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Methods and issues of teaching and learning

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LINKING PHYSICS WITH CHEMISTRY - OPPORTUNITIES IN A CONSTRUCTIVIST CLASSROOM

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ABSTRACT: Although the disciplines of chemistry and physics often focus on different aspects of phenomena in nature, there are many areas in which the two overlap. At the introductory level of instruction for example, fundamental concepts like mass, rates of change, force, and energy are important in both disciplines. Such topics are usually introduced in chemistry courses as needed, with little or no attention paid to the difficulties that students encounter when confronting them for the first time. Since chemistry courses often precede physics courses, particularly in science curricula in the United States, the challenges associated with helping students to understand such concepts can provide an opportunity to improve instruction in chemistry, and other science courses as well. This paper describes how these concepts are introduced and developed in a college freshman chemistry curriculum for science majors, and how this has led to changes in topic development in other physical science courses. The work has been guided by educational research findings, and feedback obtained over the course of a decade from the authors' active learning environments. [*Chem. Educ. Res. Pract.*: 2003, *4*, 189-204]

KEY WORDS: *common topics in physics and chemistry; constructing concepts; operational definitions; rates of change; force; energy*

INTRODUCTION

Many years ago, a former professor of one of the authors once described a chemist as an individual who makes inexact measurements on very pure substances, and a physicist as an individual who makes very exact measurements on impure substances. A modern day chemist or physicist might be offended by such a pronouncement, but this description can serve as a first attempt at drawing distinctions. At the introductory level of instruction at least, we might say that physics seeks to describe systematically the behavior of large *objects*, and phenomena such as light, electricity, and sound, without immediately invoking an atomic foundation. Chemistry, in contrast, seeks to describe systematically the behavior of *substances*, relying on an atomic foundation for its descriptions. Phenomena such as light and electricity serve more as probes to help chemists describe the behavior of matter, and less as subjects of study in their own right. When we think of the word “change” as it is used in an introductory physics course, images of motion and force might come to mind. When we think of the word “change” as it is used in an introductory chemistry course, images of substance transformation more likely arise.

TABLE 1: *Topics that may appear in both introductory chemistry and physics courses.*

- measurement, unit conversion, graphical representation, and functional relationships;
- fundamental properties of matter - mass, volume, density;
- applications of the force concept - weight, buoyancy, pressure, molecular collisions, various types of bonding (electrostatics), the behavior of charged particles in electric and magnetic fields;
- states of matter - the behavior of gases, liquids, and solids; phase changes; solutions and other mixtures;
- rates of change, gradients, and equilibrium;
- types of energy, energy conservation, various thermodynamic concepts, electrochemical cells;
- atomic and nuclear structure, spectroscopy, orbital motion, properties of waves, vibrational motion, electromagnetic radiation, radioactivity.

In spite of these differences, when we look at the content of introductory chemistry and physics courses, we find many topics that are common to both. Table 1 lists a number of these that can be found by referring to introductory chemistry and physics textbooks.

Although the overlap is extensive, it is important to acknowledge the different underpinnings of each discipline, mentioned above, and the particular challenges they pose for students and instructors in introductory courses. In physics, major challenges center on linking observations in the see-touch world with abstract representations using vectors and mathematical equations. In chemistry, major challenges center on linking observations in the see-touch world with inferences about the behavior of particles in the atomic realm, and symbolic representations of molecular and atomic species. Helping students to describe familiar phenomena using technical vocabulary is a major challenge in both disciplines. For example, the vernacular of the practicing physicist or physics educator can lead to misconceptions about the nature of the force concept (Touger, 1991). In chemistry, the invisible nature of the submicroscopic world can leave students unclear about the meaning of fundamental concepts such as element, compound, or mixture (Nakhleh, 1992; Toomey et. al., 2001). Quantitative problem solving is a very challenging aspect of both disciplines (Arons, 1990; Cohen, 2000), although the types of problems differ in each. It is probably fair to say that these challenges contribute to each course appearing on the “killer course list” at institutions of higher learning.

The information explosion that is occurring in all areas of knowledge has led to increased overlap among the traditional disciplines in the natural sciences. Areas like biochemistry, biophysics, astrochemistry, and material science are blurring the traditional boundaries. There is a Journal of Physical Chemistry, and a Journal of Chemical Physics. As a result of this blurring, the tendency has increased for material, which used to be the specific domain of one area, to spill over into another. This has certainly been the case with physics and chemistry, as descriptions in the latter have become more quantitative, particularly with the introduction of quantum theory and molecular mechanics to the discipline.

Further difficulties for students of chemistry can arise as a result of this spilling over of material from physics, even in introductory chemistry courses. For example, in an effort to provide a more sophisticated description of phenomena, there can be the temptation for instructors and textbook authors to pull mathematical equations out of a hat with little or no development. Students may have little familiarity with the related concepts, and more often than not, little real understanding emerges from such an approach (Tsaparlis, 1997a, 1997b; Coll & Taylor, 2002).

These problems notwithstanding, it is important to elucidate connections between chemistry, physics, and other natural sciences. The growing volume of factual information in the various disciplines has the potential to obscure unifying connections, particularly for novice learners. However, certain concepts such as energy, force, equilibrium, and rates of change span the natural sciences, and can serve as unifying focal points (Garafalo & LoPresti, 1993). Finding an appropriate level of presentation for a diverse population of learners provides an additional challenge to instructors as they go about this task.

Some common ground on how to meet the various challenges associated with teaching chemistry and physics has emerged over the past 30 years from the area of research in teaching and learning. Some of the key findings are summarized here:

- Learners construct understanding. They do not simply mirror what they read or are told (Taber, 2001; Resnick, 1983).
- An environment in which students actively work with material and obtain rapid feedback is better than one in which they passively listen (Mazur, 1997; Lochhead & Whimby, 1987).
- Students must be able to link new information to what they already know (Bransford, et. al., 1999; Ausubel, et. al., 1978).
- Understanding is related to how knowledge is organized (Reif, 1983,1986).
- Misconceptions are easy to develop and difficult to dislodge (Taber, 2001; McDermott,1984).
- Qualitative understanding of concepts is as important as the ability to perform quantitative calculations (Cohen, et. al., 2000; Arons, 1976, 1986).
- Many students come to college with poorly developed formal reasoning skills (Bitner, 1991; Chiapetta, 1976).
- It takes time to develop formal reasoning skills and to construct understanding of science concepts, suggesting that less information should be presented, but in more detail (Taber, 2002; Johnstone, 1997, 2000; Arons, 1986).

A common set of skills is necessary for success in both disciplines. These include observing, comparing, and classifying, symbolic representation, proportional reasoning, controlling variables, drawing inferences, predicting consequences, formulating and testing hypotheses, and evaluating arguments (Bitner, 1991).

At the introductory level of instruction, fundamental concepts like mass, rates of change, force, and energy are important in both chemistry and physics courses. Such topics are usually introduced in chemistry courses as needed, with little or no attention paid to the difficulties that students encounter when confronting them for the first time. Since chemistry courses often precede physics courses, particularly in science curricula in the United States, the challenges associated with helping students to understand such concepts can provide an opportunity to improve instruction in chemistry, and other science courses as well. This paper describes how these concepts are introduced and developed in a college freshman chemistry curriculum for science majors, and how this has led to changes in topic development in other physical science courses. The work has been guided by educational research findings, and feedback obtained over the course of a decade from the authors' active learning environments.

BACKGROUND

One of the authors began experimenting with alternative presentations to those in traditional chemistry texts in the mid-1980's at the Massachusetts College of Pharmacy and Health Sciences (MCPHS) (Garafalo & LoPresti, 1986; Garafalo et. al., 1988). Initially, the other author was a student exposed to these presentations, who later became a contributor to the development effort. Frustration with the poor performance of many students in prior years, a growing appreciation of principles that span and unify the natural sciences, and the willingness of a biologist colleague to join the experiment, were factors that catalyzed the process. The work eventually led to an integrated chemistry and biology curriculum, which was taught for several years at MCPHS (Garafalo & LoPresti, 1993).

Initially, the concept of energy was chosen as the integrating theme, based on its universal importance. Eventually, a summary of various physical concepts, as well as Newton's three laws of motion, inverse square laws for gravitational and electrical attraction, and the first and second laws of thermodynamics were introduced in the first few meetings of the chemistry course. Even though the emphasis was on qualitative understanding of concepts, and not on cranking out numerical answers from equations, in retrospect, this approach amounted to a preconstructed summary of physics, presented in a vacuum. When the concepts were drawn upon later in the year, many students still struggled with them. In addition, many complained that initially the course seemed more like one in physics than one in chemistry.

By 1990, the transition to teaching the chemistry course primarily from materials of our own creation was complete, and the commercial textbook was abandoned. In that year we were also introduced to constructivist learning theory (Lochhead, 1990), with its key points, summarized in the last section. With regard to physics concepts, research in teaching and learning indicated that it is critical to proceed in a way in which key vocabulary words acquire meaning through their use in describing direct experience (Arons, 1990). Such an approach takes time, and the challenge became balancing a constructivist development of these unifying physical concepts against maintaining the integrity of our chemistry / biology curriculum. With the tenet "less is more" staring one in the face, what to leave out of the curriculum becomes as important as what to put in.

We began incorporating active learning strategies into presentations, including Socratic lines of questioning, think-aloud sessions in the classroom, laboratory, and help sessions, and writing for understanding in the laboratory. This has and continues to serve as the source of feedback that drives the evolution of the curriculum. More details on this informal action research approach are described elsewhere (Cohen et. al. 2000; Toomey et. al. 2001). The integrated biology / chemistry curriculum ended with the departure of our biologist colleague in 1992, but the effort to improve the way in which fundamental physical concepts are taught in freshman chemistry continues. Recently, these efforts have been expanded to include chemistry and physical science courses at Northwest Missouri State University. The goal is to create a logical sequence of topics *for students* , which links content to the development of reasoning skills, in guided inquiry environments.

Table 2 summarizes the topics that comprise the current first semester of freshman chemistry at MCPHS, and provides a reference for the reader. This paper focuses primarily upon the development of the concepts in Units 2, 4, 5, and 8, which serve as a foundation for much of the material presented throughout the remainder of the year in chemistry.

TABLE 2: *Units comprising semester I of freshman chemistry.*

1. Mathematical Foundations
2. Introduction to Measurement
3. Observations about Matter
4. Ideas about Motion
5. The Concept of Force
6. Making Inferences about the Atomic Realm
7. Introduction to the Periodic Table
8. The Concept of Energy
9. Gradients and Equilibrium
10. Matter with a Charge

INTRODUCING FUNDAMENTAL CONCEPTS

Concepts like volume, mass, and time interval, are fundamental to both chemistry and physics, and have their roots in the way we experience the world around us. Since the physical sciences are intimidating to many individuals, an approach that starts by connecting the student to his or her surroundings seemed like a good idea. Early efforts to introduce language associated with describing the physical world attempted to use a philosophical approach. Students were asked what they thought was most fundamental about the way they experienced the world around them, with the hope that discussion would lead them to primitive concepts like separation, duration, and number. This was largely unsuccessful, since most students invoked things like the need for food, sleep, and money when confronted with the question.

After a few years of frustration with this approach and the physics summary, which it preceded, two changes were made to the course introduction, which have remained in place. First, students are asked to reflect upon the power of symbols in allowing them to communicate ideas. Essentially all students acknowledge that assigning meaning to a set of written symbols such as “d o g” allows us, in this case, to talk about dogs in the absence of one. The importance of understanding symbols in all learning, not just in the sciences, becomes apparent. This introduction sets the stage for several days devoted to the fundamentals of proportional reasoning (Unit 1). The focus is on helping students to connect the manipulation of objects and the comparison of quantities with the associated symbolic representations. The approach relies on concrete examples that deal with familiar quantities like dollars, gallons, miles, and hours (Cohen et. al., 2000).

The second change involved the approach to introducing fundamental physical concepts, which is now based on the idea of qualitative opposites. It is pointed out that humans like to make comparisons and that this has led to the creation of descriptive pairs of opposites such as “near and far,” “many and few,” and “fast and slow.” In this approach the focus is on the direct experiences that lead to the descriptive pairs, and not on the rather abstract idea for students that there are such things as primitive concepts.

Going beyond the qualitative to make quantitative statements about, for example, the extent to which two objects are separated, requires that measurements be made (Unit 2). It is stressed that whether one counts standard spaces to determine extent of separation, standard squares to determine amount of surface covered, or standard objects to determine relative attraction of objects by the earth, the measurement process always involves comparing, counting and reporting a number with a label. The measurement process serves as the basis for operational (and concrete) definitions of important scientific concepts including distance, length, area, volume, gravitational mass, and the intensive quantity density, in week two of the course. In the laboratory, students practice reading scales and reporting values with the appropriate uncertainty as they make length and volume measurements. The subject matter provides further opportunity for students to practice their proportional reasoning skills as applied to unit conversions.

Students are fairly familiar with concepts like distance, area, and volume, although the important idea of counting standard squares or cubes is less obvious to some. However, gravitational mass is another story. Many students confuse the concepts of weight and mass, and are unsure of the difference between a balance and a spring scale. Much of this confusion arises from exposure to incorrect use of terminology, such as expressing a weight in kilograms instead of newtons, so initially the focus is on the qualitative idea of attraction by the earth, with no mention of terms like mass, weight, force, or gravity. The traditional chemist’s definition of mass, as an indication of the amount of matter in an object, is avoided.

Instead, discussions of what would be observed when objects are balanced against standard blocks on the earth and on the moon lead to an operational definition of the gravitational mass of an object in terms of *relative* attraction (Toomey et. al., 2003).

The qualitative idea is introduced that a given object can be attracted to a greater or lesser extent, depending upon which heavenly body it happens to rest, but the quantitative definition of weight in terms of a measured force is delayed. Blocks of equal mass but varying volume, and equal volume but varying mass, are used in laboratory two, to help students clarify the concept of density. At this point, the opportunity arises to connect macroscopic observations about the behavior of matter with inferences about the nature of an invisible submicroscopic world. This is the first time speculation is put forth that all matter may be composed of tiny particles. A Socratic line of questioning is used to help students connect the idea of greater attraction with that of greater number of submicroscopic particles (not necessarily atoms), and greater density with a greater number of particles per unit volume (Toomey et. al., 2003).

The next section of the course deals with observations that help humans better characterize types of matter (Unit 3). The content is the domain of the introductory chemistry course, but no attempt is made to rush to descriptions of the atomic realm. Here, technical concepts are defined not in terms of operational procedures, but in terms of observed properties and adherence to certain laws (Toomey et. al., 2001). For example, properties like fluidity or rigidity are used to define solids, liquids, and gases, while constant composition is used to distinguish compounds from mixtures. The idea of particles bonding at the submicroscopic level is hinted at when considering chemical reactions, phase changes, and dissolution of solutes, but quantitative aspects of the presentation are limited to percent composition by mass. Formulas, the mole concept, and atomic structure are all delayed until later in the year (Toomey et. al., 2001).

DESCRIBING CHANGE

Avoiding formulas and atomic structure focuses students on the qualitative aspects of changes that occur as a result of processes like compound formation or phase transitions. Students are asked to consider that we can also observe qualitative changes associated with objects physically moving through space. The ability to make statements about how rapidly something changes is important, whether it is change associated with the motion of an object, or change associated with the conversion of one substance into another. Since it is easier to talk about something that can be seen, it may be easier to start with descriptions of the motion of macroscopic objects (Unit 4), rather than descriptions of changes associated with the behavior of unobservable molecules. The idea is introduced that some repeating phenomenon, like the flashing of a light or the motion of a pendulum, can serve as a counter to help us measure event durations. The second is introduced as the standard unit of determining durations, which is a fraction of the repeating event we call the day (Note 1), and a clock is described as an instrument that keeps a running count of seconds.

With this foundation, students are then asked to consider how one goes about answering the question “how fast is something moving?” Discussion centers on the multi-step process of recording locations and corresponding clock readings, selecting a time interval and the corresponding displacement, making the ratio of these two quantities, and finally evaluating it, to provide an operational definition of the concept, average velocity. Careful attention is paid to distinguishing between location and displacement, and distinguishing between clock reading (a location on the face of a clock) and time interval (Arons, 1990). Multiple representations of the motion of objects are given, including pictures with words, numerical data sets, and graphs (location vs. clock reading and velocity vs. clock reading). The discussion is limited to simple motion in one dimension, and students analyze cases that represent objects traveling at constant velocity (including zero velocity), constant acceleration, and nonconstant acceleration in the classroom and in laboratory four.

Using a graph that represents nonconstant motion, students are shown that progressively shorter time intervals lead to the idea of an "instantaneous" velocity, one determined over a very tiny (but nonzero) time interval. Care is taken to explain that statements like "what is the velocity at clock reading 4?," actually mean, "what is the velocity during a very tiny time interval centered around clock reading 4?" In earlier treatments, time was spent describing the concepts of zero duration (an instant) and instantaneous location, but we have found it better in the limited time available to avoid such terms and focus on the idea that entries listed in data sets refer to objects and clock hands *as they pass* locations on their respective scales, rather than *occupying* locations on these scales (Note 2).

A ratio of instantaneous velocity change to time interval is used to define acceleration, but students gain a clearer picture of the concept by analyzing data sets or pictures of displacement in successive time intervals of equal duration, or by analyzing x vs. t or v vs. t graphs. By investigating velocity vs. clock reading and acceleration vs. clock reading graphs, students determine that areas correspond to displacements and instantaneous velocities respectively on such plots. Predictive equations like $x = (1/2)at^2$ and $v = at$ are specifically avoided, since no time is available to provide a meaningful construction of their origin. However, the equation $x = vt$ for constant velocity situations is mentioned, and it is stressed that an accelerating object with an instantaneous velocity of say, 10 m/s "at" a particular clock reading, will not travel 10 meters in the next second.

The challenges associated with grasping these ideas cannot be overstated, and require that instructors use their time constraints to be selective about the ideas they choose to treat. The amount of coverage given to the description of motion and force (Unit 5, described below) is limited to nine hours, including three in the laboratory, in which students analyze data sets, plot graphs, and interpret situations in terms of the forces exerted on stationary objects. There are many misconceptions associated with the concepts of velocity and acceleration (McDermott, 1984; Arons, 1990), and no pretense is made toward students eliminating them all in this simple introduction. The intent is to focus on some that deter students from creating a clear picture of the concept of rate of change. These include difficulty with distinguishing constant motion from constant acceleration, correlating graphs with pictures and data sets, and distinguishing a clock reading from a time interval.

We chose to introduce this particular material, which is more the domain of physics than that of chemistry, since it is easier to explore the subtle points mentioned above by referring to changes in location of a tangible object, rather than by referring to changes associated with the behavior of invisible particles. The concept of rate of change appears again several times throughout the course in more abstract examples. These include thermal equilibration of objects at different temperatures, rates of chemical reactions, and rates of energy change in electrochemical cells (instantaneous cell potentials). Instantaneous velocity is also revisited in discussions of conservation of energy. Our intent is to provide an opportunity for students to strengthen their interpretive skills, and to clarify the basic ideas with each repeated exposure.

THE CONCEPT OF FORCE

The treatment of velocity and acceleration leads naturally to the concept of force, which appears in many places in chemistry courses. Research has shown that the concept is elusive, not only because of difficulties associated with the idea of acceleration (McDermott, 1984), but also because of lack of time devoted to operationally defining the concept (Arons, 1990), and incorrect locutions that have found there way into everyday usage and instructional presentations (Touger, 1991).

With regard to language, phrases like “force pulls on the object”, “gravity acts on objects”, “earth’s gravity”, and “force of friction” can create the misconception that forces are some type of agent or attribute possessed by objects like the earth or a floor. Touger (1991) stresses that the idea of a force as a causal agent is misleading, and that educators should take care to describe the term as referring to an *interaction* during which an agent has the potential to create a change in motion of some object.

The concept is introduced through an exercise in which students must assign common words to three different classes of nouns. For example, words like “ball” or “ring” are nouns that identify physical objects, while words like “talent” or “brilliance” belong to the class of nouns that identifies attributes or qualities. Finally, words like “eclipse” or “wedding” belong to the class of nouns that identifies interactions or events. It is to this latter class that the word force belongs. Students are asked to consider whether or not a solar eclipse *causes* the shadow of the moon to be cast on the surface of the earth. Most students agree that the word “eclipse” merely describes the event during which the shadow is cast. It is pointed out that the word “force” refers to a situation in which an *agent* creates a change in motion of some object. The agent is causal, not the force (the interaction). Therefore, phrases like “gravity pulls” are seen to be misleading. In addition, since the verb “to force” is not used in this context, the phrase “exerts a force” must be clearly interpreted as meaning “creates (or has the potential to create) a change in motion.” Students are given the opportunity to identify, qualitatively, agents and the objects upon which they exert forces, and spend the remainder of the year constructively correcting each other’s language whenever they talk about forces.

Only after these activities is the magnitude of a force considered. Arons (1990) stresses that force is not a primitive concept, and that the equation $F = ma$ must be supplemented with extended discussion. Students consider two different data sets of location vs. clock reading for a puck that we imagine is pushed across very slippery ice. The situation in which the acceleration is twice as great is *defined* as the situation in which the exerted force on the puck is twice as great. The standard object is introduced to define the newton, the standard unit of force measurement, and then different objects are exposed to the same magnitude force to define the concept of inertial mass. The coverage is limited to situations that will help students construct the definitions and reinforce the previously introduced concepts of velocity and acceleration. Data sets comprise examples of constant and nonconstant forces, including the effect of a spring exerting a force on an object in outer space, and then losing contact. This is used to expand the conditions under which an object exhibits inertia to include constant velocity.

The presentation introduces the idea of contact vs. noncontact forces, cycles back to discuss the difference between gravitational mass and weight, and distinguishes between inertial mass and gravitational mass (Toomey et. al., 2003; Arons, 1990). Situations during which no acceleration occurs are described in a qualitative fashion. The idea that a table can push against an object is clarified with pictures of compressed atoms in the table’s surface. (This anticipates later qualitative discussions of particle confinement and location-momentum relationships for atomic species.) Care is taken when describing a box being pushed across the floor with constant velocity, since initially many students mistakenly equate a condition of constant velocity with constant force in a frictionless environment. Once they accept that constant force implies constant acceleration in the frictionless environment, many point to the constant box velocity to affirm that no force is being exerted, in spite of the need to push it in order to keep it in motion. Pictures that exaggerate the deformation of atoms in the floor and box surface as the motion occurs help to show that the floor is exerting a counter force in the opposite direction to that of the motion of the box. (This anticipates later discussions of internal energy changes in objects.) No equations related to frictional forces are presented.

The force concept reappears in several places throughout the remainder of the year: the discussion of gas pressure and its interpretation via the Kinetic Theory, the idea of a pressure gradient balancing a concentration gradient in osmosis, attraction and repulsion of charged objects, particularly ions, Rutherford's scattering experiments, experiments to determine charge / mass ratios of atomic particles, and use of the force concept in developing the concept of energy.

Once again, qualitative descriptions are important. For example, when introducing the Kinetic Theory of Gases, students are shown that greater molecular velocity means greater change in velocity when comparing elastic collisions with the container wall, and that this suggests the wall is capable of exerting different magnitude forces on molecules. Then exaggerated pictures of the wall and molecule being deformed upon impact are used to get the idea across that greater force exerted *on* the molecule by the wall implies greater force exerted *by* the molecule on the wall. In an effort not to overwhelm the students, once again, what is omitted is as important as what is presented. No formal reference to Newton's Third Law about equal and opposite forces is made. It is sufficient for students to see that the molecule and wall are exerting forces on each other, so that the pressure exerted by a gas is clearly understood in terms of the behavior of its molecules (Note 3).

It can be argued that an approach that takes the time to develop the concepts of acceleration and force in the fashion described here is more than what is needed to develop topics like the Kinetic Theory or energy in an introductory chemistry course. However, we would rather cut some content in other areas and provide students with an opportunity to begin to construct an understanding of these universally important concepts, rather than pull the concepts and accompanying equations "out of a hat" and pretend that students can apply them to relevant situations without any difficulty. A first-time exposure to the concepts in freshman year anticipates their presentation in courses like physics and physical chemistry for some students. Most students at MCPHS take only one semester of physics and many of these have commented on how useful the initial exposure is in freshman chemistry.

THE CONCEPT OF ENERGY

In earlier versions of the curriculum, the concept of energy was introduced directly after the section on force, but students complained that the course seemed too much like a physics course. At present, the unit on force leads into a discussion of the concept of pressure and the gas laws (Unit 6), followed by the periodic table, chemical formulas and the mole concept (Unit 7). The unit introducing the concept of energy follows (Unit 8).

Initial discussion focuses on the behavior of a dropped block as it falls to earth. Even though we are observing change as the block approaches the floor, there is something about this event that does not change. The quantity $mgh + (1/2)mv^2$ (where the symbols have their usual meanings) remains constant for the dropped object. (The situation in which the object hits the floor is not considered initially.) This is the second conserved quantity that students confront, the first being the somewhat more concrete idea of conservation of matter (mass) in a chemical reaction. The terms gravitational potential energy (GPE) and kinetic energy (KE) are introduced, as well as energy conversion. Students discuss how changes in m, g, h, and v affect GPE and KE, and perform simple energy conservation calculations, revisiting the concept of instantaneous velocity in the process. It is pointed out that one must exert a force in order to increase an object's GPE, and as a consequence, the object itself now has the potential to exert forces on other objects, by lifting them, or setting them in motion. The forces exerted by a moving object are apparently capable of disrupting the bonding between atoms and molecules when, for example, a bullet shatters a plate.

A similar, simple, qualitative discussion of KE/PE interconversion is introduced, using a spring that obeys Hooke's law. The general equation describing work-kinetic energy interconversion ($F\Delta x = \Delta[1/2]mv^2$) is avoided, since insufficient time exists in an introductory chemistry course to deal with the misconceptions that can arise from its incorrect application (Arons, 1990; Bauman, 1992). Instead, the phrase "doing work" is used to describe situations in which an agent exerts a force on an object, and as a result, the agent experiences a decrease in its energy. It is pointed out that more work is done when an object is lifted to a given height, or set in motion, in cases where friction is a factor, and care is taken to avoid the incorrect notion of work being converted into heat. In fact, no mention of greater molecular motion is made at this time. Reference is made only to the idea introduced earlier of atoms on contacting surfaces exerting forces on each other, necessitating the greater expenditure of energy by the agent. This sets the stage for later correctly distinguishing work interactions from heat interactions (Fenn, 1982).

The concept of internal energy arises when students consider the relationship between GPE lost by a dropped object, and its corresponding temperature increase once it hits the floor. A new ratio is introduced, specific heat capacity, and evidence is revisited and introduced that connects higher temperatures with greater molecular motion. (In this introduction, no distinction is drawn between constant volume and constant pressure heat capacities.) Students then spend time describing the energy conversions associated with a bouncing ball coming to rest, a ball of putty hitting and sticking to a wall, and a box sliding across the floor and coming to a stop. The terms coherent and incoherent motion are introduced (Note 4). Consideration is given in the classroom and in the laboratory to thermal interactions between samples of matter of different size and different composition, to bring forth the idea that there can be more to an internal energy change than just change in temperature.

This introduction concludes with a qualitative discussion of the energy concept. It is pointed out that phrases like, "object possesses GPE," or "object possesses KE", can be misleading. It is the location of an object *relative* to the surface of the earth that leads us to say it possesses GPE, and the velocity of an object *relative* to stationary surroundings that leads us to say it possesses KE. In fact, it is better to talk about the earth-object system as increasing in potential energy when an object is lifted, rather than the object itself "possessing" potential energy, since lifting it in outer space produces no change in GPE. Consider also a situation in which one travels as fast and in the same direction as a bullet. The bullet "has" no kinetic energy relative to this individual, and therefore poses no threat. This discussion helps to make it clear that the word "energy" is a noun belonging to the "quality" or "attribute" class, rather than the "object" or "interaction" class. Things that "possess" energy possess the quality of being able to make changes in their surroundings (they can exert forces on things), due to their position or motion. The correct use of other vocabulary words is also stressed at this time. In particular, the verb "to heat" is used in science, but the noun "heat" has a very restricted meaning. In this course it is avoided entirely, and reference is made only to heat *interactions* (Fenn, 1982). The time spent on clarifying language is important, since most students initially are not clear about the nature of energy. This underscores the importance of the general need to pay attention to language in the teaching of science (Johnstone & Selepeng, 2001). The introduction to energy comprises 10 hours of instruction, including five hours in the laboratory.

In the second semester, the energy concept is used many times, and the foundation just described is revisited. The analogy to an earth-object system losing or gaining GPE is made when discussing energy absorption and emission by an atom, with the corresponding movement of electrons to and from higher energy levels. It is stressed in the latter case that the electromagnetic force is relevant, since it is so much stronger than the gravitational force (Note 5).

A system comprising a block and spring is used to review the idea of energy transformation, prior to its discussion in chemical reactions. The state in which a compressed spring (or stretched spring) is in contact with a motionless block (high potential energy / low kinetic energy) is contrasted with one in which the spring has relaxed, creating motion in the block (low potential energy / high kinetic energy). Since many chemical reactions are capable of producing thermal energy or motion of electrons in a wire when they take place in an electrochemical cell, the suggestion is made that reactants in such processes represent a state of high potential energy (in this case high chemical potential energy), while the products represent a state of low chemical potential energy.

When quantitative calculations involving enthalpy and free energy changes are introduced, it is essential to get the idea across of a chemical system going to a higher or lower energy state at *constant temperature* (McGlashan, 1966). Defining the system change as reactants, at 25°C, going to products, also at 25°C, with the surroundings as a place where the energy is liberated, helps to make this clearer. This is important since liberated energy often is initially trapped in the reaction vessel with the products. As a result, students mistakenly view this as an energy increase for the system upon formation of products. When discussing electrochemical cells, the idea of electrons going from a high to a low potential energy situation surfaces again. The idea of energy transformation is reinforced when students consider the GPE increase of an object lifted by a motor run by a battery, and the corresponding decrease of electron potential energy in the chemical system used to run the battery.

The question arises as to the nature of the high and low chemical potential energy states in the reactants and products, and the stage is set for the discussion of bond strength. A Born-Haber cycle is used to discuss ionic bonding. It is stressed that the Octet Rule may be useful in predicting chemical formulas, but energy considerations show that the completion of octets is not what drives chemical reactions (Taber & Watts, 2000). Consideration of covalent bond formation is more challenging, and only a qualitative description is presented. Once again, the idea of closer approach of electrons and nuclei, and lower system energy, is stressed for bound as opposed to unbound hydrogen atoms. The analogy to an earth-object system decreasing in energy is again used with care (Note 6).

Students are asked to recall that electrons changing their positions with respect to nuclei can result in the release of electromagnetic radiation, which can create motion in atomic-sized particles. In this way a *rough* picture of the energy-liberating process emerges. No discussion of quantum mechanics and the inability to make exact pictures of events at the atomic level is presented in this course. Entropy effects in chemical energy release are also not discussed at this time, but are considered later in the course. While such an approach may seem overly simplistic, evidence suggests that students have a difficult time with more conventional approaches to bonding using orbitals (Tsaparlis, 1997a, 1997b; Coll & Taylor, 2002; Taber, 2002; Gillespie, 1996, 2001). The present approach, while theoretically naive, is still challenging to students, but its level of abstraction is much lower than that in quantum descriptions (Note 7).

DISCUSSION

This paper is meant to inform other chemistry educators about some of the issues that surround the presentation of certain physical concepts at the introductory level, and to suggest ways that can be helpful in making those concepts better understood within the context of chemistry instruction. Our enthusiasm for conveying insights gained through years of reflection on a given topic has been tempered by the fact that such insights are not immediately transferable to students. Grounding presentations in concrete experience, paying attention to proper use of vocabulary, coupling content to the development of reasoning skills, and providing enough time for students to work with ideas in a feedback-rich environment are all essential to improving the chances that they will develop such insights for themselves. Such an approach takes time, and demands that instructors be selective in choosing content. In the freshman chemistry course described here, the author has eliminated extensive coverage of descriptive chemistry and an introduction to organic chemistry, and provided a more limited presentation of certain topics (Toomey et. al., 2001). For example, when considering colligative properties, only osmosis and freezing point depression are covered. In addition, the presentation tries to minimize student exposure to the counterintuitive aspects of quantum descriptions of phenomena. These content decisions are consistent with an approach to freshman chemistry that is more physical in nature. The authors do not suggest that their approach is *the* solution to better instruction in chemistry. A more descriptive presentation, by contrast, with less emphasis on physical concepts, would demand cutting content in other areas. The most important thing is giving students time to construct understanding and to develop reasoning skills, whatever the focus of the course.

Many of the approaches used in the freshman chemistry course at MCPHS, have now been introduced in several courses at Northwest Missouri State University (Northwest). A large number of students at Northwest take introductory chemistry, which is taught by several instructors who are expected to cover certain specific content in the two-semester sequence. A given student may have any of five different instructors, and may not have the same instructor from one semester to the next. Within these constraints, the author has restructured the presentation in each of his semester courses, starting with demonstrations or data sets derived from easily visualized situations, to develop operational definitions or familiarity with qualitative aspects of the previously mentioned concepts. The focus is primarily on energy. In a physical science laboratory course, taken by many education majors, hands-on, inquiry-based laboratories are used to help students develop reasoning skills, while introducing the concepts mentioned earlier. The presentation is coordinated with classroom presentations as much as possible, and the concepts are reinforced when the course, which initially focuses on physics, turns to topics in chemistry. This approach is consistent with recent reports calling for physics to precede chemistry in science instruction in the United States (Lederman, 2001).

The disciplines of physics and chemistry are enmeshed in physical chemistry, perhaps more than in any other course. Even though exposure to numerous topics is required in this course, the author aims to strike a balance between qualitative presentations that review or introduce physical concepts, and more traditional quantitative presentations. More often than not, prior introduction of qualitative descriptions improves comprehension of the quantitative treatments.

Helping students to construct an understanding of physical concepts like force and energy is important, since even fundamental ideas like these can get lost in the information explosion that is currently occurring in all disciplines of science. For college-level students, such topics can serve as unifying themes that span the disciplines; for more advanced students, understanding such concepts is essential to maintaining perspective on philosophical questions, such as those relating to the nature of time, or causality (Fraser, 1987; Griffin, 1986; Bohm, 1980, 1957). Taber (2001) notes that critics have suggested the constructivist research program is in decline. However, for individuals who are interested in the roots of scientific concepts, making connections among disciplines, and using these to improve the nature of science instruction, the guiding principles of constructivist learning theory will continue to be valuable.

NOTES

1. At this point, no mention is made of defining the second in terms of the period of electromagnetic radiation emitted by excited cesium atoms.

2. Paradoxes arise when one attempts to represent time as a series of durationless instants (Capek, 1971; Wolf, 1981). In our earlier treatments, some time was spent later in the year discussing Zeno's paradoxes (Wolf, 1981), in an effort to prepare students for calculus, but this approach has been discontinued. The exact nature of time is a subject of debate among philosophers and some physicists, and the interested reader is referred to appropriate references (Griffin, 1986; Capek, 1971; Fraser, 1987; Wolf, 1981). The fact that a notion as fundamental as time is the subject of such debate points to the need for science educators to take care in creating their presentations (see instantaneous quantities in Arons, 1990), and to respect the difficulties that students encounter when working with such ideas.

3. Some students are aware of Newton's Third Law, but express confusion, commenting that the wall must exert a greater force than the molecule, since the molecule goes through a dramatic change in motion and the wall does not. We avoid the very subtle idea of there being equal and opposite forces exerted by the molecule and the wall on one another instant to instant (see Note 2, and references cited there). Instead, it is pointed out via simple pictures that both the molecule and the wall contribute to creating the "compressed molecule / wall state," and then this recreates the original uncompressed condition except for the fact that the molecule has changed direction. Once again, no pretense is made about this presentation giving students complete mastery of concepts. It is difficult to discern the two separate actions taking place during contact forces. However, Arons (1990) asserts that one cannot fully understand the force concept without the Third Law, since without it there is no basis for separating two interacting objects and applying the Second Law to each. Our presentation serves the purpose of helping students to interpret gas pressure in terms of the forces exerted by molecules, and leaves the formal analysis of the Third Law to a physics course.

4. An article by Krim (1996) gives a good discussion of the conversion of coherent motion to incoherent motion in cases where friction is a factor.

5. Some authors take issue with the idea of ignoring kinetic energy effects in such discussions (Rioux & DeKock, 2002). Even though the net energy of the atom decreases when an electron drops to an energy level that is closer to the nucleus, the kinetic energy of the electron actually *increases.* (This is consistent with the Virial Theorem and the Heisenberg Principle.) In recent years, a qualitative discussion has been added to our presentation, which describes the electron as "buzzing" about the nucleus, rather than orbiting it like a planet around the sun. Mention is made, without proof, of the fact that electron momentum, and therefore kinetic energy, increases with greater confinement (Heisenberg Principle), while the total atomic energy decreases. Qualitative evidence for greater kinetic energy with greater confinement is presented, but no mention is made of wave / particle duality.

6. The approach that is used is consistent with the idea that the drop in potential energy reflects a contraction of electron density toward the nuclei, rather than any buildup at the midpoint of the bond (Baird, 1986; Nordholm, 1988). Once again, electron kinetic energy increases, but the net system energy decreases (see Note 5 and reference quoted there). Alternative treatments of the bond formation process lead to a picture in which it is the *initial decrease* in kinetic energy due to electron delocalization that serves as the impetus for bond formation (Baird, 1986; Nordholm, 1988, Nordholm et. al. 1997). The fact remains that the net result is lower energy in the bonded system.

7. It is useful to read some of the conceptual difficulties experienced by the founders of quantum mechanics as they created the atomic description of matter (Heisenberg, 1971; Schrodinger, 1953). A readable description of the physicist's interpretation of quantum descriptions of phenomena is given in Feynman (1985). Such material lends support to the idea of using more concrete developments of chemical bond formation and the associated liberation of energy in introductory presentations.

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