Chemistry in the Earth System Unit 3

Atoms and Elements

Background for Teachers and Instructional Suggestions

The previous instructional segment examined the thermal interactions of objects by looking at the ***energy*** of microscopic particles that make them up. Students observed that different materials have different thermal properties, but they do not yet have a good explanation about what causes these differences. In fact, their **model** of these particles does not yet differ much from the **model** they developed in 5th grade that objects are made of particles too small to be seen (*5-PS1-1*), modified slightly by the middle grade level where they defined some particles as molecules that are made of groups of atoms held together in simple structures (*MS-PS1-1*). This instructional segment is the first time that students actually discuss what an atom is and how it can explain so many of the properties they have observed.

HS-PS1-1 requires that high school students build upon this understanding by applying the periodic table as a **model** to "*predict the relative properties of elements based on the patterns of electrons in the outermost (valence) energy level of atoms"*. The NRC Framework states that:

> "By the end of grade 12, students should understand that "each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons. The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms. The stability of matter is increased when the electric and magnetic field energy is minimized. A stable molecule has less energy, by an amount known as the binding energy, than the same set of atoms separated, and one must provide at least this energy in order to take the molecule apart." (National Research Council 2012)

The PE’s at the middle grade level do not require students to develop a **model** of the atom’s internal workings. This sequence differs from the 1998 California Science Content Standards where the internal workings of the atom were introduced in grade 8, and it is conceivable that students highly proficient in the *CA NGSS* PE’s for the middle grade level have never heard the words protons, neutrons, and electrons. The *CA NGSS* learning progression has been designed so that this material is introduced at a time when it is developmentally appropriate and integrates with their learning in other disciplines (in this case, a formal description of electrical attraction with Coulomb’s Law in high school physics). Students do, however, have significant experience recognizing ***patterns*** and **asking questions** about them. They have **analyzed data** about the bulk properties of matter and are ready to begin relating them to the components that make up atoms.

It should be emphasized that *HS-PS1-1* is best accomplished not by memorization, but by understanding and applying the underlying models of atomic ***structure*** and interaction. This instructional segment emphasizes the application of such **models** and the principle of ***cause and effect*** to predict and explain properties. Although students are not expected to derive models of atomic structure, they are expected to apply **models** to make reasonable predictions of elemental properties such as the reactivity and the types and numbers of bonds formed. Students learn that the properties of the elements repeat in a periodic fashion, and understand that the periodic table is a very useful **model** for understanding and predicting bulk properties of elements as well as the reactions between elements.

Dmitri Mendeleev, who developed the predecessor of the modern periodic table, realized that the physical and chemical properties of elements were related to their atomic mass in a 'periodic' way, and arranged the 63 known elements so that groups with similar properties fell into vertical columns in his table. Students can build a mental model of how the periodic table is arranged by an analogous activity in which they arrange color chips from a paint store into a matrix based on color and hue. Students can understand the power of such models by predicting the existence of color/hue chips that were removed from the final matrix before the chips were distributed, mirroring the process Mendeleev used to predict the existence of elements not yet known.

This instructional segment emphasizes the recognition and use of patterns. ***Patterns*** are a key crosscutting concept because they result from underlying causes. Observed ***patterns*** not only guide organization and classification, but also prompt **questions** about relationships and the factors that influence them, and thereby lead to a discussion of ***cause and effect***. When chemists organized elements in order of increasing relative atomic mass, they noticed repeating, or periodic patterns. For example, they noticed trends in chemical reactivity were punctuated by elements that were seemingly inert as shown in the high ionization energies of the Noble gasses in Figure 4. These patterns led chemists to suppose that there were underlying causes that created these patterns. The recognition of these patterns thus contributed to our understanding of atomic theory, the key model that students are expected to apply in this instructional segment. Using dynamic computer-based periodic tables, students can easily investigate a variety of properties (such as atomic radius, first ionization energy and electron affinity) and observe periodic patterns that provide evidence of ***patterns*** in underlying atomic ***structure***.

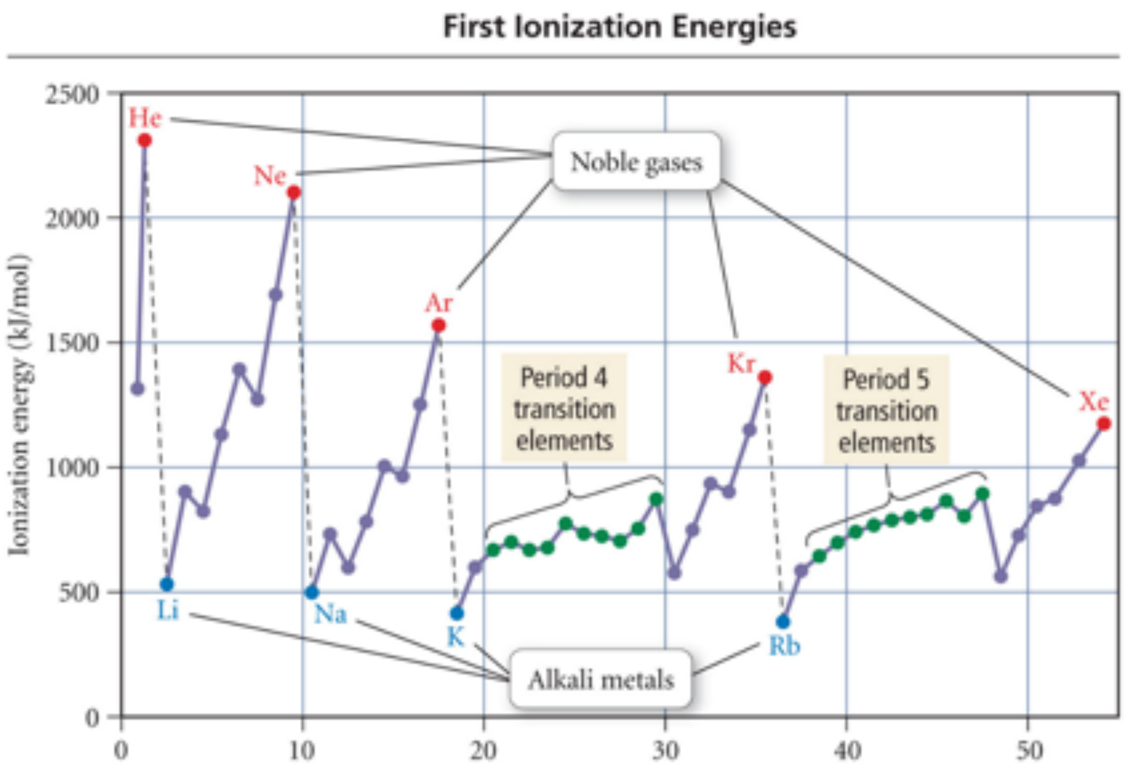

Figure 4 Table of first ionization energies

This instructional segment does not require students to memorize trends within the periodic table. Rather, it requires students to predict trends within the periodic table based upon an application of **models** of atomic ***structure*** that are reflected in trends within the periodic table (Figure 5). For example, students should be able to predict that sodium is likely to lose electrons when interacting with other elements because it has only one loosely held electron in its valence shell, as indicated by its position in the first family. Similarly, they should be able to predict that sodium will react strongly with chlorine because chlorine tends to gain electrons due to its high electronegativity associated with its nearly filled valence shell as indicated by its position in the seventh family. Finally, they should be able to predict that the resulting sodium cation and chloride anion will be attracted to each other and form an ionic bond by applying the principles of electrostatic attraction (Figure 5).

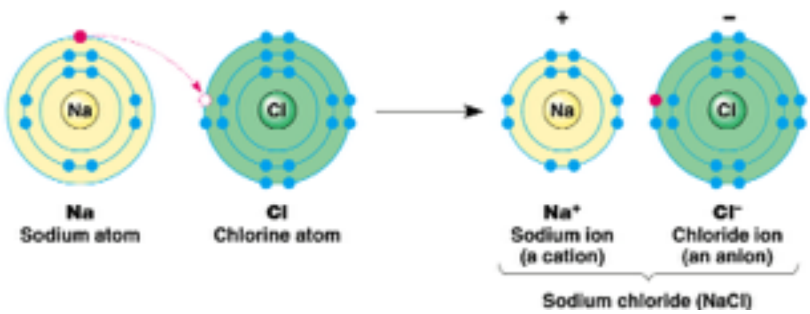

Figure 5 Students can predict bond formation

Mastery of performance expectation *HS-PS1-1* is foundational for achieving *HS-PS1-2* in which students are expected to "*construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties".* Note that this PE requires that students be able to **construct explanations** and **argue from evidence** based on the disciplinary core ideas (*PS1.A Structure and Property of Matter***)** associated with *HS-PS1-1*.

It is not sufficient for students to memorize and blindly apply rules for chemical bonding. Rather, they must develop **explanations** for why atoms of main-group elements tend to combine in such a way that each atom has a filled outer (valence) shell, giving it the same electronic configuration as a noble gas (octet rule). To meet this PE, students must describe thermodynamic principles that dictate that atoms will react to with one another in order to transition to a more stable (lower energy) state. Filled orbitals, such as occur in a full ‘octet’ state, result in an energy minimum. In addition, the electrons present in the different orbitals of the same sub-shell in a full octet can freely exchange their positions, leading to a decrease in exchange ***energy*** and thus a lower net energy. The energy state is also affected by its electrical charge. Since opposites attract, an electrically neutral state has lower energy, and thus is more stable, than an electrically charged state. After learning these principles, students can apply them to explain covalent, polar covalent, and ionic bonding as modeled in Figure 6. Students should be able to use such diagrams in their **explanations**, pointing out that the energy of the system is minimized, and thus the resulting compound is more stable, when the valence shells are filled either by gaining or loosing electrons, as in ionic bonds, or by sharing them, as in covalent bonds. In addition, they can predict that the oppositely charged ions in an ionic bond are attracted to each other, creating a lower energy state in the resulting ionic compound, than when the ions were separated. For example, students should be able to **explain** that table salt (NaCl) is the result of Na^+ ions and Cl^- ions bonding. If sodium metal and chlorine gas mix under the right conditions, they will form salt as the sodium loses an electron, and the chlorine gains that electron. In the process, a great amount of light and heat is released, and the resulting salt thus has much lower energy and is relatively unreactive and stable, and will not undergo any explosive reactions like the sodium and chlorine that it is made of.

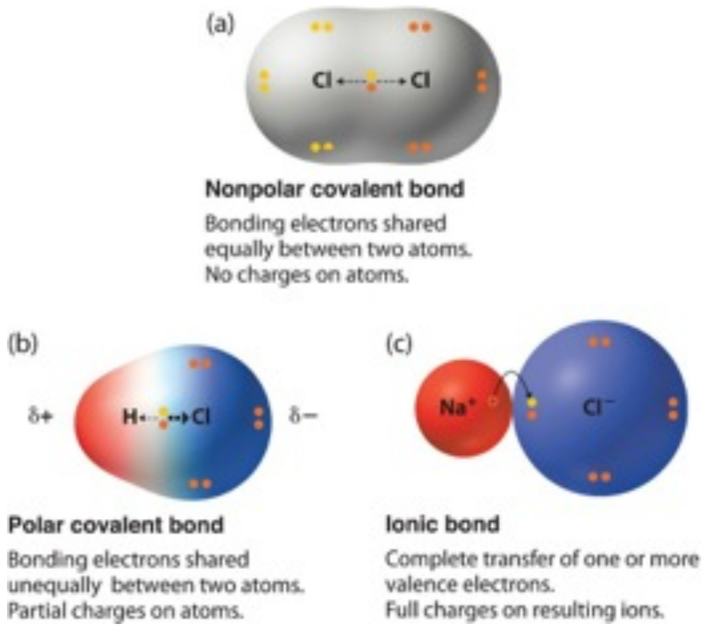

Figure 6 - Students should be able to explain models of covalent, polar covalent, and ionic bonding

Once again, it is important to note that *HS-PS1-2* requires students to **construct explanations** and **argue from evidence**, rather than memorize facts and trends. Students should understand the basis for trends and ***patterns*** shown in Figure 7 exist, and be able to **explain** (***cause and effect***) the types of chemical reactions and resulting bonds that occur between elements. Once students understand the reasons for the trends observed in the periodic table, they can subsequently predict chemical reactions of significance in both the physical and biological realm. For example, by noting that carbon is in the fourth family, students should conclude that it therefore has four valence electrons that can be shared by such elements as hydrogen and oxygen and explain the existence of hydrocarbons based upon valence electron patterns.

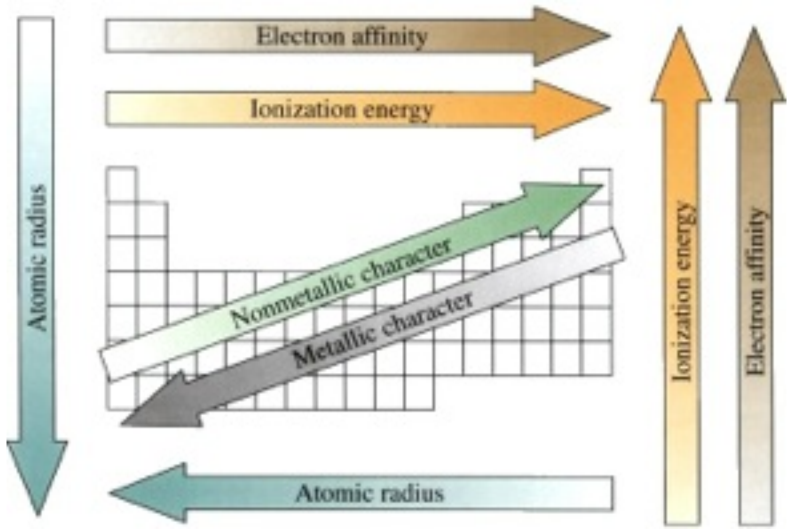

Figure 7 Students should understand the basis for trends and patterns in the periodic table, and be able to explain the types of chemical reactions and resulting bonds that occur between elements.

An understanding of atomic structure and the periodic table lays a foundation for understanding the properties of bulk matter such as melting point, boiling point, vapor pressure and surface tension. Although early chemists strived to understand phases of ***matter*** and the peculiar properties of pure substances, today's students can easily access such **information** from textbooks or the Internet. Unfortunately, easy access often equates to shallow understanding, and it is therefore important that students gain tangible experiences with such properties.

Students should be able to construct **models** of the phases of ionic and covalent ***matter*** by observing ***patterns*** in each phase witnessed at the macro level. For example, ionic compounds exhibit higher melting points and electrical conductivity compared to covalent compounds. Strong electrostatic interactions between ions in ionic compounds give them their macroscopic properties, while the sharing of electrons in covalent bonds gives covalent compounds a different set of properties. The idea is to engage students in the connection of behavior at the atomic level to the observed behavior at the macroscopic. They can use **investigations** or various forms of media such as textbooks or the Internet to connect the properties of the various solids such as strength of the structure, hardness, malleability, ductility, conductivity, and melting points to its observable structure. Spending time learning more about the properties of pure substances, both elements and compounds, will reinforce *HS-PS1-2*.

Students will now be more prepared to **explain** how reactions can be used to identify substances. Rather than memorizing trends in such properties, performance objective *HS-PS1-3* requires students to "*plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles*". For example, students could **plan and carry out an investigation** to compare the boiling points of varying solutions of salt water, with the inference that higher boiling points indicate stronger electrical forces between the particles.

Students can begin to construct a **model** of particles in solids based on their behavior and seek causal relationships between their structure and behavior. Similar studies can be made to establish the properties of pure liquids and gases. Students should start making inferences about the spacing between particles/molecules in solids, liquids and gases. Traditional instruction often jumps directly into the gas laws without students first establishing the actual properties beyond simple definitions. Students should engage in developing their own understanding of how gases have mass, for instance. This can be done by filling multiple zip top plastic bags with different types of gases that are denser than air, such as carbon dioxide and oxygen, and massing each to learn that there are differences in the mass of different gases even though they have the same volume.

Additionally, students should begin to appreciate the unique properties of various pure substances, and understand how atomic and molecular structure determines the ***functions*** and properties that substances exhibit on the macro-***scale***. The special properties of water, such as its high heat capacity, low density in solid form, strong cohesion and adhesion, capillary action, high surface tension, and excellent ability to dissolve polar substances, are particularly important to biological, environmental, and chemical systems, and are determined by its unique ***structure***. Water has an incredible range of properties that play important roles for different types of systems. Observing the interaction between different types of compounds in water, their solubility, their ability to conduct electricity, and any ***changes*** in temperature gives additional data that can be used to support students' **arguments** regarding properties of different substances. This should lead students to **ask questions** that will lead to collecting additional data concerning why water affects so many substances of varying types. Once again, students should rely on the ***patterns*** they observe to form the **questions** that will lead to the ***cause*** of such behaviors. At the conclusion of this instructional segment, students should be able to articulate their **arguments** regarding the properties of ***matter*** and be able to classify different compounds based on their current model.