

## AP CHEMISTRY

# UNIT 3

# Properties of Substances and Mixtures



**18–22%**  
AP EXAM WEIGHTING



**~14–15**  
CLASS PERIODS

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# Properties of Substances and Mixtures



## Developing Understanding

### ESSENTIAL QUESTIONS

- How do interactions between particles influence the properties of pure substances and mixtures?
- Why does the smell of perfume only last for a short time?
- Why can you swim in water, but you can't walk through a wall?
- How does the spacing and motion of particles relate to a substance's state of matter and the properties of gases?
- How can you determine the structure and concentration of a chemical species in a mixture?

Transformations of matter can be observed in ways that are generally categorized as either a chemical or physical change. The shapes of the particles involved and the space between them are key factors in determining the nature of physical changes. The properties of solids, liquids, and gases reflect the relative orderliness of the arrangement of particles in those states, their relative freedom of motion, and the nature and strength of the interactions between them. There is a relationship between the macroscopic properties of solids, liquids, and gases, as well as the structure of the constituent particles of those materials on the molecular and atomic scale. In subsequent units, students will explore chemical transformations of matter.

## Building the Science Practices

2.C 2.D 2.E 3.C 4.C 4.D 5.C 5.F

This unit requires students to draw upon claims made in Unit 2 about molecular geometry and polarity to support claims about intermolecular forces between molecules. Further, students will practice illustrating such claims by constructing particle representations of pure solids, liquids, gases, and solutions.

This unit also requires students to build proficiency with mathematical reasoning skills, essential for success in the remainder of the course. Students should be able to explain relationships between variables in an equation (e.g., the ideal gas law) and then estimate the approximate value of one variable within an equation when the value of another variable changes. Students will practice these skills when choosing and implementing experimental procedures, making observations, and/or collecting data to address a question. Students can then determine the accuracy and precision of the data as well as manipulate it with known mathematical equations to support their claims (e.g., concentration of a substance, properties of substances in a mixture).

## Preparing for the AP Exam

On the AP Exam (in both the multiple-choice and the free-response section), students are required to compare the physical properties of substances and relate them to the attractive forces between particles. Students often struggle with questions that require them to determine the forces of attraction that are present between molecules. Moreover, it can be challenging for them to determine which forces are most important in explaining the differences in physical properties, such as melting points, boiling points, and vapor pressures of molecules in the solid and/or liquid state.

Students also confuse the terms intramolecular and intermolecular forces. Another common mistake students make is to simplify their explanations about governing intermolecular forces in a substance by using terms such as "strong" and "weak." Teachers can ensure that students can identify an actual intermolecular force and explain its strength in relation to other forces at play.

## SUGGESTED SKILL

 Model Analysis

## 4.D

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.



## AVAILABLE RESOURCES

- Classroom Resource > [Guided Inquiry Activities for the Classroom: Lesson 3](#)
- The Exam > [2017 Chief Reader Report](#)

## TOPIC 3.1

# Intermolecular and Interparticle Forces

## Required Course Content

### LEARNING OBJECTIVE

**3.1.A**

Explain the relationship between the chemical structures of molecules and the relative strength of their intermolecular forces when:

- The molecules are of the same chemical species.
- The molecules are of two different chemical species.

### ESSENTIAL KNOWLEDGE

**3.1.A.1**

London dispersion forces are a result of the Coulombic interactions between temporary, fluctuating dipoles. London dispersion forces are often the strongest net intermolecular force between large molecules.

- Dispersion forces increase with increasing contact area between molecules and with increasing polarizability of the molecules.
- The polarizability of a molecule increases with an increasing number of electrons in the molecule and the size of the electron cloud. It is enhanced by the presence of pi bonding.
- The term “London dispersion forces” should not be used synonymously with the term “van der Waals forces.”

**3.1.A.2**

The dipole moment of a polar molecule leads to additional interactions with other chemical species.

- Dipole-induced dipole interactions are present between a polar and nonpolar molecule. These forces are always attractive. The strength of these forces increases with the magnitude of the dipole of the polar molecule and with the polarizability of the nonpolar molecule.

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## LEARNING OBJECTIVE

### 3.1.A

Explain the relationship between the chemical structures of molecules and the relative strength of their intermolecular forces when:

- The molecules are of the same chemical species.
- The molecules are of two different chemical species.

## ESSENTIAL KNOWLEDGE

- Dipole-dipole interactions are present between polar molecules. The interaction strength depends on the magnitudes of the dipoles and their relative orientation. Interactions between polar molecules are typically greater than those between nonpolar molecules of comparable size because these interactions act in addition to London dispersion forces.
- Ion-dipole forces of attraction are present between ions and polar molecules. These tend to be stronger than dipole-dipole forces.

### 3.1.A.3

The relative strength and orientation dependence of dipole-dipole and ion-dipole forces can be understood qualitatively by considering the sign of the partial charges responsible for the molecular dipole moment, and how these partial charges interact with an ion or with an adjacent dipole.

### 3.1.A.4

Hydrogen bonding is a strong type of intermolecular interaction that exists when hydrogen atoms covalently bonded to the highly electronegative atoms (N, O, and F) are attracted to the negative end of a dipole formed by the electronegative atom (N, O, and F) in a different molecule, or a different part of the same molecule.

### 3.1.A.5

In large biomolecules, noncovalent interactions may occur between different molecules or between different regions of the same large biomolecule.

## SUGGESTED SKILL

 Model Analysis

## 4.C

Explain the connection between particulate-level and macroscopic properties of a substance using models and representations.



## AVAILABLE RESOURCES

- AP Chemistry Lab Manual > [Investigation 6: What's in That Bottle?](#)

## TOPIC 3.2

# Properties of Solids

## Required Course Content

### LEARNING OBJECTIVE

**3.2.A**

Explain the relationship among the macroscopic properties of a substance, the particulate-level structure of the substance, and the interactions between these particles.

### ESSENTIAL KNOWLEDGE

**3.2.A.1**

Many properties of liquids and solids are determined by the strengths and types of intermolecular forces present. Because intermolecular interactions are overcome completely when a substance vaporizes, the vapor pressure and boiling point are directly related to the strength of those interactions. Melting points also tend to correlate with interaction strength, but because the interactions are only rearranged, in melting, the relations can be more subtle.

**3.2.A.2**

Particulate-level representations, showing multiple interacting chemical species, are a useful means to communicate or understand how intermolecular interactions help to establish macroscopic properties.

**3.2.A.3**

Due to strong interactions between ions, ionic solids tend to have low vapor pressures, high melting points, and high boiling points. They tend to be brittle due to the repulsion of like charges caused when one layer slides across another layer. They conduct electricity only when the ions are mobile, as when the ionic solid is melted (i.e., in a molten state) or dissolved in water or another solvent.

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## LEARNING OBJECTIVE

### 3.2.A

Explain the relationship among the macroscopic properties of a substance, the particulate-level structure of the substance, and the interactions between these particles.

## ESSENTIAL KNOWLEDGE

### 3.2.A.4

In covalent network solids, the atoms are covalently bonded together into a three-dimensional network (e.g., diamond) or layers of two-dimensional networks (e.g., graphite). These are only formed from nonmetals and metalloids: elemental (e.g., diamond, graphite) or binary compounds (e.g., silicon dioxide and silicon carbide). Due to the strong covalent interactions, covalent solids have high melting points. Three-dimensional network solids are also rigid and hard, because the covalent bond angles are fixed. However, graphite is soft because adjacent layers can slide past each other relatively easily.

### 3.2.A.5

Molecular solids are composed of distinct, individual units of covalently-bonded molecules attracted to each other through relatively weak intermolecular forces. Molecular solids generally have a low melting point because of the relatively weak intermolecular forces present between the molecules. They do not conduct electricity because their valence electrons are tightly held within the covalent bonds and the lone pairs of each constituent molecule. Molecular solids are sometimes composed of very large molecules or polymers.


### 3.2.A.6

Metallic solids are good conductors of electricity and heat, due to the presence of free valence electrons. They also tend to be malleable and ductile, due to the ease with which the metal cores can rearrange their structure. In an interstitial alloy, interstitial atoms tend to make the lattice more rigid, decreasing malleability and ductility. Alloys typically retain a sea of mobile electrons and so remain conducting.

### 3.2.A.7

In large biomolecules or polymers, noncovalent interactions may occur between different molecules or between different regions of the same large biomolecule. The functionality and properties of such molecules depend strongly on the shape of the molecule, which is largely dictated by noncovalent interactions.

## SUGGESTED SKILL

 *Representing Data and Phenomena*

## 3.C

Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).



## AVAILABLE RESOURCES

- The Exam > 2017 Chief Reader Report

## TOPIC 3.3

# Solids, Liquids, and Gases

## Required Course Content

### LEARNING OBJECTIVE

**3.3.A**

Represent the differences between solid, liquid, and gas phases using a particulate-level model.

### ESSENTIAL KNOWLEDGE

**3.3.A.1**

Solids can be crystalline, where the particles are arranged in a regular three-dimensional structure, or they can be amorphous, where the particles do not have a regular, orderly arrangement. In both cases, the motion of the individual particles is limited, and the particles do not undergo overall translation with respect to each other. The structure of the solid is influenced by interparticle interactions and the ability of the particles to pack together.

**3.3.A.2**

The constituent particles in liquids are in close contact with each other, and they are continually moving and colliding. The arrangement and movement of particles are influenced by the nature and strength of the forces (e.g., polarity, hydrogen bonding, and temperature) between the particles.

**3.3.A.3**

The solid and liquid phases for a particular substance typically have similar molar volume because, in both phases, the constituent particles are in close contact at all times.

**3.3.A.4**

In the gas phase, the particles are in constant motion. Their frequencies of collision and the average spacing between them are dependent on temperature, pressure, and volume. Because of this constant motion, and minimal effects of forces between particles, a gas has neither a definite volume nor a definite shape.

**Exclusion Statement:** Understanding/interpreting phase diagrams will not be assessed on the AP Exam.

## TOPIC 3.4

## Ideal Gas Law

## SUGGESTED SKILL

 *Mathematical Routines*

## 5.C

Explain the relationship between variables within an equation when one variable changes.



## AVAILABLE RESOURCES

- The Exam > 2017 Chief Reader Report

## Required Course Content

## LEARNING OBJECTIVE

## 3.4.A

Explain the relationship between the macroscopic properties of a sample of gas or mixture of gases using the ideal gas law.

## ESSENTIAL KNOWLEDGE

## 3.4.A.1

The macroscopic properties of ideal gases are related through the ideal gas law:

EQN:  $PV = nRT$ .

## 3.4.A.2

In a sample containing a mixture of ideal gases, the pressure exerted by each component (the partial pressure) is independent of the other components. Therefore, the partial pressure of a gas within the mixture is proportional to its mole fraction ( $X$ ), and the total pressure of the sample is the sum of the partial pressures.

EQN:  $P_A = P_{total} \times X_A$ ,

where  $X_A$  = moles A/total moles;

EQN:  $P_{total} = P_A + P_B + P_C + \dots$

## 3.4.A.3

Graphical representations of the relationships between  $P$ ,  $V$ ,  $T$ , and  $n$  are useful to describe gas behavior.



## SUGGESTED SKILL

 Model Analysis

## 4.A

Predict and/or explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.

## TOPIC 3.5

# Kinetic Molecular Theory

## Required Course Content

### LEARNING OBJECTIVE

**3.5.A**

Explain the relationship between the motion of particles and the macroscopic properties of gases with:

- The kinetic molecular theory (KMT).
- A particulate model.
- A graphical representation.

### ESSENTIAL KNOWLEDGE

**3.5.A.1**

The kinetic molecular theory (KMT) relates the macroscopic properties of gases to motions of the particles in the gas. The Maxwell-Boltzmann distribution describes the distribution of the kinetic energies of particles at a given temperature.

**3.5.A.2**

All the particles in a sample of matter are in continuous, random motion. The average kinetic energy of a particle is related to its average velocity by the equation:

$$\text{EQN: } KE = \frac{1}{2} mv^2.$$

**3.5.A.3**

The Kelvin temperature of a sample of matter is proportional to the average kinetic energy of the particles in the sample.

**3.5.A.4**

The Maxwell-Boltzmann distribution provides a graphical representation of the energies/velocities of particles at a given temperature.

## TOPIC 3.6

# Deviation from Ideal Gas Law

## Required Course Content

**LEARNING OBJECTIVE****3.6.A**

Explain the relationship among non-ideal behaviors of gases, interparticle forces, and/or volumes.

**ESSENTIAL KNOWLEDGE****3.6.A.1**

The ideal gas law does not explain the actual behavior of real gases. Deviations from the ideal gas law may result from interparticle attractions among gas molecules, particularly at conditions that are close to those resulting in condensation. Deviations may also arise from particle volumes, particularly at extremely high pressures.

**SUGGESTED SKILL***Argumentation***6.E**

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

**AVAILABLE RESOURCES**

- The Exam > [2019 Chief Reader Report](#)

## SUGGESTED SKILL

 *Mathematical Routines*

## 5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).



## AVAILABLE RESOURCES

- AP Chemistry Lab Manual > [Investigation 7: Using the Principle That Each Substance Has Unique Properties to Purify a Mixture: An Experiment in Applying Green Chemistry in Purification](#)

## TOPIC 3.7

# Solutions and Mixtures

## Required Course Content

## LEARNING OBJECTIVE

## 3.7.A

Calculate the number of solute particles, volume, or molarity of solutions.

## ESSENTIAL KNOWLEDGE

## 3.7.A.1

Solutions, also sometimes called homogeneous mixtures, can be solids, liquids, or gases. In a solution, the macroscopic properties do not vary throughout the sample. In a heterogeneous mixture, the macroscopic properties depend on location in the mixture.

## 3.7.A.2

Solution composition can be expressed in a variety of ways; molarity is the most common method used in the laboratory.

$$\text{EQN: } M = n_{\text{solute}} / L_{\text{solution}}$$

## TOPIC 3.8

# Representations of Solutions

## Required Course Content

**LEARNING OBJECTIVE****3.8.A**

Using particulate models for mixtures:

- Represent interactions between components.
- Represent concentrations of components.


**ESSENTIAL KNOWLEDGE****3.8.A.1**

Particulate representations of solutions communicate the structure and properties of solutions, by illustration of the relative concentrations of the components in the solution and/or drawings that show interactions among the components.

**Exclusion Statement:** Colligative properties will not be assessed on the AP Exam.

**Exclusion Statement:** Calculations of molality, percent by mass, and percent by volume for solutions will not be assessed on the AP Exam.

**SUGGESTED SKILL**

 **Representing Data and Phenomena**


**3.C**

Represent visually the relationship between the structures and interactions across multiple levels or scales (e.g., particulate to macroscopic).

**AVAILABLE RESOURCES**

- The Exam > **2021 Chief Reader Report**

## SUGGESTED SKILL

 Question and Method

## 2.C

Identify experimental procedures that are aligned to the question (which may include a sketch of a lab setup).



## AVAILABLE RESOURCES

- AP Chemistry Lab Manual > [Investigation 5: Sticky Question: How Do You Separate Molecules That Are Attracted to One Another?](#)

## TOPIC 3.9

# Separation of Solutions and Mixtures

## Required Course Content

### LEARNING OBJECTIVE

**3.9.A**

Explain the results of a separation experiment based on intermolecular interactions.

### ESSENTIAL KNOWLEDGE

**3.9.A.1**

The components of a liquid solution cannot be separated by filtration. They can, however, be separated using processes that take advantage of differences in the intermolecular interactions of the components.

- Chromatography (paper, thin-layer, and column) separates chemical species by taking advantage of the differential strength of intermolecular interactions between and among the components of the solution (the mobile phase) and with the surface components of the stationary phase. The resulting chromatogram can be used to infer the relative polarities of components in a mixture.
- Distillation separates chemical species by taking advantage of the differential strength of intermolecular interactions between and among the components and the effects these interactions have on the vapor pressures of the components in the mixture.

## TOPIC 3.10

# Solubility

**SUGGESTED SKILL***Model Analysis***4.D**

Explain the degree to which a model or representation describes the connection between particulate-level properties and macroscopic properties.

### Required Course Content

**LEARNING OBJECTIVE****3.10.A**

Explain the relationship between the solubility of ionic and molecular compounds in aqueous and nonaqueous solvents, and the intermolecular interactions between particles.

**ESSENTIAL KNOWLEDGE****3.10.A.1**

Substances with similar intermolecular interactions tend to be miscible or soluble in one another.

## SUGGESTED SKILL

 Model Analysis

## 4.A

Predict and/or explain chemical properties or phenomena (e.g., of atoms or molecules) using given chemical theories, models, and representations.



## AVAILABLE RESOURCES

- AP Chemistry Lab Manual > [Investigation 1: What is the Relationship Between the Concentration of a Solution and the Amount of Transmitted Light Through the Solution?](#)

## TOPIC 3.11

# Spectroscopy and the Electromagnetic Spectrum

## Required Course Content

**LEARNING OBJECTIVE****3.11.A**

Explain the relationship between a region of the electromagnetic spectrum and the types of molecular or electronic transitions associated with that region.

**ESSENTIAL KNOWLEDGE****3.11.A.1**

Differences in absorption or emission of photons in different spectral regions are related to the different types of molecular motion or electronic transition:

- Microwave radiation is associated with transitions in molecular rotational levels.
- Infrared radiation is associated with transitions in molecular vibrational levels.
- Ultraviolet/visible radiation is associated with transitions in electronic energy levels.

## TOPIC 3.12

## Properties of Photons

## SUGGESTED SKILL

Mathematical  
Routines

## 5.F

Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).

## Required Course Content

## LEARNING OBJECTIVE

## 3.12.A

Explain the properties of an absorbed or emitted photon in relationship to an electronic transition in an atom or molecule.

## ESSENTIAL KNOWLEDGE

## 3.12.A.1

When a photon is absorbed (or emitted) by an atom or molecule, the energy of the species is increased (or decreased) by an amount equal to the energy of the photon.

## 3.12.A.2

The wavelength of the electromagnetic wave is related to its frequency and the speed of light by the equation:


$$\text{EQN: } c = \lambda \nu.$$

The energy of a photon is related to the frequency of the electromagnetic wave through Planck's equation:

$$\text{EQN: } E = h\nu.$$



## SUGGESTED SKILL

 Question and Method

## 2.E

Identify or describe potential sources of experimental error.



## AVAILABLE RESOURCES

- The Exam > [2021 Chief Reader Report](#)

## TOPIC 3.13

## Beer-Lambert Law

## Required Course Content

## LEARNING OBJECTIVE

## 3.13.A

Explain the amount of light absorbed by a solution of molecules or ions in relationship to the concentration, path length, and molar absorptivity.

## ESSENTIAL KNOWLEDGE

## 3.13.A.1

The Beer-Lambert law relates the absorption of light by a solution to three variables according to the equation:

$$\text{EQN: } A = \epsilon bc.$$

The molar absorptivity,  $\epsilon$ , describes how intensely a chemical species absorbs light of a specific wavelength. The path length,  $b$ , and concentration,  $c$ , are proportional to the number of light-absorbing particles in the light path.

## 3.13.A.2

In most experiments the path length and wavelength of light are held constant. In such cases, the absorbance is proportional only to the concentration of absorbing molecules or ions. The spectrophotometer is typically set to the wavelength of maximum absorbance (optimum wavelength) for the species being analyzed to ensure the maximum sensitivity of measurement.