

Article

The Trouble with Chemical Energy: Why Understanding Bond Energies Requires an Interdisciplinary Systems Approach

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Helping students understand “chemical energy” is notoriously difficult. Many hold inconsistent ideas about what energy is, how and why it changes during the course of a chemical reaction, and how these changes are related to bond energies and reaction dynamics. There are (at least) three major sources for this problem: 1) the way biologists talk about chemical energy (which is also the way we talk about energy in everyday life); 2) the macroscopic approach to energy concepts that is common in physics and physical sciences; and 3) the failure of chemistry courses to explicitly link molecular with macroscopic energy ideas. From a constructivist perspective, it is unlikely that students can, without a coherent understanding of such a central concept, attain a robust and accurate understanding of new concepts. However, changes are on the horizon, guided by the increasing understanding that difficult concepts require coherent, well-designed learning progressions and the new National Research Council Framework for K–12 Science Education. We provide supporting evidence for our assertions and suggestions for an interdisciplinary learning progression designed to better approach the concept of bond energies, a first step in an understanding chemical energy and behavior of reaction systems that is central to biological systems.

INTRODUCTION

As Richard Feynman wrote, “It is important to realize that in physics today, we have no knowledge of what energy is” (Feynman *et al.*, 1963). Be that as it may, most educators agree that an understanding of energy and energy changes is crucial both for science, technology, engineering, and mathematics (STEM) students and scientifically knowledgeable citizens. Most national-level curriculum reform efforts identify energy as a core concept for all STEM disciplines, and the new National Research Council (NRC) Framework for K–12 Science Education (NRC, 2012) proposes that energy be con-

sidered both a “disciplinary core idea” and as a “crosscutting concept”—the only topic to be singled out in this way. Energy has also been described as a “unifying theme” of science (Lancor, 2012), so it is ironic that, among different disciplines, the concept of energy is treated in ways that are quite discipline-specific and often not obviously compatible. Formal instruction on energy is typically introduced to students in the context of the physical sciences, usually through considerations of macroscopic systems. In chemistry, energy must be understood at the atomic and molecular level and is typically introduced in terms of the potential and kinetic energy of particles, with the discussion then moving on to thermodynamics, enthalpy, internal energy, entropy, and Gibbs energy. Unfortunately, any understanding of energetics per se is often lost in courses that concentrate on algorithmic problem sets (Hadfield and Wieman, 2010). Biology courses, in turn, often make do with shorthand descriptions of the energy stored in specific molecules, rather than considering the nonequilibrium systems of the coupled reactions actually involved. What is abundantly clear is that, in each of the three disciplines, students struggle with the concepts of energy and energy changes. It has been shown that students conceptualize energy differently depending on the context (e.g., in different

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university courses; Lancor, 2012). It is little wonder that student problems with understanding energy are widespread and readily documented, if one looks for them (Goldring and Osborne, 1994; Barak *et al.*, 1997; Barker and Millar, 2000; Coehlo, 2009), but very difficult to overcome (Jewett, 2008).

In this paper, we approach the problem of facilitating student understanding of energy, specifically in the context of the chemical bond, because it is a persistent obstacle to student mastery of a wide range of chemical and biological concepts and skills. We look at where conceptual confusions originate and how they persist, and describe the approach we have taken in the context of a new introductory general chemistry curriculum, Chemistry, Life, the Universe and Everything (CLUE) to address these issues.

THE PROBLEMS WITH “CHEMICAL ENERGY”

Nowhere are students' problems with understanding energy more apparent than with the concept of “chemical energy,” which, in addition to its obvious role in chemistry, plays a central role in the biological sciences—from the macroscopic (ecological and physiological) to the molecular. From the earliest grades, students are taught that energy is stored in food, and learn later on that the “high-energy bonds” in ATP provide energy for metabolic processes. They learn about biomolecules interacting with each other, so that substrates “fit,” jigsaw puzzle-like, into an enzyme's active site, and that hydrogen bonds stabilize the DNA double helix.¹ All of these ideas require knowledge and application of energy concepts at the molecular level. However, it is also true that, for many students (and instructors for that matter), the details of a molecular-level application of energy ideas are rife with problems, including an appreciation of the roles of entropic effects, activation energies, and reaction mechanisms. We focus here on a single aspect of the problem: understanding the energetics of bond formation and breaking.

The misconception that students believe energy is released when bonds break is well documented (Storey, 1992; Hong, 1998; Barker and Millar, 2000; Teichert and Stacy, 2002; Galley, 2004). This idea is pervasive and very difficult to modify during the course of traditional instruction. For example, there is remarkable consistency in the literature showing that, even after instruction, about half of the students still believe that bond breaking releases energy (Hong, 1998; Barker and Millar, 2000). We have investigated student understanding of the energy changes on bonding, using student interviews and written responses to open-ended questions (Gonzales, 2011), and have come to a similar conclusion: on average, about half the students retain problematic and conflicting ideas about the energy associated with bond formation and breaking as they progress through an undergraduate chemistry curriculum. Even graduate students and postdoctoral researchers retain these misconceptions (Gonzales, 2011). As Teichert and Stacey (2002) noted, while some students are consistent in their discussions (whether they are right or wrong), many others hold internally discordant positions; for example, students may imply that energy is required to form bonds, while at the same time stating that energy is released when bonds

break. It may be that students are confusing the idea of activation (added) energy, thinking that it is necessary to *form* bonds, which then in turn releases energy. What is clear is that they are not thinking logically in terms of a progression through a particular reaction, and these inconsistencies reflect a failure to have synthesized the energy/bond concepts into a coherent whole. If, as Teichert and Stacey propose (and we concur), they reflect incomplete reconciliation of distinct concepts, these implicit and contradictory assumptions are likely to produce confusions and inconsistencies when students attempt to apply them to real situations.

The Origins of Student Difficulties with Chemical Energy: An Interdisciplinary Problem

The inability to understand the origin of the energy changes associated with chemical interactions at the molecular level is a significant impediment to a coherent approach to biological processes and must be addressed explicitly. It is our contention that the problems students have in understanding energy changes at the molecular level—the level that is largely relevant to chemical, molecular, cellular, and developing (as opposed to physiological and ecological) biological systems—are exacerbated by a number of factors that stem from students' earlier experiences with energy and the fact that these are (generally) not explicitly acknowledged in the context of later instruction. Most constructivist theories of learning put great emphasis on students' prior knowledge (Vygotsky, 1978; Novak, 2002; Kintsch, 2009), and we would posit that the way students are taught about energy in general, and chemical energy in particular, makes it quite difficult for students to extend their understanding to new areas in an accurate and productive manner.

Biology

To understand why many students construct and retain a mental model in which chemical bonds contain energy that is then released as bonds break, we must look at the collective history of how this idea became so prevalent. First, the everyday use of the word “energy” is sometimes in conflict with the scientific usage, and nowhere is this more the case than in discussions of chemical energy. For example: food is labeled with its energy content (although, as we will discuss later, it is not the food, but rather the food and the system of reactants that determines the energy that can be extracted). The language students are exposed to—starting early and then repeatedly throughout their science instruction—tends to reinforce this idea. In biology, students are taught that energy from the sun is captured by plants, and then used to produce compounds within which the energy is stored, and that breaking down those compounds releases the stored energy. This statement captures an important (and true) idea, namely, that nonequilibrium systems, such as those found in living organisms, are open in terms of energy. Students learn this early on, and it forms the macroscopic basis for their understanding of how energy is transferred and transformed in biological systems. Unfortunately, as they progress through the curriculum, these ideas are typically applied without much modification to molecular-level systems (which do not behave in the same “obvious” way as macroscopic systems do). Thus, students may be taught that sugar molecules store

¹Even though London dispersion forces and entropic effects are equally important.

energy in their bonds, which later provides a quite compelling (but incorrect) rationale for why the bond breaking per se should produce or release energy.² Because sugar is broken down during metabolism, and energy is released, it is a simple (and logical) step to arrive at the incorrect conclusion that the energy resides within the bonds that are broken, rather than at the more abstract idea that the energy is released when more stable bonds are formed.

Physics

As students move through the K–12 system, the more general topic of energy is usually addressed first in courses identified as physics or physical science, meaning that students who take introductory biology and chemistry courses might be expected to have ideas about energy that have been shaped not only by their everyday experiences but by interaction between those ideas and the effects of instruction in the physical sciences. However, in traditional physics instruction, topics concerning energy, energy changes, and relationships are almost always presented in the context of macroscopic systems—the canonical example being the interconversion of kinetic and potential energy of an object rolling down a hill. These examples are often followed by many more “types” of energy (mechanical, electrical, chemical, thermal, and heat, to name but a few), and, as is well documented in the physics education literature (Jewett, 2008), students often have problematic ideas about energy changes, to say nothing of the relationships between forces and energy (Hestenes *et al.*, 1992). While it is often noted that physics provides the foundational concepts on which other sciences are built, it is our contention that the foundations are not present in traditional physics instruction for topics that require a molecular-level understanding. The foundations are certainly not addressed merely by trying to relate physical principles to biology, for example, presenting neuronal signaling conduction in terms of electrical circuits (when in fact, the action potential is a more complex, dynamic molecular system). That is, simply adding biological examples to a traditional physics curriculum without explicitly connecting macroscopic to molecular concepts is inappropriate. While Reif (1999) argued that a molecular-level approach would provide a more coherent approach to energy ideas, others have maintained that students must learn concepts at the macroscopic level first (Loverude *et al.*, 2003), which means that many physics courses never get to the molecular level. However, as the NRC Framework for K–12 Science Education (NRC, 2012) states, “Energy is best understood at the microscopic scale, at which it can be modeled as either motions of particles or as stored in force fields (electric, magnetic, gravitational) that mediate interactions between particles” (p. 121).

The Framework also states: “The idea that there are different forms of energy, such as thermal energy, mechanical energy, and chemical energy, is misleading, as it implies that the nature of the energy in each of these manifestations is distinct when in fact they all are ultimately, at the atomic scale, some mixture of kinetic energy, stored energy, and radiation” (p. 122). Unfortunately, this coherent approach to teaching

energy concepts is a recommendation for the future. Current students must build on an inappropriate foundation for energy concepts at the molecular level that is rarely corrected by the way energy is treated in introductory college chemistry or biology courses. That is, students typically arrive in college chemistry and biology courses ill-prepared for any discussion of energy as it relates to molecular systems, and in particular, about the topic of chemical energy and its origins. Most students have an inappropriate, fragmented, and discordant frame of reference for understanding energies of interactions at the atomic and molecular level (both bonding and intermolecular forces). Unprepared, they are then hurried through superficial presentations of the key ideas—the typical introductory molecular biology course may take a week to review energetics and reaction kinetics, but this is certainly not enough time to address the shortfalls of students’ prior education. Nor is it enough time to compensate for the damage being done in the chemistry courses.

Chemistry

While the foundations of the problem may lie in earlier courses, clearly chemists must take the major responsibility for problems students have with the concept of chemical energy. An inspection of a range of general chemistry texts shows that the most common approach is to separate the macroscopic manifestations of changes in bond energies, as measured by temperature changes, into a section devoted to thermochemistry and the First Law of Thermodynamics. Behavior at the atomic molecular level is generally treated separately in a section devoted to “bonding.” How these two topics are related is often not made explicit. While energy changes in a reaction can be approximated by a comparison of the bond strengths (the bond dissociation energies) of the reactants and the products, the implications of this idea often seem to be lost, while the details of the calculations are emphasized. It is important to note that the thermodynamic presentation of energy is discussed as thermal energy, heat, or enthalpy, while energy changes at the atomic level (see section on potential energy) are discussed in terms of potential energy and are often never explicitly reconciled.

In chemistry, students are explicitly taught that if the products have more stable (stronger) bonds than the reactants, energy will be released to the surroundings (as increased thermal motion and/or radiation), while if the reactant bonds are stronger, energy input will be required from the surroundings. The physical manifestation of this process is a change in temperature, which can be measured and used to calculate heats of reactions (enthalpy changes). In biological systems, much of the energy output is captured through coupled, networked reaction systems that drive thermodynamically unfavorable processes, such as the synthesis of substances with relatively weaker bonds (e.g., ATP). A more sophisticated approach would take into account all the other interactions, such as the intermolecular forces between species present in the reaction medium (water in biological systems), and a recognition that tabulated bond dissociation energies are measured and calculated in the gas phase, and therefore can only provide an approximation of the reaction energy change. We recognize, but do not include here, a consideration of other factors, such as activation energy and entropic effects, which are accounted for if we consider reaction mechanisms and

²This is a didaskalogenic misconception. That is, it is induced by instruction or the instructor.

focus on the change in Gibbs energy, rather than enthalpy or thermal energy changes. What is clear from examining student responses is that the common traditional instruction sequence does not produce a coherent understanding of energy changes when chemical or physical changes occur. To better understand why, we must look at how the energy changes during bond formation and bond breaking are treated at the molecular level in chemistry courses.

Potential Energy Is a Problem

In most general and organic chemistry courses (i.e., the courses that most biology majors take), the energy changes that occur during bonding and molecular interactions are treated as changes in the “potential energy” of a system as two objects (atoms or molecules) approach one another. When the potential energy reaches a minimum, the system is most stable, which can lead to the formation of a chemical bond. The bonded (stable) system is said to sit in a potential well. What is not made clear is what the term potential energy actually means in this scenario. General chemistry (and organic chemistry) textbooks (Bruice, 2010; Tro, 2010) do introduce the term potential energy. However, it is typically defined using macroscopic examples, such as the ubiquitous ball rolling down a hill, a situation in which friction, generally not identified as such, produces a behavior quite different from that seen at the molecular level. We have not found any texts that introduce the more appropriate idea that potential energy depends on the position of the objects interacting within a field. So, while the typical approach to bonding using the idea of potential energy appears to conform to the NRC Framework, which states, “Energy stored in fields within a system can also be described as potential energy” (NRC, 2012, p. 121) and “A system of objects may also contain stored (potential) energy, depending on their relative positions” (p. 123), there is no explicit bridge for students from the macroscopic to the molecular and no recognition as to how the two differ (and they do differ in significant ways). Students are typically left to their own devices to translate their experiences with potential energy in a gravitational field (which for most students means that the energy is determined by the height above the earth, rather than the distance between the interacting objects) into the language of molecules (which are typically presented in the thermochemistry section).

To gauge student thinking, we asked students in general chemistry (and other courses) about their understanding of the terms *energy*, *potential energy*, and *kinetic energy* at the macroscopic and the atomic-molecular level. None of the students discussed potential energy in terms of systems or fields, although some did talk about gravitational potential energy, but only as a consequence of the object’s height above the ground, rather than in more general terms of the relative positions of objects in fields.

Much of what they had to say revealed a lack of understanding—and a use of terms and language—that seemed to indicate many have problems making sense of the term *potential energy*. This is exacerbated by the fact that, once again, the terms we use to talk about energy (and in particular potential energy) have everyday usages that are not consistent with the way we use them in science. For example, we saw that many students believed potential energy is the potential for energy. While this is not particularly surprising, it

means they cannot understand what is being discussed. Students’ understanding of what potential energy means at the atomic-molecular level was even more fraught, as many of them tried to apply their macroscopic understandings (whatever they might be) to the molecular level, and their ideas were not any clearer when students reached organic chemistry, despite the fact that minimization of potential energy is the concept commonly used to explain stability of conformations and folding of biomolecules.

What is clear from our discussions with students is that the strategy of presenting physics ideas *en passant* in chemistry is failing to provide students with a useful understanding of potential energy. This is particularly important, because an accurate working understanding of potential energy is a prerequisite for understanding chemical energy or indeed any energy changes associated with bonding or intermolecular forces. This, coupled with our failure to successfully link atomic-molecular concepts about bonding to macroscopic topics that depend on an understanding of the origins of bond energies is, we suspect, a major reason why we are so unsuccessful in teaching chemical energy concepts. Simply put, we (biologists, physicists, and chemists) are not providing a coherent pathway for most students to develop a usable understanding of energy, particularly at the atomic-molecular level. We are failing our students by not making explicit connections among the way energy is treated in physics, chemistry, and biology. We cannot hope to make energy a cross-cutting idea or a unifying theme until substantive changes are made to all our curricula.

HOPE ON THE HORIZON?

The NRC Framework for STEM education presents a radical departure from the current approaches. It proposes simplifying the teaching of energy concepts using the ideas of energy of motion and stored (field) energy, rather than introducing long lists of energy types. This requires that the idea of energy fields (gravitational, electrical, and magnetic) be introduced early. The NRC recommendation that energy “is best understood at the microscopic scale” and “is best modeled as motions of particles or as energy stored in force fields” means that significant curriculum changes must occur at all levels in all disciplines. The Next Generation Science Standards (NGSS Achieve; www.nextgenscience.org/), which uses the Framework as the scaffold for what students should learn and the order in which they should learn it, will also emphasize the idea that students must learn about energy in a more interdisciplinary manner, with explicit connections to the atomic-molecular level, rather than solely at the macroscopic level. If these changes are implemented, they will not only affect the K–12 education system, they will also mean that college-level approaches to teaching energy must also change, because, ideally, future students will arrive at our doors with more robust and generally applicable prior understandings about energy—but that day is a long way off.

In the meantime, we who teach courses at the introductory college level, must explicitly acknowledge these difficulties and address them in an interdisciplinary way. While this may be akin to putting a Band-Aid on a problem that can be addressed only by K–14 education reform, it is also clear that

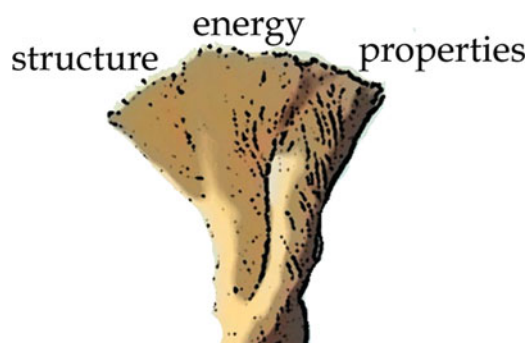


Figure 1. The interconnected learning progressions of structure, properties and, energy.

effective reform requires college-level faculty buy-in and curriculum changes in all three disciplines. This is particularly critical from the perspective of training future K–12 science teachers, who learn their science content largely from the curricula we require them to take. If we insist on clinging to an ineffective and incoherent approach to presenting the major unifying theme of K–12 science reform, it is unlikely that those reforms will succeed.

BUILDING A NEW CHEMISTRY CURRICULUM AND A LEARNING PROGRESSION

One possible approach to this problem is the development of an interdisciplinary learning progression for energy at the college level. There is now growing acknowledgment that difficult concepts (such as energy) must be developed in a logical, scaffolded sequence. These learning progressions are gaining increasing traction, particularly in the K–12 educational arena (Corcoran *et al.*, 2009; Stevens *et al.*, 2010), but there are also a number of efforts to bring this approach to college-level courses (Cooper *et al.*, 2012). They speak to the overall importance of a coherent curriculum that explicitly addresses the difficult ideas we expect students to master.

In our case, we are building on an interdisciplinary collaboration (M.M.C. in chemistry and M.W.K. in molecular biology) to develop a National Science Foundation (NSF)-funded, two-semester general chemistry curriculum: Chemistry, Life, the Universe and Everything, or CLUE. CLUE is based on three explicit, interconnected learning progressions: structure, properties, and energy as shown in Figure 1. We have

published elsewhere a comparison study of our structure–properties learning progression (Cooper *et al.*, 2012), and our longitudinal studies of these curricula are ongoing. We provide here a short description of the associated learning progression that involves development of understanding atomic and molecular interactions as an example of the kinds of interdisciplinary curriculum reform that are possible.

Our approach to energy begins in chapter 1 and extends through the whole curriculum, rather than being limited to the “energy” chapters, which in a traditional curriculum involves presenting the First Law of Thermodynamics (enthalpy changes and bond energies) in the first semester and the Second Law of Thermodynamics (entropy and Gibbs energy) in the second semester. In CLUE, students are introduced to energy changes involved with atomic and molecular interactions and the explicit connections between potential energy decrease (the energy stored in the electric field as the atoms or molecules approach) and the kinetic energy released are made explicit early and often. Simulations showing the interconversion of potential and kinetic energy at the molecular level are explored, and the idea that energy is transferred by molecular collisions (or photons) is emphasized (Figure 2).

As has been suggested by others (Nahum *et al.*, 2007), bonding and intermolecular forces are treated as a continuum, rather than as separate concepts, so students are explicitly exposed to the commonalities between all types of interactions between atoms and molecules, a concept that in its simplest form can be considered as a system moving to a more stable state by minimizing the potential energy. We devote a much larger part of the curriculum to the discussion of energy concepts at the molecular level, because we are (now) well aware that this is crucial for student understanding. We also take the time to make explicit the connections between the concept of potential energy minimization and the macroscopic manifestation of this phenomenon, namely, the temperature changes that occur as the result of molecular-level interactions and the impact of temperature on the stability of interactions. We also use the concept of systems (in a chapter called “Systems Thinking”) to clearly frame the connections between the molecular and the macroscopic. The point, made repeatedly, is that when considering energy changes at the molecular level, just as at the macroscopic level, it is important to define the system.

Our approach to bond energies and thermochemistry is to emphasize that energy is *stored in a system of molecules*

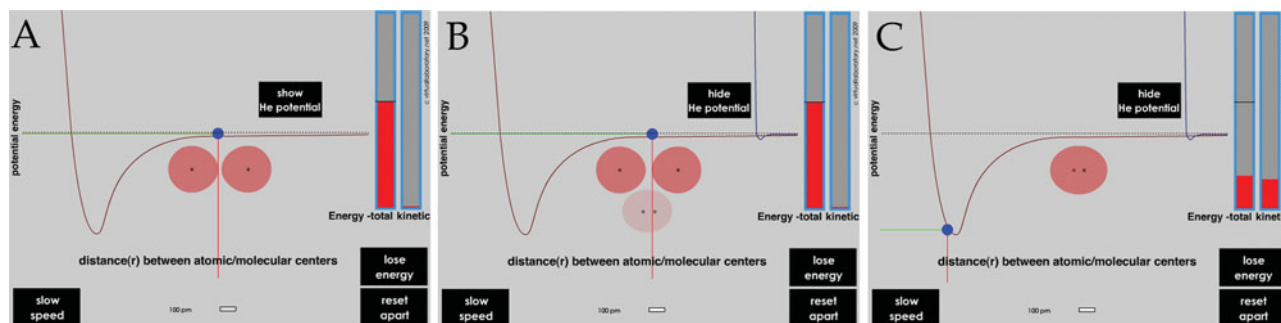


Figure 2. Simulations showing how (A) potential, (B) kinetic, and (C) total energy change as atoms approach each other, and the role of collisions in transferring energy.

(rather than in a particular molecule). The idea that kinetic energy, transferred to and within the system by molecular collisions, can break stable bonds and is released (back into the surroundings) when new bonds are formed is critical. The underlying core idea being that the energy changes occur as a result of a chemical (or physical) change and are a consequence of the relative strengths of the interactions in the reactants, products, and surrounding *system*. Emphasizing that the energy changes that occur during a reaction depend on the nature of the reactants and products in the system, and not simply one of the reactants, is critical. If we consider the combustion of methane in excess oxygen, the products are CO_2 and H_2O ($\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$), but if the oxygen is limiting, the products are carbon and H_2O ($\text{CH}_4 + \text{O}_2 \rightarrow \text{C} + 2\text{H}_2\text{O}$). The energy change for these two reactions is quite different, because the systems of reactants and products are different. Yet if we use the rationale of energy being stored in a fuel, then the energy “contained” in methane would be (in fact must be) the same for both systems. Similarly, the idea that a set amount of energy is stored in a given amount of food is inherently misleading, because the exact reactions that take place determine the energy that can be extracted in a particular system. This is an idea that makes the composition of our intestinal bacterial ecosystem and genetic effects on nutrient utilization and intestinal ecology relevant and understandable. The problem, of course, is that biological systems are complex (orders of magnitude more complex than the systems that are typically dealt with in physics or chemistry) and dramatically influenced by the exact nature of the organismic system. The simplified statement that energy is somehow independent of the system in which it is “utilized” ignores this critical biological reality. While simplification is often necessary, it needs to be accompanied by an explicit acknowledgment and appreciation of what is being simplified.

As we think about systems in the context of CLUE, we consider the role of entropy early on in determining the energy that is available to drive other processes (such as unfavorable reactions). As students become more comfortable with these ideas, we introduce entropic concepts and Gibbs energy from the perspective of probabilities and increasing numbers of energy states. Gibbs energy is treated as a proxy for the Second Law of Thermodynamics. That is: Gibbs energy is not a different kind of energy, but rather is the available (accessible) energy. As has been noted by others (Sozbilir, 2002), understanding Gibbs energy and entropic factors (Garvin-Doxas and Klymkowsky, 2008) is another difficulty faced by students and their instructors. While this part of the CLUE learning progression will be discussed elsewhere, it is worth noting that the CLUE curriculum is a work in progress, a process that involves longitudinal studies of students from CLUE and traditional courses.

CONCLUSIONS AND RECOMMENDATIONS

It is clear that under our present education system, students are not presented with a coherent view of energy and energetics and, not surprisingly, are unable to develop a robust understanding of energy changes that accompany chemical reactions and molecular interactions. While this problem may manifest itself most strongly when we talk to biology and chemistry students, it has its roots in the way physics courses

teach energy, in the way biology courses talk about chemical energy, and in the disconnected and piecemeal approach to energy typically found in a traditional chemistry sequence. While there is hope on the horizon in the way these concepts are treated in the NRC Framework and the NGSS, change will not occur without interdisciplinary reforms at the college level to provide support for future teachers and to help students bridge the macroscopic–molecular gap that is so problematic.

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REFERENCES

- Barak J, Gorodetsky M, Chipman D (1997). Understanding of energy in biology and vitalistic conceptions. *Int J Sci Educ* 19, 21–30.
- Barker V, Millar R (2000). Student’s reasoning about basic chemical thermodynamics and chemical bonding: what changes occur during a context-based post-16 chemistry course? *Int J Sci Educ* 22, 1171–1200.
- Bruice P (2010). *Organic Chemistry*, 6th ed., New York: Prentice Hall.
- Coehlo RL (2009). On the concept of energy: how understanding its history can improve physics teaching. *Sci Educ* 18, 963–983.
- Cooper MM, Underwood SM, Hilley CZ, Klymkowsky MW (2012). Development and assessment of a molecular structure and properties learning progression. *J Chem Educ* 89, 1351–1357.
- Corcoran T, Mosher FA, Rogat A (2009). *Learning Progressions in Science: An Evidence Based Approach to Reform*, New York: Consortium for Policy Research in Education/Teachers College–Columbia University.
- Feynman RP, Leighton RB, Sands M (1963). *The Feynman Lectures on Physics*, 2nd ed., New York: Addison-Wesley.
- Galley W (2004). Exothermic bond breaking: a persistent misconception. *J Chem Educ* 81, 523–525.
- Garvin-Doxas K, Klymkowsky MW (2008). Understanding randomness and its impact on student learning: lessons from the Biology Concept Inventory (BCI). *CBE Life Sci Educ* 7, 227–233.
- Goldring H, Osborne J (1994). Students’ difficulties with energy and related concepts. *Phys Educ* 29, 26.
- Gonzales AO (2011). Assessment of conceptual understanding of atomic structure, covalent bonding, and bond energy. Unpublished master’s thesis, Clemson, SC: Clemson University.
- Hadfield LC, Wieman CE (2010). Student interpretations of equations related to the first law of thermodynamics. *J Chem Educ* 87, 750–755.
- Hestenes D, Wells M, Swackhamer G (1992). Force concept inventory. *Phys Teach* 30, 141–158.
- Hong KB (1998). Students’ understandings of chemical bonds and the energetics of chemical reactions. *J Res Sci Teach* 35, 569–581.
- Jewett JW (2008). Energy and the confused student I: work. *Phys Teach* 46, 38–43.
- Kintsch W (2009). Learning and constructivism. In: ed. S Tobias and TM Duffy, *Constructivist Instruction: Success or Failure?* New York: Routledge, 223–241.
- Lancor RA (2012). Using student-generated analogies to investigate conceptions of energy: a multidisciplinary study. *Int J Sci Educ*, DOI:10.1080/09500693.2012.714512.

Loverude ME, Kautz CH, Heron PRL (2003). Helping students develop an understanding of Archimedes' principle. I. Research on student understanding. *Am J Phys* 71, 1178–1187.

Nahum TL, Mamlok-Naaman R, Hofstein A, Krajcik J (2007). Developing a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge. *Sci Educ* 91, 579–603.

National Research Council (2012). *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, Washington, DC: National Academies Press. www.nap.edu/openbook.php?record_id=13165.

Novak J (2002). Meaningful learning: the essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Sci Educ* 86, 548–571.

Reif F (1999). Thermal physics in the introductory physics course: why and how to teach it from a unified atomic perspective. *Am J Phys* 67, 1051–1062.

Sozbilir M (2002). Turkish chemistry undergraduate students' misunderstandings of Gibbs free energy. *Univ Chem Educ* 6, 73–82.

Stevens SY, Delgado C, Krajcik JS (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *J Res Sci Teach* 47, 687–715.

Storey RD (1992). Textbook errors and misconceptions in biology: cell energetics. *Am Biol Teach* 54, 161–166.

Teichert MA, Stacy AM (2002). Promoting understanding of chemical bonding and spontaneity through student explanation and integration of ideas. *J Res Sci Teach* 39, 464–496.

Tro N (2010). *Chemistry: A Molecular Approach*, 2nd ed., New York: Prentice Hall.

Vygotsky LS (1978). In: *Mind in Society: Development of Higher Psychological Processes*, 14th ed., ed. M Cole, V John-Steiner, S Scribner, and E Souberman, Cambridge, MA: Harvard University Press.