

The Story of Chemistry

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Introduction

How does "The Story of Chem" relate to the AP Chemistry Curriculum Framework?

Last year, the great Wizard of AP released a new document from behind his curtain in the Diamond City (the Emerald City was not quite expensive enough for the Wizard's taste). This document, known as the AP Chemistry Curriculum Framework lays out the course in terms of "Big Ideas," "Enduring Understandings," "Essential Knowledge," and "Learning Objectives." You can view this document online if you want, but it's written more for teachers than for students. What we will try to do in "The Story of Chem" is synthesize the most important parts of the curriculum framework into a more or less coherent narrative that explains all the most important ideas covered in the course. Essentially, the "Story" is your yellow brick road on your quest to meet the Wizard in May. Along the way, you are likely to need to rely on the brains, hearts, and courage of your fellow travelers (as well as your own)!

We think it's important that you are able to recognize the language used in the curriculum framework, because it is likely to be similar to the language used on the AP Test. So whenever possible in the "Story," which is written in our language, we will intersperse the relevant parts of the curriculum framework, which is written in the Wizard's language. So when you see anything labeled "AP-BI," for example, you will know that we are quoting the Wizard. The key below explains the abbreviations:

Abbreviation	What it stands for	What does that mean?
<u>AP-BI</u>	"Big Idea" from the AP Chem Curriculum Framework	There are 6 of these that supposedly outline the whole course. These are smaller chunks into which the Big
AP-EU	"Enduring Understanding" from the Framework	Ideas are divided. As the name implies, hopefully you will remember and apply these things even later in life. These are the details that you need to know about a particular topic.
AP-EK	"Essential Knowledge" from the Framework	These are clues as to how the AP Test questions will be written. They tell you what you need to know and be able to do in order to answer questions on the test.
AP-LO	"Learning Objective" from the Framework	

All of the Big Ideas, Enduring Understandings, Essential Knowledge, and Learning Objectives have been quoted directly from the AP Chemistry Course description, which can be downloaded from

http://media.collegeboard.com/digitalServices/pdf/ap/2013advances/AAP-ChemistryCED_Effective_Fall_2013.pdf

The Story of Chemistry

Part A: Chemistry is Based on a Few Fundamental Principles

Back in the early nineteenth century, chemistry was a completely empirical science. Chemists built catalogs of information about what chemicals would react with each other and what they would produce. However, there was very little theoretical framework holding these catalogs of information together. Two hundred years of developments in atomic theory and physics have changed the face of chemistry. Today, we can use some fundamental physical concepts, applied to atoms and molecules, to explain most chemical phenomena.

This chapter essentially lays out the ideas that we will refer to constantly all year. And we mean constantly. Most of the important concepts that we use later in the year (such as electronegativity) can be seen as applications of these fundamentals. Even at the very end of the year, we will keep coming back to these ideas. So seriously, you need to know and (hopefully) love them.

- 1) Coulomb's Law of Electrostatic Forces – This is the law that basically says the following:
 - a. Opposite charges attract, like charges repel.
 - b. The larger the charges, the stronger the attraction or repulsion.
 - c. The closer the charges are, the stronger the attraction or repulsion.

- 2) Conservation of Energy and Mass – This is the idea that mass and energy can be neither created nor destroyed. They can, however, be transformed and transferred – that's where all the fun stuff happens! If you study particle physics, you will see that energy and mass can be interconverted. For the purposes of this course, however, assume that mass and energy are distinct quantities. The total mass of a sample of matter never changes, and the total energy of an isolated system never changes.

- 3) Kinetic vs. Potential Energy – Energy is the ability to make stuff move (or more correctly but less intuitively, the ability to make stuff accelerate). There are two types of energy in the universe – kinetic and potential
 - Kinetic energy is the energy of anything that's moving. Most often, we think of the kinetic energy of big objects, but it can also be the kinetic energy of many small particles, such as:
 - o thermal energy (energy of collections of moving atoms and molecules)
 - o sound energy (energy of pockets of air or another medium vibrating)
 - o wind energy (energy of lots of air particles moving in one direction)

 - o Electromagnetic Radiation (a.k.a. light) is a form of energy that is “wicked complicated” (That's a technical term). For our purposes, we will consider it to be a kind of kinetic energy. But recognize that light really is in a category by itself, in many ways. When you take Electricity and Magnetism in college, maybe you'll reach a deeper understanding of light.

 - Potential energy is energy that is stored. It is not currently making anything move. Basically, what that means is that there is a force pushing on an object, so the object has the potential to accelerate in the direction of the force. Objects have potential energy because of how they are arranged relative to other objects. For example, objects have gravitational potential energy because of where they are relative to the Earth. Potential energy “wants” to become kinetic energy if it can. Of course, there may be something holding it back from becoming kinetic, in which case it will wait until it can be “set free.” Some examples:
 - o A stretched rubber band, when released, sails through the air.
 - o A pencil placed too close to the edge of a table falls to the ground.
 - o Two oppositely charged soda cans, if not held apart, will move toward each other.

In chemistry, we are generally dealing with very large numbers of atoms and molecules at any given point in time. The main manifestation of kinetic energy will be the temperature of a sample of matter. Recall from physics that temperature measures the average kinetic energy of a sample of particles. The molecules in the sample will have a wide range of kinetic energies; some move very fast, some move very slowly and most lie somewhere in between. Potential energy, in this course, is essentially stored based on the arrangements of atoms and molecules (and the protons and electrons within them). So for us, the interplay between kinetic and potential energy will be seen as the relationship between temperature and particle arrangement.

When a reaction occurs and the temperature goes up, there was an increase in kinetic energy. There must have been a corresponding decrease in potential energy. So in such a situation, we say that “energy was released.” In other words, stored energy was “set free.” Whenever a reaction causes the temperature to go down, we say that “energy was absorbed,” because kinetic energy has been turned into potential. It is best if you master this language early on.

4) Quantum Mechanics – I am including this here as a single principle, but really it is a whole theory built on a bunch of different principles. The fact of the matter is that you and I will probably never understand quantum mechanics. So we will be best served if we don’t try. At this point, we will just have to accept the conclusions of quantum mechanics. This will be unsatisfying for some of you, and I apologize. But someday, after taking multivariable calculus and linear algebra, maybe you can take some courses in quantum mechanics and reach all those same conclusions yourself. We will get into all the specifics in a week or so. For now, just accept our nebulous definition of quantum mechanics below:

- Quantum mechanics – n., a weird theory that describes things that happen on a very very small scale, like in an atom. This weird theory does not follow the laws of nature we’re used to observing.

So that’s it. Everything we do in this course, with maybe one or two exceptions, can be explained using the principles listed above. When you try to explain stuff, your first instinct should be to come back to this list. If you can’t explain what you need to explain using any principles above (which shouldn’t happen very often), just wave your hands in the air and say “Quantum mechanics!” or “Relativistic effects!” (as in Einstein’s theory of relativity) three times. In most scientific circles, this is an acceptable explanation. However, it will earn you no credit on exams.

AP-EU 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.

AP-EK 5.A.1: Temperature is a measure of the average kinetic energy of atoms and molecules.

AP-LO 5.2 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.

AP-EK 5.A.2: The process of kinetic energy transfer at the particulate scale is referred to in this course as heat transfer, and the spontaneous direction of the transfer is always from a hot to a cold body.

AP-LO 5.3 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.

AP-EU 5.B: Energy is neither created nor destroyed, but only transformed from one form to another.

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Part B: Matter is made of atoms, which have a positive nucleus surrounded by electrons.

AP-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.

AP-EU 1.A: All matter is made of atoms. There are a limited number of types of atoms; these are the elements.

When you finish this course, we hope you see the world like a chemist. The first part of seeing the world as a chemist is to recognize all the atoms around you. We know that they're too small to see, but our hope is that you develop your imagination this year to the point where you can look at a bottle of water and conjure up images of little things that are shaped like Mickey Mouse's head bouncing off each other. When trying to explain phenomena you see around you, we want your first instinct to be to approach it from the perspective of the atoms involved. We want you to learn to think like an atom, a concept that may seem absurd to you at this point. But before you can think like an atom, the first step is to know what they're made of, how they're laid out, and how we know what we know about them.

This unit is broken down into two parts. First, we'll talk about the structure of the atom. Then we'll spend some time getting to know the personalities of atoms of different elements in the periodic table. Some of them are easy-going, others are tough. We'll talk about how their structures determine their personalities and how the periodic table helps us know who's who.

Chapter 2: Electrons are arranged in energy levels around the nucleus, which is made of protons and neutrons.

Things you should know:

- 1) The idea of the atom and the accepted models for the way atoms behave have been shaped by evidence gathered by chemists and physicists over the last two centuries. Like all scientific models, the atomic model can always be revised when new evidence is found.
- 2) The nucleus is made of protons and neutrons, which contribute most of the mass to an atom.
 - a. Protons determine the identity of an atom.
 - b. Neutrons, to a chemist, are essentially dead weight.
 - c. Isotopes are atoms of the same element with different numbers of neutrons. They are more or less chemically equivalent.
- 3) Mass spectrometry is one experimental technique that provides us with data about the masses of atoms and molecules.
- 4) Quantum mechanics is a bizarre theory that happens to explain lots of phenomena that occur at the atomic level. Quantum mechanics is very difficult to understand, so in this course we will just take some of the conclusions the theory produces and use them.
- 5) Based on quantum theory, electrons are arranged in a complex set of energy levels and sublevels around the nucleus. An electron CANNOT be in between energy levels.
- 6) Energy levels closer to the nucleus are lower in potential energy, while those farther from the nucleus are higher in potential energy.
- 7) Electrons tend to go into the lowest energy states available, but sometimes can gain energy and move to higher energy levels. When electrons change energy levels, light is usually given off or absorbed. This is how we get much of our info about the energy levels.

- 8) Scientists use spectroscopy to study atoms and molecules. Someone using this technique shines light on a sample and observes which wavelengths get absorbed by the sample.
- Infrared light can be absorbed by molecules to make them vibrate more quickly. This gives us information about the types of bonds between atoms.
 - Visible and ultraviolet light can be absorbed by atoms to make their electrons move to higher energy levels. This gives us information about the arrangement of electrons and energy levels.

AP-EK 1.B.1: The atom is composed of negatively charged electrons, which can leave the atom, and a positively charged nucleus that is made of protons and neutrons. The attraction of the electrons to the nucleus is the basis of the structure of the atom. Coulomb's law is qualitatively useful for understanding the structure of the atom.

AP-LO 1.5 The student is able to explain the distribution of electrons in an atom or ion based upon data.

AP-LO 1.6 The student is able to analyze data relating to electron energies for patterns and relationships.

AP-EK 1.B.2: The electronic structure of the atom can be described using an electron configuration that reflects the concept of electrons in quantized energy levels or shells; the energetics of the electrons in the atom can be understood by consideration of Coulomb's law.

AP-LO 1.7 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.

AP-LO 1.8 The student is able to explain the distribution of electrons using Coulomb's law to analyze measured energies.

AP-EU 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.

AP-EK 1.D.1: As is the case with all scientific models, any model of the atom is subject to refinement and change in response to new experimental results. In that sense, an atomic model is not regarded as an exact description of the atom, but rather a theoretical construct that fits a set of experimental data.

AP-LO 1.13 Given information about a particular model of the atom, the student is able to determine if the model is consistent with specified evidence.

AP-EK 1.D.2: An early model of the atom stated that all atoms of an element are identical. Mass spectrometry data demonstrate evidence that contradicts this early model.

AP-LO 1.14 The student is able to use data from mass spectrometry to identify the elements and the masses of individual atoms of a specific element.

AP-EK 1.D.3: The interaction of electromagnetic waves or light with matter is a powerful means to probe the structure of atoms and molecules, and to measure their concentration.

AP-LO 1.15 The student can justify the selection of a particular type of spectroscopy to measure properties associated with vibrational or electronic motions of molecules.

AP-LO 1.16 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.

AP-EK 1.C.2: The currently accepted best model of the atom is based on the quantum mechanical model.

AP-LO 1.12 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.

Chapter 3: Properties of an atom are based on the relationship between the electrons and the nucleus.

Things you should know:

- 1) The outermost electrons, called valence electrons, are most important in determining atomic properties.
- 2) Two factors, number of protons and valence energy level, are most important in determining the properties of atoms and ions.
 - a. Higher energy levels are further from the nucleus, so electrons are not held as tightly (greater distance \square weaker force).
 - b. More protons in the nucleus lead to a greater attraction between the outermost electron and the nucleus (greater charge \square stronger force).
 - c. The inner electrons "shield" the outer ones from feeling the full attraction of the nucleus. We can estimate the "effective" nuclear charge, Z_{eff} , by accounting for this shielding effect.
- 3) We separate the periodic table into metals, which have a relatively weak hold on valence electrons, and nonmetals, which have a relatively strong hold on their valence electrons.
- 4) Many elemental properties can be explained based on the number of valence electrons and how strongly attracted to the nucleus they are. These properties include:
 - a. The typical charge on ions of the element
 - b. The ionization energy of an atom of the element
 - c. The radius of an atom of the element
 - d. The radius of an ion formed by the element
 - e. The electronegativity of an atom of the element

AP-EU 1.B: The atoms of each element have unique structures arising from interactions between electrons and nuclei.

AP-EU 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.

AP-EK 1.C.1: Many properties of atoms exhibit periodic trends that are reflective of the periodicity of electronic structure.

AP-LO 1.9 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.

AP-LO 1.10 Students can justify with evidence the arrangement of the periodic table and can apply periodic properties to chemical reactivity.

AP-LO 1.11 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.

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Part C: Atoms can bond with each other in different ways, depending on what types of atoms are involved.

AP-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.

AP-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.

In the real world, an atom rarely exists on its own. It would get too lonely! Atoms usually bond to other atoms. Why? Well, remember that everything in the universe usually tries to reach its lowest possible potential energy. Electrons on one atom might be able to be at a lower potential energy if they are shared with another atom or transferred to an atom with a stronger pull on its electrons. So in essence, the answer is that atoms bond with each other in order to make their electrons reach the lowest potential energy possible.

Chapter 4: We can classify substances based on their atomic-level structure and the types of forces holding them together.

AP-EU 2.C: The strong electrostatic forces of attraction holding atoms together in a unit are called chemical bonds.

AP-LO 2.17 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.

AP-EU 2.D: The type of bonding in the solid state can be deduced from the properties of the solid state.

AP-LO 2.22 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.

Section 4-1: When metal atoms get together, they share electrons in a common pool, usually making metallic solids.

Things you should know:

- 1) Metal atoms don't hold onto electrons very tightly.
- 2) When you put a bunch of metal atoms together, they stack up in a repeating pattern (think of oranges at the grocery store) and share their valence electrons in a common pool.
 - a. There are different ways of stacking the atoms; these lead to the wide variety of densities, melting points, etc. seen among metals.
 - b. Electrons in the common pool are free to move anywhere throughout the metallic solid. They are not stuck on one individual atom.
- 3) Metallic bonding explains the properties of metals, including:
 - a. malleability and ductility – the ability to be shaped and drawn into wires
 - b. conductivity – the ability to conduct an electric current or transfer heat readily

- 4) Metals can be mixed with each other to form alloys.
- In interstitial alloys, the atoms of one metal form their normal repeating pattern, and the atoms of the other element fit into the empty spaces between atoms of the first.
 - In substitutional alloys, the atoms of one element replace some atoms of the other in their usual structure.

AP-EK 2.C.3: Metallic bonding describes an array of positively charged metal cores surrounded by a sea of mobile valence electrons.

AP-LO 2.20 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.

AP-EK 2.D.2: Metallic solids are good conductors of heat and electricity, have a wide range of melting points, and are shiny, malleable, ductile, and readily alloyed.

AP-LO 2.25 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.

AP-LO 2.26 Students can use the electron sea model of metallic bonding to predict or make claims about the macroscopic properties of metals or alloys.

AP-LO 2.27 The student can create a representation of a metallic solid that shows essential characteristics of the structure and interactions present in the substance.

AP-LO 2.28 The student is able to explain a representation that connects properties of a metallic solid to its structural attributes and to the interactions present at the atomic level.

Section 4-2: When metal atoms meet nonmetal atoms, the nonmetal atoms steal electrons, making ionic solids.

Things you should know:

- Metal atoms have a weak hold on electrons, while nonmetal atoms have a strong hold.
- Nonmetal atoms are usually strong enough to remove an electron (or electrons) from metal atoms.
 - The nonmetal atom gains electrons and becomes a negative ion.
 - The metal atom loses electrons and becomes a positive ion.
 - Elements in groups 1-3, 13, and 15-17 tend to follow the "octet rule," forming ions with 8 valence electrons.
- The positive and negative ions are attracted to each other, forming an ionic solid.
- Ionic bonding explains the properties of ionic compounds, including:
 - high melting points
 - brittleness
 - no electrical conductivity in the solid state
 - electrical conductivity when molten (liquid) or dissolved in water

AP-EK 2.C.2: "Ionic bonding results from the net attraction between oppositely charged ions, closely packed together in a crystal lattice."

AP-LO 2.19 The student can create visual representations of ionic substances 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).

AP-EK 2.D.1: Ionic solids have high melting points, are brittle, and conduct electricity only when molten or in solution.

AP-LO 2.23 The student can create a representation of an ionic solid that shows essential characteristics of the structure and interactions present in the substance.

AP-LO 2.24 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.

Section 4-3: When nonmetal atoms meet each other, they share electrons, making covalent bonds. Covalent bonding can lead to the formation of network solids, polyatomic ions, or molecules.

Things you should know:

- 1) Nonmetal atoms have a strong pull on their valence electrons.
- 2) When multiple nonmetal atoms meet, none of them is strong enough to steal electrons from the others (as in ionic bonding), and they are not willing to share electrons in a loosely held pool (as in metallic bonding). The compromise is that nonmetal atoms share pairs of electrons, forming covalent bonds.
- 3) When nonmetal atoms bond in an unbroken, repeating pattern, the result is called a network solid. The strength of covalent bonds explains the properties of network solids, including
 - a. extreme hardness
 - b. extremely high melting points
 - c. thermally insulating
 - d. usually electrically insulating, with some exceptions
- 4) When several atoms get together and covalently bond, we call the resulting particle a molecule. The bonds holding the molecule itself together are strong, but the attractions between molecules are relatively weak when compared to bonds. Composition of molecules explains many properties of molecular solids, including:
 - a. usually low but widely varying melting points
 - b. electrically insulating as solids, when molten, and when dissolved
- 5) When a molecule as a whole steals electrons from metal atoms, gaining a negative charge, we call it a "polyatomic ion." Polyatomic ions will bond ionically with oppositely charged ions, forming an ionic solid.

AP-EK 2.D.3: Covalent network solids generally have extremely high melting points, are hard, and are thermal insulators. Some conduct electricity.

AP-LO 2.29 The student can create a representation of a covalent solid that shows essential characteristics of the structure and interactions present in the substance.

AP-LO 2.30 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.

AP-EK 2.D.4: Molecular solids with low molecular weight usually have low melting points and are not expected to conduct electricity as solids, in solution, or when molten.

AP-LO 2.31 The student can create a representation of a molecular solid that shows essential characteristics of the structure and interactions present in the substance.

AP-LO 2.32 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.

Chapter 5: Molecules have different shapes and can be polar or nonpolar.

Section 5-1: We draw Lewis dot structures to represent molecules.

Things you should know:

- 1) Covalent bonding can be described by drawing Lewis dot structures for molecules.
- 2) Covalent bonds can be single, double or triple.
 - a. The term “bond order” refers to whether a bond is single (bond order = 1), double (b.o. = 2), or triple (b.o. = 3).
 - b. Triple bonds are the shortest and strongest, while single bonds are the longest and weakest.
 - c. Two atoms may not form more than three bonds with each other (with some rare exceptions beyond the scope of this course).
- 3) Atoms in molecules usually follow the octet rule, with some exceptions.
 - a. Molecules with an odd number of electrons, known as free radicals, must have an atom with only 7 valence electrons.
 - b. Boron (B) often has only 6 valence electrons in Lewis structures (although these structures are not always great representations of the behavior of boron compounds).
 - c. Atoms of elements in periods 3-7 (e.g., S, P, I, etc.) sometimes have 10 or 12 valence electrons in Lewis structures.

Section 5-2: We can use the Lewis structure to determine the shape and polarity of molecules.

Things you should know:

- 1) If the two atoms sharing electrons in a covalent bond have very different strengths, the electrons are not shared equally. One end becomes partially positive and the other end becomes partially negative. We call these bonds polar.
- 2) Each pair of electrons around an atom wants to be as far apart from the others as possible.
- 3) Molecules have different shapes based on the number of valence electron pairs around the central atom.
- 4) If the partial charges in a molecule are asymmetrically arranged, then the molecule is considered “polar” because it has a positive pole and a negative pole. If the partial charges are symmetrically the same around the outside, or if there are no partial charges, then the molecule is nonpolar. For large molecules, it is possible for part of the molecule to be considered polar and part to be nonpolar.
- 5) Polar molecules will be attracted to other polar molecules – we’ll come back to this idea later.

AP EK 2.C.4: The localized electron bonding model describes and predicts molecular geometry using Lewis diagrams and the VSEPR model.

AP-LO 2.21 The student is able to use Lewis diagrams and VSEPR to predict the geometry of molecules, identify hybridization [which you will see in Chapter 6], and make predictions about polarity.

AP-EK 2.C.1: In covalent bonding, electrons are shared between the nuclei of two atoms to form a molecule or polyatomic ion. Electronegativity differences between the two atoms account for the distribution of the shared electrons and the polarity of the bond.

AP-LO 2.18 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.

Section 5-3: Organic compounds are based on carbon, and life is based on organic compounds.

Things you should know:

- 1) Organic compounds are built on a backbone of carbon and hydrogen and nearly always follow the octet rule. These facts allow us to draw abbreviated structures for these compounds.
- 2) The properties of an organic compound are determined by the “functional groups” attached to the carbon backbone.

Chapter 6: In order for covalent bonding to occur, atomic orbitals on neighboring atoms must overlap.

Things you should know:

- 1) In order to bond, orbitals on neighboring atoms must overlap.
- 2) Atomic orbitals (i.e., s, p, d, f) can mathematically recombine to form new orbitals with new shapes.
 - a. Orbitals can combine in phase or out of phase. When they combine in phase, the new orbitals are bigger in the region of overlap. When they combine out of phase, the new orbitals are smaller in the region of overlap.
 - b. When atomic orbitals on the same atom combine with each other, we call the resulting orbitals hybrid orbitals. The hybrid orbitals have different shapes from the original atomic orbitals. The hybridization of the orbitals on an atom is determined by its electron pair geometry.
 - c. When orbitals on neighboring atoms overlap, the resulting orbitals are called molecular orbitals. While we won't go into detail, molecular orbital theory is very important to a higher-order understanding of bonding (so you'll see it again if you keep studying chemistry).
 - d. Two types of bonds, called sigma and pi, can be made from different arrangements of overlapping orbitals.
- 3) Molecular orbitals can be used to explain the properties of some semi-conducting solids.
 - a. Solids have a low-energy "band" of bonding MO's that are filled and a high energy "band" of antibonding MO's that are empty.
 - b. In metals, there is no gap between the two bands, so electrons can pass freely from one to the other.
 - c. In semi-conductors, there is a relatively small gap between bands. Semi-conductors may be "doped" by adding impurities. This creates a substance that is either negative charge-carrying (n-doped) or positive charge-carrying (p-doped).
 - d. In insulators, there is a large gap between the two bands, so electrons cannot move between them. Thus, the substance does not conduct electricity.

The Story of Chemistry

Part D: The properties of substances and mixtures can be explained based on the bonding between atoms to make molecules and the interactions among molecules and/or ions.

AP-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.

AP-EU 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.

Chapter 7: The different forces of attraction between molecules result in a wide variety of properties in molecular compounds.

Section 7-1: Molecules can be attracted to each other by a variety of intermolecular forces, all of which are manifestations of the electrostatic force.

Things you should know:

- 1) Intermolecular forces are all based on electrostatic attractions. Opposites attract!
 - a. Ions have full charges. That leads to very strong attraction called ionic bonding.
 - b. Molecules that are polar have partially charged poles. That leads to relatively strong attractions called dipole forces.
 - c. Polar molecules that contain H covalently bonded to N, O, or F have especially strong dipole forces called hydrogen bonds.
 - d. Nonpolar molecules have no partially-charged ends. The attraction between them results from the random movement of electrons and is very weak. These attractions are called dispersion forces.
 - e. Dispersion forces are present between any two molecules. The strength of dispersion forces is roughly proportional to the size of the electron cloud.

AP-EU 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.

AP-EK 2.B.1: London dispersion forces are attractive forces present between all atoms and molecules. London dispersion forces are often the strongest net intermolecular force between large molecules.

AP-LO 2.11 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.

AP-EK 2.B.2: Dipole forces result from the attraction among the positive ends and negative ends of polar molecules. Hydrogen bonding is a strong type of dipole-dipole force that exists when very electronegative

atoms (N, O, and F) are involved.

AP-LO 2.12 The student can qualitatively analyze data regarding real gases to identify deviations from ideal behavior and relate these to molecular interactions.

AP-LO 2.13 The student is able to describe the relationships between the structural features of polar molecules and the forces of attraction between the particles.

AP-LO 2.14 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.

AP-EK 5.D.3: Noncovalent and intermolecular interactions play important roles in many biological and polymer systems.

AP-LO 5.11 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.

Section 7-2: The state of matter in which a substance exists is determined by the balance between the strength of interparticle forces and the amount of kinetic energy its particles have.

Things you should know:

- 1) The interparticle forces can be generally ranked in terms of strength. From strongest to weakest: covalent network bonding > ionic attraction > H-bonding > dipole attraction > dispersion forces
- 2) Temperature measures the average kinetic energy of a collection of particles.
- 3) In a sample of a substance, some particles have low kinetic energy and some have high, with the average somewhere in the middle.
- 4) The state of matter in which a substance exists is determined by the balance among three factors:
 - a. The strength of intermolecular attraction – stronger attraction favors solid
 - b. The temperature – higher temperature favors gas
 - c. The pressure – higher pressure favors the densest state of matter (usually solid)

AP-EK 2.A.1: The different properties of solids and liquids can be explained by differences in their structures, both at the particulate level and in their supramolecular structures.

AP-LO 2.3 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.

AP-EK 2.B.3: Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions.

AP-LO 2.1 Students can predict properties of substances based on their chemical formulas, and provide explanations of their properties based on particle views.

AP-LO 2.15 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. (See Chapter 16 about entropy)

AP-LO 2.16 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.

AP-EU 5.D: Electrostatic forces exist between molecules as well as between atoms or ions,

and breaking the resultant intermolecular interactions requires energy.

AP-EK 5.D.1: Potential energy is associated with the interaction of molecules; as molecules draw near each other, they experience an attractive force.

Chapter 8: Substances can be mingled with each other to make various kinds of mixtures.

Things you should know:

- 1) When one substance, called a solute, dissolves into another substance, called the solvent, the resulting mixture is called a solution.
 - a. Solutions have the same properties and composition throughout.
 - b. The molecules (or ions) of the solute have completely separated from one another.
Therefore, no particles in the solution are large enough to scatter visible light (although individual molecules may absorb visible light).
 - c. Components of a solution cannot be separated by filtration, but may be separable by chromatography or distillation.
- 2) In order for one substance to dissolve in another substance, the intermolecular forces between them must be compatible.
- 3) Substances with incompatible intermolecular forces (e.g., a polar solvent like water and a nonpolar solute like vegetable oil) will not form solutions. When mixed, they may form a suspension. If the solute can be broken into small chunks, the two substances may form a
- 4) Some compounds, called electrolytes, split into separate ions when dissolved in water. Examples of electrolytes are ionic compounds and acids.

AP-EK 2.A.3: Solutions are homogenous mixtures in which the physical properties are dependent on the concentration of the solute and the strengths of all interactions among the particles of the solutes and solvent.

AP-LO 2.7 The student is able to explain how solutes can be separated by chromatography based on intermolecular interactions.

AP-LO 2.8 The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent.

AP-LO 2.9 The student is able to create or interpret representations that link the concept of molarity with particle views of solutions.

AP-LO 2.10 The student can design and/or interpret the results of a separation experiment (filtration, paper chromatography, column chromatography, or distillation) in terms of the relative strength of interactions among and between the components.

Chapter 9: The behavior of gases can be explained by a few simple principles.

Things you should know:

- 1) A gas is a collection of particles (atoms and/or molecules) that are very far apart and moving quickly and randomly.
- 2) A gas sample can be described using four variables: Pressure, Temperature, Volume, and number of moles.

- 3) If two conditions are met, then we call the gas “ideal,” and the mathematical relationship among the variables is $PV = nRT$. If the conditions are not met, then the gas may deviate from ideal behavior. The conditions are:
- The gas particles should feel negligible attraction to one another.
 - The gas particles must be far enough apart that the volume of the particles themselves is negligible.
- 4) In a mixture of gases, the lighter gas particles move more quickly than the heavier gas particles.

AP-EK 2.A.2: The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently.

AP-LO 2.4 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.

AP-LO 2.5 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.

AP-LO 2.6 The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases.

The Story of Chemistry

Part E: Substances can react with each other, rearranging the bonds to make new substances.

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

When most people think about chemistry, they think about reactions. Now that we have the intellectual tools and a solid understanding of how substances are built, we're ready to explain how they react with each other. Don't forget that everything we talk about here can be explained using the same principles we've used throughout the course.

Chapter 10: Changes in matter can be either chemical or physical. We can classify chemical reactions to make them easier to understand and to predict the results of future reactions.

Things you should know:

- Chemical and physical changes are distinguished by the types of interactions being changed.
 - During chemical reactions, bonds (either ionic or covalent) are broken and/or formed.
 - During physical changes, intermolecular interactions may change, but bonds remain intact.
- There are several different ways to classify reactions, but we'll focus on a few.
 - In synthesis reactions, two reactants combine to form a single product.
 - In decomposition reactions, one reactant breaks up into two or more products.
 - In combustion reactions, a fuel reacts with oxygen. If the fuel contains carbon and hydrogen, then the products will be carbon dioxide and water.

- d. In precipitation reactions, two solutions of ionic compounds are mixed, and an insoluble ionic solid is formed.
 - e. In acid-base neutralization reactions, a proton (H^+ ion) is exchanged between two molecules. The proton donor is called an acid and the proton acceptor is called a base.
 - f. In oxidation-reduction (redox) reactions, electrons are transferred from one atom, molecule, or ion to another.
- 3) If you memorize the types, it should allow you to make some predictions about what will happen when two substances are mixed.

AP-EU 1.E: Atoms are conserved in chemical and physical processes.

AP-EK 1.E.1: Physical and chemical processes can be depicted symbolically; when this is done, the illustration must conserve all atoms of all types.

AP-LO 1.17 The student is able to express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings.

AP-EK 5.D.2: At the particulate scale, chemical processes can be distinguished from physical processes because chemical bonds can be distinguished from intermolecular interactions.

AP-LO 5.10 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.

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

AP-EK 3.A.1: A chemical change may be represented by a molecular, ionic, or net ionic equation.

AP-LO 3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views.

AP-LO 3.2 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.

AP-EU 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.

AP-EK 3.B.1: Synthesis reactions are those in which atoms and/or molecules combine to form a new compound. Decomposition is the reverse of synthesis, a process whereby molecules are decomposed, often by the use of heat.

AP-LO 3.5 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.

AP-LO 3.6 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.

AP-EK 3.B.2: In a neutralization reaction, protons are transferred from an acid to a base.

AP-LO 3.7 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.

AP-EK 3.B.3: In oxidation-reduction (redox) reactions, there is a net transfer of electrons. The species that loses

electrons is oxidized, and the species that gains electrons is reduced.

AP-LO 3.8 The student is able to identify redox reactions and justify the identification in terms of electron transfer.

Chapter 11: Chemical reactions and physical changes can absorb or release energy depending on the relative strength of the interactions being broken and the interactions being formed.

Things you should know:

- 1) Physical changes, such as phase changes and dissolving, involve breaking up certain intermolecular interactions and allowing others to occur.
 - a. Breaking up intermolecular attractions absorbs energy (i.e., turns kinetic into potential energy).
 - b. Forming new intermolecular attractions releases energy (i.e., turns potential into kinetic energy).
- 2) Reactions generally involve bond breaking and bond making.
 - a. Breaking bonds absorbs energy (i.e., turns kinetic into potential energy).
 - b. Making new bonds releases energy (i.e., turns potential into kinetic energy).
- 3) When a reaction happens, energy will either be absorbed or released, depending on the relative strength of the attractions being broken and the attractions being formed.
- 4) Energy can be transferred from one system to another by heat (faster moving molecules bumping into slower-moving ones) or by work (such as when a gas expands, pushing outward on its surroundings).
- 5) We can measure the amount of energy given off or absorbed in a reaction by using calorimetry. We measure the temperature change of an object and calculate the amount of heat using $q=mc\Delta T$.

AP-EU 3.C: Chemical and physical transformations may be observed in several ways and typically involve a change in energy.

AP-EK 3.C.1: Production of heat or light, formation of a gas, and formation of a precipitate and/or a color change are possible evidences that a chemical change has occurred.

AP-LO 3.10 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.

AP-EK 3.C.2: Net changes in energy for a chemical reaction can be endothermic or exothermic.

AP-LO 3.11 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.

AP-EK 5.B.1: Energy is transferred between systems either through heat transfer or through one system doing work on the other system.

AP-EK 5.B.2: When two systems are in contact with each other and are otherwise isolated, the energy that comes out of one system is equal to the energy that goes into the other system. The combined energy of the two systems remains fixed. Energy transfer can occur through either heat exchange or work.

AP-LO 5.4 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.

AP-LO 5.5 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.

AP-EK 5.B.3: Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions.

AP-LO 5.6 The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the 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.

AP-EK 5.B.4: Calorimetry is an experimental technique that is used to determine the heat exchanged/transferred in a chemical system.

AP-LO 5.7 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.

AP-EU 5.C: Breaking bonds requires energy, and making bonds releases energy.

AP-EK 5.C.1: Potential energy is associated with a particular geometric arrangement of atoms or ions and the electrostatic interactions between them.

AP-EK 5.C.2: The net energy change during a reaction is the sum of the energy required to break the bonds in the reactant molecules and the energy released in forming the bonds of the product molecules. The net change in energy may be positive for endothermic reactions where energy is required, or negative for exothermic reactions where energy is released.

AP-LO 5.8 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.

AP-EU 5.D: Electrostatic forces exist between molecules as well as between atoms or ions, and breaking the resultant intermolecular interactions requires energy.

AP-EK 5.D.1: Potential energy is associated with the interaction of molecules; as molecules draw near each other, they experience an attractive force.

AP-LO 5.9 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.

AP-LO 5.1 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.

Chapter 12: We can calculate the amounts of reactants and products involved in a reaction using stoichiometry.

Things you should know:

- 1) Chemical reactions follow the law of conservation of mass. The atoms that you start with will be the same as the atoms you end up with. It is just the way they are bonded that changes.
- 2) A balanced chemical equation gives the ratio of moles of one substance to moles of another substance involved in a reaction.
- 3) In order to do stoichiometric calculations, you need to get to moles, because the balanced chemical equation gives the ratio of moles of each reactant and product involved in the reaction.
- 4) We can convert to moles from any of the following:
 - a. Mass

- b. Concentration and volume of a solution
- c. Pressure, temperature, and volume of a gas

AP-EK 1.A.3: The mole is the fundamental unit for counting numbers of particles on the macroscopic level and allows quantitative connections to be drawn between laboratory experiments, which occur at the macroscopic level, and chemical processes, which occur at the atomic level.

AP-LO 1.4 The student is able to connect the number of particles, moles, mass, and volume of substances to one another, both qualitatively and quantitatively.

AP-EK 3.A.2: Quantitative information can be derived from stoichiometric calculations that utilize the mole ratios from the balanced chemical equations. The role of stoichiometry in real-world applications is important to note, so that it does not seem to be simply an exercise done only by chemists.

AP-LO 3.3 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.

AP-LO 3.4 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.

Chapter 13: We can apply what we know about bonding, chemical reactions, and stoichiometry to analyze the composition and purity of samples of matter.

Things you should know:

- 1) Any compound contains a fixed ratio of atoms of one element to atoms of another element. When that ratio is in terms of lowest whole numbers, it is called the empirical formula for the compound.
- 2) The percent by mass of each element in a compound can be used to determine its empirical formula.
- 3) Several methods exist for determining the concentration of a substance in solution.
 - a. The absorbance of light by a solution is proportional to the concentration of solute. If a suitable wavelength for analysis can be found and the absorbance can be measured, this technique can yield concentration without altering the composition of the solution.
 - b. If you add an ionic compound to a solution to form a precipitate, then you can collect the precipitate, determine its mass, and use the data to determine the concentration of the original solution. This is known as gravimetric analysis.
 - c. Titration is a technique where another solution is added in small increments until a visible change in the solution occurs, indicating that equivalent numbers of moles of both reactants have been added. Stoichiometric calculations then yield the original concentration.

AP-EK 1.A.1: Molecules are composed of specific combinations of atoms; different molecules are composed of combinations of different elements and of combinations of the same elements in differing amounts and proportions.

AP-LO 1.1 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.

AP-EK 1.A.2: Chemical analysis provides a method for determining the relative number of atoms in a substance, which can be used to identify the substance or determine its purity.

AP-LO 1.2 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.

AP-LO 1.3 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.

AP EK 1.E.2: Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation.

AP-LO 1.18 The student is able to apply conservation of atoms to the rearrangement of atoms in various processes.

AP-LO 1.19 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.

AP-LO 1.20 The student can design, and/or interpret data from, an experiment that uses titration to determine the concentration of an analyte in a solution.

AP-LO 3.9 The student is able to design and/or interpret the results of an experiment involving a redox titration.

The Story of Chemistry

Part F: We can gain insight into reactions by studying how fast they occur and the relative amounts of reactants and products at equilibrium.

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

Chapter 14: Reactions can happen slowly or quickly depending on how frequently and effectively the reactant particles collide with each other.

Things you should know:

- 1) Reactions generally involve bond breaking and/or bond making.
 - a. Breaking bonds absorbs energy.
 - b. Making new bonds releases energy.
- 2) In order to react, the reactant particles must collide
 - a. In the right orientation.
 - b. With enough energy to overcome the activation energy (this energy is needed to start breaking the bonds).
- 3) If you increase concentration of reactants, they collide more frequently, increasing the rate of reaction.
- 4) If you increase the temperature, molecules move more quickly. Therefore, they collide more frequently and with more energy, increasing the rate of reaction.
- 5) A catalyst provides an alternative pathway for the reaction. The activation energy of the alternative mechanism is lower, increasing the reaction rate.

- 6) The mathematical relationship between reaction rate and concentration of reactants is called the rate law.
- 7) Most reactions occur by a series of steps, not all at once. We call this series of steps the reaction mechanism.
- 8) If we know the rate law, we can get some idea of what the reaction mechanism looks like.

AP-EU 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.

AP-EK 4.A.1: The rate of a reaction is influenced by the concentration or pressure of reactants, the phase of the reactants and products, and environmental factors such as temperature and solvent.

AP-LO 4.1 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.

AP-EK 4.A.2: The rate law shows how the rate depends on reactant concentrations.

AP-LO 4.2 The student is able to analyze concentration vs. time data to determine the rate law for a zeroth-, first-, or second-order reaction.

AP-EK 4.A.3: The magnitude and temperature dependence of the rate of reaction is contained quantitatively in the rate constant.

AP-LO 4.3 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.

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

AP-EK 4.B.1: Elementary reactions can be unimolecular or involve collisions between two or more molecules.

AP-LO 4.4 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.

AP-EK 4.B.2: Not all collisions are successful. To get over the activation energy barrier, the colliding species need sufficient energy. Also, the orientations of the reactant molecules during the collision must allow for the rearrangement of reactant bonds to form product bonds.

AP-LO 4.5 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.

AP-EK 4.B.3: A successful collision can be viewed as following a reaction path with an associated energy profile.

AP-LO 4.6 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.

AP-EU 4.C: Many reactions proceed via a series of elementary reactions.

AP-LO 4.7 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.

AP-EK 4.C.1: The mechanism of a multistep reaction consists of a series of elementary reactions that add up to the overall reaction.

AP-EK 4.C.2: In many reactions, the rate is set by the slowest elementary reaction, or rate-limiting step.

AP-EK 4.C.3: Reaction intermediates, which are formed during the reaction but not present in the overall reaction, play an important role in multistep reactions.

AP-EU 4.D: Reaction rates may be increased by the presence of a catalyst.

AP-EK 4.D.1: Catalysts function by lowering the activation energy of an elementary step in a reaction mechanism, and by providing a new and faster reaction mechanism.

AP-LO 4.8 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.

AP-EK 4.D.2: Important classes in catalysis include acid/base catalysis, surface catalysis, and enzyme catalysis.

AP-LO 4.9 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.

AP-EK 5.E.5: A thermodynamically favored process may not occur due to kinetic constraints (kinetic vs. thermodynamic control).

Chapter 15: Reactions that are reversible will reach equilibrium when the forward and reverse reaction rates are equal.

AP-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.

Things you should know:

- 1) Any reaction can theoretically go in the reverse direction, as long as the products are trapped in a closed system.
- 2) If you start with only reactants and no products, then at first, the forward reaction rate is much higher than the reverse reaction rate. As the reaction proceeds and more products are made, the reverse rate will start to rise and the forward rate will start to fall.
- 3) When the forward and reverse rates are equal, the concentrations remain constant and the reaction is at equilibrium.
- 4) For a given reaction at a given temperature, the ratio of products to reactants (with some exponents included) will reach a fixed value called the equilibrium constant, K .
- 5) If K is large, then the reaction goes mostly toward products. If K is small, the reaction stays mostly with reactants.
- 6) We can do a variety of calculations based around the equilibrium constant for a reaction.
- 7) If a reaction is at equilibrium and you change something about the conditions, the reaction will adjust and re-establish equilibrium. We call this idea LeChatelier's Principle.

AP-EU 6.A: Chemical equilibrium is a dynamic, reversible state in which rates of opposing processes are equal.

AP-EK 6.A.1: In many classes of reactions, it is important to consider both the forward and reverse reaction.

AP-LO 6.1 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.

AP-EK 6.A.2: The current state of a system undergoing a reversible reaction can be characterized by the extent to which reactants have been converted to products. The relative quantities of reaction components are quantitatively described by the reaction quotient, Q .

AP-LO 6.2 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 .

AP-EK 6.A.3: When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.

AP-LO 6.3 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.

AP-LO 6.4 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.

AP-LO 6.5 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 .

AP-LO 6.6 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.

AP-EK 6.A.4: The magnitude of the equilibrium constant, K , can be used to determine whether the equilibrium lies toward the reactant side or product side.

AP-LO 6.7 The student is able, for a reversible reaction that has a large or small K , to determine which chemical species will have very large versus very small concentrations at equilibrium.

AP-EU 6.B: Systems at equilibrium are responsive to external perturbations, with the response leading to a change in the composition of the system.

AP-EK 6.B.1: Systems at equilibrium respond to disturbances by partially countering the effect of the disturbance (Le Chatelier's principle).

AP-LO 6.8 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.

AP-LO 6.9 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.

AP-EK 6.B.2: A disturbance to a system at equilibrium causes Q to differ from K , thereby taking the system out of the original equilibrium state. The system responds by bringing Q back into agreement with K , thereby establishing a new equilibrium state.

AP-LO 6.10 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 .

The Story of Chemistry

Chapter 16: The laws of thermodynamics describe the essential role of energy and explain and predict the direction in which reactions and other changes will occur.

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

In order to have a reference state to compare other situations to, we define “standard conditions.” This set of conditions includes, most importantly, that the concentrations of all species is 1 mol/L.

Section 16-1: Enthalpy is the formal word for chemical potential energy (sort of).

Things you should know:

- 1) Enthalpy is technically the total energy content of a system at constant pressure. For our purposes, enthalpy will generally manifest itself as a measure of the chemical potential energy associated with the attractions and repulsions among atoms and molecules.

- 2) Enthalpy is symbolized by the letter H, and change in enthalpy for a reaction by ΔH .
 - a. If ΔH is positive, then the potential energy of the atoms and molecules is increasing, and the reaction is endothermic (KE \square PE).
 - b. If ΔH is negative, then the potential energy of the atoms and molecules is decreasing, and the reaction is exothermic (PE \square KE).

- 3) The enthalpy change for a reaction is independent of the reaction pathway, because the reactants and products have the same amount of potential energy no matter how you get from start to finish.

- 4) We can calculate the enthalpy change for a reaction in various ways:
 - a. We can use calorimetry, measuring a temperature change and assuming that it correlates to the change in potential energy.
 - b. In a reaction, breaking bonds absorbs energy and forming bonds releases energy. By adding the bond energies of the broken bonds and subtracting from them the bond energies of the bonds formed, we can estimate ΔH .
 - c. We can use the “enthalpy of formation” as a measure of the amount of potential energy in a substance. By subtracting the reactants potential energy from the products potential energy, we can calculate ΔH .

See the enduring understandings, essential knowledge, and learning objectives from Chapter 11.

Section 16-2: The entropy (disorder) of the universe is constantly increasing.

Things you should know:

- 1) Entropy (symbolized S) is a complex mathematical/statistical idea that can best be summed up as “disorder” or “randomness.”
- 2) Solids generally have less entropy than liquids, which have less entropy than gases.
- 3) When more particles are present, the entropy is greater.
- 4) A sample of particles has greater entropy at higher temperature.
- 5) In the grand scheme of the universe, things are constantly becoming more and more random. This is called the second law of thermodynamics.

AP-EK 5.E.1: Entropy is a measure of the dispersal of matter and energy.

AP-LO 5.12 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.

Section 16-3: Gibbs free energy connects entropy and enthalpy and allows us to predict in which direction processes will proceed.

Things you should know:

- 1) A chemical reaction will be thermodynamically favorable if the entropy of the universe increases (2nd Law).
- 2) Gibbs free energy (symbolized G) is an idea constructed so that it tells us which direction of a reaction will be favorable under the second law.
- 3) $\Delta G = \Delta H - T\Delta S$
- 4) If $\Delta G < 0$, the products are more thermodynamically favorable than the reactants, and the reaction will proceed in the forward direction toward equilibrium.
- 5) There is a mathematical relationship between the equilibrium constant, K, and the ΔG for a reaction.
- 6) The relationship between ΔG and K allows us to predict how K will change as temperature changes.

AP-EU 5.E: Chemical or physical processes are driven by a decrease in enthalpy or an increase in entropy, or both.

AP-EK 5.E.2: Some physical or chemical processes involve both a decrease in the internal energy of the components ($\Delta H^\circ < 0$) under consideration and an increase in the entropy of those components ($\Delta S^\circ > 0$). These processes are necessarily “thermodynamically favored” ($\Delta G^\circ < 0$).

AP-LO 5.13 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.

AP-EK 5.E.3: If a chemical or physical process is not driven by both entropy and enthalpy changes, then the Gibbs free energy change can be used to determine whether the process is thermodynamically favored.

AP-LO 5.14 The student is able to determine whether a chemical or physical process is thermodynamically favorable by calculating the change in standard Gibbs free energy.

AP-EK 5.E.4: External sources of energy can be used to drive change in cases where the Gibbs free energy change is positive.

AP-LO 5.15 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.

AP-LO 5.16 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.

AP-LO 5.17 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.

AP-EK 5.E.5: A thermodynamically favored process may not occur due to kinetic constraints (kinetic vs. thermodynamic control).

AP-LO 5.18 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.

AP-EU 6.D: The equilibrium constant is related to temperature and the difference in Gibbs free energy between reactants and products.

AP-EK 6.D.1: When the difference in Gibbs free energy between reactants and products (ΔG°) is much larger than the thermal energy (RT), the equilibrium constant is either very small (for $\Delta G^\circ > 0$) or very large (for $\Delta G^\circ < 0$). When ΔG° is comparable to the thermal energy (RT), the equilibrium constant is near 1.

AP-LO 6.25 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.

The Story of Chemistry

Part G: Some specific types of compounds and reactions warrant more detailed study.

By this point, we've covered all the fundamental ideas of the course. Hooray for us! All that's left is to look in more detail at some specific types of compounds and reactions. Most of these reactions are very important in chemical applications, particularly biology. Enjoy! We're almost done!

Chapters 17-19: Water can split up into H^+ (acid) and OH^- (base), allowing for acid/base equilibrium in all aqueous systems. (This one's so important that we're calling it three chapters in one!)

Note: Much of this is repeated from the previous section.

Things you should know:

- 1) The equilibrium $H_2O(l) \rightleftharpoons H^+(aq) + OH^-(aq)$ is very important in any aqueous system.
- 2) Acids are compounds that increase the concentration of H^+ and bases are compounds that increase the concentration of OH^- (sometimes by taking H^+ away from H_2O).
- 3) When $[H^+]$ goes up, $[OH^-]$ goes down, and vice versa.
- 4) The strength of an acid or a base is a measure of the extent to which it ionizes in solution.
- 5) Acid strength and base strength depend on the structure of the compounds themselves, and we can explain the strength using all of the same old fundamental concepts.
- 6) A salt (ionic compound) may be acidic, basic, or neutral depending on the identity of the cation and anion.
- 7) We use the pH scale to measure the concentration of H^+ in a solution.
- 8) Indicators are compounds that change color when the concentration of H^+ changes.
- 9) A buffer solution uses a weak acid/weak base conjugate pair in order to keep the pH roughly constant.
- 10) A titration is an experiment performed in order to investigate the strength of an acid and/or its concentration in a given solution.
- 11) We can perform a variety of calculations surrounding acid/base equilibria.

AP-EU 6.C: Chemical equilibrium plays an important role in acid-base chemistry and in solubility.

AP-EK 6.C.1: Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.

AP-LO 2.2 The student is able to explain the relative strengths of acids and bases based on molecular structure, interparticle forces, and solution equilibrium.

AP-LO 6.11 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.

AP-LO 6.12 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.

AP-LO 6.13 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 pKa for a weak acid, or the pKb for a weak base.

AP-LO 6.14 The student can, based on the dependence of Kw on temperature, reason that neutrality requires $[H^+] = [OH^-]$ as opposed to requiring $pH = 7$, including especially the applications to biological systems.

AP-LO 6.15 The student can identify a given solution as containing a mixture of strong acids and/or bases and calculate or estimate the pH (and concentrations of all chemical species) in the resulting solution.

AP-LO 6.16 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.

AP-LO 6.17 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.

AP-EK 6.C.2: The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pKa allows one to determine the protonation state of a molecule with a labile proton.

AP-LO 6.18 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.

AP-LO 6.19 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 pKa associated with the labile proton.

AP-LO 6.20 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.

Chapter 20: The solubility of ionic compounds can be an interesting equilibrium and is affected by acids, bases, and complex ions.

Things you should know:

- 1) When an ionic compound dissolves, the equilibrium constant expression contains nothing in the denominator because the "reactant" is a solid.
- 2) We can calculate the extent to which a compound dissolves based on its equilibrium constant.
- 3) When a common ion is added to the solution, an ionic compound becomes less soluble.
- 4) An acidic salt can react with base, so it is more soluble in a basic solution. A basic salt can react with acid, so it is more soluble in acidic solution.
- 5) The formation of a complex ion can effectively remove a metal ion from the solubility equilibrium, making a compound more soluble.

AP-EU 6.C: Chemical equilibrium plays an important role in acid-base chemistry and in solubility.

AP-EK 6.C.3: The solubility of a substance can be understood in terms of chemical equilibrium.

AP-LO 6.21 The student can predict the solubility of a salt, or rank the solubility of salts, given the relevant Ksp values.

AP-LO 6.22 The student can interpret data regarding solubility of salts to determine, or rank, the relevant Ksp

values.

AP-LO 6.23 The student can interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility.

AP-LO 6.24 The student can analyze the enthalpic and entropic changes associated with the dissolution of a salt, using particulate level interactions and representations.

Chapter 21: Reactions where electrons are exchanged, called oxidation-reduction reactions or redox reactions, can be carried out by sending the electrons through a wire.

Things you should know:

- 1) "Oxidation state" is an elaborate bookkeeping technique that we use to keep track of who gains electrons and who loses electrons in a redox reaction.
- 2) We can imagine splitting the reaction up into two half reactions – one where something loses electrons (oxidation) and one where something gains electrons (reduction).
- 3) The "standard reduction potential" for a half reaction serves as a measurement of how much potential energy changes when that reaction happens.
- 4) Using a table of standard reduction potentials, we can calculate the potential energy difference for a reaction as a whole. This will tell us if the reaction is spontaneous or not.
- 5) If we want, we can physically separate the two half reactions and make the electrons travel along a wire. We can then use the movement of the electrons to do useful work for us, like running a motor or lighting a bulb. This is how a battery works.
- 6) If a redox reaction is not spontaneous, we can force it to happen by applying an external source of electrical potential energy.
- 7) We can count the electrons as they travel through a wire, allowing us to do stoichiometric calculations.

AP-EK 3.C.3: Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.

AP-LO 3.12 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.

AP-LO 3.13 The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions.

Appendices: You will need a bunch of mathematical skills and tools to master all this stuff.

Appendix I: A number is meaningless without units. Converting between units is an important skill.

Things you should know:

- 1) Units are the connection between numbers and the physical world.
- 2) Some units are fundamental (e.g., meters), while others are compound units made by multiplying and dividing fundamental units (e.g., $1 \text{ Joule} = 1 \text{ kg m}^2 \text{ s}^{-2}$).
- 3) We will use the unit cancellation method to convert from one unit to another. In this method, a unit in the numerator can be cancelled out by the same unit in the denominator.)

Appendix II: We record very big or very small quantities in scientific notation.

Things you should know:

- 1) Numbers with positive powers of ten are large (greater than 1). Numbers with negative powers of ten are small (less than 1).
- 2) When multiplying numbers in scientific notation, add the exponents on ten. When dividing, subtract the bottom exponent from the top.

Appendix III: There are a number of pieces of lab equipment that we will use frequently.

Things you should know:

- 1) In order to conduct an experiment and correctly report your findings you need to know the proper name for the equipment.
- 2) Each piece of equipment used for measurement has its own inherent precision. You need to use the right piece of equipment for the right measurement.

Appendix IV: Graphical representations are a powerful way to present data.

Things you should know:

- 1) A good graph tells a story about the relationship between two (or more) things.
- 2) When you make a graph, you should include enough information for the viewer to “read” its story clearly.
- 3) To create graphs electronically, you will use either Excel or Google docs.

Appendix V: Creating and using models.

Things you should know:

- 1) Models attempt to explain data and are derived from experimental observations, though they are simplistic views of reality.
- 2) Models can be used in an attempt to understand new situations, though any new data may change the model.

Appendix VI: We will need to solve many equations to master chemistry.

Things you should know:

- 1) While the variables may change from one equation to another, the rules of algebra are always the same.

- 2) If there are n unknown quantities, then n equations are needed in order to solve. For example, if trying to solve for two variables, we will need two equations.

Appendix VII: You will not have a calculator on the multiple-choice section of the AP Test. Be prepared to use some estimation skills.

Things you should know:

- 1) When estimating, round off all numbers to one or two digits.
- 2) Look for numbers that are multiples of one another that may cancel out.
- 3) When multiplying by ten, move the decimal point to the right. When dividing by ten, move the decimal point to the left.

Appendix VIII: Making and/or diluting solutions.

Things you should know:

- 1) The steps in creating a solution appear simple, but are very important and easily done incorrectly.
- 2) We can use a stock solution to create new solutions of different molarities via dilution.

Appendix IX: When making scientific measurements, it is important to keep track of exactly how many digits of a number we actually know.

Things you should know:

- 1) When making measurements, we record all the certain digits plus one estimated digit.
- 2) The digits we know with some certainty are called "significant figures" (sig figs).
- 3) Scientists follow some conventions to keep track of the number of sig figs in measured and calculated quantities.

Appendix X: Asking scientific questions and designing investigations.

Things you should know:

- 1) It all begins with a question.
- 2) The variable that is controlled is called the independent variable. The one that is measured as the outcome is the dependent variable.
- 3) In order to design an experiment, you need to make sure you have the correct equipment and procedure to provide you with the information you desire.

Appendix XI: The opposite of raising a number to a power is taking the logarithm.

Things you should know:

- 1) Taking a logarithm is essentially the opposite of raising the base number to a power.
- 2) We will work with logarithms on base 10 (known simply as log) and on base e (known as \ln , for "natural logarithm").
- 3) $\log(10^x) = x$