

AP Chemistry Curriculum

Theme – This course, in accordance with the College Board, “is designed to be the equivalent of the general chemistry course usually taken during the first college year.” Topics introduced in first-year chemistry class are reviewed and expanded and new concepts are introduced. This course is structured around the six big ideas articulated in the AP Chemistry curriculum framework provided by the College Board. The six big ideas involve the study of matter and the changes that matter undergoes.

Strand – Big Idea 1: The chemical elements are fundamental building materials of matter, and all matter can be understood in terms of arrangements of atoms. These atoms retain their identity in chemical reactions.

Topic: Enduring understanding 1.A: All matter is made of atoms. There are a limited number of types of atoms; these are the elements.

Content Statement/Learning Targets

- The student can justify the observation that the ratio of the masses of the constituent elements in any pure sample of that compound is always identical on the basis of the atomic molecular theory.
- The student is able to select and apply mathematical routines to mass data to identify or infer the composition of pure substances and/or mixtures.
- The student is able to select and apply mathematical relationships to mass data in order to justify a claim regarding the identity and/or estimated purity of a substance.
- The student is able to connect the number of particles, moles, mass, and volume of substances to one another, both qualitatively and quantitatively.

Content Elaborations

The concept of atoms as the building blocks of all matter is a fundamental premise of the discipline of chemistry. This concept provides the foundation for conceptualizing, interpreting, and explaining the macroscopic properties and transformations observed inside and outside the laboratory in terms of the structure and properties of the constituent materials. The concept of the mole enables chemists to relate measured masses in the laboratory to the number of particles present in a sample. These two concepts also provide the basis for the experimental determination of the purity of a sample through chemical analysis. The most important aspect of chemistry is not the memorization of the laws and definitions, but rather the ability to explain how the laws and relationships arise because of the atomic nature of matter.

Topic: Enduring understanding 1.B: The atoms of each element have unique structures arising from interactions between electrons and nuclei.

Content Standards/Learning Targets

- The student is able to explain the distribution of electrons in an atom or ion based upon data.
- The student is able to analyze data relating to electron energies for patterns and relationships.
- The student is able to describe the electronic structure of the atom, using PES data, ionization energy data, and/or Coulomb’s law to construct explanations of how the energies of electrons within shells in atoms vary.
- The student is able to explain the distribution of electrons using Coulomb’s law to analyze measured energies.

Content Elaborations

The shell model arises from experimental data. The shell model forms a basis for understanding the relative energies of electrons in an atom. The model is based on Coulomb’s law and qualitatively predicts ionization energies, which can be measured in the lab. Understanding how the shell model is consistent with the experimental data is a key learning goal for this content, beyond simple memorization of the patterns of electron configurations.

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Topic: Enduring understanding 1.C: Elements display periodicity in their properties when the elements are organized according to increasing atomic number. This periodicity can be explained by the regular variations that occur in the electronic structures of atoms. Periodicity is a useful principle for understanding properties and predicting trends in properties. Its modern-day uses range from examining the composition of materials to generating ideas for designing new materials.

Content Standards/Learning Targets

- The student is able to predict and/or justify trends in atomic properties based on location on the periodic table and/or the shell model.
- Students can justify with evidence the arrangement of the periodic table and can apply periodic properties to chemical reactivity.
- The student can analyze data, based on periodicity and the properties of binary compounds, to identify patterns and generate hypotheses related to the molecular design of compounds for which data are not supplied.
- The student is able to explain why a given set of data suggests, or does not suggest, the need to refine the atomic model from a classical shell model with the quantum mechanical model.

Content Elaborations

Although a simple shell model is not the currently accepted best model of atomic structure, it is an extremely useful model that can be used qualitatively to explain and/or predict many atomic properties and trends in atomic properties. In particular, the arrangement of electrons into shells and subshells is reflected in the structure of the periodic table and in the periodicity of many atomic properties. Many of these trends in atomic properties are important for understanding the properties of molecules, and in being able to explain how the structure of the constituent molecules or atoms relates to the macroscopic properties of materials. Students should be aware that the shells reflect the quantization inherent in quantum mechanics and that the labels given to the atomic orbitals are examples of the quantum numbers used to label the resulting quantized states. Being aware of the quantum mechanical model as the currently accepted best model for the atom is important for scientific literacy.

Topic: Enduring understanding 1.D: Atoms are so small that they are difficult to study directly; atomic models are constructed to explain experimental data on collections of atoms.

Content Standards/Learning Targets

- Given information about a particular model of the atom, the student is able to determine if the model is consistent with specified evidence.
- The student is able to use data from mass spectrometry to identify the elements and the masses of individual atoms of a specific element.
- The student can justify the selection of a particular type of spectroscopy to measure properties associated with vibrational or electronic motions of molecules.
- The student can design and/or interpret the results of an experiment regarding the absorption of light to determine the concentration of an absorbing species in a solution.

Content Elaborations

Because the experimental measurement of ionization energy provides a window into the overall electronic structure of the atom, this content provides rich opportunities to explore how scientific models can be constructed and refined in response to available data. The modern use of mass spectrometry provides another example of how experimental data can be used to test or reject a scientific model.

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Topic: Enduring understanding 1.E: Atoms are conserved in physical and chemical processes.

Content Standards/Learning Targets

- The student is able to express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings.
- The student is able to apply conservation of atoms to the rearrangement of atoms in various processes.
- The student can design, and/or interpret data from, an experiment that uses gravimetric analysis to determine the concentration of an analyte in a solution.
- The student can design, and/or interpret data from, an experiment that uses titration to determine the concentration of an analyte in a solution.

Content Elaborations

The conservation of mass in chemical and physical transformations is a fundamental concept, and is a reflection of the atomic model of matter. This concept plays a key role in much of chemistry, in both quantitative determinations of quantities of materials involved in chemical systems and transformations, and in the conceptualization and representation of those systems and transformations.

Content Vocabulary

- absorption
- analyte
- atom
- atomic mass unit (amu)
- atomic radius
- attractive
- average atomic mass
- Avogadro's number
- Beer-Lambert
- compounds
- core electrons
- Coulomb's Law
- Dalton's model
- electromagnetic waves
- electrostatic
- electron configurations
- electronegativity
- electrons
- emission
- empirical formula

Academic Vocabulary

- absorption
- abundant
- analogy
- analyze
- apply
- approximate
- balanced
- characteristic
- clarify
- classify
- compare
- comprised
- continuum
- contract
- correlate
- criteria
- directly proportional
- displacement
- distinguish
- dynamic

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- equivalence point
- frequency
- gravimetric analysis
- ion
- ionic radius
- ionization energy
- isotope
- mass percent
- mass spectrometry
- mixture
- molar mass
- mole
- molecular formula
- molecules
- neutrons
- orbital
- periodicity
- photoelectron spectroscopy (PES)
- photons
- Planck's equation/constant
- potential energy
- protons
- pure substance
- qualitative
- quantitative
- quantum mechanical model
- repulsive
- shell model
- stoichiometry
- subshell
- titration
- valence electrons
- wavelength
- emission
- emit
- estimate
- evaluate
- example
- hypothesize
- infer
- interact
- interpret
- inversely proportional
- magnitude
- manipulate
- observe
- pattern
- plausible
- postulate
- predict
- procedure
- proportional
- propose
- qualitative
- quantify
- quantitative
- rank
- sequence
- simultaneous
- spectrum
- static
- stationary
- subscript
- transfer
- transparent
- trend
- valid
- vary

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	<ul style="list-style-type: none">• yields
Formative Assessments Homework problem sets, lab activities, quizzes, classroom discussions.	Summative Assessments Unit Test, Formal lab reports.

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Strand: Big Idea 2: Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules and the forces between them.

Topic: Enduring understanding 2.A: Matter can be described by its physical properties. The physical properties of a substance generally depend on the spacing between the particles (atoms, molecules, ions) that make up the substance and the forces of attraction among them.

Content Standards/Learning Targets

- Students can predict properties of substances based on their chemical formulas, and provide explanations of their properties based on particle views.
- The student is able to explain the relative strengths of acids and bases based on molecular structure, interparticle forces, and solution equilibrium.
- The student is able to use aspects of particulate models (i.e., particle spacing, motion, and forces of attraction) to reason about observed differences between solid and liquid phases and among solid and liquid materials.
- The student is able to use KMT and concepts of intermolecular forces to make predictions about the macroscopic properties of gases, including both ideal and nonideal behaviors.
- The student is able to refine multiple representations of a sample of matter in the gas phase to accurately represent the effect of changes in macroscopic properties on the sample.
- The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases.
- The student is able to explain how solutes can be separated by chromatography based on intermolecular interactions.
- The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent.
- The student is able to create or interpret representations that link the concept of molarity with particle views of solutions.
- The student can design and/or interpret the results of a separation experiment (filtration, paper chromatography, column

Content Elaborations

There is a relationship between the macroscopic properties of solids, liquids, and gases, and the structure of the constituent particles of those materials on the molecular and atomic scale. The properties of solids, liquids, and gases also 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. For gases, volumetric relationships can be used to describe ideal behavior, and a conceptual understanding of that behavior can be constructed based on the atomic model and a relatively simple kinetic molecular theory (KMT).

Solutions are an important class of mixtures; of particular importance is a conceptual understanding on the molecular level of the structure and composition of a liquid solution. In addition, the energetics of solution formation can be understood qualitatively through consideration of the interactions and structure of the components before and after the creation of the solution.

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<p>chromatography, or distillation) in terms of the relative strength of interactions among and between the components.</p>	
<p>Topic: Enduring understanding 2.B: Forces of attraction between particles (including the noble gases and also different parts of some large molecules) are important in determining many macroscopic properties of a substance, including how the observable physical state changes with temperature.</p>	
<p>Content Standards/Learning Targets</p> <ul style="list-style-type: none"> • The student is able to explain the trends in properties and/or predict properties of samples consisting of particles with no permanent dipole on the basis of London dispersion forces. • The student can qualitatively analyze data regarding real gases to identify deviations from ideal behavior and relate these to molecular interactions. • The student is able to describe the relationships between the structural features of polar molecules and the forces of attraction between the particles. • The student is able to apply Coulomb’s law qualitatively (including using representations) to describe the interactions of ions, and the attractions between ions and solvents to explain the factors that contribute to the solubility of ionic compounds. • The student is able to explain observations regarding the solubility of ionic solids and molecules in water and other solvents on the basis of particle views that include intermolecular interactions and entropic effects. • The student is able to explain the properties (phase, vapor pressure, viscosity, etc.) of small and large molecular compounds in terms of the strengths and types of intermolecular forces. 	<p>Content Elaborations</p> <p>Chemists categorize intermolecular interactions based on the structural features giving rise to the interaction. Although there are some trends in the relative strengths of these interactions, the specific structure and size of the particles involved can play a very important role in determining the overall strength of a particular intermolecular (or intramolecular) interaction. The properties of condensed phases and of many crucial biological structures are determined by the nature and strength of these interactions. Deviation from ideal gas behavior is generally a reflection of the presence of intermolecular interactions between gas particles. Thus, in all phases, the structure of particles on the molecular level is directly related to the properties of both the particles themselves and the behavior of macroscopic collections of those molecules.</p>
<p>Topic: Enduring understanding 2.C: The strong electrostatic forces of attraction holding atoms together in a unit are called chemical bonds.</p>	
<p>Content Standards/Learning Targets</p> <ul style="list-style-type: none"> • The student can predict the type of bonding present between two atoms in a binary compound based on position in the periodic table and the electronegativity of the elements. • The student is able to rank and justify the ranking of bond polarity on the basis of the locations of the bonded atoms in the periodic table. • The student can create visual representations of ionic substances 	<p>Content Elaborations</p> <p>Covalent bonds, ionic bonds, and metallic bonds are distinct from (and significantly stronger than) typical intermolecular interactions. Electronegativity can be used to reason about the type of bonding present between two atoms. Covalent chemical bonds can be modeled as the sharing of one or more pairs of valence electrons between two atoms in a molecule. The extent to which this sharing is unequal can be predicted from the relative electronegativities of the atoms involved; the relative</p>

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that connect the microscopic structure to macroscopic properties, and/or use representations to connect the microscopic structure to macroscopic properties (e.g., boiling point, solubility, hardness, brittleness, low volatility, lack of malleability, ductility, or conductivity).

- The student is able to explain how a bonding model involving delocalized electrons is consistent with macroscopic properties of metals (e.g., conductivity, malleability, ductility, and low volatility) and the shell model of the atom.
- The student is able to use Lewis diagrams and VSEPR to predict the geometry of molecules, identify hybridization, and make predictions about polarity.

electronegativities can generally be understood through application of the shell model and Coulomb's law. The Lewis structure model, combined with valence shell electron pair repulsion (VSEPR), can be used to predict many structural features of covalently bonded molecules and ions. Ionic bonding is the phrase used to describe the strong Coulombic interaction between ions in an ionic substance. The bonding in metals is characterized by delocalization of valence electrons.

Topic: Enduring understanding 2.D: The type of bonding in the solid state can be deduced from the properties of the solid state.

Content Standards/Learning Targets

- The student is able to design or evaluate a plan to collect and/or interpret data needed to deduce the type of bonding in a sample of a solid.
- The student can create a representation of an ionic solid that shows essential characteristics of the structure and interactions present in the substance.
- The student is able to explain a representation that connects properties of an ionic solid to its structural attributes and to the interactions present at the atomic level.
- The student is able to compare the properties of metal alloys with their constituent elements to determine if an alloy has formed, identify the type of alloy formed, and explain the differences in properties using particulate level reasoning.
- Students can use the electron sea model of metallic bonding to predict or make claims about the macroscopic properties of metals or alloys.
- The student can create a representation of a metallic solid that shows essential characteristics of the structure and interactions present in the substance.
- The student is able to explain a representation that connects properties of a metallic solid to its structural attributes and to the

Content Elaborations

In solids, the properties of the material reflect the nature and strength of the interactions between the constituent particles. For this reason, the type of bonding that predominates in a solid material, and the nature of the interactions between the particles comprising the solid, can generally be inferred from the observed macroscopic properties of the material. Properties such as vapor pressure, conductivity as a solid and in aqueous solution, and relative brittleness or hardness can generally be explained in this way.

Although recognizing the properties that can be associated with a particular type of bonding is valuable in categorizing materials, relating those properties to the structure of the materials on the molecular scale, and being able to make reasoned predictions of the properties of a solid based on its constituent particles, provides evidence of deeper conceptual understanding.

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interactions present at the atomic level.

- The student can create a representation of a covalent solid that shows essential characteristics of the structure and interactions present in the substance.
- The student is able to explain a representation that connects properties of a covalent solid to its structural attributes and to the interactions present at the atomic level.
- The student can create a representation of a molecular solid that shows essential characteristics of the structure and interactions present in the substance.
- The student is able to explain a representation that connects properties of a molecular solid to its structural attributes and to the interactions present at the atomic level.

Content Vocabulary

- allotrope
- amorphous
- bond energy
- bond length
- Capillary action
- chemical change
- chromatography
- conductivity
- covalent bonds
- dilution
- dipole
- dipole moment
- dipole-dipole force
- dipole-induced dipole
- distillation
- ductility
- endothermic
- exothermic
- formal charge
- heterogeneous mixture

Academic Vocabulary

- absorption
- abundant
- analogy
- analyze
- apply
- approximate
- balanced
- characteristic
- clarify
- classify
- compare
- comprised
- continuum
- contract
- correlate
- criteria
- directly proportional
- displacement
- distinguish
- dynamic

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- homogenous mixture
- hybridization
- hydrogen bonding
- hydrophilic
- hydrophobic
- ideal gas
- immiscible
- intermolecular attractions
- interstitial alloys
- ionic bonds
- kinetic molecular theory
- Lewis structures
- London dispersion forces
- macroscopic
- malleability
- Maxwell-Boltzman
- metallic bonds
- miscible
- molar volume
- molarity
- molecular orbital theory
- physical change
- pi bond
- sigma bond
- solubility
- solutes
- solution
- solution equilibrium
- solvent
- structural isomers
- substitutional alloys
- substrate
- surface tension
- translation
- vapor pressure
- emission
- emit
- estimate
- evaluate
- example
- hypothesize
- infer
- interact
- interpret
- inversely proportional
- magnitude
- manipulate
- observe
- pattern
- plausible
- postulate
- predict
- procedure
- proportional
- propose
- qualitative
- quantify
- quantitative
- rank
- sequence
- simultaneous
- spectrum
- static
- stationary
- subscript
- transfer
- transparent
- trend
- valid
- vary

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<ul style="list-style-type: none"> • viscosity • volatility • VSEPR models 	<ul style="list-style-type: none"> • yields
<p>Formative Assessments Homework problem sets, lab activities, quizzes, classroom discussions.</p>	<p>Summative Assessments Unit Test, Formal lab reports.</p>
<p>Resources</p> <p>Kotz, J. and Treichel, P. (2003). McDonald, A. & McGahey, P. (Eds.), <u>Chemistry and Chemical Reactivity, Fifth Edition</u>, (pp 118-199). U.S.: Thomson Learning. ISBN 0-03-033604-X</p> <p>The College Board. <u>AP Chemistry Guided Inquiry Experiments: Applying the Science Practices</u>. 2013.</p> <p>Slowinski, E., Wolsey, W. and Materson, W. (1989). <u>Chemistry Principles in the Laboratory, Fifth Edition</u>. U. S.:Saunders College Publishing. ISBN 0-03005939-9</p> <p>Vonderbrink, S. (1995). <u>Laboratory Experiments for Advanced Placement Chemistry</u>. Batavia, IL: Flinn Scientific. ISBN 1-877991-34-1</p>	

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Strand: Big Idea 3: Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons.

Topic: Enduring understanding 3.A: Chemical changes are represented by a balanced chemical equation that identifies the ratios with which reactants react and products form.

Content Standards/Learning Targets:

- Students can translate among macroscopic observations of change, chemical equations, and particle views.
- The student can translate an observed chemical change into a balanced chemical equation and justify the choice of equation type (molecular, ionic, or net ionic) in terms of utility for the given circumstances.
- The student is able to use stoichiometric calculations to predict the results of performing a reaction in the laboratory and/or to analyze deviations from the expected results.
- The student is able to relate quantities (measured mass of substances, volumes of solutions, or volumes and pressures of gases) to identify stoichiometric relationships for a reaction, including situations involving limiting reactants and situations in which the reaction has not gone to completion.

Content Elaborations –

Chemical reactions are the primary means by which transformations in matter occur. Chemical equations for reactions efficiently communicate the rearrangements of atoms that occur during a chemical reaction. Describing a chemical change can include different forms of the equation, such as molecular, ionic, and net ionic. The equation provides information about atoms, ions and/or molecules reacting (not how they react) at the particulate level, as well as quantitative information about stoichiometry at the macroscopic level. Many chemical reactions involve small whole number ratios of reactants and products as expressed by the stoichiometric coefficients of the balanced equation. Many modern materials are composed of non-stoichiometric combinations of the constituent elements.

Topic: Enduring understanding 3.B: Chemical reactions can be classified by considering what the reactants are, what the products are, or how they change from one into the other. Classes of chemical reactions include synthesis, decomposition, acid-base, and oxidation-reduction reactions.

Content Standards/Learning Targets:

- The student is able to design a plan in order to collect data on the synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions.
- The student is able to use data from synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions.
- The student is able to identify compounds as Bronsted-Lowry acids, bases, and/or conjugate acid-base pairs, using proton-transfer reactions to justify the identification.

Content Elaborations –

There are a vast number of possible chemical reactions. In order to study and make predictions and comparisons concerning such a wide array of reactions, chemists have devised ways to classify them. Because of their prevalence in the laboratory and in real-world applications, two categories of reactions that are of particular importance are acid-base reactions and oxidation reduction reactions. Also, a key contribution of chemistry to society is the creation of new materials or compounds that benefit the health and welfare of people in the community. Most often the creation of new materials or compounds can be considered as synthesis reactions,

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- The student is able to identify redox reactions and justify the identification in terms of electron transfer.
- The student is able to design and/or interpret the results of an experiment involving a redox titration.

another important reaction category

Topic: Enduring understanding 3.C: Chemical and physical transformations may be observed in several ways and typically involve a change in energy.

Content Standards/Learning Targets

- The student is able to evaluate the classification of a process as a physical change, chemical change, or ambiguous change based on both macroscopic observations and the distinction between rearrangement of covalent interactions and noncovalent interactions.
- The student is able to interpret observations regarding macroscopic energy changes associated with a reaction or process to generate a relevant symbolic and/or graphical representation of the energy changes.
- The student can make qualitative or quantitative predictions about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws.
- The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions.

Content Elaborations

An important component of a full understanding of chemical change involves direct observation of that change; thus, laboratory experiences are essential for the AP Chemistry student to develop an appreciation of the discipline. At the AP course level, observations are made on macroscopically large samples of chemicals; these observations must be used to infer what is occurring at the particulate level. This ability to reason about observations at one level (macroscopic) using models at another level (particulate) provides an important demonstration of conceptual understanding and requires extensive laboratory experience. The difference between physical and chemical change is best explained at the particulate level. Laboratory observations of temperature change accompanying physical and chemical transformations are manifestations of the energy changes occurring at the particulate level. This has practical applications, such as energy production via combustion of fuels (chemical energy conversion to thermal energy) and/or batteries (chemical energy conversion to electrical energy).

Content Vocabulary

- amphoteric
- Bronsted-Lowery acid/base
- coefficients
- conjugate acid/base pairs
- decomposition reactions
- electrochemistry
- electrolytic cell
- excess reactant
- Faraday's Law
- galvanic cell

Academic Vocabulary

- absorption
- abundant
- analogy
- analyze
- apply
- approximate
- balanced
- characteristic
- clarify
- classify

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- Gibbs Free Energy
- half-cell reactions
- ionic equation
- law of definite proportions
- limiting reactant
- molecular equation
- net ionic equation
- oxidation-reduction reactions
- precipitate
- proportionality
- Standard Cell Potential
- Standard Reduction Potentials
- synthesis reactions

- compare
- comprised
- continuum
- contract
- correlate
- criteria
- directly proportional
- displacement
- distinguish
- dynamic
- emission
- emit
- estimate
- evaluate
- example
- hypothesize
- infer
- interact
- interpret
- inversely proportional
- magnitude
- manipulate
- observe
- pattern
- plausible
- postulate
- predict
- procedure
- proportional
- propose
- qualitative
- quantify
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- spectrum
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- stationary
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- transparent
- trend
- valid
- vary
- yields

Formative Assessments

Homework problem sets, lab activities, quizzes, classroom discussions.

Summative Assessments

Unit Test, Formal lab reports.

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Strand: Big Idea 4: Rates of chemical reactions are determined by details of the molecular collisions.

Topic: Enduring understanding 4.A: Reaction rates that depend on temperature and other environmental factors are determined by measuring changes in concentrations of reactants or products over time.

Content Standards/Learning Targets

- The student is able to design and/or interpret the results of an experiment regarding the factors (i.e., temperature, concentration, surface area) that may influence the rate of a reaction.
- The student is able to analyze concentration vs. time data to determine the rate law for a zeroth-, first-, or second-order reaction.
- The student is able to connect the half-life of a reaction to the rate constant of a first-order reaction and justify the use of this relation in terms of the reaction being a first-order reaction.

Content Elaborations

The rate of a reaction is the rate at which reactants are converted to products, and is given in terms of the change in concentrations with time. Rates of reactions span a wide range, and generally increase with reactant concentrations and with temperature. The rate may be measured by monitoring concentrations as a function of time, and the results of many experiments may be summarized with a mathematical expression known as the rate law. The rate law gives the dependence of the rate on reactant concentrations, and contains a proportionality constant called the rate constant.

Topic: Enduring understanding 4.B: Elementary reactions are mediated by collisions between molecules. Only collisions having sufficient energy and proper relative orientation of reactants lead to products.

Content Standards/Learning Targets:

- The student is able to connect the rate law for an elementary reaction to the frequency and success of molecular collisions, including connecting the frequency and success to the order and rate constant, respectively.
- The student is able to explain the difference between collisions that convert reactants to products and those that do not in terms of energy distributions and molecular orientation.
- The student is able to use representations of the energy profile for an elementary reaction (from the reactants, through the transition state, to the products) to make qualitative predictions regarding the relative temperature dependence of the reaction rate.

Content Elaborations –

Reactions proceed through elementary steps involving one or more reactants. In a unimolecular reaction, collisions with other molecules activate the reactant such that it is converted into product. In bimolecular and higher-order reactions, collisions between reactants lead to formation of products, provided both the energy of the collision and the relative orientation of reactants are favorable for reaction. A successful collision can be viewed as proceeding along some single reaction coordinate. The energy profile along this reaction coordinate provides a useful construct for reasoning about the connection between the energetics of a reaction and the rate of the reaction. In particular, this profile includes the activation energy required to overcome the energy barrier between reactants and products.

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Topic: Enduring understanding 4.C: Many reactions proceed via a series of elementary reactions.

Content Standards/Learning Targets

- The student is able to evaluate alternative explanations, as expressed by reaction mechanisms, to determine which are consistent with data regarding the overall rate of a reaction, and data that can be used to infer the presence of a reaction intermediate.

Content Elaborations

Many reactions proceed through a series of elementary reactions or steps, and this series of steps is referred to as the reaction mechanism. The steps of the mechanism sum to give the overall reaction; the balanced chemical equation for the overall reaction specifies the stoichiometry. The overall rate of the reaction is an emergent property of the rates of the individual reaction steps. For many reactions, one step in the reaction mechanism is sufficiently slow so that it limits the rate of the overall reaction. For such reactions, this rate-limiting step sets the rate of the overall reaction. Reaction intermediates, which are formed by a step in the reaction mechanism and then consumed by a following step, play an important role in multistep reactions, and their experimental detection is an important means of investigating reaction mechanisms.

Topic: Enduring understanding 4.D: Reaction rates may be increased by the presence of a catalyst.

Content Standards/Learning Targets

- The student can translate among reaction energy profile representations, particulate representations, and symbolic representations (chemical equations) of a chemical reaction occurring in the presence and absence of a catalyst.
- The student is able to explain changes in reaction rates arising from the use of acid-base catalysts, surface catalysts, or enzyme catalysts, including selecting appropriate mechanisms with or without the catalyst present.

Content Elaborations

Catalysts, such as enzymes in biological systems and the surfaces in an automobile's catalytic converter, increase the rate of a chemical reaction. Catalysts may function by lowering the activation energy of an elementary step in a reaction, thereby increasing the rate of that elementary step, but leaving the mechanism of the reaction otherwise unchanged. Other catalysts participate in the formation of a new reaction intermediate, thereby providing a new reaction mechanism that provides a faster pathway between reactants and products.

Content Vocabulary

- activation energy
- Arrhenius equation
- bimolecular
- catalyst
- collision theory
- elementary steps
- first order
- half-life

Academic Vocabulary

- absorption
- abundant
- analogy
- analyze
- apply
- approximate
- balanced
- characteristic

AP Chemistry Curriculum

- kinetics
- reaction intermediate
- reaction mechanism
- reaction rate
- second order
- transition state
- unimolecular
- zero order

- clarify
- classify
- compare
- comprised
- continuum
- contract
- correlate
- criteria
- directly proportional
- displacement
- distinguish
- dynamic
- emission
- emit
- estimate
- evaluate
- example
- hypothesize
- infer
- interact
- interpret
- inversely proportional
- magnitude
- manipulate
- observe
- pattern
- plausible
- postulate
- predict
- procedure
- proportional
- propose
- qualitative
- quantify
- quantitative

AP Chemistry Curriculum

- rank
- sequence
- simultaneous
- spectrum
- static
- stationary
- subscript
- transfer
- transparent
- trend
- valid
- vary
- yields

Formative Assessments

Homework problem sets, lab activities, quizzes, classroom discussions.

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Unit Test, Formal lab reports.

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AP Chemistry Curriculum

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Strand: Big Idea 5: The laws of thermodynamics describe the essential role of energy and explain and predict the direction of changes in matter.

Topic: Enduring understanding 5.A: Two systems with different temperatures that are in thermal contact will exchange energy. The quantity of thermal energy transferred from one system to another is called heat.

Content Standards/Learning Targets

- The student is able to create or use graphical representations in order to connect the dependence of potential energy to the distance between atoms and factors, such as bond order (for covalent interactions) and polarity (for intermolecular interactions), which influence the interaction strength.
- The student is able to relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell- Boltzmann distribution.
- The student can generate explanations or make predictions about the transfer of thermal energy between systems based on this transfer being due to a kinetic energy transfer between systems arising from molecular collisions.

Content Elaborations

The particles in chemical systems are continually undergoing random motion. The temperature of a system is a direct measure of the average kinetic energy associated with this random motion. When chemical systems that have different temperatures are placed in thermal contact, kinetic energy is transferred from the hotter object to the cooler object until the temperatures become equal. This transfer of kinetic energy is referred to in this course as heat transfer. An understanding of heat as the transfer of energy between a system at higher temperature and a system at lower temperature is fundamental. Many practical applications exist, such as weather prediction, design of heating and cooling systems, and regulation of the rates of chemical reactions.

Topic: Enduring understanding 5.B: Energy is neither created nor destroyed, but only transformed from one form to another.

Content Standards/Learning Targets:

- The student is able to use conservation of energy to relate the magnitudes of the energy changes occurring in two or more interacting systems, including identification of the systems, the type (heat versus work), or the direction of energy flow.
- The student is able to use conservation of energy to relate the magnitudes of the energy changes when two nonreacting substances are mixed or brought into contact with one another.
- The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the

Content Elaborations –

The conservation of energy plays an important role in reasoning about the transfer of energy in chemical systems. A molecular system has energy that is a function of its current state. The energy of a system changes when the state of the system changes; for instance, when the temperature of the system changes, when a substance melts or boils, or when a chemical reaction occurs, the energy changes. Conservation of energy implies that any change in the energy of a system must be balanced by the transfer of energy either into or out of the system. This energy transfer can take the form of either heat transfer or work. Work includes all forms of energy

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heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to $P\Delta V$ work.

- The student is able to design and/or interpret the results of an experiment in which calorimetry is used to determine the change in enthalpy of a chemical process (heating/cooling, phase transition, or chemical reaction) at constant pressure.

transfer other than heat transfer.

Examples of mechanical work include the expansion of a gas against a piston in engines. The change in energy associated with a chemical process is an important aspect of such processes characterizing, for instance, the amount of energy that can be obtained from a fuel system. Because the change in energy associated with a given process is proportional to the amount of substance undergoing that process, this change is best described on a per mole (or per gram) basis, as in heat capacities (for heating/cooling), enthalpies of fusion or vaporization (for physical transformations), and enthalpies of reaction (for chemical transformations). Calorimetry provides a convenient means to measure changes in energy, and thus is used experimentally to determine heat capacities or enthalpies of physical and chemical transformations.

Topic: Enduring understanding 5.C: Breaking bonds requires energy, and making bonds releases energy.

Content Standards/Learning Targets

- The student is able to draw qualitative and quantitative connections between the reaction enthalpy and the energies involved in the breaking and formation of chemical bonds.

Content Elaborations

Chemical bonds arise from attractive interactions between negatively charged electrons and the positively charged nuclei of the atoms that make up the bond. As electrons approach a positive charge, the potential energy of a system is lowered. Therefore, having electrons shared between atoms results in the system being in a lower energy state, which can only happen if energy is somehow released. Thus, making chemical bonds releases energy. The converse is true for the opposing process. In order to break a chemical bond, energy must be put into the system to overcome the attractive interaction between the shared electrons and the nuclei of the bonded atoms. When considering chemical reactions, however, it is important to recognize that in most cases both bond breaking and bond formation occurs. The overall energy change is determinable from looking at all the energy inputs (to break bonds) and the energy outputs (from the formation of bonds). There are several ways to calculate energy changes for reactions, including traditionally used methods involving enthalpy of formation. One compelling conceptual model for this calculation is to use average bond energies or enthalpies to determine the energy change of a reaction. Many practical examples of chemistry take place in solvents (often water); thus, the determination of overall changes in energy for a reaction

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must include consideration of any solvent interactions with reactants and products. Energy may appear in different forms, such as potential energy or kinetic energy. In chemical systems, the stored energy is called chemical energy, and the energy of motion (translational, rotational, or vibrational) is called thermal energy. Chemical energy is the potential energy associated with chemical systems. The amount of chemical energy in a system changes when the chemicals are allowed to react. The energy transferred to or from the surroundings when a chemical system undergoes a reaction is often in the form of thermal energy.

Topic: Enduring understanding 5.D: Electrostatic forces exist between molecules as well as between atoms or ions, and breaking the resultant intermolecular interactions requires energy.

Content Standards/Learning Target

- The student is able to make claims and/or predictions regarding relative magnitudes of the forces acting within collections of interacting molecules based on the distribution of electrons within the molecules and the types of intermolecular forces through which the molecules interact.
- The student can support the claim about whether a process is a chemical or physical change (or may be classified as both) based on whether the process involves changes in intramolecular versus intermolecular interactions.
- The student is able to identify the noncovalent interactions within and between large molecules, and/or connect the shape and function of the large molecule to the presence and magnitude of these interactions.

Content Elaborations

The same essential interaction that forms chemical bonds, electrostatic attraction, also explains the attractive forces as non-bonded atoms draw near each other. When atoms approach each other, there is always an electrostatic attraction between the positive charges of the nucleus in each atom and the electrons of the approaching atom. When a chemical bond does not form between the two atoms, this attraction is described as an intermolecular force. For molecular systems, these intermolecular forces are understood in terms of charge distributions leading to dipoles (permanent or induced) that then attract each other. The most common categories for these interactions are (a) dipole-dipole, (b) dipole-induced dipole, and (c) induced dipole-induced dipole (dispersion) forces. Hydrogen bonding is an important, specialized form of dipole-dipole interactions.

These forces may occur (a) between small molecules, (b) between different large molecules, or (c) between different regions of the same large molecule. The distinction at the particulate level between electrostatic interactions of nonbonded atoms and those of chemically bonded atoms provides the cleanest distinction between a chemical and physical process. A physical process generally involves nonbonded interactions, and a chemical process involves breaking and/or forming covalent bonds. In many systems involving large molecules (both biochemical systems and synthetic polymer systems), the nonbonded interactions play important roles in the observed functions of the systems.

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Topic: Enduring understanding 5.E: Chemical or physical processes are driven by a decrease in enthalpy or an increase in entropy, or both.

Content Standards/Learning Targets

- The student is able to use representations and models to predict the sign and relative magnitude of the entropy change associated with chemical or physical processes.
- The student is able to predict whether or not a physical or chemical process is thermodynamically favored by determination of (either quantitatively or qualitatively) the signs of both ΔH° and ΔS° , and calculation or estimation of ΔG° when needed.
- The student is able to determine whether a chemical or physical process is thermodynamically favorable by calculating the change in standard Gibbs free energy.
- The student is able to explain how the application of external energy sources or the coupling of favorable with unfavorable reactions can be used to cause processes that are not thermodynamically favorable to become favorable.
- The student can use Le Chatelier's principle to make qualitative predictions for systems in which coupled reactions that share a common intermediate drive formation of a product.
- The student can make quantitative predictions for systems involving coupled reactions that share a common intermediate, based on the equilibrium constant for the combined reaction.
- The student can explain why a thermodynamically favored chemical reaction may not produce large amounts of product (based on consideration of both initial conditions and kinetic effects), or why a thermodynamically unfavored chemical reaction can produce large amounts of product for certain sets of initial conditions.

Content Elaborations

One of the most powerful applications of thermodynamic principles is the ability to determine whether a process corresponding to a physical or chemical change will lie toward the reactant or product side when the process reaches a steady equilibrium state. The standard change in Gibbs free energy, $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$, is used to make this determination. If $\Delta G^\circ < 0$, then products are favored at equilibrium, and the forward process is considered to be "thermodynamically favored." Conversely, if $\Delta G^\circ > 0$, then reactants are favored at equilibrium, and the reverse process is considered to be "thermodynamically favored." Both the enthalpy change (ΔH°) and the entropy change (ΔS°) are closely related to the structure and nature of the components of the system; for this reason, it is often possible to make qualitative determinations concerning the sign (and magnitude) of ΔG° without explicit calculation. Enthalpy changes are closely related to the relative bond energies (and relative strengths of intermolecular interactions) of the reactants and products; entropy changes are generally related to the states of the components and the number of individual particles present. In this way, the Gibbs free energy provides a framework based on molecular structure and intermolecular interactions for understanding why some chemical reactions are observed to proceed to near completion, while others reach equilibrium with almost no products being formed. Some processes that are not thermodynamically favored (for example, the recharging of a battery) can be driven to occur through the application of energy from an external source — in this case, an electrical current. Importantly, in biochemical systems, some reactions that oppose the thermodynamically favored direction are driven by coupled reactions. Thus, a cell can use energy to create order (a direction that is not thermodynamically favored) via coupling with thermodynamically favored reactions. For example, many biochemical syntheses are coupled to the reaction in which ATP is converted to ADP + phosphate.

In some cases, processes that are thermodynamically favored are not observed to occur because of some kinetic constraint; quite often there is a high activation energy to overcome in order for the process to proceed. Thus, although Gibbs free energy can be used to determine which direction

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of a chemical process is thermodynamically favored, it provides no information about the rate of the process, or the nature of the process on the microscopic scale.

Content Vocabulary

- calorimetry
- conservation of energy
- enthalpy
- entropy
- Gibbs Free Energy
- heat vs. energy
- Hess's Law
- Kelvin
- kinetic control
- kinetic energy (average)
- molar enthalpy of fusion
- molar enthalpy of vaporization
- net energy in a reaction
- potential energy
- specific heat capacity
- spontaneous
- standard enthalpy of formation
- surroundings
- system
- thermal equilibrium
- thermodynamically favored
- thermodynamics
- work

Academic Vocabulary

- absorption
- abundant
- analogy
- analyze
- apply
- approximate
- balanced
- characteristic
- clarify
- classify
- compare
- comprised
- continuum
- contract
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- directly proportional
- displacement
- distinguish
- dynamic
- emission
- emit
- estimate
- evaluate
- example
- hypothesize
- infer
- interact
- interpret
- inversely proportional

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- magnitude
- manipulate
- observe
- pattern
- plausible
- postulate
- predict
- procedure
- proportional
- propose
- qualitative
- quantify
- quantitative
- rank
- sequence
- simultaneous
- spectrum
- static
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- subscript
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- valid
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Strand: Big Idea 6: Any bond or intermolecular attraction that can be formed can be broken. These two processes are in a dynamic competition, sensitive to initial conditions and external perturbations.

Topic: Enduring understanding 6.A: Chemical equilibrium is a dynamic, reversible state in which rates of opposing processes are equal.

Content Standards/Learning Targets

- The student is able to, given a set of experimental observations regarding physical, chemical, biological, or environmental processes that are reversible, construct an explanation that connects the observations to the reversibility of the underlying chemical reactions or processes.
- The student can, given a manipulation of a chemical reaction or set of reactions (e.g., reversal of reaction or addition of two reactions), determine the effects of that manipulation on Q or K .
- The student can connect kinetics to equilibrium by using reasoning about equilibrium, such as Le Chatelier’s principle, to infer the relative rates of the forward and reverse reactions.
- The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K , use the tendency of Q to approach K to predict and justify the prediction as to whether the reaction will proceed toward products or reactants as equilibrium is approached.
- The student can, given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, K .
- The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K , use stoichiometric relationships and the law of mass action (Q equals K at equilibrium) to determine qualitatively and/or quantitatively the conditions at equilibrium for a system involving a single reversible reaction.
- The student is able, for a reversible reaction that has a large or small K , to determine which chemical species will have very large

Content Elaborations

A collection of molecules undergoing a reversible reaction can adopt a number of configurations that are constrained by the stoichiometry and that can be ordered by the extent to which the reactants have been converted to products. As reactants are converted to products, the reactant concentrations drop; thus, the rate of the forward reaction decreases. Simultaneously, the product concentrations increase and the rate of the reverse reaction increases. At some intermediate point, the concentrations of reactants and products are such that the rates of the forward and reverse reactions balance, and there is no net conversion between reactants and products. A system that has reached this state is at chemical equilibrium. The relative proportions of reactants and products at equilibrium is specified by the equilibrium constant, K , which may be used both quantitatively (to predict concentrations at equilibrium) and qualitatively (to reason about the relative amounts of reactants and products present at equilibrium).

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versus very small concentrations at equilibrium.

Topic: Enduring understanding 6.B: Systems at equilibrium are responsive to external perturbations, with the response leading to a change in the composition of the system.

Content Standards/Learning Targets:

- The student is able to use Le Chatelier's principle to predict the direction of the shift resulting from various possible stresses on a system at chemical equilibrium.
- The student is able to use Le Chatelier's principle to design a set of conditions that will optimize a desired outcome, such as product yield.
- The student is able to connect Le Chatelier's principle to the comparison of Q to K by explaining the effects of the stress on Q and K .

Content Elaborations –

Chemical equilibrium is a dynamic state in which the rates of the forward and reverse reactions are equal. A change in conditions, such as addition of a chemical species, change in temperature, or change in volume, can cause the rate of the forward and reverse reactions to fall out of balance. Such a change is called a stress on the system. The system is then temporarily out of equilibrium, and there is a net conversion between reactants and products until a new equilibrium state is established. This net conversion is referred to as a shift of the chemical reaction. Le Chatelier's principle provides a convenient means to reason qualitatively about the direction of the shift in an equilibrium system resulting from various possible stresses.

Topic: Enduring understanding 6.C: Chemical equilibrium plays an important role in acid-base chemistry and in solubility.

Content Standards/Learning Targets

- The student can generate or use a particulate representation of an acid (strong or weak or polyprotic) and a strong base to explain the species that will have large versus small concentrations at equilibrium.
- The student can reason about the distinction between strong and weak acid solutions with similar values of pH, including the percent ionization of the acids, the concentrations needed to achieve the same pH, and the amount of base needed to reach the equivalence point in a titration.
- The student can interpret titration data for monoprotic or polyprotic acids involving titration of a weak or strong acid by a strong base (or a weak or strong base by a strong acid) to determine the concentration of the titrant and the pK_a for a weak acid, or the pK_b for a weak base.
- The student can, based on the dependence of K_w on temperature, reason that neutrality requires $[H^+] = [OH^-]$ as opposed to requiring $pH = 7$, including especially the applications to biological systems.
- The student can identify a given solution as containing a mixture of

Content Elaborations

The proton-exchange reactions of acid-base chemistry are reversible reactions that reach equilibrium quickly, and much of acid-base chemistry can be understood by applying the principles of chemical equilibrium. Most acid-base reactions have either large or small K , and so qualitative conclusions regarding the equilibrium state can often be drawn without extensive computations. The dissolution of a solid in a solvent is also a reversible reaction that often reaches equilibrium quickly, and so can be understood by applying the principles of chemical equilibrium.

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strong acids and/or bases and calculate or estimate the pH (and concentrations of all chemical species) in the resulting solution.

- The student can identify a given solution as being the solution of a monoprotic weak acid or base (including salts in which one ion is a weak acid or base), calculate the pH and concentration of all species in the solution, and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations.
- The student can, given an arbitrary mixture of weak and strong acids and bases (including polyprotic systems), determine which species will react strongly with one another (i.e., with $K > 1$) and what species will be present in large concentrations at equilibrium.
- The student can design a buffer solution with a target pH and buffer capacity by selecting an appropriate conjugate acid-base pair and estimating the concentrations needed to achieve the desired capacity.
- The student can relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the pK_a associated with the labile proton.
- The student can identify a solution as being a buffer solution and explain the buffer mechanism in terms of the reactions that would occur on addition of acid or base.
- The student can predict the solubility of a salt, or rank the solubility of salts, given the relevant K_{sp} values.
- The student can interpret data regarding solubility of salts to determine, or rank, the relevant K_{sp} values.
- The student can interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility.
- The student can analyze the enthalpic and entropic changes associated with the dissolution of a salt, using particulate level interactions and representations.

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Topic: Enduring understanding 6.D: The equilibrium constant is related to temperature and the difference in Gibbs free energy between reactants and products.

Content Standards/Learning Targets

- The student is able to express the equilibrium constant in terms of ΔG° and RT and use this relationship to estimate the magnitude of K and, consequently, the thermodynamic favorability of the process.

Content Elaborations

The magnitude of the equilibrium constant, K , specifies the relative proportion of reactants and products present at equilibrium. This is directly related to the change in Gibbs free energy associated with the reaction, ΔG° . The species that have the lower free energy (reactants versus products) have larger relative concentrations at equilibrium. For both reactants and products to be present with significant concentrations at equilibrium, i.e., for K to be near 1, the magnitude of ΔG° must be roughly equivalent to the thermal energy (RT).

Content Vocabulary

- autoionization of water
- buffer
- conjugate acid/base pairs
- dynamic equilibrium
- endergonic
- equilibrium
- equilibrium constant
- equivalence point
- exergonic
- forward rate
- hydronium
- LeChatelier's principle
- monoprotic acids
- pH
- pKa
- pOH
- polyprotic acids
- reaction quotient
- reverse rate
- solubility
- solubility product constant
- strong acids

Academic Vocabulary

- absorption
- abundant
- analogy
- analyze
- apply
- approximate
- balanced
- characteristic
- clarify
- classify
- compare
- comprised
- continuum
- contract
- correlate
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- directly proportional
- displacement
- distinguish
- dynamic
- emission
- emit

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- titrant
- weak acids

- estimate
- evaluate
- example
- hypothesize
- infer
- interact
- interpret
- inversely proportional
- magnitude
- manipulate
- observe
- pattern
- plausible
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