# UNIT 5

# Making Molecules

## Lewis Structures and Molecular Geometries

## Unit Overview

This unit covers the basics of bonding and takes us from a two-dimensional model of atoms and molecules into three dimensions. It begins by examining valence electrons and why atoms lose, gain, or share electrons to fill their outer shell. Understanding how individual atoms combine and the three-dimensional shapes of molecules enables students to predict many physical and chemical properties of substances.

### Learning Objectives and Applicable Standards

Participants will be able to:

1. Predict the Lewis dot structure for covalent or ionic molecules.

2. Identify the geometry of molecules.

3. Describe a compound's physical properties, such as boiling point and solubility, based on intermolecular forces.

### Key Concepts and People

1. **Valence Electrons:** Atoms act to obtain a full outer shell of electrons, which confers stability.

2. **Lewis Dot Structures:** The number of valence electrons controls the number of electrons each atom tends to lose, gain, or share in a chemical reaction. Lewis dot structures are a simple, useful method for visualizing the number of valence electrons.

3. **Ionic Bonding:** Ionic bonds occur when atoms have very different electronegativities, and one atom gives up electrons to the other to form ions. Oppositely charged ions attract each other and pair up due to Coulombic forces.

4. **Covalent Bonds and the Octet Rule:** Covalent bonds form when atoms share electrons. The octet rule states that elements will work to get a total of eight valence electrons. Elements can share electrons through covalent bonds to achieve a complete octet.

5. **Polarity and Basic Lewis Structures:** In covalent bonds, the more electronegative

atom pulls the electron clouds closer than the less electronegative atom, which leads to polar covalent ponds. In a polar covalent pond, the more electronegative atom will have a slightly negative charge, while the other atom will have a slightly positive charge.

6. **Advanced Lewis Structures:** Sometimes, when molecules form where the normal patterns of bonding are not followed, or if the molecules are actually charged molecular ions, the atoms themselves can have a formal charge on them.

7. **VSEPR and Molecular Geometries:** Valence shell electron pair repulsion (VSEPR) theory predicts the 3-D shape of molecules based upon the extent of electron-pair repulsion.

8. **Hybrid Orbitals:** When an electron is shared between two different atoms in a covalent bond, the two electron clouds that correspond to each of the atomic orbitals merge to become a larger cloud. This combination of atomic orbitals is called a "molecular orbital."

9. **Intermolecular Forces:** There are forces of attraction that exist between molecules themselves. These intermolecular forces, while much weaker than ionic and covalent bonds, have important effects on the way molecules, once formed, interact with one another. Molecular forces include hydrogen bonding, dipole-dipole forces, and London dispersion forces.

10. **Physical Properties of Molecules:** Molecular structure determines the types of intermolecular forces that hold molecules together. The stronger these forces, the more energy it takes to move the molecules apart from each other. This affects physical properties of molecules such as melting point, boiling point, viscosity, and solubility.

# Video

Molecules can form when atoms bond together by sharing electrons and can be represented by a useful shorthand called Lewis structures. These visual representations provide information to predict the three-dimensional shapes of molecules using valence shell electron pair repulsion ("VSEPR") theory. Understanding how atoms bond within molecules provides insight into cell replication. Building on this knowledge, the shapes of molecules reveal the effectiveness of important antibiotics such as penicillin, and scientists can manipulate shapes of molecules to help design new cancer-treating drugs.

## VIDEO CONTENT

### Host Science Explanation
### "Lewis Structures and Radicals"

Making molecules of a particular shape and function can have important implications for fighting disease. Dr. Beth Taylor, Chemistry Instructor at the Massachusetts Institute of Technology, explains Lewis structures using water and a hydroxyl radical as examples. Radicals have a lone, unpaired electron and thus are highly reactive. Hydroxyl radicals can damage DNA, but are also part of the mechanism by which white blood cells destroy bacteria.

### Current Chemistry Research
### "Free Radicals in Cell Replication"

By understanding how radicals work, scientists can come up with solutions to shut down the ones that harm our health. Christina Zimanyi, a graduate student in the laboratory of Dr. Catherine Drennan at the Massachusetts Institute of Technology, studies free radicals. She uses X-ray crystallography to image an enzyme called ribonucleotide reductase (RNR). RNR has an oxygen radical that helps start the reactions that make DNA, which is essential for cell division. By understanding the pathway of this radical, researchers could investigate ways to inhibit its function in cancer cells, thus inhibiting the cancer cell's ability to divide.

### Laboratory Demonstration:
### "The Geometry of Molecules"

Electron pairs repel each other, and thus will automatically arrange themselves in a molecule as far away from each other as possible. Valence Shell Electron Pair Repulsion (VSEPR) Theory allows us to predict the geometries of molecules based on this repulsion. Harvard University Lecture Demonstrator Daniel Rosenberg uses balloons to represent pairs of electrons to visualize how they mutually repel. He uses the arrangement of balloons to represent the major shapes in VSEPR: octahedral, trigonal bipyramidal, tetrahedral, trigonal planar, and linear.

### History of Science
### "Penicillin and VSEPR"

Alexander Fleming discovered the antibiotic penicillin in 1928. It is the geometry of penicillin that makes it an effective antibiotic. The molecule contains a four-membered ring called a "beta-lactam." The geometry of this ring causes the penicillin molecules to form covalent bonds with an enzyme that is responsible for building the cell walls of bacteria cells. This reaction kills the activity of the enzyme and causes the bacterial cells to perish.

### Real World Application
### "Designing New Cancer Drugs"

Molecular geometry is an important factor in the development of drugs to fight diseases such as cancer. Dr. Alexander Taylor and the other scientists at Constellation Pharmaceuticals wish to specifically target essential proteins in cancer cells. They adjust the geometry of molecules to specifically fit into the binding pockets of these proteins. Polarity, the distribution of electrons in a molecule, is also a consideration in drug development because polar molecules will bind more tightly within a polar binding pocket.

# Unit Text

## Content Overview

Unit 5 expands on the discussion of electron configuration in Unit 4 by focusing on the importance of valence electrons and their role in bonding. The text explores using Lewis dot symbolism to represent valence electrons on single atoms and bonding in molecules, and includes many examples of Lewis dot structures for molecules involving multiple bonds, expanded octets, and resonance structures. Valence Shell Electron Pair Repulsion Theory, or VSEPR, allows students to predict the shape of molecules in three dimensions, which relates directly to the geometry of hybrid or molecular orbitals. The arrangement of orbitals also has an impact on how well molecules stick to each other. These intermolecular forces control physical properties, such as boiling point and solubility.

## Sidebar Content

1. **Linus Pauling:** Linus Pauling made many important contributions to chemistry research in the 20th century, including the concept of hybrid orbitals, which is critical to understanding chemical bonding.

2. **DNA and $Mg^{2+}$**: DNA is a polymer that contains negatively charged phosphate groups that should repel each other. Magnesium cations help to neutralize the environment in the nucleus of a cell and allow the DNA strand to remain intact.

3. **Resonance**: When it is possible to draw more than one acceptable Lewis structure for a given molecule, where all the connections are the same in both structures but the *location of the electrons* is different, we call these structures "resonance structures."

4. **Radicals**: Radicals are molecules or atoms that have an unpaired electron.

5. **Expanded Octet Geometries**: Some compounds can have more than 8 electrons in their valence shell, like $PF_5$ or $SF_6$. This creates different kinds of geometries such as trigonal bipyramidal and octahedral.

6. **Oil Spills and Tar Balls**: Crude oil spills contain a mixture of different sized hydrocarbons. Hydrocarbons only have London forces between them, so the rate at which they evaporate is dependent on the size of the hydrocarbon. When an oil spill happens, the smaller hydrocarbons evaporate first, but the larger ones can form together creating big tar balls, which can persist for a long time.

# Interactives

## Historical Timeline of Chemistry

This interactive illustrates how different discoveries build upon, disprove, or reinforce previous theories. This not only reinforces basic chemistry concepts, but also emphasizes the nature of science. Key figures mentioned in this unit are listed on the timeline.

## During the Session

### Before Facilitating this Unit

Molecular geometry can be a difficult concept for students to grasp. The goal of this unit is to give students a way to visualize the shapes of molecules. The course guide outlines several options for students to see and touch models, depending on the technology and equipment available.

### Tips and Suggestions

1. **A symmetrical 2-D structure does not mean there is a symmetrical 3-D structure.** For example, the Lewis dot structure for water can be drawn linearly, but water actually has a bent geometry.

2. **Every chemistry student should understand why bent geometries correspond to polar molecules, even though the Lewis dot structure appears symmetrical.** Bent geometries are especially important for students to understand hydrogen bonding.

3. **Advanced level classes should discuss examples of expanded octets and more complicated geometries, such as square planar and T-shaped.** High school classes do not necessarily need to delve into as much detail, but should understand the differences among tetrahedral, trigonal pyramidal, and bent.

4. **Many students confuse intermolecular forces and bonding.** Emphasize the fact that breaking intermolecular forces does not mean breaking covalent bonds. Boiling water creates steam, not oxygen and hydrogen gas.

### Starting the Session: Checking Prior Thinking

You might assign students a short writing assignment based on the following questions, and then spend some time discussing prior thinking. This will help elicit prior thinking and misconceptions.

1. List five objects whose shape determines its function.

2. What would happen if you tried to push two electrons together? Explain.

3. Why don't oil and water mix?

### Before Watching the Video

Students should be given the following questions to consider while watching:

1. What is an octet? Why do atoms want a full octet?

2. Why would scientists care about the 3-D structures of molecules?

3. What is polarity?

### Watch the Video

### After Watching the Video

Use these additional questions as follow-up, either as a group discussion or as short writing assignments.

1. Why are radicals so reactive?

2. Why would stopping the activities of the enzyme RNR help to fight cancer?

3. What does Christina Zimanyi use to visualize the shape of RNR?

4. How do the bond angles in penicillin cause it to function as an antibiotic medicine?

# Group Learning Activities

## Two Molecular Shapes Activities

### Objective

The following two activities—**PhET Simulation: Molecular Shapes** and **Building Molecules**—allow students to visualize the 3-D shapes of molecules. PhET, a project at the University of Colorado at Boulder, uses education research to design online STEM interactives. The programs are free to use. **Building Molecules** allows students to physically hold and make molecules, which may help some students who have difficulty visualizing 3-D shapes in 2-D spaces.

## PhET Simulation: Molecular Shapes

### List of Materials

- **Computer or tablet with internet access** (one per group). If computers or tablets are unavailable, this could be done as a demonstration. The simulations' website is http://phet.colorado.edu/en/simulation/molecule-shapes

- **Chart with the following columns:** Chemical Formula, Lewis Dot Structure, 3-D Sketch, # of Electron Densities, # of Lone Pairs, and Molecular Geometry. Some suggested molecules include $CO_2$, $CH_2O$, $CH_4$, $NH_3$, $H_2O$, $BF_3$, $SF_6$, $PCl_5$, and $XeF_4$. The entire chart will fit on a single, double-sided sheet of paper if the document is in a landscape orientation.

### Set Up
Create handout as described in the list of materials.

### Procedure
1. Log on to http://phet.colorado.edu/en/simulation/molecule-shapes
2. While working in small groups, fill out the chart.

### Discussion
After performing this activity, ask students if they noticed any patterns. Emphasize the fact that patterns exist in geometries, so once you know the geometry of $CH_4$, you know the geometry of $CF_4$, $CBr_4$, $CI_4$, $NH_4^+$, etc. For each of the molecules listed, have students brainstorm other molecules that would have the exact same geometry. Discuss the list as a class. Have students explain why a given molecule has a particular shape and why it's important to know the shape of a molecule.

### Hazards
There is no increased risk of harm to do this activity.

### Disposal
There are no special disposal considerations.

## Building Molecules

### List of Materials
- **A molecular modeling kit or toothpicks and gum drops.**
- **Chart with the following columns:** Chemical Formula, Lewis Dot Structure, 3-D Sketch, # of Electron Densities, # of Lone Pairs, and Molecular Geometry. Some suggested molecules include $CO_2$, $CH_2O$, $CH_4$, $NH_3$, $H_2O$, $BF_3$, $SF_6$, $PCl_5$, and $XeF_4$. The entire chart will fit on a single sheet of paper double-sided if the document is in a landscape format.

### Set Up
Create handout described in the list of materials.

### Procedure
While working in small groups, use the materials to make the 3-D molecules listed on the sheet and fill out the chart.

### Discussion
After performing this activity ask students if they noticed any patterns. Emphasize the fact that patterns exist in geometries, so once you know the geometry of $CH_4$, you know the geometry of $CF_4$, $CBr_4$, $CI_4$, $NH_4^+$, *etc.*

### Hazards
There is no increased risk of harm to do this activity.

### Disposal
Throw all disposable materials into the garbage and wipe down tables or desks following the activity.

## IMF and Surface Tension Activity

### Objective
In this activity, students count the number of drops of three different types of liquids (water, methanol, and acetone) that can fit on a penny without spilling over the sides. The number of drops that fit on the surface of the penny relates to the intermolecular forces holding the molecules together. Water and methanol both exhibit hydrogen bonding, whereas acetone has only dipole-dipole interactions. Water's hydrogen bonds are stronger than methanol's intermolecular forces, so it will have the largest number of drops. Stronger IMFs correspond to more drops being able to fit on the surface of the penny.

### List of Materials
- One penny per group
- Small dropper bottle of water (one per group, or groups can share)
- Small dropper bottle of methanol (one per group, or groups can share)
- Small dropper bottle of acetone (one per group, or groups can share)
- Rinse bottle of water
- An organic waste container (fume hood).

### Procedure
1. One drop at a time, count the number of drops of water that will fit onto the surface of a penny before the water pours off. Record results. Repeat for a total of three trials for consistency.

2. Rinse the penny and work area with water and dry with a paper towel.

3. Repeat for methanol and acetone.

### Discussion
The following questions can help students reflect on this exercise:

1. The penny held the greatest number of drops of which liquid?

2. The penny held the least number of drops of which liquid?

3. Which liquid has the strongest intermolecular forces? Explain your reasoning.

4. What intermolecular forces are present in each of the three liquids? It may help to draw

a diagram to explain your answer.

5. Intermolecular forces in molecules affect their surface tension. Surface tension is defined by Merriam-Webster as: "the attractive force exerted upon the surface molecules of a liquid by the molecules beneath that tends to draw the surface molecules into the bulk of the liquid and makes the liquid assume the shape having the least surface area." How does this relate to how much of each liquid fits on a penny?

### Hazards
It is good lab practice to review a chemical's Material Safety Data Sheet (MSDS) before working with any chemical. Follow instructions on the MSDS and encourage students to review them. Wear safety glasses/ goggles and gloves while performing this experiment. The room should be well ventilated.

### Disposal
Use caution disposing of acetone and methanol. They should be placed in the appropriate hazardous waste container.

# In-Class Chemical Demonstrations

## Balloon Demonstration of Molecular Geometries

### Objective
Electrons automatically rearrange themselves to spread out as much as possible. We can easily simulate this using balloons to represent areas of electron density around a central atom.

### List of materials

- 6 balloons

### Procedure

1. Inflate 6 balloons.
2. Tie them together in the middle so that they make an octahedral shape.
3. Pop one balloon and shake the balloons until they resemble a trigonal bipyramidal geometry.
4. Continue until all of the balloons are popped.

### Discussion
The following questions can help guide students to think about what they learned by observing this demonstration.

1. What do the balloons represent?

2. Why do any given number of balloons always take the same shape?

## Bending Water

### Objective

Water is a polar molecule, and can be attracted by static electricity. Students sometimes have a difficult time remembering that water is polar, and this demonstration will give them visual evidence that a water molecule acts like a tiny magnet.

### List of materials

- A balloon, nylon comb, or any item that can become charged by static electricity
- A water faucet or buret filled with water

### Procedure

1. Inflate the balloon, if necessary.
2. Adjust the faucet or buret to produce a small, even stream of water.
3. Charge the balloon, comb, or other item by rubbing it against your clothing or through your hair.
4. Hold the charged item about an inch away from the stream of water.
5. Repeat the process while varying the size of the stream of water, the amount of charge on the item, and the distance between the charged item and the stream of water.

### Discussion

The following questions can help guide students to think about what they learned by observing this demonstration.

1. Why does the water bend toward the charged item?
2. What was the effect of having a larger or smaller stream of water?
3. What was the effect of having more charge or holding the item closer to the stream of water?
4. What do you think would happen if we had a stream of oil or hexanes, a non-polar molecule?

# Going Deeper (In-class Discussion or Reflection)

Instructors should allow up to 30 minutes for discussion at the end of the session, or students can use the time to reflect on one or more of these questions in their journals.

1. Which geometries are always polar? Why?
2. Which is stronger a covalent bond or an IMF? Why?
3. Why do chemists focus on valence electrons?
4. Draw a diagram on the molecular level of water boiling.

## Before the Next Unit

Learners should read the Unit 5 text if they haven't already done so. They may wish to read one or more of the reading assignments from the list below, or, if you choose to have them use the course materials outside of class, they can watch the Unit 6 video and/or read the Unit 6 text as an assignment before the next session.

## References and Additional Resources

Gillespie, Ronald James and Hargittai, Istvan. *The VSEPR Model of Molecular Geometry*. Boston, MA: Dover, 1991, 2012.

PhET Interactive Simulations. "Molecule Shapes." University of Colorado at Boulder. Accessed February 3, 2013. http://phet.colorado.edu/en/simulation/molecule-shapes

Schmidt, Hans-Jurgen, et al. "Students' understanding of boiling points and intermolecular forces." *Chemistry Education Research and Practices*. 10 (2009): 265-272. Accessed June 9, 2013. http://pubs.rsc.org/en/content/articlelanding/2009/rp/b920829c

Tan, Kim-Chwee Daniel and David F. Treagust, "Evaluating Students' Understanding of Chemical Bonding," *School Science Review* 81 (294), September 1999. Accessed October 24, 2014. https://www.ase.org.uk/journals/school-science-review/1999/09/294/1186/SSR294Sept1999p75.pdf.

## For Professional Development

In addition to watching the videos, reading the text, and going through the activities listed in the course guide, participants taking this course for professional development should read the following papers and answer the corresponding reflection questions. Participants should then complete the accompanying professional development assignments.

### Further Reading & Reflection Questions

Nahum, Tami Levy, Rachel Mamlok-Naaman, and Avi Hofsein. "A New 'Bottum-Up' Framework for Teaching Chemical Bonding." Journal of Chemical Education 85:12 (2008): 1680-1685. Accessed July 23, 2013. http://stwww.weizmann.ac.il/menu/staff/Rachel_Mamlok/Bonding%20%20A%20new%20framework.pdf

Nahum et al, "Developing a New Teaching Approach for the Chemical Bonding Concept Aligned With Current Scientific and Pedagogical Knowledge," *Science Education* (2007). Accessed October 24, 2014. http://deepblue.lib.umich.edu/bitstream/handle/2027.42/56057/20201_ftp.pdf

1. Do you agree with any of the difficulties that the authors present about the traditional approach to teaching chemical bonding? If so, which ones and why? If not, why not?
2. What advantages do you see in using the "bottom-up" framework presented in this paper to teach chemistry? Do you see any disadvantages? What may be challenging in using this bottom-up approach?
3. Does this paper influence how you will approach teaching chemical bonding in the future? Why or why not? How, if at all, would you incorporate the bottom-up framework?

Cooper, Melanie M., Nathaniel Grove, Sonia M. Underwood, and Michael W. Klymkowsky. "Lost in Lewis Structures: An Investigation of Student Difficulties in Developing Representational Competence." *Journal of Chemical Education*. 87:8 (2010): Accessed July 25, 2013. http://educationgroup.mit.edu/HHMIEducationGroup/wp-content/uploads/2011/04/13-Cooper-etal-2010.pdf

1. Were you surprised by the results of this study? Why or why not?
2. Do you agree with the authors' suggestions on how to better teach Lewis structures and their significance? Why or why not?
3. How would you use the constructivist model to teach Lewis structures? Does this paper influence how you will teach or assess these topics?

## Professional Development Assignments

1. After reading the papers above and reflecting on the questions presented, develop a lesson plan designed to teach material presented in this unit.
2. Using a group activity or classroom demonstration presented in this course guide, show how you would implement it in your classroom. Where would it fit into your curriculum or standards? Would you change the demonstration or activity in any way? How would you assess student learning?