 = sp^3$  = electronically tetrahedral  
3) Arrangement of atoms = tetrahedral

1) Steric number =  $3 + 0 = 3$   
2)  $3 = sp^2$  = electronically trigonal planar  
3) Arrangement of atoms = trigonal planar

1) Steric number =  $3 + 0 = 3$   
2)  $3 = sp^2$  = electronically trigonal planar  
3) Arrangement of atoms = trigonal planar



It is not necessary to describe the geometry of hydrogen atoms. Each hydrogen atom is monovalent, so the geometry is irrelevant. Geometry is only relevant when an atom is connected to at least two other atoms. For our purposes, we can also disregard the geometry of the oxygen atom in a  $C=O$  double bond because it is connected to only one atom:

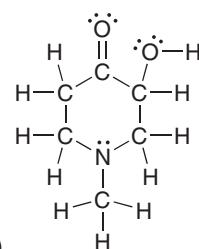


can disregard the geometry of this oxygen

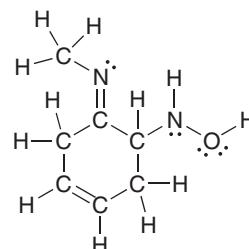
**PRACTICE the skill** 1.25 Predict the geometry for the central atom in each of the compounds below:

- (a)  $NH_3$  (b)  $H_3O^+$  (c)  $BH_4^-$  (d)  $BCl_3$  (e)  $BCl_4^-$  (f)  $CCl_4$  (g)  $CHCl_3$  (h)  $CH_2Cl_2$

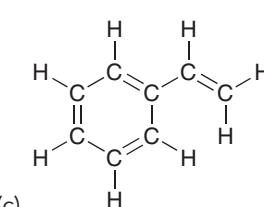
1.26 Predict the geometry for all atoms except hydrogen in the compounds below:



(a)



(b)



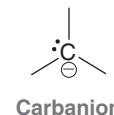
(c)

**APPLY the skill**

1.27 Compare the structures of a carbocation and a carbanion:



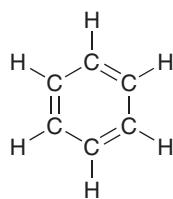
Carbocation



Carbanion

In one of these ions, the central carbon atom is trigonal planar; in the other it is trigonal pyramidal. Assign the correct geometry to each ion.

**1.28** Identify the hybridization state and geometry of each carbon atom in benzene. Use that information to determine the geometry of the entire molecule:



Benzene

→ need more **PRACTICE?** Try Problems 1.39–1.41, 1.50, 1.55, 1.56, 1.58

## 1.11 Dipole Moments and Molecular Polarity

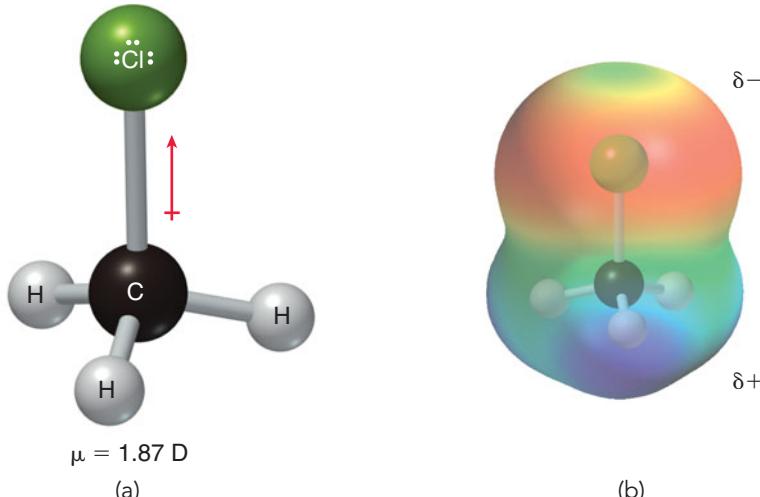
Recall that induction is caused by the presence of an electronegative atom, as we saw earlier in the case of chloromethane. In Figure 1.44a the arrow shows the inductive effect of the chlorine atom. Figure 1.44b is a map of the electron density, revealing that the molecule is polarized. Chloromethane is said to exhibit a dipole moment, because *the center of negative charge and the center of positive charge are separated from one another by a certain distance*. The **dipole moment** ( $\mu$ ) is used as an indicator of polarity, where  $\mu$  is defined as the amount of partial charge ( $\delta$ ) on either end of the dipole multiplied by the distance of separation ( $d$ ):

$$\mu = \delta \times d$$

Partial charges ( $\delta+$  and  $\delta-$ ) are generally on the order of  $10^{-10}$  esu (electrostatic units) and the distances are generally on the order of  $10^{-8}$  cm. Therefore, for a polar compound, the dipole moment ( $\mu$ ) will generally have an order of magnitude of around  $10^{-18}$  esu · cm. The dipole moment of chloromethane, for example, is  $1.87 \times 10^{-18}$  esu · cm. Since most compounds will have a dipole moment on this order of magnitude ( $10^{-18}$ ), it is more convenient to report dipole moments with a new unit, called a **debye** (D), where

$$1 \text{ debye} = 10^{-18} \text{ esu} \cdot \text{cm}.$$

Using these units, the dipole moment of chloromethane is reported as 1.87 D. The debye unit is named after Dutch scientist Peter Debye, whose contributions to the fields of chemistry and physics earned him a Nobel Prize in 1936.

**FIGURE 1.44**

- (a) Ball-and-stick model of chloromethane showing the dipole moment.
- (b) An electrostatic potential map of chloromethane.



Measuring the dipole moment of a particular bond allows us to calculate the percent **ionic character** of that bond. As an example, let's analyze a C—Cl bond. This bond has a bond length of  $1.772 \times 10^{-8}$  cm, and an electron has a charge of  $4.80 \times 10^{-10}$  esu. If the bond were 100% ionic, then the dipole moment would be

$$\begin{aligned}\mu &= e \times d \\ &= (4.80 \times 10^{-10} \text{ esu}) \times (1.772 \times 10^{-8} \text{ cm}) \\ &= 8.51 \times 10^{-18} \text{ esu} \cdot \text{cm}\end{aligned}$$

or 8.51 D. In reality, the bond is not 100% ionic. The experimentally observed dipole moment is measured at 1.87 D, and we can use this value to calculate the percent ionic character of a C—Cl bond:

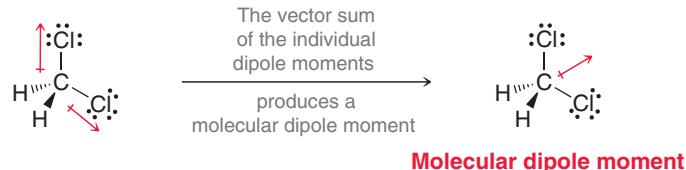
$$\frac{1.87 \text{ D}}{8.51 \text{ D}} \times 100\% = 22\%$$

Table 1.4 shows the percent ionic character for a few of the bonds that we will frequently encounter in this text. Take special notice of the C=O bond. It has considerable ionic character, rendering it extremely reactive. Chapters 20–22 are devoted exclusively to the reactivity of compounds containing C=O bonds.

**TABLE 1.4 PERCENT IONIC CHARACTER FOR SEVERAL BONDS**

BOND	BOND LENGTH ( $\times 10^{-8}$ CM)	OBSERVED $\mu$ (D)	PERCENT IONIC CHARACTER
C—O	1.41	0.7 D	$\frac{(0.7 \times 10^{-18} \text{ esu} \cdot \text{cm})}{(4.80 \times 10^{-10} \text{ esu})(1.41 \times 10^{-8} \text{ cm})} \times 100\% = 10\%$
O—H	0.96	1.5 D	$\frac{(1.5 \times 10^{-18} \text{ esu} \cdot \text{cm})}{(4.80 \times 10^{-10} \text{ esu})(0.96 \times 10^{-8} \text{ cm})} \times 100\% = 33\%$
C=O	1.227	2.4 D	$\frac{(2.4 \times 10^{-18} \text{ esu} \cdot \text{cm})}{(4.80 \times 10^{-10} \text{ esu})(1.23 \times 10^{-8} \text{ cm})} \times 100\% = 41\%$

Chloromethane was a simple example, because it has only one polar bond. When dealing with a compound that has more than one polar bond, it is necessary to take the vector sum of the individual dipole moments. The vector sum is called the **molecular dipole moment**, and it takes into account both the magnitude and the direction of each individual dipole moment. For example, consider the structure of dichloromethane (Figure 1.45). The individual dipole moments partially cancel, but not completely. The vector sum produces a dipole moment of 1.14 D, which is significantly smaller than the dipole moment of chloromethane because the two dipole moments here partially cancel each other.



**FIGURE 1.45**

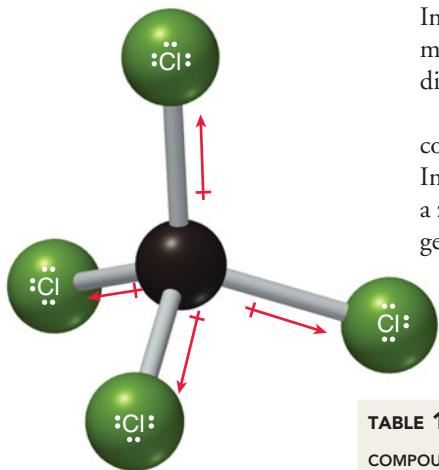
The molecular dipole moment of dichloromethane is the net sum of all dipole moments in the compound.

The presence of a lone pair has a significant effect on the molecular dipole moment. The two electrons of a lone pair are balanced by two positive charges in the nucleus, but the lone pair is separated from the nucleus by some distance. There is, therefore, a dipole moment associated with every lone pair. Common examples are ammonia and water (Figure 1.46).



**FIGURE 1.46**

The net dipole moments of ammonia and water.



**FIGURE 1.47**  
A ball-and-stick model of carbon tetrachloride. The individual dipole moments cancel to give a zero net dipole moment.

In this way, the lone pairs contribute significantly to the magnitude of the molecular dipole moment, although they do not contribute to its direction. That is, the direction of the molecular dipole moment would be the same with or without the contribution of the lone pairs.

Table 1.5 shows experimentally observed molecular dipole moments (at 20°C) for several common solvents. Notice that carbon tetrachloride ( $\text{CCl}_4$ ) has no molecular dipole moment. In this case, the individual dipole moments cancel each other completely to give the molecule a zero net dipole moment ( $\mu = 0$ ). This example (Figure 1.47) demonstrates that we must take geometry into account when assessing molecular dipole moments.

**TABLE 1.5 DIPOLE MOMENTS FOR SOME COMMON SOLVENTS (AT 20°C)**

COMPOUND	STRUCTURE	DIPOLE MOMENT	COMPOUND	STRUCTURE	DIPOLE MOMENT
Methanol	$\text{CH}_3\text{OH}$	2.87 D	Ammonia	$:\text{NH}_3$	1.47 D
Acetone		2.69 D	Diethyl ether		1.15 D
Chloromethane	$\text{CH}_3\text{Cl}$	1.87 D	Methylene chloride	$\text{CH}_2\text{Cl}_2$	1.14 D
Water	$\text{H}_2\text{O}$	1.85 D	Pentane		0 D
Ethanol		1.66 D	Carbon tetrachloride	$\text{CCl}_4$	0 D

## SKILLBUILDER



### 1.9 IDENTIFYING THE PRESENCE OF MOLECULAR DIPOLE MOMENTS



#### LEARN the skill

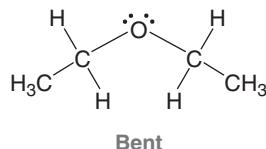
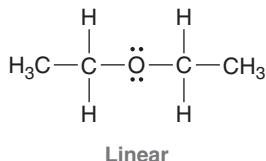
Identify whether each of the following compounds exhibits a molecular dipole moment. If so, indicate the direction of the net molecular dipole moment:

- (a)  $\text{CH}_3\text{CH}_2\text{OCH}_2\text{CH}_3$       (b)  $\text{CO}_2$



#### SOLUTION

- (a) In order to determine whether the individual dipole moments cancel each other completely, we must first predict the molecular geometry. Specifically, we need to know if the geometry around the oxygen atom is linear or bent:



**STEP 1**  
Predict the molecular geometry.



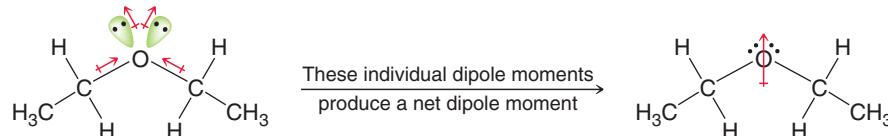
To make this determination, we use the three-step method from the previous section:

1. The steric number is 4.
2. Therefore, the hybridization state must be  $sp^3$ , and the arrangement of electron pairs must be tetrahedral.
3. Ignore the lone pairs, and the oxygen has a bent geometry.

After determining the molecular geometry, now draw all dipole moments and determine whether they cancel each other. In this case, they do not fully cancel each other:

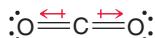
**STEP 2**  
Identify the direction of all dipole moments.

**STEP 3**  
Draw the net dipole moment.



This compound does in fact have a net molecular dipole moment, and the direction of the moment is shown above.

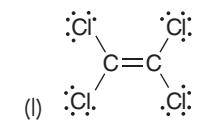
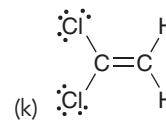
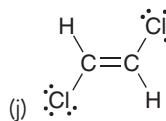
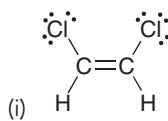
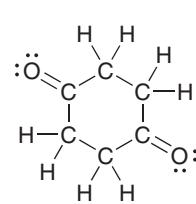
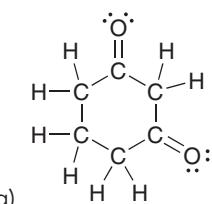
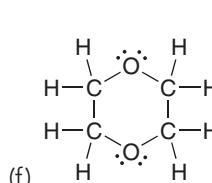
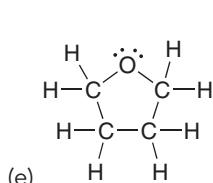
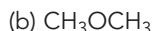
- (b) Carbon dioxide ( $\text{CO}_2$ ) has two  $\text{C}=\text{O}$  bonds, each of which exhibits a dipole moment. In order to determine whether the individual dipole moments cancel each other completely, we must first predict the molecular geometry. We apply our three-step method: the steric number is 2, the hybridization state is  $sp$ , and the compound has a linear geometry. As a result, we expect the dipole moments to fully cancel each other:



In a similar way, the dipole moments associated with the lone pairs also cancel each other, and therefore  $\text{CO}_2$  does not have a net molecular dipole moment.

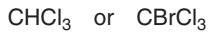
### PRACTICE the skill

- 1.29** Identify whether each of the following compounds exhibits a molecular dipole moment. For compounds that do, indicate the direction of the net molecular dipole moment:



### APPLY the skill

- 1.30** Which of the following compounds has the larger dipole moment? Explain your choice:



- 1.31** Bonds between carbon and oxygen ( $\text{C}-\text{O}$ ) are more polar than bonds between sulfur and oxygen ( $\text{S}-\text{O}$ ). Nevertheless, sulfur dioxide ( $\text{SO}_2$ ) exhibits a dipole moment while carbon dioxide ( $\text{CO}_2$ ) does not. Explain this apparent anomaly.

→ need more PRACTICE? Try Problems 1.37, 1.40, 1.43, 1.61, 1.62

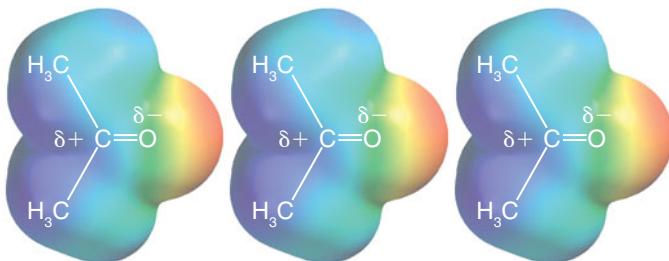
## 1.12 Intermolecular Forces and Physical Properties

The physical properties of a compound are determined by the attractive forces between the individual molecules, called **intermolecular forces**. It is often difficult to use the molecular structure alone to predict a precise melting point or boiling point for a compound. However, a few simple trends will allow us to compare compounds to each other in a relative way, for example, to predict which compound will boil at a higher temperature.

All intermolecular forces are *electrostatic*—that is, these forces occur as a result of the attraction between opposite charges. The electrostatic interactions for neutral molecules (with no formal charges) are often classified as (1) **dipole-dipole interactions**, (2) hydrogen bonding, and (3) fleeting dipole-dipole interactions.

### Dipole-Dipole Interactions

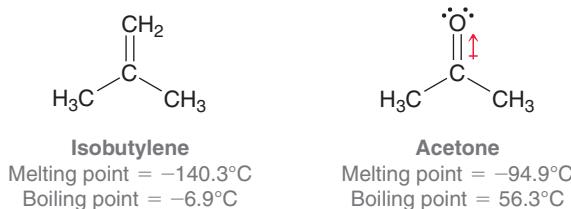
Compounds with net dipole moments can either attract each other or repel each other, depending on how they approach each other in space. In the solid phase, the molecules align so as to attract each other (Figure 1.48).



**FIGURE 1.48**

In solids, molecules align themselves so that their dipole moments experience attractive forces.

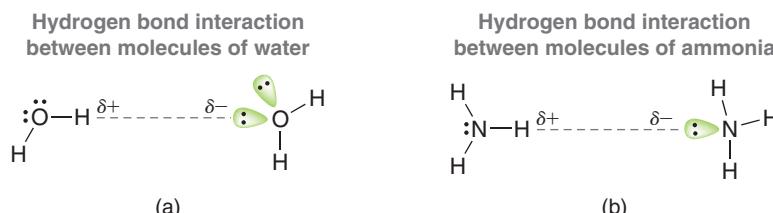
In the liquid phase, the molecules are free to tumble in space, but they do tend to move in such a way so as to attract each other more often than they repel each other. The resulting net attraction between the molecules results in an elevated melting point and boiling point. To illustrate this, compare the physical properties of isobutylene and acetone:



Isobutylene lacks a significant dipole moment, but acetone does have a net dipole moment. Therefore, acetone molecules will experience greater attractive interactions than isobutylene molecules. As a result, acetone has a higher melting point and higher boiling point than isobutylene.

### Hydrogen Bonding

The term **hydrogen bonding** is misleading. A hydrogen bond is not actually a “bond” but is just a specific type of dipole-dipole interaction. When a hydrogen atom is connected to an electronegative atom, the hydrogen atom will bear a partial positive charge ( $\delta+$ ) as a result of induction. This  $\delta+$  can then interact with a lone pair from an electronegative atom of another molecule. This can be illustrated with water or ammonia (Figure 1.49). This attractive interac-



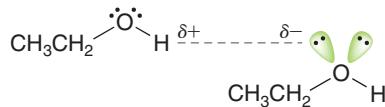
**FIGURE 1.49**

(a) Hydrogen bonding between molecules of water. (b) Hydrogen bonding between molecules of ammonia.

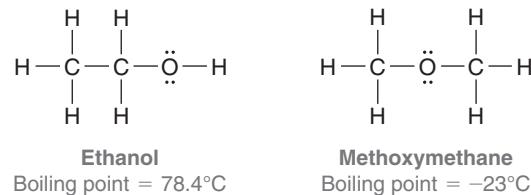


tion can occur with any **protic** compound, that is, any compound that has a proton connected to an electronegative atom. Ethanol, for example, exhibits the same kind of attractive interaction (Figure 1.50).

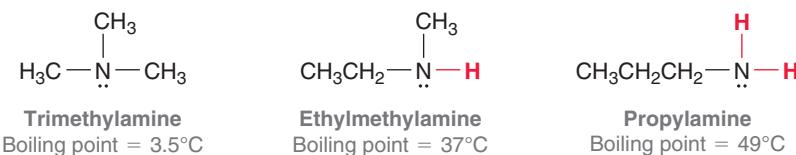
**FIGURE 1.50**  
Hydrogen bonding between molecules of ethanol.



This type of interaction is quite strong because hydrogen is a relatively small atom, and as a result, the partial charges can get very close to each other. In fact, the effect of hydrogen bonding on physical properties is quite dramatic. At the beginning of this chapter, we briefly mentioned the difference in properties between the following two constitutional isomers:



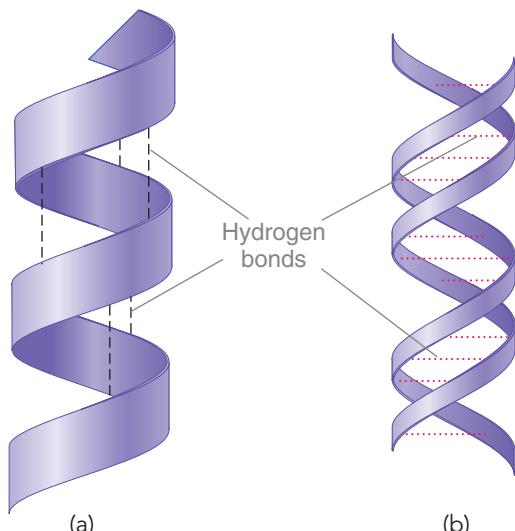
These compounds have the same molecular formula, but they have very different boiling points. Ethanol experiences intermolecular hydrogen bonding, giving rise to a very high boiling point. Methoxymethane does not experience intermolecular hydrogen bonding, giving rise to a relatively lower boiling point. A similar trend can be seen in a comparison of the following amines:



Once again, all three compounds have the same molecular formula ( $\text{C}_3\text{H}_9\text{N}$ ), but they have very different properties as a result of the extent of hydrogen bonding. Trimethylamine does not exhibit any hydrogen bonding and has a relatively low boiling point. Ethylmethylamine does exhibit hydrogen bonding and therefore has a higher boiling point. Finally, propylamine, which has the highest boiling point of the three compounds, has two N—H bonds and therefore exhibits even more hydrogen-bonding interactions.

Hydrogen bonding is incredibly important in determining the shapes and interactions of biologically important compounds. Chapter 25 will focus on proteins, which are long molecules that coil up into specific shapes under the influence of hydrogen bonding (Figure 1.51a). These shapes ultimately determine their biological function. Similarly, hydrogen bonds hold together individual strands of DNA to form the familiar double-helix structure.

As mentioned earlier, hydrogen “bonds” are not really bonds. To illustrate this, compare the energy of a real bond with the energy of a hydrogen-bonding interaction. A typical single bond (C—H, N—H, O—H) has a bond strength of approximately 400 kJ/mol. In contrast, a hydrogen-bonding interaction has an average strength of approximately 20 kJ/mol. This leaves us with the obvious question: why do we call them hydrogen *bonds* instead of just hydrogen *interactions*? To answer this question, consider the double-helix structure of DNA (Figure 1.51b). The two strands are joined by hydrogen bonding interactions that function like rungs of a very long, twisted ladder. The net sum of these interactions is a significant factor that contributes to the structure of the double



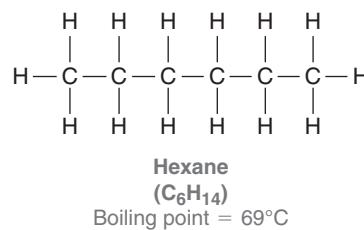
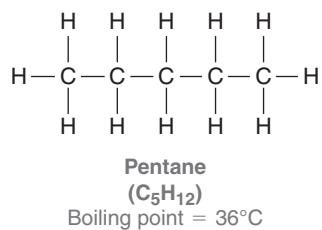
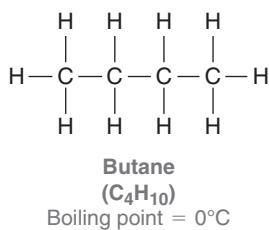
**FIGURE 1.51**  
(a) An alpha helix of a protein.  
(b) The double helix in DNA.

**LOOKING AHEAD**  
The structure of DNA is explored in more detail in Section 24.9.

helix, in which the hydrogen-bonding interactions appear *as if* they were actually bonds. Nevertheless, it is relatively easy to “unzip” the double helix and retrieve the individual strands.

### Fleeting Dipole-Dipole Interactions

Some compounds have no permanent dipole moments, and yet analysis of boiling points indicates that they must have fairly strong intermolecular attractions. To illustrate this point, consider the following compounds:



#### LOOKING AHEAD

Hydrocarbons will be discussed in more detail in Chapters 4, 17, and 18.

These three compounds are **hydrocarbons**, compounds that contain only carbon and hydrogen atoms. If we compare the properties of the hydrocarbons above, an important trend becomes apparent. Specifically, the boiling point appears to increase with increasing molecular weight. This trend can be justified by considering the fleeting, or transient, dipole moments that are more prevalent in larger hydrocarbons. To understand the source of these temporary dipole moments, we consider the electrons to be in constant motion, and therefore, the center of negative charge is also constantly moving around within the molecule. On average, the center of negative charge coincides with the center of positive charge, resulting in a zero dipole moment. However, at any given instant, the center of negative charge and the center of positive charge might not coincide. The resulting transient dipole moment can then induce a separate transient dipole moment in a neighboring molecule, initiating a fleeting attraction between the two mol-

## PRACTICALLY SPEAKING ))

### Biomimicry and Gecko Feet

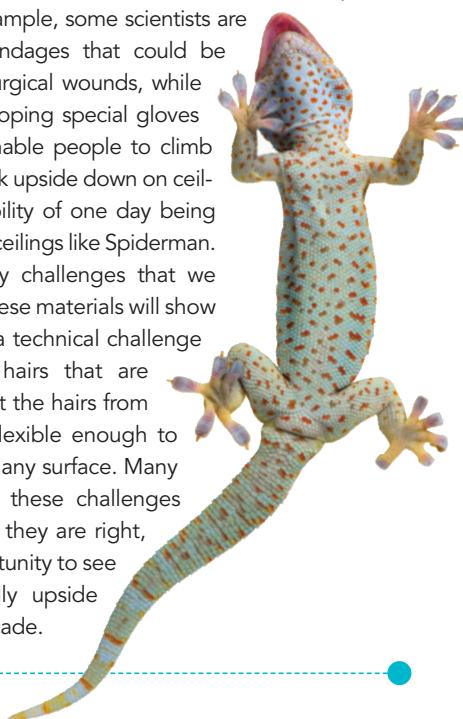
The term biomimicry describes the notion that scientists often draw creative inspiration from studying nature. By investigating some of nature’s processes, it is possible to mimic those processes and to develop new technology. One such example is based on the way that geckos can scurry up walls and along ceilings. Until recently, scientists were baffled by the curious ability of geckos to walk upside down, even on very smooth surfaces such as polished glass.

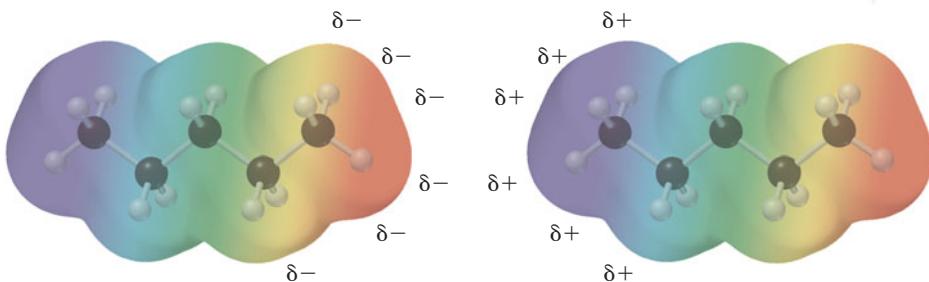
As it turns out, geckos do not use any chemical adhesives, nor do they use suction. Instead, their abilities arise from the intermolecular forces of attraction between the molecules in their feet and the molecules in the surface on which they are walking. When you place your hand on a surface, there are certainly intermolecular forces of attraction between the molecules of your hand and the surface, but the microscopic topography of your hand is quite bumpy. As a result, your hand only makes contact with the surface at perhaps a few thousand points. In contrast, the foot of a gecko has approximately half a million microscopic flexible hairs, called *setae*, each of which has even smaller hairs.

When a gecko places its foot on a surface, the flexible hairs allow the gecko to make extraordinary contact with the surface, and the resulting London dispersion forces are collectively strong enough to support the gecko.

In the last decade, many research teams have drawn inspiration from geckos and have created materials with densely packed microscopic hairs. For example, some scientists are developing adhesive bandages that could be used in the healing of surgical wounds, while other scientists are developing special gloves and boots that would enable people to climb up walls (and perhaps walk upside down on ceilings). Imagine the possibility of one day being able to walk on walls and ceilings like Spiderman.

There are still many challenges that we must overcome before these materials will show their true potential. It is a technical challenge to design microscopic hairs that are strong enough to prevent the hairs from becoming tangled but flexible enough to allow the hairs to stick to any surface. Many researchers believe that these challenges can be overcome, and if they are right, we might have the opportunity to see the world turned literally upside down within the next decade.



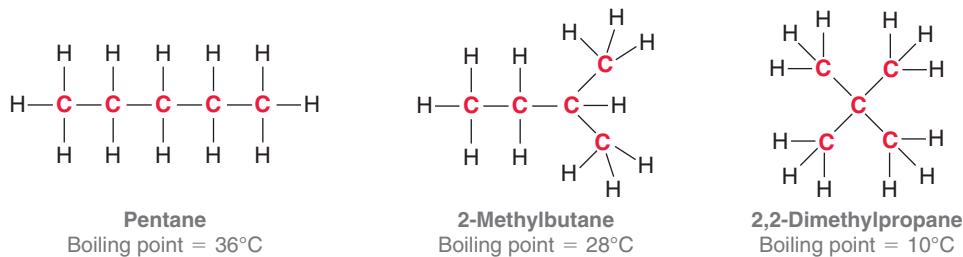
**FIGURE 1.52**

The fleeting attractive forces between two molecules of pentane.

molecules (Figure 1.52). These attractive forces are called **London dispersion forces**, named after German-American physicist Fritz London. Large hydrocarbons have more surface area than smaller hydrocarbons and therefore experience these attractive forces to a larger extent.

London dispersion forces are stronger for higher molecular weight hydrocarbons because these compounds have larger surface areas that can accommodate more interactions. As a result, compounds of higher molecular weight will generally boil at higher temperatures. Table 1.6 illustrates this trend.

A branched hydrocarbon generally has a smaller surface area than its corresponding straight-chain isomer, and therefore, branching causes a decrease in boiling point. This trend can be seen by comparing the following constitutional isomers of  $C_5H_{12}$ :

**TABLE 1.6 BOILING POINTS FOR HYDROCARBONS OF INCREASING MOLECULAR WEIGHT**

STRUCTURE	BOILING POINT (°C)	STRUCTURE	BOILING POINT (°C)
$\begin{array}{c} H \\   \\ H-C-H \\   \\ H \end{array}$	-164	$\begin{array}{ccccccc} & H & H & H & H & H & H \\ &   &   &   &   &   &   \\ H-C & -C & -C & -C & -C & -C & -H \\ &   &   &   &   &   &   \\ & H & H & H & H & H & H \end{array}$	69
$\begin{array}{cc} H & H \\   &   \\ H-C & -C-H \\   &   \\ H & H \end{array}$	-89	$\begin{array}{ccccccc} & H & H & H & H & H & H \\ &   &   &   &   &   &   \\ H-C & -C & -C & -C & -C & -C & -H \\ &   &   &   &   &   &   \\ & H & H & H & H & H & H \end{array}$	98
$\begin{array}{ccc} H & H & H \\   &   &   \\ H-C & -C & -C-H \\   &   &   \\ H & H & H \end{array}$	-42	$\begin{array}{ccccccc} & H & H & H & H & H & H \\ &   &   &   &   &   &   \\ H-C & -C & -C & -C & -C & -C & -H \\ &   &   &   &   &   &   \\ & H & H & H & H & H & H \end{array}$	126
$\begin{array}{cccc} H & H & H & H \\   &   &   &   \\ H-C & -C & -C & -C-H \\   &   &   &   \\ H & H & H & H \end{array}$	0	$\begin{array}{ccccccc} & H & H & H & H & H & H \\ &   &   &   &   &   &   \\ H-C & -C & -C & -C & -C & -C & -C-H \\ &   &   &   &   &   &   \\ & H & H & H & H & H & H \end{array}$	151
$\begin{array}{ccccc} H & H & H & H & H \\   &   &   &   &   \\ H-C & -C & -C & -C & -C-H \\   &   &   &   &   \\ H & H & H & H & H \end{array}$	36	$\begin{array}{ccccccc} & H & H & H & H & H & H \\ &   &   &   &   &   &   \\ H-C & -C & -C & -C & -C & -C & -C-H \\ &   &   &   &   &   &   \\ & H & H & H & H & H & H \end{array}$	174

# SKILLBUILDER

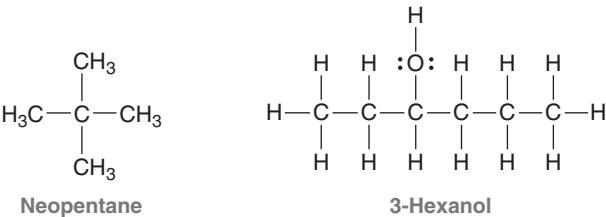
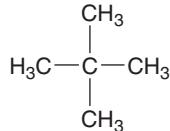


## 1.10 PREDICTING PHYSICAL PROPERTIES OF COMPOUNDS BASED ON THEIR MOLECULAR STRUCTURE



### LEARN the skill

Determine which compound has the higher boiling point, neopentane or 3-hexanol:



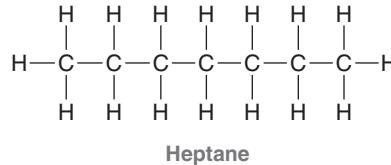
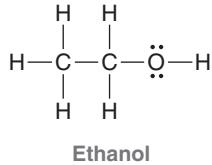
### SOLUTION

When comparing boiling points of compounds, we look for the following factors:

1. Are there any dipole-dipole interactions in either compound?
2. Will either compound form hydrogen bonds?
- 3a. How many carbon atoms are in each compound?
- 3b. How much branching is in each compound?

The second compound above (3-hexanol) is the winner in all of these categories. It has a dipole moment, while neopentane does not. It will experience hydrogen bonding, while neopentane will not. It has six carbon atoms, while neopentane only has five. And finally, it has a straight chain, while neopentane is highly branched. Each of these factors alone would suggest that 3-hexanol should have a higher boiling point. When we consider all of these factors together, we expect that the boiling point of 3-hexanol will be significantly higher than neopentane.

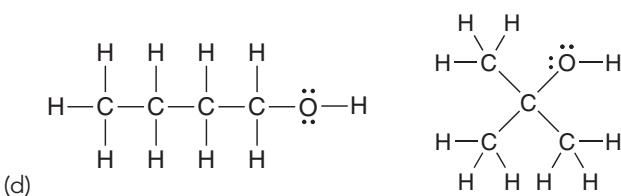
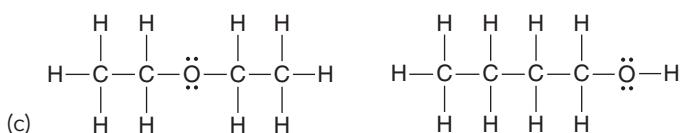
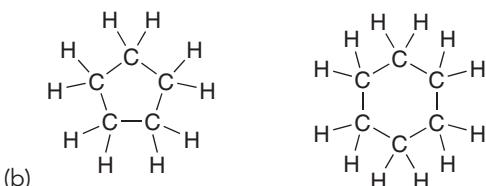
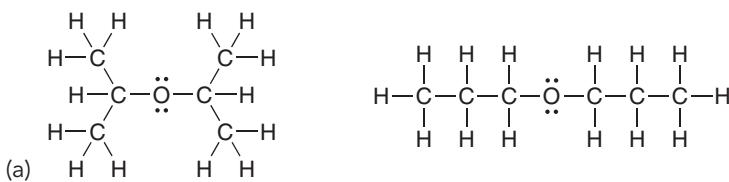
When comparing two compounds, it is important to consider all four factors. However, it is not always possible to make a clear prediction because in some cases there may be competing factors. For example, compare ethanol and heptane:



Ethanol will exhibit hydrogen bonding, but heptane has many more carbon atoms. Which factor dominates? It is not easy to predict. In this case, heptane has the higher boiling point, which is perhaps not what we would have guessed. In order to use the trends to make a prediction, there must be a clear winner.

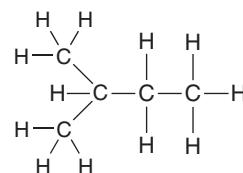
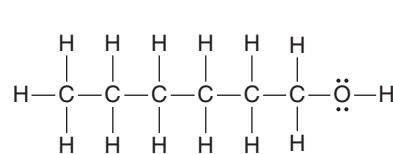
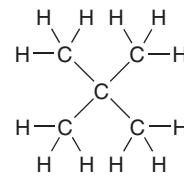
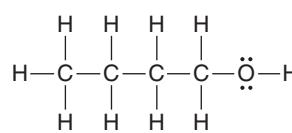
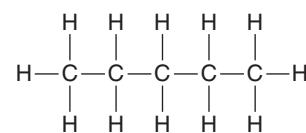


**PRACTICE the skill** 1.32 For each of the following pairs of compounds, identify the higher boiling compound and justify your choice:



## APPLY the skill

**1.33** Arrange the following compounds in order of increasing boiling point:

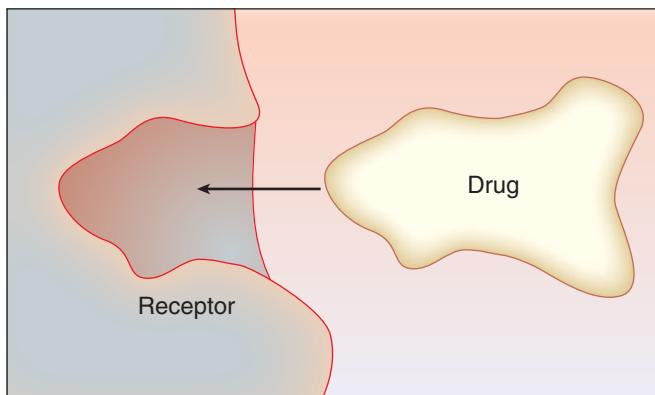


→ need more **PRACTICE?** Try Problems 1.52, 1.53, 1.60

## MEDICALLY SPEAKING )))

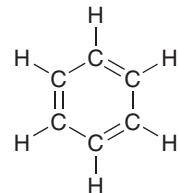
### Drug-Receptor Interactions

In most situations, the physiological response produced by a drug is attributed to the interaction between the drug and a biological receptor site. A receptor is a region within a biological macromolecule that can serve as a pouch in which the drug molecule can fit:



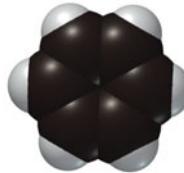
Initially, this mechanism was considered to work much like a lock and key. That is, a drug molecule would function as a key, either fitting or not fitting into a particular receptor. Extensive research on drug-receptor interactions has forced us to modify this simple lock-and-key model. It is now understood that both the drug and the receptor are flexible, constantly changing their shapes. As such, drugs can bind to receptors with various levels of efficiency, with some drugs binding more strongly and other drugs binding more weakly.

How does a drug bind to a receptor? In some cases, the drug molecule forms covalent bonds with the receptor. In such cases, the binding is indeed very strong (approximately 400 kJ/mol for each covalent bond) and therefore irreversible. We will see an example of irreversible binding when we explore a class of anti-cancer agents called nitrogen mustards (Chapter 7). For most drugs, however, the desired physiological response is meant to be temporary, which can only be accomplished if a drug can bind reversibly with its target receptor. This requires a weaker interaction between the drug and the receptor (at least weaker than a covalent bond). Examples of weak interactions include hydrogen-bonding interactions (20 kJ/mol) and London dispersion forces (approximately 4 kJ/mol for each carbon atom participating in the interaction). As an example, consider the structure of a benzene ring, which is incorporated as a structural subunit in many drugs.

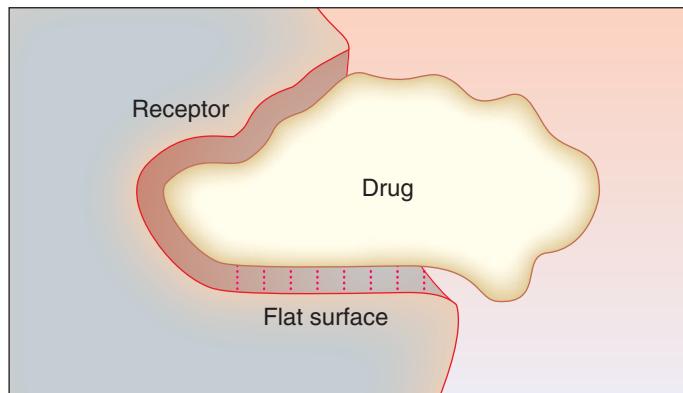


Benzene

In the benzene ring, each carbon is  $sp^2$  hybridized and therefore trigonal planar. As a result, a benzene ring represents a flat surface:



If the receptor also has a flat surface, the resulting London dispersion forces can contribute to the reversible binding of the drug to the receptor site:



This interaction is roughly equivalent to the strength of a single hydrogen-bonding interaction. The binding of a drug to a receptor is the result of the sum of the intermolecular forces of attraction between a portion of the drug molecule and the receptor site. We will have more to say about drugs and receptors in the upcoming chapters. In particular, we will see how drugs make their journey to the receptor, and we will explore how drugs flex and bend when interacting with a receptor site.

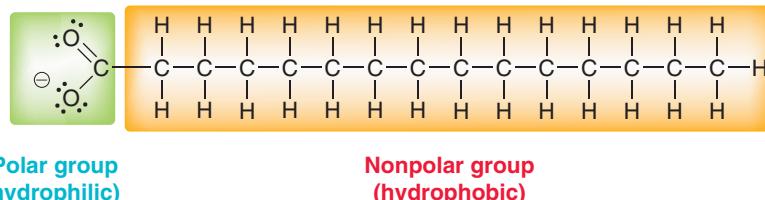


## 1.13 Solubility

Solubility is based on the principle that “like dissolves like.” In other words, polar compounds are soluble in polar solvents, while nonpolar compounds are soluble in nonpolar solvents. Why is this so? A polar compound experiences dipole-dipole interactions with the molecules of a polar solvent, allowing the compound to dissolve in the solvent. Similarly, a nonpolar compound experiences London dispersion forces with the molecules of a nonpolar solvent. Therefore, if an article of clothing is stained with a polar compound, the stain can generally be washed away with water (like dissolves like). However, water will be insufficient for cleaning clothing stained with nonpolar compounds, such as oil or grease. In a situation like this, the clothes can be cleaned with soap or by dry cleaning.

### Soap

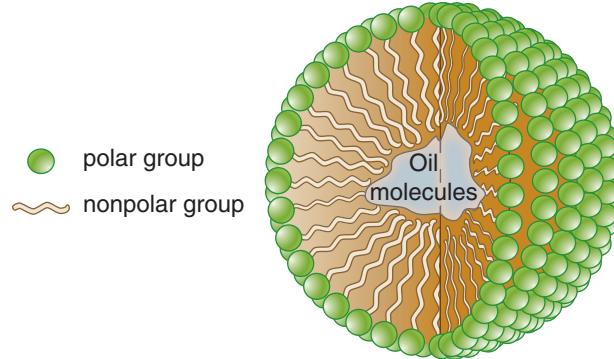
Soaps are compounds that have a polar group on one end of the molecule and a nonpolar group on the other end (Figure 1.53).



**FIGURE 1.53**

The hydrophilic and hydrophobic ends of a soap molecule.

The polar group represents the **hydrophilic** region of the molecule (literally, “loves water”), while the nonpolar group represents the **hydrophobic** region of the molecule (literally, “afraid of water”). Oil molecules are surrounded by the hydrophobic tails of the soap molecules, forming a **micelle** (Figure 1.54).



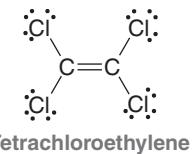
**FIGURE 1.54**

A micelle is formed when the hydrophobic tails of soap molecules surround the nonpolar oil molecules.

The surface of the micelle is comprised of all of the polar groups, rendering the micelle water soluble. This is a clever way to dissolve the oil in water, but this technique only works for clothing that can be subjected to water and soap. Some clothes will be damaged in soapy water, and in those situations, dry cleaning is the preferred method.

### Dry Cleaning

Rather than surrounding the nonpolar compound with a micelle so that it will be water soluble, it is actually conceptually simpler to use a nonpolar solvent. This is just another application of the principle of “like dissolves like.” Dry cleaning utilizes a nonpolar solvent, such as tetrachloroethylene, to dissolve the nonpolar compounds. This compound is nonflammable, making it an ideal choice as a solvent. Dry cleaning allows clothes to be cleaned without coming into contact with water or soap.



# REVIEW OF CONCEPTS AND VOCABULARY

## SECTION 1.1

- Organic compounds contain carbon atoms.

## SECTION 1.2

- Constitutional isomers** share the same molecular formula but have different connectivity of atoms and different physical properties.
- The predictable number of bonds usually formed by an atom of an element is its **valence**. Carbon is generally **tetravalent**, nitrogen **trivalent**, oxygen **divalent**, and hydrogen and the halogens **monovalent**.

## SECTION 1.3

- A **covalent bond** results when two atoms share a pair of electrons.
- Covalent bonds are illustrated using **Lewis structures**, in which electrons are represented by dots.
- Second-row elements generally obey the **octet rule**, bonding to achieve noble gas electron configuration.
- A pair of unshared electrons is called a **lone pair**.

## SECTION 1.4

- A **formal charge** occurs when atoms do not exhibit the appropriate number of valence electrons; formal charges must be drawn in Lewis structures.

## SECTION 1.5

- Bonds are classified as (1) **covalent**, (2) **polar covalent**, or (3) **ionic**.
- Polar covalent bonds exhibit **induction**, causing the formation of **partial positive charges** ( $\delta+$ ) and **partial negative charges** ( $\delta-$ ). **Electrostatic potential maps** present a visual illustration of partial charges.

## SECTION 1.6

- Quantum mechanics** describes electrons in terms of their wavelike properties.
- A **wave equation** describes the total energy of an electron when in the vicinity of a proton. Solutions to wave equations are called **wavefunctions** ( $\psi$ ), where  $\psi^2$  represents the probability of finding an electron in a particular location.
- Atomic orbitals** are represented visually by generating three-dimensional plots of  $\psi^2$ ; nodes indicate that the value of  $\psi$  is zero.
- An occupied orbital can be thought of as a cloud of **electron density**.
- Electrons fill orbitals following three principles: (1) the **Aufbau principle**, (2) the **Pauli exclusion principle**, and (3) **Hund's rule**. Orbitals with the same energy level are called degenerate orbitals.

## SECTION 1.7

- Valence bond theory** treats every bond as the sharing of electron density between two atoms as a result of the con-

structive interference of their atomic orbitals. **Sigma ( $\sigma$ ) bonds** are formed when the electron density is located primarily on the bond axis.

## SECTION 1.8

- Molecular orbital theory** uses a mathematical method called the **linear combination of atomic orbitals** (LCAO) to form molecular orbitals. Each molecular orbital is associated with the entire molecule, rather than just two atoms.
- The bonding MO of molecular hydrogen results from constructive interference between its two atomic orbitals. The antibonding MO results from destructive interference.
- An **atomic orbital** is a region of space associated with an individual atom, while a molecular orbital is associated with an entire molecule.
- Two molecular orbitals are the most important to consider: (1) the **highest occupied molecular orbital**, or HOMO, and (2) the **lowest unoccupied molecular orbital**, or LUMO.

## SECTION 1.9

- Methane's tetrahedral geometry can be explained using four degenerate  **$sp^3$ -hybridized orbitals** to achieve its four single bonds.
- Ethylene's planar geometry can be explained using three degenerate  **$sp^2$ -hybridized orbitals**. The remaining  $p$  orbitals overlap to form a separate bonding interaction, called a  $\pi$  bond. The carbon atoms of ethylene are connected via a  $\sigma$  bond, resulting from the overlap of  $sp^2$  hybridized atomic orbitals, and via a  $\pi$  bond, resulting from the overlap of  $p$  orbitals, both of which comprise the double bond of ethylene.
- Acetylene's linear geometry is achieved via  **$sp$ -hybridized** carbon atoms in which a triple bond is created from the bonding interactions of one  $\sigma$  bond, resulting from overlapping  $sp$  orbitals, and two  $\pi$  bonds, resulting from overlapping  $p$  orbitals.
- Triple bonds are stronger and shorter than double bonds, which are stronger and shorter than single bonds.

## SECTION 1.10

- The geometry of small compounds can be predicted using valence shell electron pair repulsion (VSEPR) theory, which focuses on the number of  $\sigma$  bonds and lone pairs exhibited by each atom. The total, called the steric number, indicates the number of electron pairs that repel each other.
- A tetrahedral arrangement of orbitals indicates  **$sp^3$  hybridization** (steric number 4). A compound's geometry depends on the number of lone pairs and can be tetrahedral, trigonal pyramidal, or bent.
- A trigonal planar arrangement of orbitals indicates  **$sp^2$  hybridization** (steric number 3); however, the geometry may be bent, depending on the number of lone pairs.
- Linear geometry indicates  **$sp$  hybridization** (steric number 2).



## SECTION 1.11

- **Dipole moments** ( $\mu$ ) occur when the center of negative charge and the center of positive charge are separated from one another by a certain distance; the dipole moment is used as an indicator of polarity (measured in debyes).
- The percent ionic character of a bond is determined by measuring its dipole moment. The vector sum of individual dipole moments in a compound determines the **molecular dipole moment**.

## SECTION 1.12

- The physical properties of compounds are determined by intermolecular forces, the attractive forces between molecules.
- **Dipole-dipole interactions** occur between two molecules that possess permanent dipole moments. Hydrogen bond-

ing, a special type of dipole-dipole interaction, occurs when the lone pairs of an electronegative atom interact with an electron-poor hydrogen atom. Compounds that exhibit hydrogen bonding have higher boiling points than similar compounds that lack hydrogen bonding.

- **London dispersion forces** result from the interaction between transient dipole moments and are stronger for larger alkanes due to their larger surface area and ability to accommodate more interactions.

## SECTION 1.13

- Polar compounds are soluble in polar solvents; nonpolar compounds are soluble in nonpolar solvents.
- Soaps are compounds that contain both **hydrophilic** and **hydrophobic** regions. The hydrophobic tails surround nonpolar compounds, forming a water-soluble micelle.

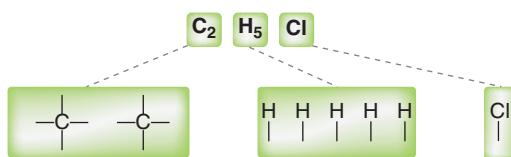
# KEY TERMINOLOGY

antibonding MO	17	electrostatic potential maps	12	London dispersion forces	37	<i>sp</i> <sup>2</sup> -hybridized orbitals	21
atomic orbitals	13	formal charge	8	lone pair	7	<i>sp</i> <sup>3</sup> -hybridized orbitals	19
Aufbau principle	14	HOMO	18	LUMO	18	steric number	25
bent	26	Hund's rule	15	micelle	41	tetrahedral	26
bonding MO	17	hybridized atomic orbitals	18	molecular dipole moment	31	tetravalent	3
constitution	3	hydrocarbons	36	molecular orbital theory	17	trigonal planar	27
constitutional isomers	3	hydrogen bonding	34	molecular orbitals	17	trigonal pyramidal	26
constructive interference	16	hydrophilic	41	monovalent	3	trivalent	3
covalent bond	5	hydrophobic	41	nodes	14	valence	3
debye	30	induction	10	octet rule	7	valence bond theory	16
degenerate orbitals	14	intermolecular forces	34	Pauli exclusion principle	14	valence electrons	5
destructive interference	16	ionic bond	10	pi ( $\pi$ ) bond	21	VSEPR theory	25
dipole-dipole interactions	34	ionic character	31	polar covalent bond	9	wave equation	12
dipole moment	30	Lewis structures	5	protic	35	wavefunction	12
divalent	3	linear	28	quantum mechanics	12		
electron density	13	linear combination of atomic orbitals	17	sigma ( $\sigma$ ) bond	16		
electronegativity	9			<i>sp</i> -hybridized orbitals	22		

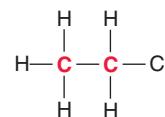
# SKILLBUILDER REVIEW

## 1.1 DETERMINING THE CONSTITUTION OF SMALL MOLECULES

**STEP 1** Determine the valency of each atom in the compound.



**STEP 2** Determine how the atoms are connected. Atoms with highest valency should be placed at the center, and monovalent atoms should be placed at the periphery.



Try Problems 1.1–1.4, 1.34, 1.46, 1.47, 1.54.

## 1.2 DRAWING THE LEWIS DOT STRUCTURE OF AN ATOM

**STEP 1** Determine the number of valence electrons.

N → **Group 5A**  
(five electrons)

**STEP 2** Place one electron by itself on each side of the atom.



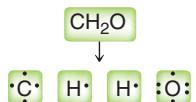
**STEP 3** If the atom has more than four valence electrons, the remaining electrons are paired with the electrons already drawn.



→ Try Problems 1.5–1.9.

## 1.3 DRAWING THE LEWIS STRUCTURE OF A SMALL MOLECULE

**STEP 1** Draw all individual atoms.



**STEP 2** Connect atoms that form more than one bond.



**STEP 3** Connect hydrogen atoms.



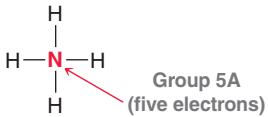
**STEP 4** Pair any unpaired electrons, so that each atom achieves an octet.



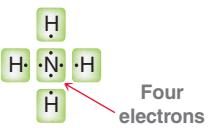
→ Try Problems 1.10–1.12, 1.35, 1.38, 1.42.

## 1.4 CALCULATING FORMAL CHARGE

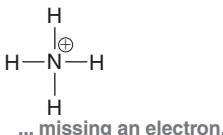
**STEP 1** Determine appropriate number of valence electrons.



**STEP 2** Determine the number of valence electrons in this case.



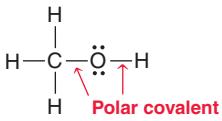
**STEP 3** Assign a formal charge.



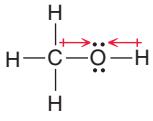
→ Try Problems 1.13, 1.14, 1.41.

## 1.5 LOCATING PARTIAL CHARGES

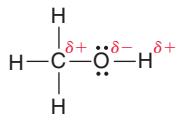
**STEP 1** Identify all polar covalent bonds.



**STEP 2** Determine the direction of each dipole.



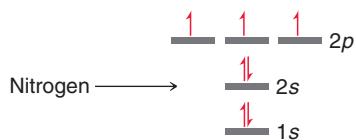
**STEP 3** Indicate location of partial charges.



→ Try Problems 1.15, 1.16, 1.36, 1.37, 1.48, 1.57.

## 1.6 IDENTIFYING ELECTRON CONFIGURATIONS

**STEP 1** Fill orbitals using Aufbau principle, Pauli exclusion principle, and Hund's rule.



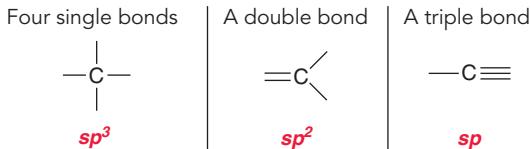
**STEP 2** Summarize using the following notation:



→ Try Problems 1.17, 1.18, 1.44.



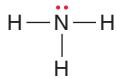
## 1.7 IDENTIFYING HYBRIDIZATION STATES



→ Try Problems 1.22, 1.23, 1.55, 1.56, 1.58.

## 1.8 PREDICTING GEOMETRY

**STEP 1** Determine the steric number by adding the number of  $\sigma$  bonds and lone pairs.



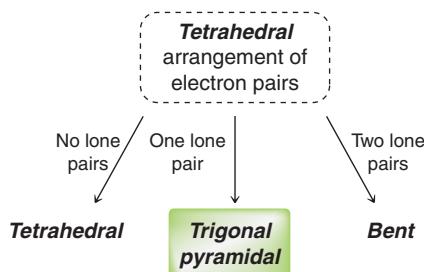
# of  $\sigma$  bonds = 3  
# of lone pairs = 1

**Steric number = 4**

**STEP 2** Use steric number to determine hybridization state and electronic geometry.

4	→	$sp^3$	→	Tetrahedral
3	→	$sp^2$	→	Trigonal planar
2	→	$sp$	→	Linear

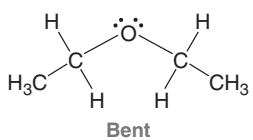
**STEP 3** Ignore lone pairs and describe geometry.



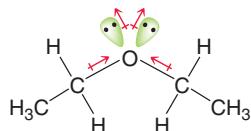
→ Try Problems 1.25–1.28, 1.39–1.41, 1.50, 1.55, 1.56, 1.58.

## 1.9 IDENTIFYING MOLECULAR DIPOLE MOMENTS

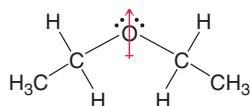
**STEP 1** Predict geometry



**STEP 2** Identify direction of all dipole moments.



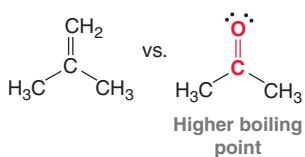
**STEP 3** Draw net dipole moment.



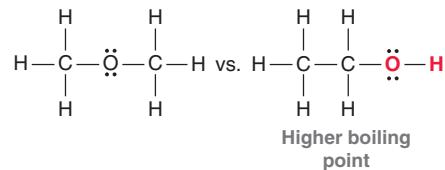
→ Try Problems 1.29–1.31, 1.37, 1.40, 1.43, 1.61, 1.62.

## 1.10 PREDICTING PHYSICAL PROPERTIES

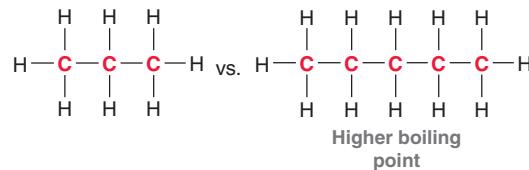
**STEP 1** Identify dipole-dipole interactions.



**STEP 2** Identify H-bonding interactions.



**STEP 3** Identify number of carbon atoms and extent of branching.



→ Try Problems 1.32, 1.33, 1.52, 1.53, 1.60.

## PRACTICE PROBLEMS



Note: Most of the Problems are available within WileyPLUS, an online teaching and learning solution.

**1.34** Draw structures for all constitutional isomers with the following molecular formulas:

- (a)  $C_4H_{10}$     (b)  $C_5H_{12}$     (c)  $C_6H_{14}$   
 (d)  $C_2H_5Cl$     (e)  $C_2H_4Cl_2$     (f)  $C_2H_3Cl_3$

**1.35** Draw structures for all constitutional isomers with the molecular formula  $C_4H_8$  that have:

- (a) Only single bonds    (b) One double bond

**1.36** For each compound below, identify any polar covalent bonds, and indicate the direction of the dipole moment using the symbols  $\delta+$  and  $\delta-$ :

- (a) HBr    (b) HCl    (c)  $H_2O$     (d)  $CH_4O$

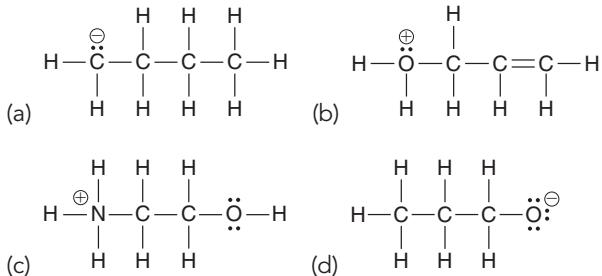
**1.37** For each pair of compounds below, identify the one that would be expected to have more ionic character. Explain your choice.

- (a) NaBr or HBr    (b) BrCl or FCl

**1.38** Draw a Lewis dot structure for each of the following compounds:

- (a)  $CH_3CH_2OH$     (b)  $CH_3CN$

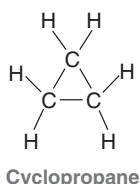
**1.39** Predict the geometry of each atom except hydrogen in the compounds below:



**1.40** Draw a Lewis structure for a compound with molecular formula  $C_4H_{11}N$  in which three of the carbon atoms are bonded to the nitrogen atom. What is the geometry of the nitrogen atom in this compound? Does this compound exhibit a molecular dipole moment? If so, indicate the direction of the dipole moment.

**1.41** Draw a Lewis structure of the anion  $AlBr_4^-$  and determine its geometry.

**1.42** Draw the structure for the only constitutional isomer of cyclopropane:



**1.43** Determine whether each compound below exhibits a molecular dipole moment:

- (a)  $CH_4$     (b)  $NH_3$     (c)  $H_2O$   
 (d)  $CO_2$     (e)  $CCl_4$     (f)  $CH_2Br_2$

**1.44** Identify the neutral element that corresponds with each of the following electronic configurations:

- (a)  $1s^22s^22p^4$     (b)  $1s^22s^22p^5$     (c)  $1s^22s^22p^2$   
 (d)  $1s^22s^22p^3$     (e)  $1s^22s^22p^63s^23p^5$

**1.45** In the compounds below, classify each bond as covalent, polar covalent, or ionic:

- (a) NaBr    (b) NaOH    (c)  $NaOCH_3$   
 (d)  $CH_3OH$     (e)  $CH_2O$

**1.46** Draw structures for all constitutional isomers with the following molecular formulas:

- (a)  $C_2H_6O$     (b)  $C_2H_6O_2$     (b)  $C_2H_4Br_2$

**1.47** Draw structures for any five constitutional isomers with molecular formula  $C_2H_6O_3$ .

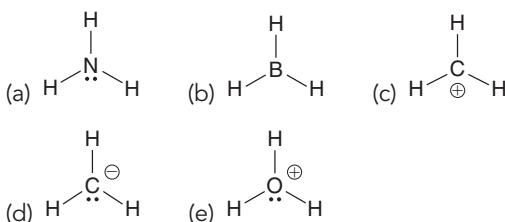
**1.48** For each type of bond below, determine the direction of the expected dipole moment.

- (a) C—O    (b) C—Mg    (c) C—N    (d) C—Li  
 (e) C—Cl    (f) C—H    (g) O—H    (h) N—H

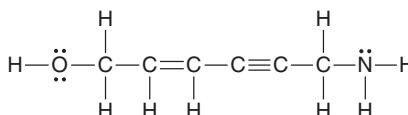
**1.49** Predict the bond angles for all bonds in the following compounds:

- (a)  $CH_3CH_2OH$     (b)  $CH_2O$     (c)  $C_2H_4$     (d)  $C_2H_2$   
 (e)  $CH_3OCH_3$     (f)  $CH_3NH_2$     (g)  $C_3H_8$     (h)  $CH_3CN$

**1.50** Identify the expected hybridization state and geometry for the central atom in each of the following compounds:

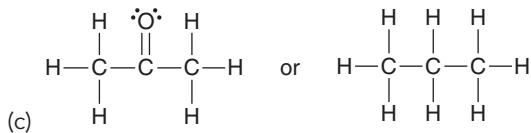
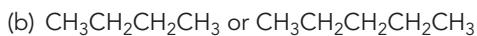
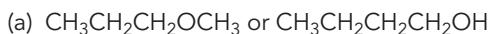


**1.51** Count the total number of  $\sigma$  bonds and  $\pi$  bonds in the compound below:

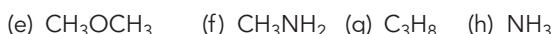
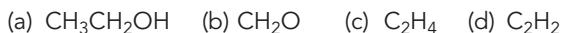




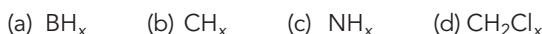
**1.52** For each pair of compounds below, predict which compound will have the higher boiling point and explain your choice:



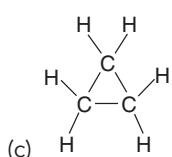
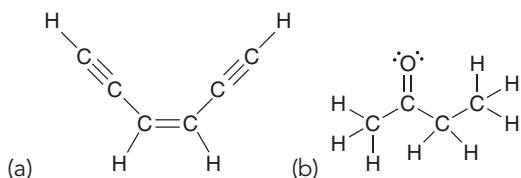
**1.53** Which of the following pure compounds will exhibit hydrogen bonding?



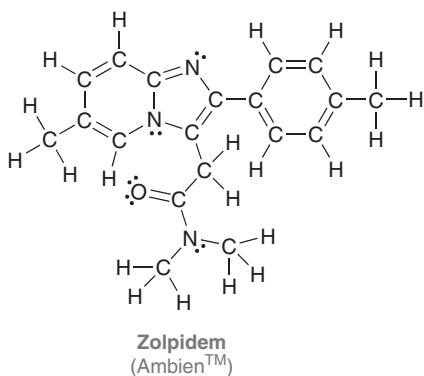
**1.54** For each case below, identify the most likely value for  $x$ :



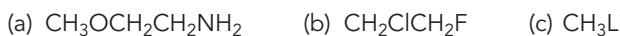
**1.55** Identify the hybridization state and geometry of each carbon atom in the following compounds:



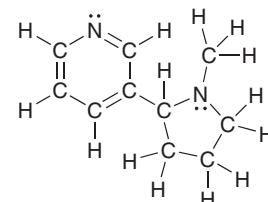
**1.56** Ambien™ is a sedative used in the treatment of insomnia. It was discovered in 1982 and brought to market in 1992 (it takes a long time for new drugs to undergo the extensive testing required to receive approval from the Food and Drug Administration). Identify the hybridization state and geometry of each carbon atom in the structure of this compound:



**1.57** Identify the most electronegative element in each of the following compounds:

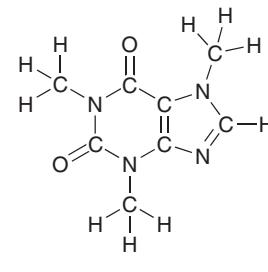


**1.58** Nicotine is an addictive substance found in tobacco. Identify the hybridization state and geometry of each of the nitrogen atoms in nicotine:



Nicotine

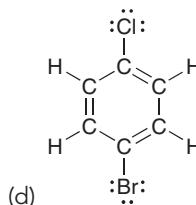
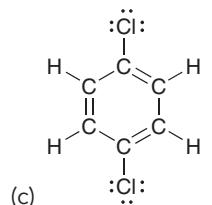
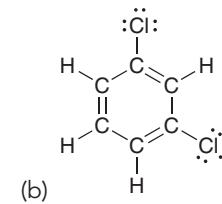
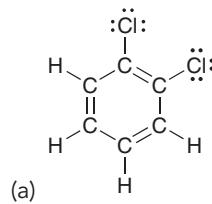
**1.59** Below is the structure of caffeine, but its lone pairs are not shown. Identify the location of all lone pairs in this compound:



Caffeine

**1.60** There are two different compounds with molecular formula  $\text{C}_2\text{H}_6\text{O}$ . One of these isomers has a much higher boiling point than the other. Explain why.

**1.61** Identify which compounds below possess a molecular dipole moment and indicate the direction of that dipole moment:

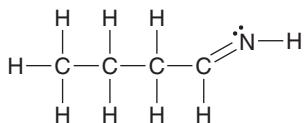


**1.62** Methylene chloride ( $\text{CH}_2\text{Cl}_2$ ) has fewer chlorine atoms than chloroform ( $\text{CHCl}_3$ ). Nevertheless, methylene chloride has a larger molecular dipole moment than chloroform. Explain.

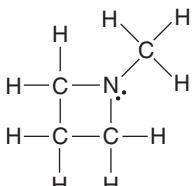
## INTEGRATED PROBLEMS

**1.63** Consider the three compounds shown below and then answer the questions that follow:

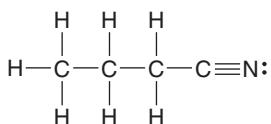
(a) Which two compounds are constitutional isomers?



Compound A



Compound B



Compound C

(b) Which compound contains a nitrogen atom with trigonal pyramidal geometry?

(c) Identify the compound with the greatest number of  $\sigma$  bonds.

(d) Identify the compound with the fewest number of  $\sigma$  bonds.

(e) Which compound contains more than one  $\pi$  bond?

(f) Which compound contains an  $sp^2$ -hybridized carbon atom?

(g) Which compound contains only  $sp^3$ -hybridized atoms (in addition to hydrogen atoms)?

(h) Which compound do you predict will have the highest boiling point? Explain.

**1.64** Propose at least two different structures for a compound with six carbon atoms that exhibits the following features:

(a) All six carbon atoms are  $sp^2$  hybridized.

(b) Only one carbon atom is  $sp$  hybridized, and the remaining five carbon atoms are all  $sp^3$  hybridized (remember that your compound can have elements other than carbon and hydrogen).

(c) There is a ring, and all of the carbon atoms are  $sp^3$  hybridized.

(d) All six carbon atoms are  $sp$  hybridized, and the compound contains no hydrogen atoms (remember that a triple bond is linear and therefore cannot be incorporated into a ring of six carbon atoms).

## CHALLENGE PROBLEMS

**1.65** Draw all constitutional isomers with molecular formula  $C_5H_{10}$  that possess one  $\pi$  bond.

**1.66** With current spectroscopic techniques (discussed in Chapters 15–17), chemists are generally able to determine the structure of an unknown organic compound in just one day. These techniques have only been available for the last several decades. In the first half of the twentieth century, structure determination was a very slow and painful process in which the compound under investigation would be subjected to a variety of chemical reactions. The results of those reactions would provide chemists with clues about the structure of the compound. With enough clues, it was sometimes (but not always) possible to determine the structure. As an example, try to determine the structure of an unknown compound, using the following clues:

- The molecular formula is  $C_4H_{10}N_2$ .
- There are no  $\pi$  bonds in the structure.
- The compound has no net dipole moment.
- The compound exhibits very strong hydrogen bonding.

You should find that there are at least two constitutional isomers that are consistent with the information above. (*Hint:* Consider incorporating a ring in your structure.)

**1.67** A compound with molecular formula  $C_5H_{11}N$  has no  $\pi$  bonds. Every carbon atom is connected to exactly two hydrogen atoms. Determine the structure of the compound.