IS3 Chemistry in the Earth System Instructional Segment 3: Atoms, Elements, and Molecules

The previous instructional segment examined the thermal interactions of objects by looking at the **energy [CCC-5]** of microscopic particles that comprise them. 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 [SEP-2]** of these particles does not yet differ much from the **model [SEP-2]** they developed in grade five: objects are made of particles too small to be seen (5-PS1-1), modified slightly in the middle grades when 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.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 3: ATOMS, ELEMENTS, AND MOLECULES

Guiding Questions

- What is inside atoms and how does this affect how they interact?
- What models can we use to predict the outcomes of chemical reactions?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-1. Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms. [Clarification Statement: Examples of properties that could be predicted from patterns could include reactivity of metals, types of bonds formed, numbers of bonds formed, and reactions with oxygen.] *[Assessment Boundary: Assessment is limited to main group elements. Assessment does not include quantitative understanding of ionization energy beyond relative trends.]*

HS-PS1-2. 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. [Clarification Statement: Examples of chemical reactions could include the reaction of sodium and chlorine, of carbon and oxygen, or of carbon and hydrogen.] *[Assessment Boundary: Assessment is limited to chemical reactions involving main group elements and combustion reactions.]*

HS-PS1-7. Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. [Clarification Statement: Emphasis is on using mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem- solving techniques.] *[Assessment Boundary: Assessment does not include complex chemical reactions.]* (Introduced here and revisited again in IS4 and IS6)

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 3: ATOMS, ELEMENTS, AND MOLECULES

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-2] Developing and Using Models [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-7] Engaging in Argument from Evidence	PS1.A: Structure and Properties of matter PS1.B: Chemical Reactions	[CCC-1] Patterns [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CA CCSS Math Connections: N-Q.1–3; MP.2

CA CCSS for ELA/Literacy Connections: SL.11–12.4; RST.9–10.7, WHST.11–12.2, 5

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

The performance expectation HS-PS1-1 requires that high school students build upon this understanding by applying the periodic table as a **model [SEP-2]** to *predict the relative properties of elements based on the patterns of electrons in the outermost (valence) energy level of atoms*. The National Research Council's *A Framework for K–12 Science Education* (*NRC Framework*) states:

> 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)

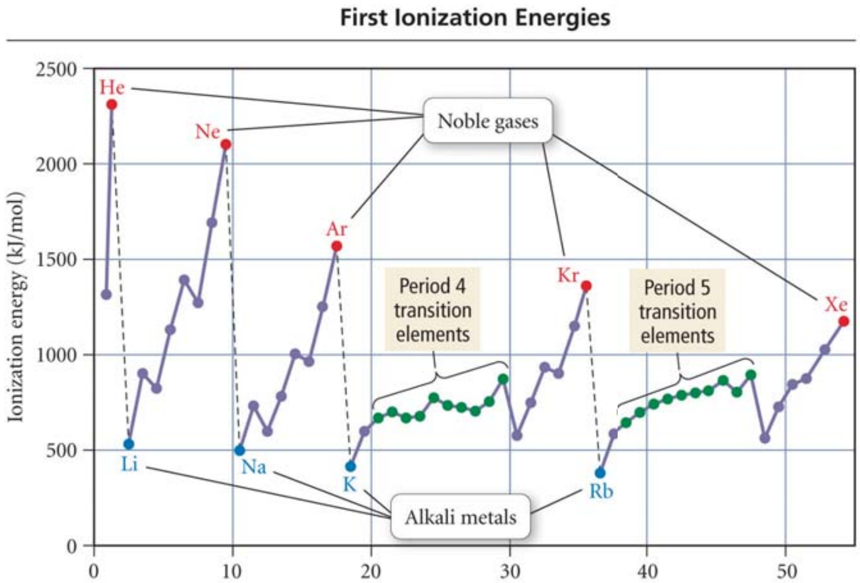
The performance expectations in the middle grades do not require students to develop a model of the atom's internal workings. This sequence differs from the 1998 California Science Content Standards in which the internal workings of the atom were introduced in eighth grade. It is conceivable that students highly proficient in the CA NGSS performance expectations for the middle grades 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 appears in high school physics). Students do, however, have significant experience recognizing **patterns [CCC-1]** and **asking questions [SEP-1]** about them. They have **analyzed data [SEP-4]** about the bulk properties of matter and are ready to begin relating them to the components that make up atoms.

Memorizing rules about the periodic table is not sufficient to meet HS-PS1-1. Instead, students must understand and apply underlying **models [SEP-2]** of atomic structure and interaction along with the principle of **cause and effect [CCC-2]**. They use these models to **explain [SEP-6]** why the properties of the elements **repeat in a periodic fashion [CCC-1]** and can use the periodicity to predict bulk properties of elements, their reactivity, and the types and numbers of bonds they will form with other 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 predictable, periodic way. He arranged the 63 elements known when he was working 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 using a physical **model [SEP-2]** as an analog. By arranging 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. This exercise mirrors the process Mendeleev used to predict the existence of elements not yet known.

Patterns [CCC-1] 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 [CCC-2]**. 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 gases in figure 7.23. 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 [SEP-2]** 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 [CCC-1]** that provide evidence of patterns in underlying atomic structure.

Figure 7.23. Patterns in the First Ionization Energy of Different Elements

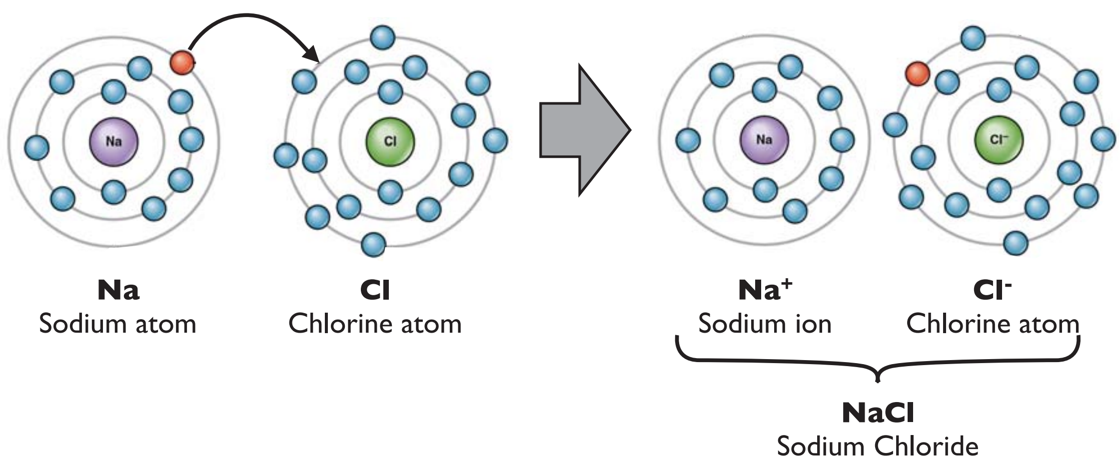


As students analyze plots of the properties of the elements as a function of atomic number, they should notice and discuss trends and patterns such as the comparatively low ionization energies of the alkali metals versus the high ionization energies of the noble gases as seen in this plot of first ionization energies. *Source*: RJHall 2010

The practice of **developing and using models [SEP-2]** in the CA NGSS often calls for students to develop their own models based on evidence they obtain directly. It took decades for the scientific community to develop models of the substructure of atoms that explain the patterns in the periodic table. One approach to helping students develop their own models is through a historical presentation of the evidence. A historical summary demonstrates how these models were repeatedly revised following revolutionary discoveries, starting with the billiard ball model and eventually culminating in Bohr's model and our modern quantum mechanical model. This sequence parallels the learning progression outlined in the CA NGSS in which students come into high school chemistry with the billiard ball model of atoms and leave with mastery of a more modern version (a quantum mechanical model of the atom is not assessed as part of the CA NGSS, so the working model adopted by individual classrooms depends on the local context. Bohr's model produces sufficient predictive power to meet the performance expectations in the CA NGSS.) Students can make these models on their own by **obtaining information [SEP-8]** from the Internet about various analogies of atomic structure (Goh, Chia, and Tan 1994) and **evaluating [SEP-8]** the limitations of these models.

Students can then interpret the trends displayed in the periodic table in light of their underlying model for atomic structure. They relate the overall order of the periodic table to the number of protons and electrons in the atom's outermost energy level. Students can then develop a simple model of interactions between atoms based on their electron configuration (figure 7.24). They should be able to use the periodic patterns of electron configuration in the periodic table to predict properties such as the overall reactivity of metals and the number of bonds an atom can form (HS-PS1-1), as well as being able to predict the outcome of simple chemical reactions (HS-PS1-2). 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 7.24. Models of Atomic Structure Explain Periodic Trends

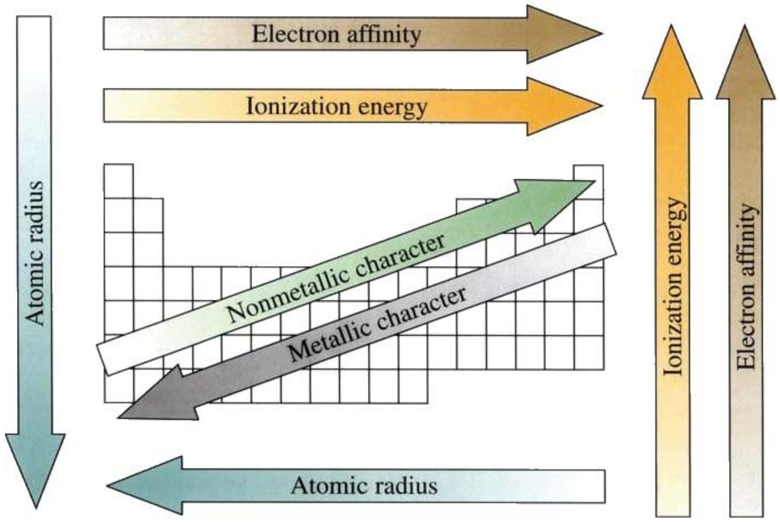


Students should predict trends within the periodic table based upon an application of models of atomic structure such as the Bohr model and octet rule illustrated here. *Source*: Adapted from OpenStax College 2013

It is not sufficient for students to memorize and blindly apply rules for chemical bonding. Rather, they must develop **explanations [SEP-6]** 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 performance expectation, students must describe thermodynamic principles that dictate that atoms will react with one another to transition to a more stable (lower energy) state. Filled orbitals, such as those that occur in a full octet state, are more symmetrical than other configurations, and such symmetry leads to greater stability. 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 of 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. 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 would not undergo any explosive reactions like the sodium and chlorine that it is made of. Students will return to this idea again when they discuss bonding energy in IS4.

HS-PS1-2 requires students to **construct explanations [SEP-6]** and **argue from evidence [SEP-7]** rather than memorize facts and trends. Students should understand the basis for **trends and patterns [CCC-1]** shown in figure 7.25 and be able to **explain [SEP-6]** the different types of chemical reactions. Once students understand the reasons for the trends observed in the periodic table, they can subsequently predict chemical reactions of significance in the physical, biological, and Earth science realms. For example, by noting that carbon is in the fourteenth 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 that make up fossil fuels based upon valence electron patterns. Students could also explore different mineral families and see how atoms can substitute for one another to produce gems with different colors or other properties (such as quartz which is called amethyst when small amounts of iron substitute into the crystal lattice).

Figure 7.25. Patterns and the Periodic Table



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. *Source*: M. d'Alessio

Cycles of Matter in Chemical Reactions

As students study these simple combinations of atoms that make molecules, students revisit the idea from the middle grades that chemical reactions rearrange atoms but **matter is conserved [CCC-5]** (MS-PS1-5, MS-LS1-7). In high school, students use chemical equations as mathematical models to illustrate the cycle of matter within these chemical systems (HS-PS1-7). Students apply these basic principles of stoichiometry through laboratory **investigations [SEP-3]**, problem solving, and reinforcement with apps and programs. The word *stoichiometry* derives from two Greek words: *stoicheion* (meaning element) and *metron* (meaning measure). Stoichiometry is based upon the law of the conservation of mass and deals with calculations about the masses of reactants and products involved in a chemical reaction. While stoichiometry can be challenging to students and teachers alike, research shows that the more time students spent in high school chemistry on stoichiometry, the greater success they had in college chemistry courses on average (Tai, Sadler, and Loehr 2005).

The law of definite **proportions [CCC-3]**, sometimes called Proust's Law, states that a chemical compound always contains exactly the same proportion of elements by mass. An equivalent statement is the law of constant composition, which states that all samples of a given chemical compound have the same elemental composition by mass. Students must learn that compounds appear in whole-number ratios of elements and that chemical reactions result in the rearrangement of these elements into other whole-number ratios. Students can develop a deeper understanding of the principles involved in HS-PS1-7 by massing and comparing the reactants and products of simple chemical reactions. For example, if students dehydrate copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) into the anhydrous salt ($CuSO_4$) by heating, they will find that the ratio of the mass of the resulting copper sulfate (dry mass) to water (the mass lost in dehydration) is always the same, regardless of how much copper sulfate pentahydrate is used. Students can infer that because the ratio of the component molecules in such a dehydration reaction remains constant, then the ratio of component elements must also remain constant. By applying **mathematical thinking [SEP-5]**, students learn to balance chemical reactions and predict relative quantities of products.

IS4 Chemistry in the Earth System Instructional Segment 4: Chemical Reactions

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

Guiding Questions

- What holds atoms together in molecules?
- How do chemical reactions absorb and release energy?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-3. Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles. [Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension.] *[Assessment Boundary: Assessment does not include Raoult's law calculations of vapor pressure.]*

HS-PS1-4. Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy. [Clarification Statement: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.] *[Assessment Boundary: Assessment does not include calculating the total bond energy changes during a chemical reaction from the bond energies of reactants and products.]*