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Corresponding Author	Family Name	<b>Cooper</b>
	Particle	
	Given Name	<b>Melanie M.</b>
	Suffix	
	Division	Department of Chemistry
	Organization	Michigan State University
	Address	East Lansing, MI, USA
Author	Family Name	<b>Klymkowsky</b>
	Particle	
	Given Name	<b>Michael W.</b>
	Suffix	
	Division	Department of Molecular, Cellular and Developmental Biology
	Organization	University of Colorado
	Address	Boulder, CO, USA
Author	Family Name	<b>Becker</b>
	Particle	
	Given Name	<b>Nicole M.</b>
	Suffix	
	Division	Department of Chemistry
	Organization	Michigan State University
	Address	East Lansing, MI, USA
Abstract	<p>“Energy” is a complex scientific concept central to all scientific disciplines. Here we describe three perspectives often used to address energy in the context of introductory college level courses: the <i>macroscopic</i>, which involves thermodynamic and mathematical treatments of energy and energy changes, the <i>atomic-molecular</i>, which relates to energy changes that result from bonding and intermolecular interactions, and the <i>quantum-mechanical</i>, which relates to energy quantization and provides the basis for understanding periodic trends, molecular structure, and electromagnetic radiation. A robust understanding of the role of energy within chemical systems requires that these three perspectives be integrated, but often they are separated into distinct sections of the course and are not explicitly connected. Moreover, prior instruction that does not explicitly address energy concepts at the molecular level almost certainly adds to student challenges. We suggest an alternate approach, illustrated by the new general chemistry course</p>	

*“Chemistry, Life, the Universe and Everything”*, in which structure, properties and energy are presented as three interconnected learning progressions, and the treatment of energy is integrated. All three energy perspectives are explicitly addressed and related to each other in increasingly more sophisticated ways, so that students are led from the structure of the atom through to networked biological reactions, and the role that energy, entropy and Gibbs energy play in these systems.

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# Chapter 17

## Energy in Chemical Systems: An Integrated Approach

Melanie M. Cooper, Michael W. Klymkowsky, and Nicole M. Becker

### 17.1 Introduction

Students are often told that chemistry is “the study of matter and the changes that it undergoes” (Chang and Goldsby 2012). What is less often emphasized is that understanding chemistry depends upon an understanding of the central role of energy in chemical systems. From the structure of individual atoms, to the folding of complex bio-molecules; from the simplest reactions, to the cascades of coupled reactions that have enabled living systems to remain organized and fight the tendency to disorder, understanding energy and energy changes are key. Unfortunately the central role of energy in the chemistry curriculum is often not made explicit, particularly in introductory college-level courses such as general and organic chemistry.

Based on a review of the literature related to students’ understanding of energy ideas in chemistry contexts and on our experiences with introductory chemistry courses, we suggest that in introductory level college chemistry courses the concept of energy is often introduced from three different perspectives: the macroscopic; the atomic-molecular; and the quantum-mechanical perspectives. We discuss these three perspectives and the ways they may (or may not) be connected within the curriculum in the following Sections.

M.M. Cooper  N.M. Becker

Department of Chemistry, Michigan State University, East Lansing, MI, USA

M.W. Klymkowsky

Department of Molecular, Cellular and Developmental Biology, University of Colorado, Boulder, CO, USA

### 17.1.1 The Macroscopic Perspective

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Although temperature change is a physical manifestation of the energy changes that take place on the atomic-molecular level, most instructional approaches to college-level chemistry do little to emphasize these origins: they do not explicitly connect the macroscopic (temperature) to the microscopic and molecular. For example, students might discuss energy changes of endothermic or exothermic reactions that are reflected by observable changes in temperature before ideas of molecular structure are introduced. Such energy changes are typically organized under the general headings of “Thermochemistry” or “Thermodynamics”. Thermochemistry is concerned with the energy changes that take place when a macroscopic chemical system undergoes change, and usually these changes are observable as changes in temperature. For most students, learning thermodynamics topics in a general chemistry course begins with calculations using specific heats and temperatures, which are then related to enthalpy ( $H$ ). Later (usually in the second semester general chemistry course), other thermodynamic functions such as entropy ( $S$ ) and Gibbs energy ( $G$ ) are also introduced, and while more abstract than observable changes in temperature changes, these functions also are related to changes in energy of macroscopic systems.

Change in Gibbs energy, for example, is a thermodynamic state function that is often represented by the equation  $\Delta G = \Delta H - T\Delta S$  (where  $\Delta H$  is the enthalpy change of a reaction,  $T$  is the temperature, and  $\Delta S$  is the entropy of the system). This function is important in that it serves a proxy for the Second Law of Thermodynamics, allowing one to make predictions about the spontaneity of a process using only variables related to the system in question. Unlike enthalpy and internal energy, Gibbs energy is not conserved (because it includes an entropic term). Gibbs energy is one of the most important and useful thermodynamic functions because it allows predictions to be made about the direction of change. Biologists, for instance, might use the Gibbs function to determine the direction of change in biological systems and to understand how coupled reactions can drive thermodynamically unfavorable processes.

However, there is evidence that traditional approaches to teaching thermodynamics topics may leave students with fragmented or even incorrect understandings about what thermodynamic variables represent and how they relate to macroscopic changes in energy that correspond to changes in chemical systems. For instance, prior literature related to students' understanding of Gibbs energy suggests that students may not develop an understanding of Gibbs energy as a proxy for the Second Law of Thermodynamics. Instead, students may conflate change in Gibbs energy for a process,  $\Delta G$ , with the amount of heat transferred in or out of a system (Thomas and Schwenz 1998) or they may believe that the magnitude of  $\Delta G$  can be used to determine the rate of reaction (Sozbilir 2002). Factors such as entropy ( $S$ ), which is often discussed in conjunction with energy changes in macroscopic systems, can be further sources of confusion. While entropy is best understood as related to the number of states or arrangements possible within a

system (Lambert 2002), students may conflate entropy and energy (Carson and Watson 2002), believing that entropy represents a form of energy.

We believe that such difficulties may be related to the fact thermodynamic treatments of energy in introductory chemistry coursework seldom build on students' prior knowledge, but rather introduce a new set of ideas that are not linked to other knowledge and may appear to the student to be introduced solely for the purpose of doing calculations rather than as a foundation upon which to predict molecular behaviors.



### 17.1.1.1 Representational Difficulties Related to Macroscopic Perspectives on Energy

In addition to the fragmented nature of energy topics within chemistry curricula, the representational tools used to communicate energy ideas may contribute to student difficulties with energy topics. As Taber (2013) noted, "Learning chemistry involves both forming concepts that are sufficiently aligned with those of other members of the chemical community, *and* adopting the systems of symbols commonly used within the chemical community so as to be able to communicate with others about these concepts" (p. 4). Thus, students must develop fluency with representational resources commonly encountered in introductory chemistry classes, such as mathematical expressions and graphical representations. Mathematical representations are especially important the use of mathematical resources to model and represent systems is a key scientific practice that has the potential to facilitate students' understanding of energy transfer and conservation in more complex systems (National Research Council 2012).

However, there is abundant evidence that students approach mathematical representations of thermodynamic functions, such as enthalpy or Gibbs Energy, in an algorithmic fashion and that even advanced chemistry students can fail to grasp what these mathematical representations of functions represent. For instance, a practicing chemist might be able to examine an equation such as  $U = q + w$  and interpret it a representation of idea that the total energy of a system is the combination of heat and work done on the system, and as a representation of the conservation of energy. Students, however, may struggle to relate variables such as heat and work to the real-world phenomena or atomic-molecular level understandings of the system. For example, Hadfield and Wieman (2010) found that students enrolled in an upper-division physical chemistry course did not consider the expression  $U = q + w$  to relate to the conservation of energy.

These difficulties may derive in part from the fact that students' everyday interpretations of energy-related terminology (for example "heat" or "work," both of which are commonly used in everyday speech) may be quite inconsistent with the way those terms are appropriately used in thermodynamic contexts (Jin and Anderson 2012; Kaper and Goedhart 2002; Lancor 2012). Thus to successfully interpret expressions such as  $U = q + w$  students must not only be able to interpret the mathematical expression, but hold understandings of terms like "energy",

“heat”, and “work” that are consistent with disciplinary understandings of those terms (Jewett 2008). This is particularly problematic since if students do not develop an appreciation of the concepts underlying thermodynamic functions, we feel it becomes nearly impossible for students to appreciate energy as a tool that they may use to predict and explain the outcomes of chemical processes.

### 17.1.2 *The Atomic-Molecular Perspective*

Energy concepts are critical to understanding how molecules form and behave and it is at the atomic-molecular level where the origins of the observable manifestations of energy change can be observed. As such, a second perspective on energy in the introductory chemistry curriculum often relates to energy at the atomic-molecular level in the context of the structure and interactions of matter.

Energy associated with bonding and intermolecular interactions are foundational parts of chemistry in that they enable predictions of molecular properties and energy transformations at the macroscopic level. It is possible to explain most of the properties and interactions of matter, ranging from the sizes of atoms to their interactions along the spectrum from London Dispersion Forces to covalent bonding, in terms of kinetic and potential energy. To understand bonding at a conceptual level in terms of energy, students must recognize that such interactions are based on attractive and repulsive forces, and that a stable interaction is formed when there is a balance between these forces, an “energy minimum” (Nahum et al. 2007). However, developing the ability to reason about energy at the atomic-molecular scale is not without difficulties. In reasoning about bond formation and stability, students may rely on heuristics such as the octet rule, rather than an understanding of how electrostatic forces contribute to bond formation (Taber 1998). Students may view ionic bonds, covalent bonds, and intermolecular interactions as distinct entities rather than understanding that all involve electrostatic interactions and energy minimization (Taber 1998). Furthermore, misconceptions related to the energetics of bonding interactions, such as the idea that bonds “store” energy and that energy is released when a covalent bond is broken are persistent sources of confusion. A number of researchers have found that even after instruction, typically over 50 % of students incorrectly believe that bonds release energy when they are broken (Barker and Millar 2000; Boo 1998).

While the construct of potential energy is often referenced when discussing intermolecular forces and bonding, chemistry curricula rarely address how electrostatic potential energy at the molecular level, which arises from electrostatic interactions, relates to the more familiar concepts such as gravitational potential energy. Unfortunately at present most students arrive at college having been exposed to kinetic and potential energy in macroscopic systems (for example a ball rolling down a hill), but in our experience, they have little understanding of how these ideas might translate to the molecular level. It is our hope that as students who experience instruction that builds upon the **NRC Framework for Science Education (NRC 2012)**

and the Next Generation Science Standards (NGSS) (Achieve 2013), they will develop a more coherent framework upon which to build some of these ideas. The NGSS emphasize the idea that energy is best treated in an interdisciplinary manner, with explicit connections between the macroscopic and the atomic molecular level. For instance, one connection that may be made is that electrostatic potential energy can be considered analogous to gravitational potential energy in that both depend on the distance between two interacting objects, both involve forces that mediate interactions between objects, and the equations relating the energy of both interactions take very similar forms. If students understand these similarities, they may be better equipped to differentiate gravitational potential energy from electrostatic potential energy in atomic-molecular systems. For example, electrostatic potential energy in the context of molecular systems differs from gravitational in that it is a far stronger interaction at the molecular level and there are two types of charges, meaning that there can be both attractive and repulsive forces, while only attractive forces are present within a gravitational field. Introductory chemistry texts often do not explicitly acknowledge the similarities, differences and difficulties in translating across scales from the macroscopic to the molecular and students are largely left to infer these for themselves.

We consider the origin of potential and kinetic energy changes at the atomic-molecular level critical to understanding the basis of thermodynamic ideas that are in common use. If students do not know how energy is transferred and stored at the atomic-molecular level, they will likely find it difficult to understand, for example, the origin of “chemical energy” – how or why chemical reactions can be used as a source of energy (from food to batteries). To this end, we must do more to ensure that students develop a robust understanding of core energy concepts (such as potential and kinetic energy) at the molecular level and to reinforce appropriate interpretations of energy as related to both macroscopic and atomic-molecular scales.

### 17.1.3 *The Quantum-Mechanical Perspective*

The third focus of energy instruction in university-level general chemistry courses centers on the idea that energy is quantized at the atomic-molecular scale. For most students (and for most people!) this idea is entirely counterintuitive as it has no counterpart in the macroscopic, observable world. Energy quantization is often taught in introductory chemistry courses primarily in connection with topics related to atomic structure. However, connections between quantization of energy from a quantum-mechanical perspective and atomic-molecular or macroscopic phenomena are seldom explicit. Rather than asking students to use the idea of energy quantization to explain phenomena such as why carbon, the building block of life, forms four bonds and not six, or why materials emit or absorb electromagnetic radiation of particular wavelengths, we typically emphasize more easily assessable ideas such as the recitation of electron configurations.

Again, there are a number of reports in the literature about students' understandings of the concepts of quantum chemistry (Taber 2002, 2004; Tsaparlis and Papaphotis 2009). Despite instruction, students may fail to grasp the relationship between energy quantization and orbital ideas in general chemistry contexts (Park and Light 2009; Taber 2002). Park and Light (2009) described the quantization of energy and the uncertainty principle as "threshold concepts". Clearly, if we want students to be able to cross this "threshold" and to relate energy ideas from the quantum-mechanical perspective to molecular-level structure as well as to macroscopic phenomena, more explicit attention is needed towards helping students connect energy ideas across the chemistry curriculum.

In summary, introductory college chemistry courses typically "cover" energy ideas from three perspectives: macroscopic, atomic-molecular, and quantum mechanical. However, in the context of most traditional courses, we feel such coverage may be fragmentary, not connected to students' earlier knowledge, and typically not set in a meaningful context.

## 17.2 How Should General Chemistry Students Learn About Energy Within an Introductory Chemistry Context?

It is clear from our analysis of traditional approaches to teaching energy concepts within the chemistry curriculum that the three dominant perspectives on energy, macroscopic, atomic-molecular, and quantum-mechanical, are rarely well-integrated. Indeed, there is ample evidence that students lack a coherent framework of energy concepts on which they can hang their understanding of energy changes associated with chemical change. While multiple perspectives on energy clearly have their place within the curricula, more must be done to help students connect energy ideas across the curriculum.

The problems inherent in traditional approaches to energy instruction are exacerbated by the fact that most assessments in traditional chemistry courses still emphasize rote problem solving and factual recall over conceptual understanding, and there may be little opportunity for students to synthesize and connect energy ideas across the curriculum. Many of the leading textbooks for general chemistry introduce energy topics in different orders (there are even editions of the same text with the topics juggled), so it is clear that there is no consensus on how to develop and connect energy concepts or even why they are important.

We believe that energy ideas must be developed in a scaffolded progression, which helps students to make sense of energy phenomena across macroscopic, atomic-molecular, and quantum mechanical levels. Our approach to designing an energy learning progression for general chemistry aims to reconcile these different perspectives and explicitly recognize places where energy is best treated by one or more of the perspectives. Our goal is to help students develop an integrated understanding of energy concepts that can help them make connections between the three perspectives discussed here.



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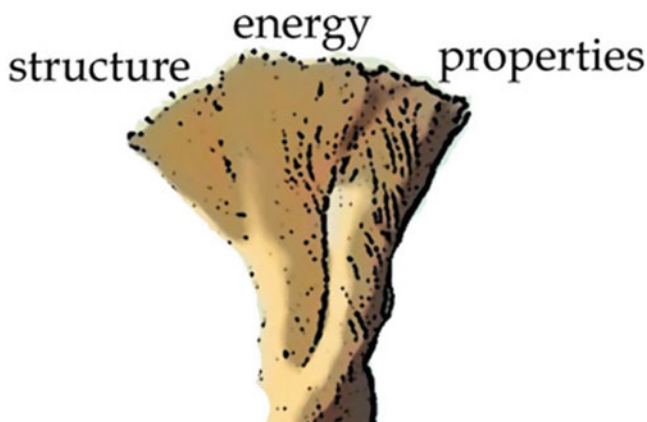


Fig. 17.1 The interconnected learning progressions of structure, properties and energy



### 17.2.1 The CLUE Approach to Energy in Chemical Systems

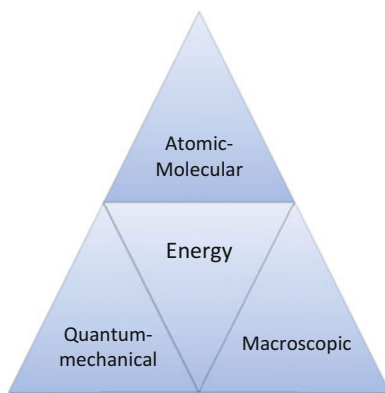
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Our current work in this direction centers on developing, teaching and assessing the outcomes for a new general chemistry curriculum: *Chemistry, Life, the Universe and Everything* (NSF DUE # 0816692).<sup>1</sup> This approach is organized around three interconnected learning progressions for core ideas: Structure, Properties and Energy, which are represented in Fig. 17.1 by three intertwined, interconnected strands. As each core idea is developed, its connections to the other core ideas are also emphasized. Our intent is to develop and connect structure, properties and energy throughout the course, rather than treating them separately. Figure 17.1 is intended to show how these strands are both intertwined and interconnected. The curriculum is structured so as to progress from simple systems, such as the atomic-level interactions of atoms and molecules, to more complex systems such as the networked reactions that drive thermodynamically unfavorable processes. At each stage in the curriculum, the three perspectives on energy are coordinated in order to give students access to a comprehensive view of the role of energy in chemical systems.

We have previously reported on assessments of learning outcomes for the structure-properties learning progression within the CLUE curriculum (Cooper et al. 2012). Here, we provide a description of the design of the progression and the connections among ideas that support the development of a more integrated and robust conceptual framework for energy as it is needed to understand chemical systems. Research on student learning outcomes for the energy learning progression is underway and will be reported elsewhere.

<sup>1</sup>Selected course materials for the course available online at <http://besocratic.colorado.edu/CLUE-Chemistry/index.html>

Fig. 17.2 Three perspectives on energy in the CLUE chemistry course



While the initial development of the curricular materials pre-dated the release of the NRC Framework for STEM education (NRC 2012), the approach we describe here closely parallels many of the disciplinary core ideas related to energy in the physical sciences in the Framework. For example the Framework recommends a more coherent approach to the teaching of energy:

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 that:

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).

While to date there is little empirical evidence that suggests that learning about molecular-level energy changes prior to learning about macroscopic energy changes in chemical systems is beneficial for students, we believe that this approach has the potential to address major impediments to student learning and to meet students where they are in terms of prior knowledge. Students who enroll in college to study STEM fields have already learned about the existence of atoms in K-12 coursework and it is highly likely that they have also been exposed to ideas about energy and energy changes at the macroscopic level. Ideally, students would come to college with a firm grasp of macroscopic energy ideas, including the relationships between different “kinds” of potential energy (gravitational, electrostatic, magnetic). Unfortunately at the moment this does not appear to be the case, and we must address energy in ways that are appropriate for understanding of foundational chemistry principles. While students’ prior knowledge related to energy ideas at the atomic-molecular level may often be fragmented and incomplete, we believe that beginning with a discussion of energy at the atomic-molecular level with explicit connections to their prior understanding of energy ideas at the macroscopic level has the potential to serve as a foundation for better understanding discussions of macroscopic energy changes.

Thus, our current work centers the development of a learning progression that begins with discussion of energy ideas at the atomic level and connects to quantum-mechanical and macroscopic descriptions of energy. In the following sections, we present an overview of this progression and illustrate the ways in which energy ideas are integral within the course structure by using examples from the two-semester general chemistry sequence.



### 17.2.1.1 Chapter 1: Atoms

The CLUE approach to energy begins with an introduction to atomic structure and interactions in their simplest form. That is, quantization of energy levels is not the starting point of this introduction; rather we aim to link to students' prior knowledge about energy and interactions at the macroscopic-level by appealing to students' understanding of gravitational force and energy minimization at the macroscopic level. We begin by asking students what they know about energy both in the macroscopic "real world" and at the molecular level, and through class discussions begin to connect the two perspectives. We emphasize both the similarities between the gravitational forces and energy changes they have learned previously (for example a roller coaster ride), and the electromagnetic force that causes attractions and repulsions at the atomic-molecular level.

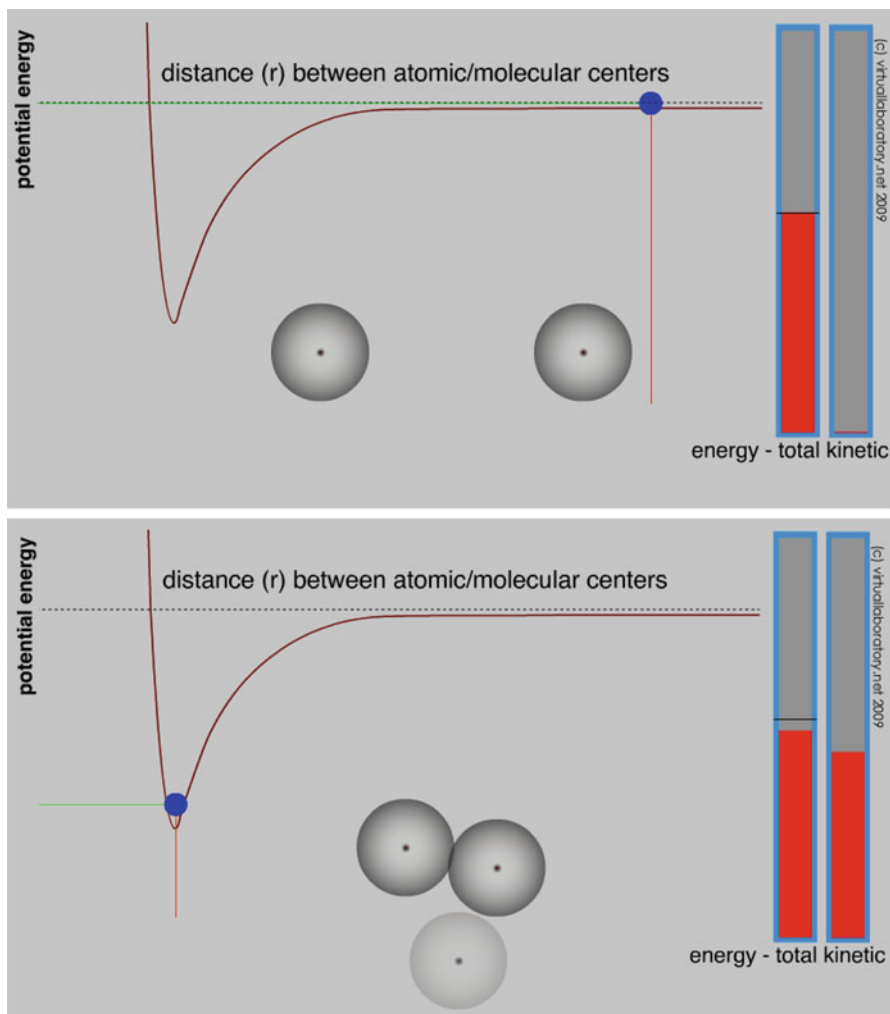
Throughout the CLUE curriculum, we use a number of activities in order to help students engage with the material. For instance the web-based simulation<sup>2</sup> shown in Fig. 17.3 uses the interactions of helium atoms as a simple model for reasoning about the potential energy changes that result from atomic-molecular interactions. The screenshots in Fig. 17.3 show a plot of potential energy versus distance between the nuclei and two bars representing the kinetic and the total energy of the system. As students interact with the simulation, for example by changing the distance between the helium atoms, they are prompted by the simulation to consider various energy changes that result from the changes they observe. The idea of energy conservation is introduced by drawing students' attention to the fact that total energy of the two-atom system remains constant as the atoms interact even though as the fluctuating dipoles in the electron clouds attract one another, the potential energy of the system decreases and the kinetic energy increases.

The activity also introduces the idea of energy minimization in chemical systems. That is, a system will adopt the lowest potential energy configuration unless another source of energy is added. In this case, the lowest energy configuration occurs as the helium atoms interact through London Dispersion interactions. A third atom can be introduced that can either accept energy and stabilize the interaction or transfer energy to the two atom system.

We conclude Chapter 1 with a comparison of the energy changes associated with the formation of different types of intermolecular interactions. For example, we

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<sup>2</sup> Available online at <http://besocratic.colorado.edu/CLUE-Chemistry/activities/LondonDispersionForce/1.2-interactions-1.html>



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**Fig. 17.3** Screenshots of the interactive simulations designed to provide students with atomic-molecular level visualizations of potential and kinetic energy and energy transfer. In the second screen shot, energy has been transferred to the “third” atom, allowing the initial pair to stabilize

compare the energies associated with interactions between helium atoms caused by London Dispersion Forces (LDFs) and contrast these with the energy changes that occur as a covalent bond is formed between two hydrogen atoms. Throughout the CLUE curriculum, bonding and intermolecular forces are treated as a continuum of interactions that minimize potential energy in the system. As suggested by others, this approach may be beneficial since it exposes students to the commonalities in various types of interactions between atoms and molecules (Nahum et al. 2007).

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**17.2.1.2 Chapter 2: Electrons and Orbitals**

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In Chapter 2, we continue our discussion of bonding and intermolecular interactions 332 by introducing the idea of quantization of energy levels at the atomic scale. 333 However, rather than emphasizing memorization of electron configurations and 334 shapes of electron orbitals, energy quantization is emphasized as an explanatory 335 principle. Using different type of assignments, e.g. in class worksheets, homework 336 assignments and on exams, students are asked to use the idea of quantized energy 337 levels to explain phenomena such as atomic emission and absorption spectra and 338 to help explain periodic trends such as effective nuclear charge (from which other 339 periodic trends such as atomic radius, ionization energy, electronegativity and 340 reactivity can be deduced). The introduction of quantized electronic energy levels 341 also facilitates a discussion of the role of core and valence electrons, which can be 342 used to reason about ideas such as why carbon has four valence electrons available 343 for bonding (as opposed to six). These ideas provide a basis for discussion of 344 bonding models in Chapter 3. 345

**17.2.1.3 Chapter 3: Elements, Bonding, and Physical Properties**

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In Chapter 3, both valence bond and molecular orbital models of bonding are 347 introduced. Again energy concepts are central to understanding the causes and 348 effects of bond formation between atoms. Bonding models are explicitly compared 349 in order to provide examples of different aspects of molecular structure for which 350 each is appropriate. The CLUE curriculum emphasizes how a model of quantized 351 molecular orbital bonding and anti-bonding orbital energies enables explanations 352 related to physical properties. Using this model, students are asked to predict and 353 explain observations such as why diamond is hard, translucent and has a very 354 high melting point, while graphite is soft, shiny and conducts electricity, while 355 also having a high melting point. Again in this chapter, the role of electrostatic 356 interactions that lower the energy of the system, and the idea that these energies 357 are quantized, are emphasized. A major aim of this chapter is to have students 358 understand the idea that bond formation releases energy from the system, and bond 359 breaking requires energy input. 360

**17.2.1.4 Chapter 4: Heterogeneous Compounds**

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In Chapter 4, we emphasize the relationship between structure of molecules 362 and their interactions. That is, we return again to ideas that were introduced in 363 Chapter 1 about atomic interactions, and revisit them in the context of more complex 364 systems. Much of this material is concerned with helping students understand 365 the formalisms of depictions of molecular structures and to learn to decode the 366 information they contain. It is not until students have had considerable practice 367

working with depictions of molecular-level structure that we begin examining the impact of molecular-level structure on energy changes and physical properties at the macroscopic level. The role of energy minimization in determining the arrangement of atoms in molecules is highlighted as central to molecular-level interactions. We choose to emphasize this idea and language because it is what students will encounter in subsequent chemistry courses where energy minimization is an important concept.



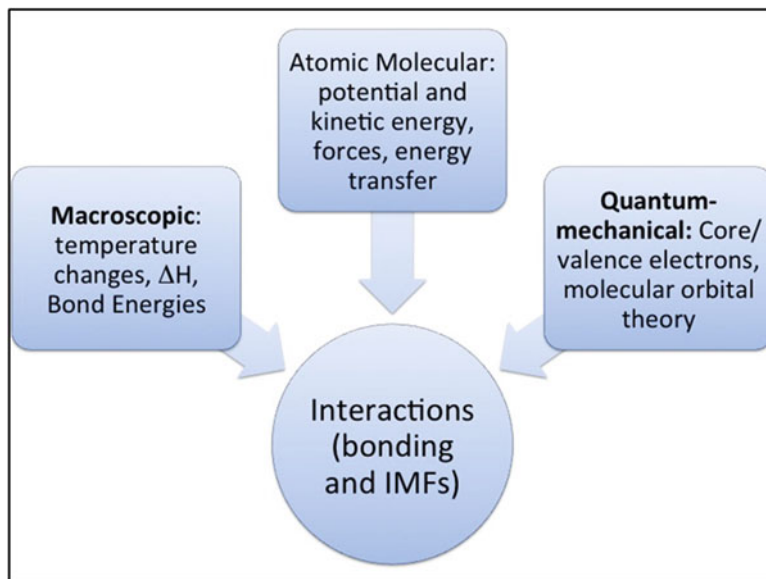
### 17.2.1.5 Chapter 5: Systems Thinking

Chapter 5 introduces a thermodynamic perspective on energy changes and aims to connect the bulk properties of substances with molecular level interactions. We begin with the concept of phase changes, since only changes in intermolecular interactions are involved. At this point in the semester, students have already worked with the idea that to change from a solid to liquid or a liquid to gas, energy must be put into the system (and conversely that to change from gas to liquid, or liquid to solid a release of energy to the surroundings must take place). They have also encountered the idea that the stronger the attraction between the particles, the more energy is required to overcome the interactions between them. We aim to link this prior knowledge related to atomic-molecular and macroscopic energy ideas by introducing further detail about associated changes at the atomic-molecular and quantum mechanical perspectives. For instance, we discuss how adding thermal energy may result in an increase in temperature by increasing the kinetic energy of the particles, but that thermal energy may also causes increases in vibrational and rotational (quantized) energy levels which do not contribute to observed temperature changes.

At this point, the state function enthalpy ( $H$ ) is introduced as a representation of the thermal energy of a system at constant pressure. Introduction to the enthalpies of phase changes and specific heats of substances allows for a quantitative discussion of ideas related to heat transfer and bond energetics. Systems at constant volume are mentioned but not emphasized at this point since most students will not encounter such systems in subsequent coursework. Using this approach, we are now able to address the idea of atomic-molecular interactions using the three perspectives on energy change as shown in Fig. 17.4.

Next, we introduce the term entropy using a probabilistic approach that is grounded in a discussion of changes at the molecular level (Lambert 2002). We also introduce the state function entropy ( $S$ ) and the Second Law of Thermodynamics, which states that the entropy of an isolated system always increases as the system evolves towards the more probable state in which energy is dispersed.

Gibbs energy ( $G$ ) is then introduced as a proxy for the total entropy of the universe. We avoid the definition of Gibbs energy as the energy available to do work, since the term “work” at the molecular level is not a very useful concept, especially



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Fig. 17.4 Three perspectives on energy changes and interactions

since it is often reserved for expansion work, for example during gas evolution. 408  
Instead, we emphasize the usefulness of the Gibbs energy function for predicting 409  
the direction of change in a chemical system and highlight the relationship between 410  
a negative Gibbs energy change and a positive total entropy change in order to 411  
illustrate the role of Gibbs energy as a proxy for total entropy. 412

Our objective in teaching thermodynamics topics in this way is to allow students 413  
to think about energy inputs and outputs as well as the molecular and macroscopic 414  
consequences of these energy changes. In concert with the concurrent development 415  
of an understanding of molecular structure, this approach is designed so that 416  
students may construct a coherent framework that allows them to predict and explain 417  
the direction of change in a chemical system. It is intended to provide a basis 418  
for understanding why some chemical processes require energy input and some 419  
produce energy, and how thermodynamically unfavorable processes can be driven 420  
by coupling them through common intermediates to more favorable processes. 421  
Figure 17.5 illustrates the ways in which molecular, quantum mechanical, and 422  
macroscopic energy ideas contribute to this framework. 423

The ideas developed in the first half of this curriculum are then used in the 424  
second semester to understand how energy (and structure and properties) affect the 425  
formation of solutions (Chapter 6), chemical reactions (Chapter 7), rate and extent 426  
of chemical reactions (Chapter 8), and how networked reactions can be used to drive 427  
thermodynamically unfavorable processes (Chapter 9). 428



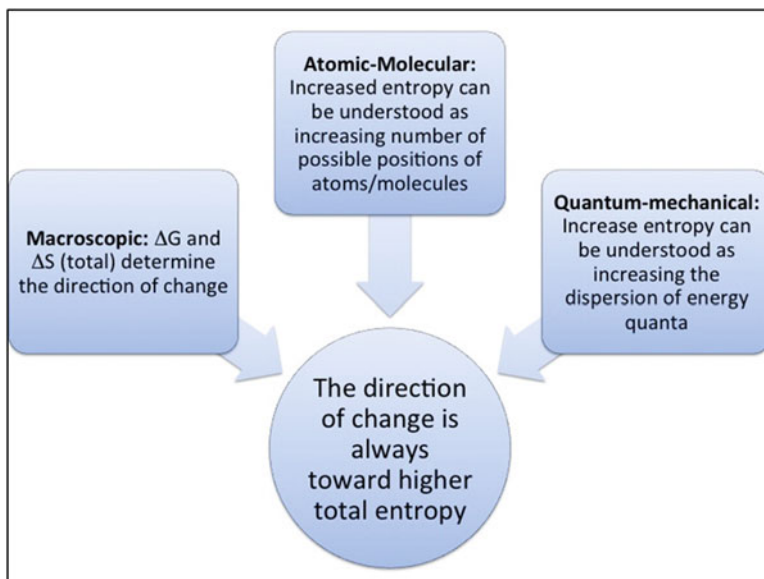


Fig. 17.5 Understanding the direction of change requires all three dimensions

### 17.3 Summary and Conclusions

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We view energy as an integral component of introductory college level chemistry courses that has the potential to provide a framework for understanding both how and why chemical changes occur. As currently implemented within typical introductory chemistry courses, the discussion of energy is fragmented and rarely makes explicit connections across the various energy topics in the curriculum. This makes it exceedingly challenging for students to build on prior knowledge since most of the ideas that students have are based on macroscopic understandings of energy and energy changes.

The learning progression for energy that we have described aims to explicitly connect three commonly used perspectives related on energy (macroscopic, atomic-molecular, and quantum mechanical). Table 17.1 summarizes topics in the curriculum where the perspectives to energy instruction may be used.

By sequencing our discussion so as to begin with a discussion of atomic structure and by connecting new topics to prior understandings, we aim to scaffold students' ability to reason about the networked reactions that drive thermodynamically unfavorable processes. The development of this learning progression and assessment of student outcomes are ongoing, with data collected from student performances and interviews being used to refine and revise this approach.

What is clear is that in chemistry we cannot continue to treat energy concepts as if students already have a robust framework to build on. We must take time to



**Table 17.1** Three perspectives on energy and phenomena that they explain

Atomic-molecular perspective needed for:	Quantum-mechanical perspective needed for:	Macroscopic perspective needed for:	
Interactions leading to potential energy minimization	Interactions of matter and electromagnetic radiation	Physical manifestations of molecular level energy changes	t1.1
Energy transfer by collisions	Energy transfer by electromagnetic radiation	Thermochemistry and thermodynamics	t1.2
Chemical and physical changes as systems	Periodic trends (effective nuclear charge etc.)	Temperature changes and chemical and physical processes	t1.3
The origins of “chemical energy”	Valence and core electrons	Gibbs energy as a proxy for the second Law of Thermodynamics, and a predictor of change	t1.4

reach back and reconstruct and re-develop energy ideas beginning at the molecular level and we must design and construct meaningful activities and assessments that encourage students to relate understandings of energy across the curriculum.

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