Chemistry and Unifying Themes of Science

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In the 1990s, the American Association for the Advancement of Science (AAAS) articulated "common themes" or core concepts in both *Science for All Americans* (1990) and its companion, *Benchmarks for Science Literacy* (AAAS, 1993), followed by the unifying themes of the *National Science Education Standards* in 1996. Both the National Research Council (NRC) and AAAS define these overarching themes as concepts that appear in many, if not all, scientific disciplines. Such themes can build connections between chemistry and other sciences, as well as between chemistry and its applications in our everyday life. Knowledge of these themes may provide a framework for unifying science and a mechanism for both learning and teaching science, shifting away from thinking of science teaching and learning as occurring only in the discrete units of physics, chemistry, biology, and earth science (Table 1). Perhaps of equal importance, these unifying concepts can and should be incorporated into science learning and teaching beginning in kindergarten and continuing throughout an entire educational career. The intent of this chapter is to briefly introduce these unifying themes and to provide examples showing (1) how these themes appear in chemistry and (2) how these themes connect to other sciences.

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Table 1. Changing Emphases

Less emphasis on	More emphasis on
Courses with little connection to other disciplines	Courses that incorporate connections to other sciences
Fragmented instruction that moves from topic to topic without connections	Integrated instruction that focuses on fundamental concepts and processes
Concepts presented in isolation from real-world applications	Concepts and processes introduced with a real-world context and explored in real-world applications
No coordination among all science disciplines to reinforce unifying themes	Coordination throughout all grades and all sciences in terms of introduction and use of unifying themes

The NRC and AAAS sets of unifying themes have many similarities (see Table 2), but a more inclusive list that combines both sets would be better. Table 2 is a compilation developed by the authors to illustrate how these themes relate to each other.

Table 2. Comparison of NSES and AAAS common Themes

NSES Unifying Theme	AAAS Common Theme
Systems, order, and organization	Systems
Evidence, models, and explanation	Models
Constancy, change, and measurement	Constancy and change
Evolution and equilibrium	
Form and function	
Energy*	Energy*

The number of unifying themes has been a topic of discussion in the past few years. For example, the NRC (2007) suggested in *Taking Science to School* that K–8 teachers should focus on a few core ideas that are expanded each year. In September 2006, the National Science Teachers Association (NSTA) asked its members about the breadth and depth of coverage of science. It found that 78% of respondents agreed and that 85% said that state standards should be centered on a few core ideas (NSTA, 2007).

The use of themes as an organizing principle in teaching science content knowledge is one way to employ unifying themes. In science, the use of unifying themes or big ideas is not only a way to organize student learning, but it is also a way of approaching the design of a course. Wiggins and McTighe (2005) describe a method of course design that engages students in inquiry and promotes learning by providing a conceptual framework for students (p. 4). Their backward design process starts by identifying desired student learning, determining acceptable data for verification of student learning, and only then moving toward planned instruction. They describe the use of "big ideas and core tasks" as a central component of desired student learning.

This chapter offers examples of how unifying themes appear in chemistry, as well as examples of how these themes might appear in biology or physics. Brief descriptions of each theme are also provided.

Systems, Order, and Organization

Systems are defined by the NSES as an "organized group of related objects or components that form a whole" (NRC, 1995, p. 116). Important aspects of a system are the presence of boundaries, related objects, flow of a resource such as energy into and out of the system and the existence of feedback. Order is the "behavior of units of matter" (NRC, 1995, p. 117) that can be predicted and described, while organization refers to a way of structuring information that helps to reveal relationships. We should comment on the NSES use of "organization." In examples provided by NSES (p. 117), the use of "organization" appears to refer to organization of information. For example, the periodic table is an organization of knowledge of elements and their reactivity. Yet, in subsequent examples, NSES appears to consider organization within nature rather than of knowledge. In this second set of examples, the NSES refers to different levels of cellular organization [cells, tissues, organs, organisms (p. 117)] or physical systems (fundamental particles, atoms, molecules). These two definitions of "organization" are preserved in the examples provided in Table 3. When teaching classification systems of organisms in a high school biology class, the biology teacher could take a few moments to introduce students to another classification scheme common in another science, e.g., chemistry and the periodic table.

Table 3. Systems, Order, and Organization

Chemistry	**Systems:** atoms, compounds, chemical reactions **Order:** classification of matter as solid, liquid, gas, or plasma **Order:** classification of types of compounds **Organization:** periodic table and periodic trends (organization of knowledge) **Organization:** electrons, neutrons, and protons as parts of atoms (organization of nature)
Biology	**Systems:** within organisms (digestive, endocrine, reproductive, circulatory, etc.) **Order:** classification of organisms (organization of knowledge) **Organization:** levels of organization with living systems (cells, tissues, organs, organisms, populations, and communities) **Organization:** food chain or food web (organization of nature)
Earth Science	**Systems:** rock systems (igneous, metamorphic, sedimentary) **Order:** layers of the atmosphere **Order:** internal structure of the earth **Organization:** topographic maps of Earth's surface (organization of knowledge) **Organization:** patterns of airflow (organization of nature)
Physics	**Systems:** machines **Order:** collective phenomena such as superconductivity and magnetism; classifications of subatomic particles **Organization:** charts showing radioactive decay pathways (organization of knowledge) **Organization:** solar systems, galaxies, superclusters (organization of nature)

Evidence, Models, and Explanation

Evidence is simply the data that scientists or students gather to answer questions. Models differ from laws or theories in that they change with the discovery of new evidence that needs to be included in an explanation. Models can be theoretical or mathematical or concrete or functional. Explanations of scientific phenomena, to be useful, must incorporate available evidence and allow for predictions of future events. A geologist could describe how seismographs provide evidence of the motion of Earth's plates and that other sciences use different motion detectors to study phenomena. For example, chemists use infrared spectrometry to study the motion of atoms in molecules. In both cases, scientists are using evidence to study and explain phenomena.

Table 4. Evidence, Models, and Explanation

Chemistry	**Evidence:** discovery of radioactivity and types of radioactivity **Evidence:** mass spectra, X-ray diffraction patterns **Evidence:** experiments leading to the discoveries of the electron, proton, neutron, and nucleus **Models:** atomic models (from billiard ball model through quantum mechanical model) **Models:** bonding models (VSEPR, hybridization) **Models:** for reaction rate (collision theory, transition-state model) **Explanation:** explanations of the direction of spontaneous reactions in terms of energy and entropy, explanation of periodic trends in terms of effective nuclear charge
Biology	**Evidence:** observations of cells or microorganisms using microscopes **Models:** models of DNA structure **Explanation:** how specific changes in organisms confer advantages for survival, how are patterns of inherited traits explained in terms of random transmission of genes.
Earth Science	**Evidence:** vibration of the earth as recorded by seismographs **Models:** convection in interior **Explanation:** plate tectonics
Physics	**Evidence:** observational data of planetary motion **Models:** description of gravitational fields **Models:** description of angular displacement **Explanation:** Newton's laws of motion

Constancy, Change, and Measurement

The behavior of objects is sometimes described in terms of how the behavior changes with time. In other instances, the object's behavior appears to be constant. For example, the energy in a system is constant, but the form of the energy may change over time. Measurement is a way to quantify change or constancy of a system or object. The tools of measurement vary with the system studied; each science has its own particular modes of measurement. A physics teacher might include descriptions of conservation of energy in terms of chemical reactions, as well as in systems.

Table 5. Constancy, Change, and Measurement

Chemistry	**Constancy:** charge of an electron, gas law constant **Constancy:** Laws of Conservation of Matter, Conservation of Energy, definite and multiple proportions **Change:** development of Atomic Theory is an example of change **Change:** changes in chemical composition or properties resulting from chemical reaction **Measurement:** Energy of reactions in bomb calorimeters
Biology	**Constancy:** homeostasis of temperature in warm-blooded animals **Change:** biochemical cycles (oxygen, carbon, nitrogen, sulfur, phosphorus, Krebs cycle) **Measurement:** bacterial growth rates
Earth Science	**Constancy:** the timescale of geologic change is so long that many quantities are nearly constant over human lifetimes. **Change:** rock cycle or water cycle **Change:** soil erosion, weather patterns, and mechanical weathering **Change:** riverbed changes with erosion **Measurement:** rates of motion of continental plates
Physics	**Constancy:** the speed of light; the total mass and energy in the universe **Change:** acceleration **Measurement:** in terms of the metric system **Measurement:** using coordinate systems

Evolution and Equilibrium

Evolution is defined by the NSES as a "series of changes, some gradual and some sporadic" that result in the behavior of organisms or objects that can be seen today. Although many associate evolution with diversity of biological organisms, it also applies to nonliving objects such as the solar system. Equilibrium, sometimes grouped with constancy and change, occurs when two processes or forces are in balanced opposition to each other. Chemical reactions reach a state of equilibrium when the rate of the forward, product-producing reaction is

Table 6. Evolution and Equilibrium

Chemistry	**Evolution:** chemical origins of life (amino acids → proteins → RNA → simple life forms) **Evolution:** nuclear fusion: creating new elements **Equilibrium:** chemical equilibrium, phase equilibrium, solubility equilibrium, acid-base equilibrium
Biology	**Evolution:** changes in DNA leading to diversity of species **Evolution:** changes of an organism to adapt to its environment **Equilibrium:** maintenance of blood pH by removal of CO_2
Earth Science	**Evolution:** formation of the planets **Evolution:** changing continents **Equilibrium:** various cycles (see above)
Physics	**Evolution:** formation of galaxies, solar systems **Evolution:** thermal equilibrium **Equilibrium:** rotational and translational equilibrium

balanced by the rate of the reverse, reactant-producing reaction. Biologists, when introducing students to species evolution, could set organismal evolution in a broader context of how other objects such as stars or chemical elements have changed over time.

Form and Function

Form and function are related to each other. The form of an object informs the observer about the function, and the function provides information about the form. For example, a plant cell has rigid cell walls that relate to the overall structure of the plant. Students should be able to infer the strength of the cell wall by noting the structure of a plant. A chemistry teacher can build upon this knowledge by leading students to understand how atomic bonding orbitals provide information about molecular shape that, in turn, ultimately relate to the rigidity of plant cell walls.

Table 7. Form and Function

Chemistry	**Form:** electron configurations of elements related to ability to gain, lose, or share electrons **Form:** molecular shape determines polarity, which determines intermolecular forces, which determine function **Form:** the unique properties of water relate to its functions **Form:** carbon's form correlates to its many possible molecules **Function:** characteristic reactions of organic molecules relate to the structure (or form) of functional groups
Biology	**Form:** differences between plant and animal cells relate to function **Form:** molecular structure of DNA and RNA influences functions **Function:** organs are functioning groups of specialized cells
Earth Science	**Form:** the different mineral forms of elements found in the earth and how they are recovered **Function:** convection currents in earth's interior determine behavior of continents
Physics	**Form:** shape of lens and whether it causes convergence or divergence of light **Form:** surface structure, whether rough or smooth, determines friction and how objects move (function) on the surface **Function:** the mechanical advantage of a simple machine is related to its form

Energy

All sciences are concerned with sources and transformations of energy. Physicists view energy mostly in terms of conservation of energy *within* a system, while biologists tend to think of energy flow *through* a system. It can be argued that chemists include both views, as the first law of thermodynamics accounts for energy in terms of conservation, but when chemists describe reactions as endothermic or exothermic, they are employing an analogy of energy flows into or out of the chemical reaction system. Biology and physics teachers alike could describe these different perceptions of energy in their courses.

Table 8. Energy

Chemistry	Conservation of energy within defined systems Spontaneity of reactions and the "drives" to minimum energy and maximum entropy; Gibbs free energy Bond formation and energy changes Average kinetic energy of gas molecules Activation energy and reaction rates Ionization energy and electron affinity Thermochemistry: principles of heat flow Energy levels in atoms: ground state vs. excited states Electrochemistry (voltaic cells vs. electrolytic cells)
Biology	Cycle of energy and matter through living and nonliving systems Biological effects of radiation
Earth Science	Changes in the earth's ecosystem powered primarily by the energy of the sun Renewable energy resources
Physics	Types of energy: mechanical, electrical, nuclear, heat energy, radiant energy, chemical energy Work and energy (laws of thermodynamics) Nuclear energy; nuclear binding energy; fission and fusion Mass-energy relationships

Conclusion

Ideally, students would construct their knowledge of these themes beginning in kindergarten and deepen their knowledge as they progress through high school and into college. The typical disciplinary focus experienced by high school science teachers in their educational experience tends to prevent deep understanding of these themes as they appear in other sciences. The lack of focus on these same themes in general science content courses of the typical curricula of elementary and middle school science teachers similarly prevents them from gaining a deep knowledge of these themes.

As teachers of chemistry, we cannot address the lack of attention to these commonalities in other science disciplines. We can, however, incorporate these common themes in our own classroom instruction in chemistry. We can help our students see how these themes provide connections between and distinctions among chemistry and other sciences such as biology, earth science, and physics. Building these connections necessitates the use of unifying themes when we teach and learn chemistry but also requires describing how those themes have or will appear in other courses for our students.

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