Khan Academy

High School Chemistry

Unit 6: States of matter

Overview

In this unit, students will explore the relationships between molecular structure, intermolecular forces, and macroscopic properties of substances.

Lesson 1: Students will apply the concept of electronegativity to predict types of bonds that form between atoms and to represent bond polarity. They will predict molecular geometry using VSEPR theory and then analyze geometry and bond polarity to determine molecular polarity.

Lesson 2: Students will use their understanding of molecular polarity to determine the types and relative strengths of intermolecular forces that exist within samples of different substances.

Lesson 3: Hands-on science activity (see below)

Lesson 4: Students will connect the relative strengths of intermolecular forces to macroscopic properties of liquids and solids and predict how properties, like boiling or melting point, compare among different substances.

Lesson 5: Students will use the kinetic molecular theory as a model to explain macroscopic properties and behavior of gases. They will analyze relationships between volume, pressure, temperature, and moles of an ideal gas using the gas laws.

Hands-on science activity

How does water form droplets on surfaces?

Students will **carry out an investigation** and **analyze and interpret data** on the behavior of several polar and nonpolar liquids. They will then **develop and use a model** of molecular polarity and intermolecular forces to **explain** their observations and make predictions related to macroscopic properties.

[Click here for links to the activity.]

Standards

Performance expectations: **HS-PS1-3 | HS-PS2-6**

Disciplinary core ideas: **HS-PS1.A.3 | HS-PS2.B.3**

Science and engineering practices:

- Developing and using models
- Planning and carrying out investigations
- Constructing explanations and designing solutions
- Analyzing and interpreting data

Crosscutting concepts:

- Structure and function
- Energy and matter
- Systems and system models
- Stability and change

[Click here to read the full standards.]

Essential questions

- What factors determine the nature and strength of attractions between molecules or atoms in a substance?
- How are macroscopic properties of substances affected by the relative strengths of intramolecular and intermolecular forces?
- What are the relationships between volume, pressure, temperature, and moles of a gas sample, and how can these relationships be used to predict changes in a system?

Lesson notes

Lesson 1: Electronegativity and bond polarity

PEs: HS-PS1-3, HS-PS2-6
DCIs: HS-PS1.A.3, HS-PS2.B.3

Resources

Video 5 | Exercise 3

Objectives	Teaching tips
• Explain the concept of **electronegativity** and its trends in the periodic table. • Analyze differences in electronegativity to predict the types of bonds that form between atoms, including **nonpolar covalent**, **polar covalent**, and ionic bonds. • Represent **bond polarity** with partial positive and negative charges. • Determine the relative polarities of different covalent bonds using electronegativity values. • Use Lewis diagrams and **VSEPR theory** to predict **molecular geometries**. • Analyze molecular geometry and bond polarity to determine **molecular polarity**.	• Guide students to review the key relationships in Coulomb's law and how these relationships explain periodic trends in atomic radius and ionization energy (Unit 2). After defining electronegativity, have students work in pairs or small groups to predict periodic trends in electronegativity. Ask them to explain their reasoning based on the Unit 2 concepts they reviewed. • Emphasize that the *difference* in electronegativity between bonding atoms determines where a bond falls along the spectrum from entirely nonpolar covalent to ionic. Analogies based on a tug-of-war are often used to explain this concept. Assign students to come up with their own analogies to demonstrate their understanding. Then, invite them to share and refine their ideas with the class. • After introducing how to use electronegativity differences to predict bond types, ask students to explain why this approach is consistent with their previous learning that ionic compounds are made up of metals and nonmetals, while covalent compounds are made up of only nonmetals. Prompt them to consider what they know about the organization of the periodic table and trends in electronegativity. • To bridge student learning from bond polarity to molecular polarity, introduce VSEPR theory using the PhET Molecule Shapes simulation. Have students work in pairs or small groups, using the *Model* section of the simulation. Instruct them to click *all* of the check boxes in order to see all available information. ○ Ask students to observe how bond angle, electron geometry, and molecular geometry change as they change the number of bonds and lone pairs around the central atom in a molecule. Guide students to answer questions like the following: ■ How does adding a bond or lone pair to the central atom affect the position of existing bonds or lone pairs in the molecule? ■ Does adding a double or triple bond have a different effect from adding a single bond? How about a lone pair?

        - What happens to the bond angle when you add more bonds or lone pairs to the central atom?
        - What happens when you click on an atom and try to move it into a different position?
        - Why do you think the bonds and lone pairs are oriented in specific ways in space relative to one another? What force is acting on them?
    - Provide a table for students to fill in using the simulation. Have them record the electron geometry, molecular geometry, and bond angle for each combination of bonds and lone pairs up to four total electron domains (2 bonds, 3 bonds, 2 bonds/1 lone pair, 4 bonds, 3 bonds/1 lone pair, 2 bonds/2 lone pairs).
    - Have students use the data they recorded in the table to predict electron geometry, molecular geometry, and bond angle for specific molecules and polyatomic ions from their chemical formulas. Ask students to draw a Lewis diagram for each molecule or ion, and then analyze the numbers of bonds and lone pairs around the central atom to make their predictions.
    - Tell students that the theory used to predict and explain the shapes of molecules is called *Valence Shell Electron Pair Repulsion Theory (VSEPR)*. Ask them to hypothesize why the theory has this name.
- Invite students to use model kits to build different molecules and compare their geometries. For example, have students create models for methane, ammonia, and water to emphasize that these molecules have the same electron geometry but different molecular geometries.
- Bring together students' understanding of molecular geometry and bond polarity by engaging them in a scaffolded exploration of molecular polarity with the PhET Molecule Polarity simulation.
    - Have students explore the *Two Atoms* section of the simulation to answer questions like those below. Ask them to provide evidence from the simulation to support their answers.
        - When you increase the electronegativity of Atom A as much as possible, what happens to the bond dipole, the partial charges, and the orientation of the molecule in the electric field? Why do these changes occur?
        - What causes the bond dipole to be as large as possible?
        - What causes there to be no bond dipole?
    - Have students explore the *Three Atoms* section of the simulation to answer questions like those below. Ask them to provide evidence from the simulation to support their answers.
        - If you increase the electronegativity of Atom A, how do the bond and molecular dipoles change?
        - If you increase the electronegativity of Atoms A ***and*** C, how do the bond and molecular dipoles change?
        - What happens to the molecular dipole when you change the bond angle to 180°?
        - Is it possible for a molecule to have bond dipoles but no molecular dipole?
        - Is it possible for a molecule to have a molecular dipole but no bond dipoles?

- Use the *Real Molecules* section of the simulation in guiding students to understand the following:
  - A molecular dipole is the vector sum of all the bond dipoles in a molecule.
  - A molecule is polar when bond dipoles do not cancel out and charge is unevenly distributed.
  - An electrostatic potential map is a model for visualizing charge distribution in a molecule.
- Have students apply their learning by predicting the molecular polarity of several new molecules. Ask them to use arrow notation and partial charges to represent the molecular dipole. Then, have them use colored pencils to create an electrostatic potential map that represents charge distribution.

Lesson 2: Intermolecular forces

PEs: HS-PS1-3, HS-PS2-6
DCIs: HS-PS1.A.3, HS-PS2.B.3

Resources

Video 3
Exercise 2

Objectives

- Identify and distinguish between **intramolecular** and **intermolecular forces**.
- Explain the nature of **London dispersion forces**, **dipole-dipole attractions**, and **hydrogen bonding**, and compare their relative strengths.
- Identify the strongest type of intermolecular forces that exist within a sample of a pure substance by analyzing either Lewis diagrams and **electrostatic potential maps** or molecular geometry and bond polarity.
- Determine the relative strengths of intermolecular forces within samples of different substances based on molecular polarity and molar mass.

Teaching tips

- Have students use blank paper and colored pencils to sketch electrostatic potential maps and label partial positive and negative charges for simple polar molecules, like water. Ask students to cut out their models, then guide them to arrange the molecules to maximize attractive forces and minimize repulsive forces. Once students have the molecules organized so that partial positive and negative charges on different molecules face toward each other, demonstrate drawing dotted lines between these charges to indicate intermolecular forces. Emphasize the distinction between the dotted lines between molecules and the solid lines between atoms *within* molecules (intramolecular forces).
- Ask students to brainstorm observations supporting the idea that attractive forces exist between molecules in a liquid. If students have trouble getting started, prompt their thinking with questions like:
  - What happens when you pour a liquid?
  - What do you see when you drop an object in a bucket of water?
- Emphasize that all intermolecular forces result from unequal charge distribution in molecules (either temporary or permanent dipoles). Have students work in pairs or small groups on whiteboards to create a storyboard showing frame-by-frame how a temporary, random uneven distribution of charge in one nonpolar molecule could induce dipoles in surrounding molecules and lead to a series of intermolecular attractions (London dispersion forces).
- Review the process for determining molecular polarity, then have students create flow charts for determining the *strongest* type of intermolecular forces that exist within a sample of a pure substance. Emphasize that London dispersion forces occur between polar molecules, as well as nonpolar molecules.
- Provide students with practice comparing the relative strengths of intermolecular forces within different substances. In addition to

	asking students to make comparisons among substances with different types of intermolecular forces, ask them to make comparisons among substances with dipole-dipole forces (based on the size of the molecular dipole moments) and among substances with London dispersion forces (based on molar mass). ● Implement the hands-on activity "*How does water form droplets on surfaces?*" in order for students to deepen their understanding of intermolecular forces by using their model to explain observed macroscopic properties of liquids (see Lesson 3).

Lesson 3: Hands-on science activity
How does water form droplets on surfaces?

PEs: HS-PS1-3, HS-PS2-6
DCIs: HS-PS1.A.3, HS-PS2.B.3

Resources

Activity
1

Description	Links
Students will **carry out an investigation** and **analyze and interpret data** on the behavior of several liquids. They will then **develop and use a model** of molecular polarity and intermolecular forces to **explain** their observations and make predictions related to macroscopic properties.	● Full activity overview (**Khan Academy article**) ● Student activity guide (**Doc** | **PDF**) ● Teacher guide (**Doc** | **PDF**)

Lesson 4: Liquids and solids

PEs: HS-PS1-3, HS-PS2-6
DCIs: HS-PS1.A.3, HS-PS2.B.3

Resources

Video 1
Exercise 2

Objectives	Teaching tips
● Explain how macroscopic properties of substances (such as state at room temperature, boiling point, melting point, and surface tension) are affected by the nature and strength of intramolecular and intermolecular forces. ● Predict the relative boiling points or rates of evaporation of different liquids based on the relative strengths of their intermolecular forces. ● Predict the relative melting points of different solids based on the types and relative strengths of electrical attractions holding them together.	● Review key student takeaways from the hands-on activity "*How does water form droplets on surfaces?*" relating the strength of intermolecular forces to macroscopic properties (Lesson 3). ● Show videos of wringing out a washcloth in space and a water strider moving across the surface of a pond, and ask students to explain these phenomena in terms of intermolecular forces. ● Refer back to Unit 4 when students learned about exothermic and endothermic reactions. Ask students to identify boiling and melting as exothermic or endothermic processes. Have them define the system and explain their reasoning. ● Present particle diagrams showing the organization of and attractions between particles in solid, liquid, and gas phases. Use these to guide students to connect the energy transferred into a solid or liquid sample to the weakening or breaking of electrostatic attractions between particles. Ask students to define the relationships between the strength of intermolecular forces, the energy required to break these forces, and the boiling point

	temperature of a substance. • Challenge students to predict the relative boiling points and/or rates of evaporation for a group of liquids. After students record their predictions, have them research the accepted values, and discuss any discrepancies between these values and their predictions. Use examples like ethanol (b.p. 78°C) versus octane (b.p. 126°C) to help students recognize that some nonpolar substances (with London dispersion forces) have stronger intermolecular attractions than some polar substances (with dipole-dipole forces or hydrogen bonding) due to the larger size and polarizability of their molecules. • Give students a list of melting points for a variety of solids (network covalent, ionic, metallic, and molecular). Have them work in pairs or small groups to look for trends in the data related to the types of electrical attractions holding the solids together (covalent bonds, ionic bonds, metallic bonds, or different types of intermolecular forces). Discuss their findings as a class, and guide students to recognize the relative strengths of the different types of attractions. Emphasize that, although molecular solids have very strong intramolecular forces (covalent bonds), it is only the *much weaker* intermolecular forces that must be overcome during a phase change. • Ask students to consider how intermolecular forces play a role in the process of separating crude oil into useful petroleum products that are essential in our daily lives. (*See the "Related phenomena" section below for more information.*)

Lesson 5: Gases

PEs: HS-PS1-3, HS-PS2-6
DCIs: HS-PS1.A.3, HS-PS2.B.3

Resources

Video: 4
Exercise: 3

Objectives	Teaching tips
• Use the **kinetic molecular theory** as a model to explain the macroscopic properties and behavior of gases. • Predict how and explain why gas pressure will change in response to changes in volume, temperature, or moles of particles in a gas sample. • Calculate changes in volume, pressure, temperature or moles of an **ideal gas** using the gas laws. • Interpret and draw particle diagrams representing the effect of changing one property of a gas (pressure, volume, temperature, or moles of particles) on another property of that gas. • Use the **ideal gas law** ($PV = nRT$) to calculate the pressure, volume, moles, or temperature of a gas sample in a given scenario.	• Spray perfume in one corner of the classroom, and ask students to raise their hands when they smell the scent. Guide students to consider how the molecules from the perfume are able to diffuse throughout the air in the room and why the scent will not remain in the room forever. This scenario helps students to recognize the following postulates of the kinetic molecular theory: ◦ Gas particles are in constant, random motion. ◦ Gas particles do not attract or repel each other. ◦ The volume of a gas depends on the volume of its container (not on the volume of individual gas particles) and will change as the volume of the container changes. • Demonstrate elastic collisions using billiard balls (or a video of billiard balls colliding) to help students visualize the behavior of individual gas particles when they collide with each other or with a surface. • Hold a textbook 20-30 cm above the surface of a table, and ask students if they expect the air to support the book when you release it. After they make a prediction, allow the book to fall to the table. Next, fill a large plastic bag with air and tie or seal it closed. Balance the textbook on top of the bag, and ask students to explain why the

• Describe and explain conditions in which gases exhibit non-ideal behavior.
• Explain the concept of **partial pressure** and determine this value for a specific gas in a mixture by applying **Dalton's law of partial pressure**.
	air is now able to support the book. Guide students to understand how gases create pressure through collisions of particles against the walls of a container, then ask them to come up with other examples where they have observed gas pressure.
	• Guide students to explore the relationships between volume, temperature, moles of particles, and pressure of a gas sample using the [PhET Gas Properties](#) simulation.
	  ○ Have students explore the *Energy* section of the simulation to see the relationship between temperature, average speed, and kinetic energy of particles.
	  ○ Have students explore the *Ideal* section of the simulation to answer questions like those below. Instruct them to click *all* of the check boxes in order to see all available information. Have students first make predictions and then gather data from the simulation to test their predictions for each question.
	  What happens to the gas pressure and the number of wall collisions per sample period when:
	    ■ You double the temperature while holding volume and number of particles constant?
	    ■ You double the volume while holding temperature and number of particles constant?
	    ■ You increase the number of particles while holding the volume and temperature constant?
	  ○ Guide students to summarize the relationships between gas pressure, temperature, volume, and number of particles using words and mathematical equations.
	  ○ Use this as a segue to introduce the ideal gas law equation and to show students how all the gas law equations can be derived from it. Guide students to understand how the gas laws can be used to calculate changes in volume, pressure, temperature or moles of a gas sample with equations like those below.
	$P_1V_1 = P_2V_2$ $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\frac{P_1}{n_1} = \frac{P_2}{n_2}$ $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$
	• Provide students with a graphic organizer, like the one below, to help them recognize and make sense of information in problems that ask them to analyze scenarios using the gas laws. Reinforce conceptual understanding by requiring students to draw a diagram of each scenario. Have them explain their quantitative answers using the kinetic molecular theory (KMT) in terms of particle motion and frequency and force of collisions with the walls of a container.

Variable	Value	Constant/ Changing	Variable	Value	Constant/ Changing
P_1			P_2		
V_1			V_2		
T_1			T_2		
n_1			n_2		
Diagram:					
Equation:					

	Calculations: **Answer:** **Explanation based on KMT:** • Use simple demonstrations to help students build conceptual understanding and get practice applying the gas laws relationships to real-world scenarios. Before carrying out each demonstration, describe what you will do, and ask students to make predictions about what they think will happen. After the demonstration, ask students to draw particle diagrams representing the changes that occurred in the gas sample. Have them explain their observations using the kinetic molecular theory in terms of particle motion and frequency and force of collisions with the walls of a container. Example demonstrations: ○ Inflate a marshmallow with a syringe or a vacuum bell jar. ○ Crush a soda can by heating a small amount of water inside until it vaporizes, then plunging the can into an ice water bath. ○ Inflate and deflate a balloon stretched over the neck of a flask by alternately placing the flask in hot water and ice water. • Revisit the *Ideal* section of the PhET Gas Properties simulation to help students conceptualize Dalton's law of partial pressure. ○ Use the arrow buttons on the upper right of the screen to add exactly 75 "heavy" particles. Ask students to observe the gas sample for 10 seconds, and record the highest pressure they see on the gauge. ○ Ask students to predict what will happen to the pressure if you add 25 "light" particles to the container, while holding temperature and volume constant. Add the particles, and ask students to record the highest pressure they see on the gauge. ○ Ask students to predict what will happen to the pressure if you remove the 75 "heavy" particles. Use the arrow buttons to remove the "heavy" particles, and ask students to record the highest pressure they see on the gauge. ○ Guide students to recognize that the total pressure of the gas sample is the sum of the pressures that each gas in a mixture would exert if it occupied the entire volume alone. ○ Allow students to try different mixtures of "heavy" and "light" gas particles to see that if a gas makes up a certain percentage of the total number of particles in a sample, then it will be responsible for that same percentage of the total pressure. • Explore how Dalton's law of partial pressure explains why a scuba diver's tank isn't filled with pure oxygen. (*See the "Related phenomena" section below for more information.*)

Related phenomena

Example phenomenon

How is crude oil separated into different substances that become essential materials for everyday products?


Fractional distillation columns at a crude oil refinery

Background information

Petroleum products refined from crude oil are essential components of almost every aspect of modern life. They are used to fuel cars, trucks, boats, and airplanes, to heat buildings, to produce electricity, and to pave roads. They are used to manufacture different types of plastic that appear in myriad applications from construction to electronics to toys to clothing, and they serve as building blocks for compounds used in pharmaceuticals and personal care products.

When crude oil is extracted from underground reservoirs, it is a black, gooey mixture of many different *hydrocarbons* (compounds made up of H and C atoms) of various sizes and molecular structures. These hydrocarbons formed over millions of years from the remains of marine organisms that were covered by layers of sand, silt, and rock. Oil refineries use a process called *fractional distillation* to separate the components of crude oil into useful petroleum products based on their differences in boiling point.

First, the crude oil is heated until the mixture of hydrocarbons vaporizes (around 600 °C or 1112 °F), and then the mixture is fed into the bottom of a *distillation tower*. This tower is a tall vertical column containing collection trays at different heights. As the vapor mixture rises in the tower, the temperature decreases, and different components of the mixture begin to condense back to the liquid phase on the collection trays at different heights. The *fraction* collected at each height, containing hydrocarbons with similar boiling points, is funneled into a separate storage tank.

Since hydrocarbons are nonpolar, their molecules are attracted to each other by London dispersion forces in the liquid and solid phases. The strength of London dispersion forces increases as molecules become larger, have more electrons, and are more polarizable. Stronger intermolecular forces require a greater input of energy to break, which corresponds to a higher boiling point temperature. As a result, fractional distillation of crude oil can be used to isolate hydrocarbons with similar molar masses.

Components with higher molar masses and higher boiling points will condense at higher temperatures and are removed at the bottom of the distillation tower. Those with lower molar masses and lower boiling points will be able to rise higher in the tower before they are cooled enough to condense and be removed. Hydrocarbons that are too volatile to condense in the tower, such as propane and butane, are collected as gases at the very top. Once the fractions are separated from each other, they can be further refined or used directly in applications.

Exploring this phenomenon helps students develop and master the following understandings:

- ☐ A molecule is nonpolar when charge is evenly distributed because bonds are nonpolar or bond dipoles cancel out.
- ☐ Nonpolar molecules are attracted by London dispersion forces when a temporary, random uneven distribution of charge in one molecule induces dipoles in surrounding molecules and leads to a series of intermolecular attractions throughout a sample of a substance.

- ☐ The strength of London dispersion forces depends on the size and polarizability of the molecules in a sample of a substance and generally increases as molar mass increases.
- ☐ Stronger intermolecular forces require more energy to break, which leads to a relatively higher boiling point for a substance.

Tips for implementing phenomenon-based learning

- Introduce the phenomenon by asking students to brainstorm ways that we use oil/petroleum products in our daily lives. Then, show them this Oil in Everyday Life infographic, and discuss additional applications that they didn't identify initially. Ask students to look for applications that surprised them and for those that have come up while studying other phenomena, such as pharmaceuticals (Unit 5), gasoline (Unit 5), and different types of plastic packaging (Unit 3).
- Provide students with the molecular structures of various hydrocarbons from different crude oil fractions, such as butane (petroleum gases), octane (gasoline), undecane (kerosene), and isocetane (diesel oil). Have students work in pairs or small groups to:
    - Determine the strongest type of intermolecular force that exists between molecules in a pure sample of each substance, and explain their reasoning.
    - Arrange the substances in order of increasing strength of intermolecular forces, and explain their reasoning.
    - Arrange the substances in order of increasing boiling point, and explain their reasoning.
- Give students a diagram of a fractional distillation tower with all of the labels removed. Share the information in the third paragraph of the background information above related to how the tower works. Then, ask students to indicate on the diagram where they would expect each of the substances they previously analyzed to exit the tower as a fraction. Discuss why smaller molecules with lower boiling points will travel higher in the tower before condensing to the liquid phase. Follow up this activity and discussion by showing a video reviewing the key aspects of the fractional distillation process.
- Use this Khan Academy video to help students understand how the process of distillation works, in general, to separate pure liquids from a mixture.
- Carry out a distillation demonstration or have students watch a video to observe the separation of components in a mixture, such as ethanol and water or water and food coloring, based on differences in boiling point.
- Assign each student or small groups of students to research common uses for one of the crude oil distillation fractions and to create an infographic sharing what they learn with their classmates. This video can provide a useful jumping off point.

Example phenomenon

Why isn't a scuba diver's tank filled with pure oxygen?

Background information

Scuba divers using tanks of compressed gas

Dalton's law of partial pressure plays a crucial role in the safe practice of scuba diving, where divers rely on compressed gas mixtures stored in tanks to breathe underwater. The air we breathe normally at sea level is about 21% oxygen, 78% nitrogen, and small percentages of other gases. According to Dalton's law of partial pressure, the pressure exerted by a mixture of gases is equal to the sum of the pressures that would be exerted by the gases individually. Since we experience 1 atm of air pressure at sea level, this corresponds to a partial pressure of 0.21 atm for oxygen and 0.78 atm for nitrogen.

As divers descend underwater, the added weight of water pressing down on them increases the total pressure of gas in their tanks by about 1 atm for every 10 m of depth. At 20 m, for example, the total pressure would be 3 atm (1 atm of air and 2 atm of water). An increase in total pressure also means an increase in the partial pressure of each gas in the mixture. Divers must be careful, because physiological complications, such as oxygen toxicity and nitrogen narcosis, can occur when the partial pressures of these gases reach critical levels.

Breathing oxygen at a partial pressure above 1.4 atm may cause convulsions and damage to lungs, eyes, and other body tissues. This means that a scuba diver with a tank of pure oxygen, could begin to experience the effects of oxygen toxicity after descending just 4 meters below the surface. Breathing nitrogen gas at increased partial pressures leads to nitrogen narcosis, an alteration in consciousness that may cause dangerously impaired judgment, coordination, and focus.

Divers use their understanding of Dalton's law of partial pressure to select safe gas mixtures in their tanks depending on the length and depth of a planned dive. Mixtures with increased percentages of oxygen (usually 32 or 36%) and less nitrogen compared to regular air are used to mitigate the physiological effects of nitrogen on longer dives. Divers can stay underwater longer, but they can't descend as far, because the partial pressure of oxygen will reach the maximum safe limit at a shallower depth.

In order to dive beyond 40 m, divers use special gas mixtures of helium with nitrogen and oxygen or just helium and oxygen. Helium is an inert gas that does not produce narcotic effects, but it is too expensive to be used for common recreational diving at shallower depths. For very deep dives, divers may need to carry multiple tanks containing different percentages of oxygen and switch from one tank to another as they descend in order to account for changes in partial pressure.

Exploring this phenomenon helps students develop and master the following understandings:

- ☐ Since particles in an ideal gas are in constant, random motion, do not attract or repel each other, and have completely elastic collisions, different gases in a mixture act independently.
- ☐ The total pressure of a gas mixture is the sum of the pressures that each gas would exert if it occupied the entire volume by itself (its partial pressure).
- ☐ If a gas makes up a certain percentage of the total number of particles in a sample, then it will be responsible for that same percentage of the total pressure.

Tips for implementing phenomenon-based learning

- Introduce students to the effects of water pressure by showing a quick video of a scuba diver descending underwater with a plastic bottle filled with air. Ask students to explain what they observe using the gas laws. Have them work in pairs or small groups with whiteboards to draw and annotate particle diagrams. After discussing their ideas as a class, ask students to hypothesize: *How does the pressure of the gas inside a diver's tank change as the diver descends underwater?*
- Given that regular air is 21% oxygen and 78% nitrogen, ask students to determine what the partial pressure of each gas would be under normal atmospheric conditions at sea level (1 atm). Have them use the kinetic molecular theory to explain why the partial pressure of oxygen doesn't affect the partial pressure of nitrogen.
- Assign students to research the physiological effects of oxygen toxicity and nitrogen narcosis, and discuss what they learned. Once students understand the potentially dire effects of partial pressure changes as divers descend, guide them to determine how deep a diver could safely go with a tank of 100% oxygen (given that oxygen toxicity can occur at a partial pressure of 1.4 atm, and total pressure increases 1 atm for every 10 m of depth).

  Note that trained divers are advised to carry their own gas analyzers to check the mixture of gases in their tanks before diving. Ask students to consider: *Why can even a seemingly small difference in the percentage of oxygen in a tank make a big difference in terms of safe depth for a dive?*
- Have students work in pairs or small groups to create their own diagrams showing:
  - The total pressure (air + water) as a diver descends underwater at 10 m intervals up to 100 m.
  - The partial pressure of oxygen in normal air at each 10 m interval.
  - The maximum safe depth to which a diver can descend while using a tank of regular air (to avoid oxygen toxicity).
- Ask students to consider what divers could do if they wanted to descend below the maximum safe depth using a tank of regular air. Prompt student thinking by asking:
  - *What are the potential effects of diving too deep using regular air?*
  - *How could changing the percentage of oxygen in a dive tank affect the safe diving depth?*

  Introduce the practice of replacing most of the nitrogen and some of the oxygen in regular air with helium. Ask students to consider:
  - *Why is helium used, rather than other gases?*
  - *Why does replacing nitrogen and some oxygen with helium increase safe diving depths?*
- Invite students to research popular scuba diving sites around the world and select one that captures their interest. Assign them to plan a safe dive by determining the percentage of oxygen needed in the gas mixture for a diver's tank based on the depth of the dive site. Have students create a brief presentation or advertising brochure that provides interesting information about the site they chose and explains their gas mixture calculations for safe diving. Invite the class to vote on the site they would like to visit, based on the presentations/brochures.
- Have students research professions that use scuba diving, such as marine archeologists or biologists, search and rescue teams, and saturation divers who repair underwater oil pipelines. Connect with a local dive club to arrange for someone to visit the class to show examples of scuba gear and to talk about diving practices and their experiences.

Common student misconceptions

Possible misconception: *All molecules with polar bonds are polar.* Students may disregard the impact of molecular geometry on the distribution of charge in a molecule and think that the presence of polar bonds is the only criterion necessary for a molecule to be polar.
Critical concepts • A molecular dipole is the vector sum of all the bond dipoles in a molecule. • A molecule is polar when charge is unevenly distributed because bond dipoles do not cancel out. • A molecule is nonpolar when charge is evenly distributed, either because bonds are nonpolar or because bond dipoles cancel out.
How to address this misconception Use the PhET Molecule Polarity simulation to demonstrate how the molecular dipole depends on the direction and size of the individual bond dipoles. Show examples in the *Real Molecules* section of the simulation, such as carbon dioxide, boron trifluoride, methane, and carbon tetrafluoride, that are nonpolar molecules with polar bonds. Use electrostatic potential maps to emphasize that the symmetry of the molecules leads to an overall even distribution of charge. Contrast this with molecules, such as hydrogen cyanide, formaldehyde, ammonia, and fluoromethane, where asymmetry leads to an overall uneven distribution of charge.

Possible misconception: *Hydrogen bonds are covalent bonds between hydrogen atoms and N, O, or F atoms.* Since covalent bonds between hydrogen and N, O, or F atoms are *necessary* for hydrogen bonds to form between molecules, students may think that these covalent bonds are *the same as* hydrogen bonds. In addition, the word "bonds" in the name of this intermolecular force may lead students to assume that hydrogen bonds are a type of intramolecular force.

Critical concepts
• Covalent bonds are intramolecular forces that exist between atoms *within* a molecule.
• Hydrogen bonds are a special case of strong dipole-dipole intermolecular forces that exist *between* polar molecules.
    ○ When hydrogen is bonded to a highly electronegative atom (N, O, or F), it results in a large dipole moment with a partial positive charge on H and a partial negative charge on the other atom.
    ○ The partially positive H atom from one molecule will attract the partially positive N, O, or F atom from another molecule.

How to address this misconception When discussing the relative strengths of intermolecular forces, be sure to emphasize that these are all distinct from and weaker than intramolecular forces (covalent, ionic, and metallic bonds). Have students draw molecular-level diagrams of liquid water, or other substances that have hydrogen bonding between the molecules in a pure sample. Students should show covalent bonds within molecules as solid lines and

intermolecular attractions (hydrogen bonds) as dotted lines. Ask students to draw a diagram showing how the sample would look different in the gas phase. Guide students to recognize that the weaker hydrogen bonds (dotted lines) between a partially positive hydrogen atom on one water molecule and the partially negative oxygen atom on another molecule would no longer be present, but the stronger covalent bonds (solid lines) between hydrogen and oxygen atoms within the molecules would remain intact.

Possible misconception: *Gas volume and pressure are directly proportional.*

Students may think that the pressure of a gas increases as its volume increases. This may stem from seeing examples where an expandable container, like a balloon, increases in volume and also increases in pressure until it breaks or explodes. Students may not take into account the impact of increasing the number of particles or the temperature inside the container, both of which will lead to increased pressure.

Critical concepts

- Gases consist of particles in constant, random motion, and gas pressure is created by particles in a gas sample colliding with the walls of their container.
- If temperature and the number of particles in a gas sample remain constant, then as the volume of the container increases, particles have more space to move. They collide with the walls of the container less frequently, and pressure decreases.
- Conversely, as the volume of the container decreases (at constant temperature), particles in the gas sample have less space to move, so they collide with the walls of the container more frequently, and pressure increases.

How to address this misconception

Provide students with many opportunities to observe this relationship in action through the PhET Gas Properties simulation and simple demonstrations, such as inflating a marshmallow. Have students use a syringe connected to a pressure gauge to collect and graph data on pressure versus volume. The negative slope of the graph provides another visual representation of the inverse relationship between these gas properties. In all cases, encourage students to recognize that temperature and moles of particles are held constant.

Unit resources

Student resources

- Unit 2 (Atomic models and periodicity): Use the resources in this Khan Academy unit to review how the relationships in Coulomb's law explain periodic trends in atomic radius and ionization energy.
- Lewis diagrams for molecules: Review how to draw Lewis diagrams for simple molecules.
- PhET Molecule Shapes and PhET Molecule Polarity: Use these simulations to investigate VSEPR theory and the effects of bond polarity and molecular geometry on molecular polarity.
- Wringing out Water on the ISS and What is Surface Tension?: Watch what happens when you wring out a washcloth in space or a water strider moves across a pond.
- Exothermic and endothermic reactions: Review energy changes in chemical reactions from Unit 4.
- PhET Gas Properties: Use this simulation to explore the relationships between volume, temperature, moles of particles, and pressure of a gas sample.
- Marshmallow in a syringe demo and Marshmallows and Shaving Cream: Observe what happens when atmospheric pressure on a marshmallow decreases in a syringe or a vacuum bell jar.
- Crushing a Can with Air Pressure: Watch a soda can crumple according to the gas laws.
- Hot and Cold Balloon Experiment: See how temperature affects the volume of a gas sample.
- Oil in Everyday Life: Use this infographic to explore applications of petroleum products in our daily lives.
- Crude Oil Distillation (diagram), Fractional Distillation (video), and Crude Oil Fractions & Their Uses (video): Use these resources to understand the process and products of fractional distillation of crude oil.
- Distillation (Khan Academy video), How to Set-up and Perform Fractional Distillation (video), and Simple Distillation (video): Use these resources to understand and observe how the process of distillation works, in general, to separate pure liquids from a mixture.
- What Happens To A Water Bottle Underwater?: See how water pressure affects air inside a plastic bottle.
- Article and video note taking template (Doc | PDF): Use this printable template for structured note taking on the articles and videos in this unit.
- Graph paper template (Doc | PDF): Use this printable template for manual graphing exercises.

Classroom implementation resources

- Weekly Khan Academy quick planning guide (Doc | PDF): Use this template to easily plan your week.
- Using Khan Academy in the classroom (Doc | PDF): Learn about teaching strategies and structures to support your students in their learning with Khan Academy.
- Differentiation strategies for the classroom (Doc | PDF): Read about strategies to support the learning of all students.
- Using phenomena with the NGSS: Learn more about how to incorporate phenomena into NGSS-aligned lessons.
- Hands-on science activities from Khan Academy: Choose from Khan Academy's collection of high-quality, ready-to-use, and free hands-on science activities. Each one is engaging, three-dimensional, phenomenon-based, and simple to implement.

NGSS standards reference guide

Performance expectations

- **HS-PS1-3:** Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.
- **HS-PS2-6:** Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.

Disciplinary core ideas

- **HS-PS1.A.3:** The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms.
- **HS-PS2.B.3:** Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.

Science and engineering practices (SEPs)

- **Developing and using models**: Students progress to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.
- **Planning and carrying out investigations:** Students progress to include investigations that provide evidence for and test conceptual, mathematical, physical, and empirical models.
- **Analyzing and interpreting data:** Students progress to introducing more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data.
- **Constructing explanations and designing solutions:** Students progress to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.

Crosscutting concepts (CCCs) and their implementation

Crosscutting concept	Unit implementation
Structure and function: The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.	Students connect molecular structure to intermolecular forces and macroscopic properties of substances.
Energy and matter (Flows, cycles, and conservation): Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.	Students consider relative amounts of energy required to weaken or break intramolecular and intermolecular forces within samples of different substances.
Systems and system models: Defining the system under study—specifying its boundaries and making explicitly a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.	Students model the behavior of gases using the kinetic molecular theory and the gas laws.
Stability and change: For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.	Students predict how gas pressure will change in response to changes in volume, temperature, or moles of particles in a gas sample.