ABSTRACT

Title of Document: INTERDISCIPLINARY REASONING ABOUT ENERGY IN AN INTRODUCTORY PHYSICS COURSE FOR THE LIFE SCIENCES

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Energy is a unifying concept that cuts across physics, chemistry, and biology. However, students who study all three disciplines can end up with a fragmented understanding of energy. This dissertation sits at the intersection of two active areas of current research: the teaching and learning of energy, and interdisciplinary science education (particularly the intersection of physics and biology).

The context for this research is an introductory physics course for undergraduate life sciences majors that is reformed to build stronger interdisciplinary connections between physics, biology, and chemistry. An approach to energy that incorporates chemical bonds and chemical reactions is better equipped to meet the needs of life sciences students than a traditional introductory physics approach that focuses primarily on mechanical energy, and so we present a curricular thread for chemical energy in the physics course.

Our first set of case studies examines student reasoning about ATP hydrolysis, a biochemically significant reaction that powers various processes in the cell. We observe students expressing both that an energy input is required to break a chemical bond (which they associate with physics) and that energy is released when the phosphate bond is broken in ATP (which they associate with biology). We use these case studies to articulate a model of interdisciplinary reconciliation: building coherent connections between concepts from different disciplines while understanding each concept in its own disciplinary context and justifying the modeling choices in deciding when to use each disciplinary model.

Our second study looks at ontological metaphors for energy: metaphors about what kind of thing energy is. Two ontological metaphors for energy that have previously been documented include energy as a substance and energy as a location. We argue for the use of negative energy in modeling chemical energy in an interdisciplinary context, and for the use of a blended substance/location ontology in reasoning about negative energy. Our data show students and experts using the blended ontology productively when the two ontologies are combined in a coherent structure, as well as students getting confused when the ontologies are not coherently combined.

INTERDISCIPLINARY REASONING ABOUT ENERGY IN AN INTRODUCTORY PHYSICS COURSE FOR THE LIFE SCIENCES

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

To Elizabeth, without whom this would not be possible,
and to Yonatan, without whom this would not be important.

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Science is a collaborative and social endeavor. Therefore, there is something artificial about putting a single name at the top of a dissertation (almost as artificial as "completing" a dissertation), when this doesn't reflect how the scientific process really works. This dissertation reflects the contributions of many people.

The core of the dissertation comprises three papers that are in various stages of publication, and those papers have 6 co-authors. Joe Redish indirectly got me into PER (I found my way to Maryland because I had read the UMD PERG's work in Richard Steinberg's classes at CCNY), got this whole project launched, and has been a supportive advisor all throughout. The "Gang of Five" — Ben Geller, Julia Gouvea, Vashti Sawtelle, Chandra Turpen, and myself — has collaborated very closely over the last 3 years. Individually and collectively, the experience of working with them has been unequaled. I have been unusually fortunate to have three postdoc mentors and a grad student partner-in-crime. I will continue to carry around a virtual version of each of the five of them in my head, to consult any time I have a question.

I thank the other members of my dissertation committee: Karen Carleton, Andy Elby, Ayush Gupta, and Wolfgang Losert. (Chandra Turpen also served as an unofficial member of the committee.) At multiple stages of the process, their suggestions and questions (in both their real and virtual forms) made me think carefully about each piece and greatly improved the final product.

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Thanks to all of the students who have participated in the first years of NEXUS/Physics and consented to be videotaped so that they could help inform better science education for future students, especially those who appear pseudonymously in this dissertation (and those who participated in interviews even if those interviews didn't make it into the final cut). Thanks to all the TAs and LAs who have made this experiment possible.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 The motivation: Andrea and Dennis

Andrea[1] was a third-year undergraduate pre-veterinary student taking an algebra-based introductory physics course. I interviewed her in October 2010, before her physics class had begun any discussion of energy. When I asked Andrea to explain how a cell gets energy, she answered fluently based on her biology background, invoking metabolic pathways, oxidative phosphorylation, and the ATPase pump. However, she started to stumble at some of my followup questions, such as "What does that mean that there's energy in the bonds?"

At the end of the interview, I thanked Andrea for her participation and told her that we were using these interviews to help develop a course that would integrate physics, biology, and chemistry. She began to volunteer her opinions on this (and I turned the camera back on):

> *What I found in classes is that even though we might talk about energy, it's more of an accepted fact in the class, like exothermic release energy, endothermic … takes in energy, whatnot, but we never really talked about how … the energy got there in the first place, how it breaks the bond, exactly what the energy is doing.*

Though Andrea perceived her biology and chemistry classes as not getting into the mechanistic details of energy processes, she expressed the expectation that her physics class would do this:

> *What happens in like physics is my understanding is we really think about the transfer of energy and where things are going. … We've never really, in any of the classes we've never really linked those all together into where the energy's coming from, how it's actually breaking bonds in the molecule, how it's actually like forming bonds in molecules as well.*

Unfortunately we were not able to schedule a second interview at the end of the semester when I could ask Andrea whether her physics class had in fact given her the tools to "really think about the transfer of energy and where things are going," in a way that could help her explain phenomena from biology and chemistry. But based on what we know about standard algebra-based physics curricula, we can reasonably

[1] All names are pseudonyms.

guess that the answer would have been no. It is likely that her physics course focused on mechanical energy at the macroscopic scale, with little or no explicit connection to biological or chemical mechanisms.

Indeed, another set of interviews the same semester (Dreyfus, Redish, & Watkins, 2012), with Dennis, another student in the same course, revealed a deep sense of disconnect. At the end of the semester, Dennis contrasted how his science classes approached energy. He said that his physics class

> *talks a lot more about physical objects, stuff like that, which you don't really talk about in bio or chem. You don't really talk about macro stuff, you kind of talk about like interactions of molecules, in biology you talk about— Chemistry, you talk more about interactions of like atoms and stuff like that. Biology, it's more about interactions of molecules.*

Dennis went further to suggest in various ways that macroscopic "energy" in physics and microscopic "energy" in biology and chemistry were not really the same entity. He referred to "a situational use of the term energy," implying that energy is not a unified entity that exists at different scales, but only a **term** that can be used in unrelated situations. Dennis did not rule out the possibility that there may be a way to make connections between these different energies, but also did not find this useful:

> *Like assuming electrons are measured in, or you know, electrical charge or something like that. It's measured in like volts. ... And then when you're measuring movement and stuff like that of actual, like, of larger bodies, you use units like force, and stuff like that. And maybe you could convert the two, between the two, but I don't really see the point. ... I'm saying even if there were a way to connect the two, which I don't, I certainly don't, can't think of a way, I don't really think there would be a point in doing so.*

The research in this dissertation is motivated by the question of how to reach students like Andrea and Dennis. Andrea desires interdisciplinary coherence about energy, but does not have access to the appropriate tools to make connections across the disciplines. Dennis sees energy in the disciplines as disconnected, and does not even see a need to connect them. And beyond this instructional question are more fundamental research questions: What does it really mean to make interdisciplinary connections? How does the interdisciplinary context affect the ways that we think and talk about energy? I explore each of these questions in depth, though this exploration is only the beginning of an answer.

1.2 The broader context: Energy and interdisciplinarity

This dissertation sits at the intersection of two very active current research themes: the teaching and learning of energy, and interdisciplinary science education that connects physics to the life sciences. Energy has been extensively studied, as a topic that is both central to all the sciences and conceptually confounding. Science classes at all levels deal with energy, and yet (as we review in chapter 2) both students and experts have difficulty pinning down what it really is. Concurrently, as science and science education look ahead to the demands of the future, there are frequent calls for increased interaction and collaboration between the sciences, at both the educational and professional level, particularly between the physical and life sciences.

This intersection of these areas—the teaching and learning of energy in interdisciplinary science education—has been widely promoted as essential to education reform. The framework for the *Next Generation Science Standards* (Quinn, Schweingruber, & Keller, 2012) includes energy among the crosscutting concepts that bridge disciplinary boundaries. Reports on biology education reform (AAAS, 2011) describe using energy as a way to connect physics and chemistry to biology. However, education research that directly addresses this crucial intersection is still limited.

One clear result from the limited existing research is that for students, energy does not necessarily serve as a bridge across disciplines, but can be highly fragmented along disciplinary lines. Our own case study of Dennis (Dreyfus et al., 2012) showed that a student's approach to integrating energy concepts across disciplines can be highly context-dependent. Hartley, Momsen, Maskiewicz, & D'Avanzo (2012) documented disciplinary differences in how physics, chemistry, and biology textbooks and instructors present energy concepts, and suggest that this contributes to student confusion. Donovan et al. (2013) note differences between physics and biology in the types of questions they ask about energy and therefore in the level of explanation that they find satisfactory. Our purpose is to address this fragmentation.

1.3 Addressing interdisciplinary fragmentation about energy: Three themes

This dissertation seeks to explore students' ideas about energy through explicitly disciplinary and interdisciplinary lenses, and thereby to begin to build up a research base to inform the interdisciplinary teaching of energy, which is essential to multiple reform efforts. There are three interwoven threads running through it, representing three of our first steps towards a solution to the problem of how to help students build interdisciplinary coherence about energy:

- **Chemical energy:** The energy that is most essential to understanding biological phenomena is "chemical energy" (the energy associated with chemical bonds and reactions), but this is at best a footnote in traditional introductory physics courses. Building a coherent framework of energy that connects physics to biology requires integrating ideas about chemical energy with the more canonical treatments of energy from physics. We developed an instructional thread on chemical energy for the NEXUS/Physics course, a reformed introductory physics course for life science majors that focuses on interdisciplinary coherence. This thread represents a pedagogical approach to connecting "physics energy" to "biology energy," and chemical energy also provides a rich context to conduct our other empirical and theoretical research.

- **Interdisciplinary reconciliation:** We want our students to build coherent connections among ideas in the disciplines. But at the same time, the disciplines remain distinct, with separate languages and modeling choices that are productive for answering the questions of interest to each discipline. The goal is not that our students will arrive at a single unified model for energy (or other cross-disciplinary concepts) that will serve them equally in explaining physical phenomena and biological phenomena. Rather, the goal is that they will learn to speak the language of each discipline fluently, while understanding the conceptual connections that bridge the disciplines and being able to make choices about which model is most productive in a given situation.
- **Ontological metaphors:** A primary way that people develop abstract concepts is through metaphors that connect these concepts to physical experiences. Thinking seriously about the learning and teaching of energy requires attending to the ontological metaphors that we use for energy: metaphors about what kind of thing energy is. Sometimes we talk about energy as a substance: this object **has** energy; energy was **released**. This helps us build intuition about conservation of energy, by building on our intuitions about conserved substances. Other times we talk about energy as a vertical location: this object was **at** a **higher** energy, and **went** to a **lower** energy. This helps us build intuition about various potential energies, drawing an analogy to our intuitions about gravity. We argue that blending the substance and location ontologies is appropriate and productive in reasoning about chemical energy. In the same way that students need to learn how to make choices about which disciplinary model is productive in a given situation, they also need to learn to make choices about which ontology (or blend of ontologies) is productive in a given situation.

1.4 Outline of the dissertation

In chapter 2, I review the research literature on the teaching and learning of energy and on interdisciplinary efforts at the intersection of physics and biology education, and introduce the resources framework, which serves as a guiding theoretical framework for the various strands of this research. In chapter 3, I describe the NEXUS/Physics course, the context in which our research was conducted, and justify why this is the appropriate context to conduct this research. This chapter also describes our research methodology and justifies the appropriateness of small-N qualitative methods.

Chapters 4–6 are the core of the dissertation. These chapters are written to stand independently, and each has been submitted for publication. Chapter 4 details a curricular thread on chemical energy that was developed for the NEXUS/Physics course, designed to support students in building interdisciplinary coherence. I describe the structure and content of the thread, the instructional goals of each component, and the intended student outcomes. Chapter 5 looks at students' interdisciplinary reasoning about the biochemically significant molecule ATP, and leverages case-study data to build up a vision for interdisciplinary reconciliation (IDR): building coherent connections between concepts from different disciplines while understanding each concept in its own disciplinary context. I situate IDR in the resources framework, and compare and contrast it with other pedagogical approaches to reconciling apparently contradictory ideas. Chapter 6 focuses on ontological metaphors for energy: metaphors about what kind of thing energy is. Two ontological metaphors for energy that have previously been documented include energy as a substance and energy as a location. I argue for the use of negative energy in modeling chemical energy in an interdisciplinary context, and for the use of a blended substance/location ontology in reasoning about negative energy. Our data show students and experts using the blended ontology productively when the two ontologies are combined in a coherent structure, as well as students getting confused when the ontologies are not coherently combined.

In chapter 7, I summarize and synthesize the results of the various studies, and discuss implications for instruction and future directions for research.

Chapter 2: Literature Review and Theoretical Framework

As discussed in chapter 1, this dissertation is at the intersection of two active areas of research: the teaching and learning of energy, and interdisciplinary science education that connects physics to the life sciences. This chapter reviews the literature on each of these areas, with a focus on identifying points of contact. In addition, the body chapters (4–6) also review literature relevant to their specific topics (on chemical energy, ATP, and ontological metaphors), so we mention those areas only briefly in this chapter, but focus here on a more general overview.

2.1 Energy

The education literature on energy is vast, as is to be expected given the centrality of energy to all of the sciences. We have undertaken an extensive survey of this literature and submitted a Resource Letter (Dreyfus, Geller, Meltzer, & Sawtelle, under review), an annotated bibliography that covers energy (with a focus on relevance to thermodynamics) and other topics in thermodynamics and statistical mechanics, as taught in physics, chemistry, and biology. To narrow the literature base to a manageable size, we limited our attention primarily to articles that included student data and/or substantial discussions of instructional implications, which excluded many articles that focused only on the science content. Within our criteria, we found that most of the literature on energy is either within physics or is "pre-disciplinary" (i.e., involves K-8 students, before "science" is split into multiple disciplines). There is relatively little that is from biology or chemistry, or that is explicitly interdisciplinary (at the high school or college level, where the disciplines are distinctly represented).

While there is topically focused physics education research on a wide variety of physics content topics (McDermott & Redish, 1999), energy is unique in two ways: 1) Energy transcends physics, and has deep significance to other scientific disciplines and the ability to make connections across disciplines. This is why energy is an appropriate context to explore the interdisciplinary issues raised in this dissertation. 2) In addition to the research on student understanding which exists in all topical areas (and often involves comparing students' "novice" ideas to canonical expert ideas), there is a long-running and ongoing conversation among experts (even within physics) about what energy really is and how we should talk about it. Thus the conversations about how students reason about energy and how energy concepts should be taught cannot be completely decoupled from this expert conversation. This is magnified when the disciplines are brought into contact, and experts share less of a common discourse. Perhaps the only other physics topic that shares both these properties is entropy, which is also covered in our Resource Letter (Dreyfus, Geller, Meltzer, et al., 2013) and is the context of another upcoming dissertation.

2.1.1 What is the nature of energy?

We begin by surveying the education literature on the nature of energy, much of which is theoretical in the sense that it does not draw on student data. A longstanding textbook definition of energy is "the ability to do work." (This definition has not gone away; in a pilot study of undergraduate students in an introductory algebra-based physics course, we found that around half of them gave some version of this definition when asked to explain what energy is, suggesting that this is still what they are encountering in middle school or high school.) This definition has been deprecated for at least four decades. Lehrman (1973) argues that "Energy is the ability to do work" is not only incomplete, but incorrect, because it ignores the Second Law of Thermodynamics, which states that not all energy has the ability to do work. Hicks (1983) shows that "the capacity to do work" makes sense in the exclusive context of mechanical energy, but not for thermal and other forms of energy. However, a number of others (Daane, Scherr, & Vokos, 2013; Pintó, Couso, & Gutierrez, 2005; Viglietta, 1990) have argued that even if "the ability to do work" does not correspond to the canonical physics concept of energy, it still needs to be addressed in order to bridge physics energy (which is conserved) to students' intuitive ideas about energy being used up. They have proposed the use of constructs such as exergy, energy degradation, and free energy to get at the actual "ability to do work."

If energy is not the ability to do work, then what is it? A widely cited starting point is the *Feynman Lectures on Physics* (Feynman, Leighton, & Sands, 2011a), which sets up an extended analogy of a child's blocks. The total number of blocks is constant, but the blocks can end up in places where we can't see them. For example, some of the blocks might end up in the toy box; in that case, the quantity that remains constant is the number of blocks seen, plus the excess weight of the toy box divided by the weight of a block. Multiple terms are added to the expression for the conserved quantity, and these terms are analogous to forms of energy. Feynman can be read as supporting both sides of what Warren (1982) labels as the conceptualist (energy is abstract) vs. materialist (energy is like a substance) divide. On the one hand, Feynman's punch line is "*there are no blocks,*" since "we have no knowledge of what energy *is*. ... However, there are formulas for calculating some numerical quantity, and when we add it all together it gives … always the same number." This is frequently understood as a conceptualist view: energy is abstract and we can't define it, but when we add up the terms in the equation, it always works. On the other hand, Feynman finds it useful to explain this by means of a substance-based metaphor (the blocks), which can be seen as supporting some elements of a materialist view even if he does not attribute an "objective existence" (Warren, 1982) to energy. On the conceptualist side are the arguments that energy cannot be defined operationally (Sexl, 1981) and that the idea of "energy storage" is misleading (Beynon, 1990). On the materialist side is the argument that talking about energy as quasi-material can be useful in thinking about energy conservation and energy transfer (Duit, 1981, 1987).

This debate has settled down as it has become clear that no one is claiming that energy "is" a material substance, and yet (as Feynman and others illustrate) there are pedagogical affordances in using material metaphors to understand energy. Thus there is a growing body of more recent work on the substance metaphor and other ontological metaphors for energy (Amin, 2009; Brewe, 2011; Lancor, 2012; Scherr, Close, McKagan, & Vokos, 2012), which we discuss in greater depth in chapter 6. Like these more recent authors, we take a pragmatic view on the nature of energy: even if energy is an abstract concept, we understand all abstract concepts through the lens of metaphors based in our experience of the physical world (such as "lens" in this sentence) (Lakoff & Johnson, 2008), and so the appropriate metaphors to use for energy are determined by their advantages and disadvantages for understanding the relevant concepts.

In addition to the general debate about what energy is, there is also the question of "forms of energy." Are they nothing more than terms in an equation? Is it useful to think about energy transformation (energy changing from one form to another)? At one extreme is the complete rejection of "forms of energy," and at the other are curricula that define many forms of energy (sound energy, elastic energy, etc.). There are also intermediate positions, such as distinguishing kinetic and potential energy, but understanding other forms (e.g. thermal energy) in terms of kinetic and potential energy. Kaper & Goedhart (2002a) look beyond the introductory course and show that in thermodynamics, there is only energy, and in that context, the idea of transforming energy between forms is meaningless. They show that the "forms of energy" language is valid only under specific constraints, e.g. a system undergoing small changes. In search of a terminology that achieves the same instructional affordances, these authors (Kaper & Goedhart, 2002b) ultimately end up with "exchange value" instead, e.g. replacing "gravitational potential energy" with "exchange value of height." Swackhamer (2005) takes a pure unitary view of energy: There is only energy (no forms of energy), it is substancelike, and we can talk about transfer (energy going from one place to another), but not transformation. Instead of gravitational potential energy, we can talk about energy stored in the gravitational field. Hilborn (2013) critiques the language of energy in the field, arguing that while this approach is self-consistent, it requires considering the fields all the way out to infinity, and therefore introduces too much conceptual complication for introductory physics. Instead, he defends the idea of potential energy associated with the configuration of a system. Papadouris, Constantinou, & Kyratsi (2008) defend "forms of energy" and energy transformation, with data showing that students had difficulty coming up with appropriate explanations of phenomena using only energy transfer.

We take a pragmatic view on the "forms of energy" question as well. We do not attempt to prescribe a single answer to this question, but encourage the coordination of multiple models for energy, along with reflection on which model is appropriate to employ in a given situation. So it may be useful to think about "chemical energy" as a "form" of energy in one situation, or to decompose it into molecular kinetic and potential energies in another situation, or to think about it simply as energy in another situation.

2.1.2 Students' reasoning about energy

We turn now to empirical studies of student reasoning about energy. A classic in the field is Watts (1983), which identifies seven "alternative frameworks" for energy based on student interviews: human-centered, depository, ingredient, obvious activity, product, functional, and flow-transfer. Watts's frameworks have been taken up by many others, including Trumper (1996, 1998), who found that pre-service physics teachers display these alternative frameworks. More recently, the original data have been revisited (Harrer, Flood, & Wittmann, 2013), from the perspective of looking for productive resources in students' reasoning about energy, rather than classifying student reasoning into well-developed stable frameworks. As we discuss in section 2.3, we share this latter approach of treating student reasoning as potentially fragmented and looking for productive resources.

A number of studies (Dawson-Tunik, 2006; Jin & Anderson, 2010; Lee & Liu, 2009; Liu & McKeough, 2005) use a stage model for the development of energy concepts (e.g. energy transfer, degradation, and conservation), and propose learning progressions for teaching energy concepts. Many of these studies use statistical methods on their student data sets to demonstrate that students who have achieved understanding of concept B have also achieved understanding of concept A, but not the reverse, suggesting that concept A is naturally learned before concept B. However, given that the students in the data are taught with existing curricula, it is not clear how the authors of these studies can exclude the possibility that the order of topics that emerges from the data simply reflects the order of topics as they are currently taught. While we propose a progression of sorts in chapter 4, we are not claiming that the order of topics in our chemical energy thread represents a progression of developmental stages. This order is based on the needs of our particular instructional context (introductory physics for the life sciences), but we can imagine the concepts being introduced in other orders for other contexts.

In the realm of student difficulties, several studies (Goldring & Osborne, 1994; Solomon, 1985) showed students saying that energy "lost to friction" becomes potential energy again; in these cases, applying the principle of conservation of energy actually leads to the wrong answer. There are also a number of papers on student reasoning about chemical bonding and ATP (Boo, 1998; Cooper & Klymkowsky, 2013; Galley, 2004; Gayford, 1986; Novick, 1976; Storey, 1992; Teichert & Stacy, 2002a), which we discuss in chapter 5, and about negative energy (Lindsey, 2014; Stephanik & Shaffer, 2012), which we discuss in chapter 6. These studies focusing on specific conceptual difficulties are valuable contributions; our work focuses on situating conceptual issues in a broader framework, so the two types of studies are complementary.

2.1.3 Energy in biology and across the disciplines

While the literature on energy in biology education is more limited, two prominent themes are the failure (by students and instructors) to make connections across hierarchical levels of biology (i.e., cells, organisms, ecosystems, etc.), and the failure to connect biology to other disciplines.

On the first theme, Jin & Anderson (2010) write about the macroscopic, atomic-molecular, and global (e.g. the atmosphere and climate change) scales, while Lin & Hu (2003) talk about the phenomenal (e.g. ecology), mechanical (e.g. cellular mechanisms), and physical (e.g. molecular processes) levels. Both argue based on their analysis of student reasoning that biology education is too compartmentalized into these levels, and call for greater coherence about energy across scales.

On the second theme, Trumper (1997) shows that pre-service biology teachers demonstrate vitalistic conceptions about energy, i.e. the idea that biological phenomena cannot be explained by physics and chemistry. Barak, Gorodetsky, & Chipman (1997) find that students' understanding of energy in biology was significantly correlated with scientific as opposed to vitalistic explanations. Chabalengula, Sanders, & Mumba (2011) show that biology students displayed conceptual difficulties when applying energy concepts in biological contexts. Cooper & Klymkowsky (2013) address the problem of learning "chemical energy," and attribute the cause of the problem to biology, physics, and chemistry curricula. All of these studies demonstrate a disconnect among the disciplines in regard to energy, and call for stronger interdisciplinary connections.

These themes of connection and disconnection across reasoning contexts are not unique to biology with its multiple levels, or to connecting biology to the physical sciences. Solbes, Guisasola, & Tarín (2009) deal with energy conservation as a unifying theme throughout physics (not only mechanics), and present an "energy-first" curricular approach also seen in Brewe (2011). Papadouris et al. (2008) show that students had difficulty seeing energy as a transphenomenological construct that provides a single explanation for different phenomena. While this conclusion has much in common with the interdisciplinary questions that we are interested in, all their cases were from "physics" contexts, involving electricity and mechanics. Thus, while our own work is situated in an interdisciplinary context, and draws heavily on the challenges that are brought to the foreground by the interaction between the disciplines, we believe it has future applications to "intradisciplinary" physics education (and perhaps biology education) as well, as we discuss in chapter 7.

2.2 The intersection of physics and biology

We now turn to the second major area of literature that we build on: the intersection of physics and biology education. Many recent reports on biology education reform have stressed the importance of increased integration between biology and physics. The Bio2010 report (National Research Council, 2003) on undergraduate biology education calls for life sciences majors to acquire a stronger foundation in the physical sciences, to be prepared for the biology of the future. The *Scientific Foundations for Future Physicians* report (AAMC/HHMI, 2009) defines scientific competencies for pre-medical students, which include "knowledge of basic physical principles and their application to the understanding of living systems." *Vision and Change in Undergraduate Biology Education* (AAAS, 2011) stresses the interdisciplinary nature of biology, and encourages biology students to develop expertise in other sciences. Though the MCAT has contributed to curricular inertia in introductory courses taken by pre-med students, the new revision (Association of American Medical Colleges, 2011) is moving in the direction of emphasizing physics topics that are relevant to biology and medicine.

The integration of biology and physics education has been an area of ferment in recent years. Introductory Physics for the Life Sciences (IPLS) sessions have been held at American Association of Physics Teachers conferences since 2009, and Meredith & Redish (2013) lay out the issues for the broader physics community. *CBE–Life Science Education* published a special issue on the intersection of physics and biology education in June 2013, and the *American Journal of Physics* is publishing one in 2014. Redish & Cooke (2013) discuss the process of negotiating the disciplinary differences between physics and biology. In 2014, the topic of the Gordon Research Conference on Physics Research and Education is “The Complex Intersection of Biology and Physics,” and there was an NSF-supported conference on Introductory Physics for the Life Sciences. All of this work demonstrates that there is growing enthusiasm for addressing issues of interdisciplinary education at the interface of physics and biology.

A number of physics courses (Christensen et al., 2013; Meredith & Bolker, 2012; O’Shea, Terry, & Benenson, 2013; Potter et al., 2014) and curricula (Benedek & Villars, 2000; Nelson, 2007) have incorporated strong connections to biology content. Research on a few of these courses has evaluated students’ conceptual understanding and attitudes, though often through assessments developed for conventional-content physics courses such as the Force and Motion Conceptual Evaluation (Thornton & Sokoloff, 1998) and the Maryland Physics Expectations survey (Redish, Saul, & Steinberg, 1998). Research that explicitly addresses how students connect ideas from multiple disciplines is still limited. This is the work that this thesis begins, and energy provides a rich context in which to do so.

Our approach to interdisciplinarity is based in a framework of *disciplinary authenticity* (Watkins, Coffey, Redish, & Cooke, 2012). Disciplinary authenticity requires engaging with the approaches of the disciplines, including their epistemologies and the questions they are interested in. Conversely, it means not simply assuming that the scientific phenomenon that one is studying means that one is authentically doing biology or physics. From this perspective, a goal is to understand how physics can be used in the service of biological understanding. Watkins et al. argue that “helping students cross disciplinary epistemological boundaries will require keeping the physics-authentic activities, but tying them more authentically to the practices of biologists.”

This dissertation represents one slice of the NEXUS/Physics research group’s current work on interdisciplinary education at the interface of physics and biology. Other papers at various stages of publication explore interdisciplinary task design and levels of authentic interdisciplinarity (Gouvea, Sawtelle, Geller, & Turpen, 2013), categorize student perceptions of the relationships between the disciplines (Geller, Dreyfus, Sawtelle, et al., 2013), study interdisciplinary coherence around entropy and the Second Law (Geller et al., 2014), and refine interdisciplinary learning goals for students. Thus, this work is situated in a larger effort that studies interdisciplinarity from multiple angles.

2.3 Theoretical framework

Like most of physics education research, this dissertation seeks to understand student learning. All research on student learning operates with some implicit set of assumptions, and so in this section we describe our theoretical framework (Redish, 2003) to make those assumptions explicit. The overarching framework that we use is the *Resources Framework*, which we engage with most directly in chapter 5 (and discuss in more detail there), but which is also present in the background in the rest of the dissertation, as we outline below. Another related theoretical perspective that we employ in chapter 6 is dynamic ontologies (which we primarily discuss in chapter 6).

The consensus view in physics education research is constructivism: the idea that learners are not blank slates, but all new knowledge is built on existing knowledge (Driver, Asoko, Leach, Scott, & Mortimer, 1994). This approach is the reason that PER across the board has a strong focus on understanding the ideas that students enter with, in order to understand student learning. However, there are two major ways of characterizing these ideas: the misconceptions model and the resources or knowledge-in-pieces framework.

Under the misconceptions model (McCloskey, 1983; Posner, Strike, Hewson, & Gertzog, 1982; Vosniadou, 1994), students possess strongly held, stable, and unitary beliefs, which differ from expert conceptions. That is, if a student holds a misconception, we would expect that student to exhibit that misconception consistently across multiple contexts. In one version of this model, students possess "naïve theories," which are similar in structure to scientific theories, and may even bear similarities to historical scientific theories; e.g., McCloskey (1983) draws a parallel between students' naïve theories of motion and the medieval impetus theory (which was supplanted by Newtonian mechanics). The difference between naïve theories and expert theories is a matter of content. The goal of instruction in the misconceptions model is to confront and replace misconceptions, or the underlying presuppositions.

In contrast, the resources framework (Hammer, 1996, 2000; Redish, 2003), which has its roots in the knowledge-in-pieces framework (diSessa, 1993; Smith, diSessa, & Roschelle, 1994), sees students' knowledge as more dynamic, with the possibility of being fragmented. Rather than a single coherent theory that differs from expert understanding, students possess a variety of resources that can be activated differentially in different contexts. For example (Hammer, 1996), a student might apply the concept "motion is caused by a force" in some circumstances but not others. Students might access particular resources in ways that lead them to incorrect conclusions. The goal of instruction is not to eliminate these resources, but to help students use their resources productively and refine their sense of when those resources are most useful. This requires looking for the seeds of productive reasoning in students' thinking.

Resources are mesoscopic (Redish, 2003); that is, they are composed of smaller elements (they are not the smallest units of cognition) but are still relatively simple building blocks when viewed from the level of individual thinking and behavior. Resources can be both conceptual (resources for understanding physical phenomena) and epistemological (Hammer, 2000) (beliefs about the nature of knowledge and learning). Conceptual resources can range from phenomenological primitives (diSessa, 1993), basic schemas based on experience in the physical world such as "more cause leads to more effect," to more complex resources that have been compiled from other elements, such as the polar coordinate system (Sayre & Wittmann, 2008). Epistemological resources include beliefs about the nature of science, such as "scientific knowledge comes from authority" or "scientific knowledge is determined by experiment," (Elby, 2001; Hammer, 1994b, 2000) and beliefs about one's current setting or activity, such as "biology knowledge is not relevant in physics class" (Hall, 2013).

Chapter 4 describes and justifies a curricular thread on chemical energy in a physics course for life science students. The approach of this thread is fundamentally constructivist, in that it is designed to build on the ideas that students bring in from biology and chemistry and to create connections to that existing knowledge, rather than to start fresh with the organization of ideas that the authors find the most logical. Furthermore, the thread starts from the assumption that students' initial ideas about energy in the disciplines are fragmented, and seeks to build coherence across those fragmented ideas, rather than assuming that students initially possess a coherent yet incorrect theory of energy across the disciplines and seeking to replace it with the correct theory.

In chapter 5, we extend the resources framework to interdisciplinary reasoning. Our analysis involves concepts (in this case, chemical bond energy) that students encounter in multiple contexts associated with multiple disciplines, and so we draw on the research on epistemological framing and context-dependent activation of resources (Hammer, Elby, Scherr, & Redish, 2005). Previous work based in the resources framework (Elby, 2001; Lising & Elby, 2005) has shown that students can compartmentalize their understanding of the physical world, and activate different resources in "physics" settings and "everyday" settings. Several pedagogical approaches have been developed to give students the opportunity to reconcile the apparently conflicting ideas that they activate in different contexts.

We turn our attention to a different type of compartmentalization, associated with "disciplinary silos." While this, too, involves the context-dependence of resources, it differs from "physics"/"everyday" compartmentalization in that both contexts represent a set of canonically correct scientific ideas. Therefore, we take the position that this context dependence can be productive, and we develop a model of interdisciplinary reconciliation in which disciplinary ideas can both be used productively in their native disciplinary contexts and connected coherently to ideas from other disciplines.

Chapter 6 addresses the ontological metaphors (metaphors about what kind of thing energy is) used by students and instructors in thinking about energy, specifically in situations involving negative energy. The resources framework is employed in multiple places in our analysis there. First of all, as we explain there, we apply the dynamic ontologies perspective (Gupta, Hammer, & Redish, 2010), in which an individual can productively place the same physics entity into multiple ontological categories depending on context, in contrast to the static ontologies model (Chi & Slotta, 1993), in which each physics entity correctly belongs in a single ontological category. This theoretical divide parallels the resources vs. misconceptions divide. The static ontologies model is a specific case of the misconceptions model, and attributes misconceptions to placing a concept in the incorrect ontological category. The prescribed instructional solution is to get students to replace their incorrect ontology with the correct ontology. The dynamic ontologies model sees ontologies as a type of conceptual resources that can be activated differentially depending on context, and so the instructional goal is for students to develop the ability to activate these ontological resources in a pattern that supports productive reasoning.

We also apply the resources framework at a smaller grain size when we look at the affordances of the various ontological metaphors for energy. We evaluate the utility of these metaphors based on the other conceptual resources that they activate for students. For example, activating the “energy is a substance” metaphor can lead to activating the conservation resource, while activating the “energy is a vertical location” metaphor can lead to activating conceptual resources associated with an intuitive sense of gravitational potential energy (e.g. it takes energy to go up a hill). As we discuss further in chapter 6, thinking about energy as negative can activate multiple resources associated with negative energy, which may be productive or unproductive in a particular situation. Finally, we suggest that the coherent coordination of ontologies, and the decision about which ontological metaphor to employ in a given situation, requires the development of epistemological resources for thinking about ontologies.

Chapter 3: Context and Methodology

3.1 The NEXUS/Physics course context

The research in this dissertation was carried out during the first two years of NEXUS/Physics (Redish et al., 2014), a reformed introductory physics course for life sciences majors at the University of Maryland. NEXUS/Physics was developed as part of the larger NEXUS (**N**ational **Ex**periment in **U**ndergraduate **S**cience Education) project (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013), a multi-campus collaboration to produce curricular materials that promote scientific reasoning and competency building across the undergraduate life sciences curriculum.

The students in the NEXUS/Physics course are a mix of sophomores, juniors, and seniors. In contrast to the typical physics course taken by life science majors (which is often taken close to the end of the undergraduate years and has little or no explicit integration with the other sciences), or a “physics first” approach (which have some advantages in positioning physics as a foundation for other sciences, but is not practical with the number of introductory biology and chemistry courses that our students have to take), NEXUS/Physics requires a year of biology and a semester of chemistry as prerequisites. This allows us to build on students’ biology and chemistry backgrounds, and to assume familiarity with biological and chemical phenomena that can be modeled in the course with physics principles. Another positive result is that the students may have stronger biology backgrounds than some of the instructional team (who come from physics backgrounds), which enables the students to be positioned as experts in certain areas and leads to an environment in which students are valuable sources of knowledge. It is hoped that the students who complete NEXUS/Physics will find physics useful in their subsequent upper-level biology courses, but we have yet to do any systematic work to investigate possible longitudinal impacts.

The structure of the course has multiple components: online reading assignments, 2.5 hours/week of lecture, 1 hour/week of recitation, 2 hours/week of laboratory, weekly homework assignments, weekly quizzes, and exams. We make reference to most of these components in the chapters that follow. Many of the elements were built on the framework of a previous reform of the algebra-based physics course (Redish & Hammer, 2009), which reformed the pedagogy but largely maintained the traditional physics content and did not incorporate an emphasis on interdisciplinary coherence.

The lectures are “flipped” in the sense that new material is introduced in online reading assignments produced for this course that students are expected to do before each lecture, and a significant fraction of the class time is used for active learning tasks including clicker questions (Crouch, Watkins, Fagen, & Mazur, 2007; Mazur, 1996) and whiteboard activities in student groups.

The recitation sections are used for group problem-solving activities, in which students work on in groups of four. Each section is facilitated by a TA and one or more undergraduate Learning Assistants (Otero, Pollock, & Finkelstein, 2010), who circulate among the student groups. The style of these activities, developed for the NEXUS/Physics course, is based on the tutorial model developed at the University of Washington (McDermott, Shaffer, & the Physics Education Group at the University of Washington, 2002), in which student groups work from a series of questions intended to guide discussion, but the format varies from problems with unambiguous correct answers to more open-ended discussion. Recitations are the component of the course in which the biology connections are often the most explicit, and in which students are most encouraged to bring in their outside biology knowledge.

The structure of the laboratories is based on the Scientific Community Labs (Kung, 2005), in which students design their own experiments to answer a question, but the laboratory activities themselves have been redesigned with a focus on physics that is relevant to biological systems and the use of modern analysis tools (K. Moore, Giannini, & Losert, 2014).

The NEXUS/Physics course represents the result of interdisciplinary conversations (Redish & Cooke, 2013) among physicists, biologists, biophysicists, chemists, and education researchers. The curriculum is designed to focus on the physics topics that are most relevant to biology, and thereby to facilitate interdisciplinary connections. The result is that, relative to the traditional introductory physics course, there is increased attention to energy, thermodynamics (including entropy (Geller et al., 2014) and free energy), statistical mechanics (including random motion and diffusion), fluids, and atomic and molecular examples. The treatment of energy, with chemical energy as an integral component of the curriculum, is the subject of chapter 4. To make room for these additional topics within a two-semester course, other topics have been reduced or eliminated, including projectile motion, momentum, rotational motion, and magnetism.

The data for this dissertation were collected in 2011–13, during the first two years of the NEXUS/Physics course. These first two years were pilot classes, with 20 to 30 students enrolled each semester. In the first year there was one section of the class; in the second year there were two sections, each taught by a different faculty member. The student population was a subset of the biology (and related fields) major population, and about half of the students were declared as pre-medical or other pre-health. Beginning in fall 2013, the NEXUS/Physics course is required for all biology majors, and has been scaled up to multiple 120-student lecture sections. The data from the scaled-up class are beyond the scope of this dissertation, but constitute a future opportunity to extend our qualitative case-study research with large-N data. The curriculum and the precise structure of the course continue to evolve in response to the experiences of the instructors and the students, so the descriptions of the course in this dissertation represent a snapshot in time.

Our research focus is on understanding interdisciplinary reasoning about energy. Therefore, we believe that the NEXUS/Physics course is the most appropriate context in which to conduct this research because this instructional context provides a space for both students and instructors to reason about energy across the disciplines.

Even though some of our findings (about interdisciplinary reconciliation and about ontological metaphors for energy) have consequences beyond the introductory physics for the life sciences (IPLS) context, and indeed beyond interdisciplinary contexts in general, we argue that NEXUS/Physics is still an appropriate context to begin the exploration of those more general issues. The interdisciplinary environment can lead to an explicit recognition of multiple disciplinary epistemologies and assumptions, and of the need for bridging these disciplinary perspectives. This need to bridge multiple locally coherent perspectives often exists within a single discipline as well, but is less visible and more difficult to identify when the multiple perspectives are not backed up by disciplinary labels and canonical sets of disciplinary content. Therefore, it makes sense to begin this research in a context where the bridging is more explicit, so that it can later be extended into other contexts where the bridging is more subtle.

3.2 Why a qualitative case-study methodology?

We use a qualitative case-study methodology for the components of this dissertation, focusing on a small number of individual students, both in interview settings and in the classroom context. The use of this methodology is determined by the nature of the questions we ask and the claims we seek to make. We are interested in the fine-grained dynamics of individual students' (Gupta & Elby, 2011; Lising & Elby, 2005) or student groups' reasoning (Scherr & Hammer, 2009; Scherr et al., 2013), and these dynamics cannot be captured by large-population quantitative measures. The motivation to examine fine-grained dynamics is based in part in our theoretical commitments (discussed in chapter 2), which do not assume stability of students' ideas, and so our models need to account for context dependence and variability.

Even if it is possible to examine a more limited set of phenomena at the population level (and we take initial steps in this direction with the exam essay question rubric discussed in chapters 4 and 5), the development and analysis of large-N assessments relies on the results of qualitative research that ascertains the appropriate issues to study, and this dissertation primarily represents that first phase. None of the existing concept inventories on energy (Miller, Streveler, Yang, & Santiago Román, 2011; Prince, Vigeant, & Nottis, 2012; Singh & Rosengrant, 2003; Swackhamer & Hestenes, 2005; Thornton & Sokoloff, 1998, n.d.; Yeo & Zadnik, 2001) is appropriate for our instructional goals. They all assess conceptual understanding of mechanical energy and/or heat and temperature, and do not substantially address issues, such as chemical energy, at the intersection of physics, biology, and chemistry. It is possible that a conceptual survey for this content could be developed, and we hope that this work will inform that development if and when it happens, but this qualitative work is a necessary precursor.

Furthermore, even if a quantitative instrument were already available, there are limits to the questions that it would help us answer. A quantitative pre/post comparison with an appropriate assessment targeted to our curricular goals could provide insight into how well the curriculum is succeeding, and could help classify students' conceptual reasoning. However, population-level results would not help us define what the interdisciplinary learning goals are in the first place, and would not get at the complexities of students' reasoning as they respond differentially to different disciplinary contexts or as they access different ontological metaphors for energy.

We use the qualitative case-study data for purposes that require examining individual students and student groups. The specific methodologies used in each study are discussed in detail in the respective chapters, but we summarize here why the focus on individual student data is most appropriate in each case.

Chapter 4 is primarily about a curriculum and is not an empirical study, but the use of student data there is intended to illustrate what the intended outcomes of the curriculum look like on an individual student level.

In chapter 5, we focus primarily on data from two students and how they attempt to reconcile ideas about chemical bond energy that they associate with different disciplines. By looking at these students' reconciliation processes and the class context, we can assemble a model for what interdisciplinary reconciliation means. We also present additional data from other students to show other examples of reconciliation with varying levels of success. Because our analysis focuses on the ways that students shift among different disciplinary resources as appropriate to the context, the dynamics of individual students' reasoning in the moment are the appropriate unit of analysis.

In chapter 6, we examine the utterances of students and instructors for ontological metaphors at a very fine-grained level, looking for evidence of blending the substance and location ontologies for energy. Because it relies on unconscious use of metaphors, this sort of evidence is fleeting and difficult to probe for deliberately. Despite the existence of many hours of video data, the data we use to support our claims represent a relatively small subset, because the richest data come from instances when the phenomena of interest emerged spontaneously without explicit interventions to draw students' attention to ontological metaphors.

While small-N qualitative data are the most appropriate data for the claims we are making, we have to be careful to make only the claims justified by this type of data, and not to use the data to generalize more broadly about all students. In keeping with this warning, our theoretical claims are central, and the purpose of the empirical data is to drive the theoretical claims forward and to provide real-world instantiation of the theory. We can use our case-study data to show that students **can** reconcile ideas about chemical bonding from physics and biology while keeping the disciplinary contexts distinct, and **can** blend the substance and location ontologies to reason productively about chemical bonds and negative energy. We can also use these data to develop models of different ways that this interdisciplinary reconciliation or ontological blending can be successful or unsuccessful. We can use this information to inform our emerging instructional goals. But we cannot draw general conclusions about what all students, or the typical student, will do.

3.3 Data collection and analysis

During the first two years of the NEXUS/Physics course, a five-person research team (Ben Geller, Julia Gouvea, Vashti Sawtelle, Chandra Turpen, and the author) collected extensive data on the course. This large corpus of data is used both in this dissertation and in a number of other papers (Geller et al., 2014; Geller, Dreyfus, Gouvea, et al., 2013; Geller, Dreyfus, Sawtelle, et al., 2013; Gouvea et al., 2013; Sawtelle, Sikorski, Turpen, & Redish, 2013), and we expect that it can be a source of further research well into the future.

We videotaped each session of the class, with one camera in the back of the room capturing the professor and a view of the entire class, and two cameras and microphones recording student groups' discussions. Each day, one or more members of the research team sat in the class and took real-time notes on what was happening during each time segment. This created a record of the video data to enable later access to specific moments (which would otherwise be next to impossible, with hundreds of hours of video), and enabled the research team to follow up with students during interviews about what was happening in class in a specific way, and to identify emergent research themes. We also recorded two student groups per section for each recitation activity. (During the first year, this meant two groups total, and during the second year, when there were two sections of the course, we recorded four groups.) During the second year of the course, when the new laboratories were introduced, we recorded a sample of student groups doing the labs. We scanned all exams, quizzes, and homework assignments that students handed in on paper, and maintained electronic copies of homework that students submitted online as well as responses to the online reading assignments.

The research team conducted 48 semi-structured interviews with 23 students during the two pilot years. The entire class was invited to sign up to participate in interviews, and most of the students who opted in ended up participating in interviews (and in most cases, those who did not participate had scheduling conflicts). The nature of the interviews varied. Some interviews were topical, with questions designed to probe student reasoning about specific content areas, before and after those topics were addressed in class. Other interviews were longitudinal case studies, with the same student interviewed at multiple points during the semester, answering both general questions about the class and questions about specific tasks. In both types of interviews, students were sometimes asked to talk through how they had solved a particular homework, recitation, exam, or quiz problem. One interview (Anita, in chapter 6) included stimulated recall (Lyle, 2003; Sawtelle, Brewe, Goertzen, & Kramer, 2012), in which Anita was shown a video of herself from class and was asked to explain what she had been thinking. (Anita had already been participating in case-study interviews, and the author was interested in following up with her about a particular episode in class.)

The five-member research team met regularly to analyze videos as a group. Individual members selected episodes based on their own research interests, and the group analyzed the episodes, usually spending significant time on relatively short clips. The video analysis included both inductive (looking at a piece of video to identify relevant research themes) and deductive (starting with a theory and set of research questions and applying them to the video) approaches (Derry et al., 2010) at various times.

The exam essay question data in chapter 4, and all the data in chapter 5 (interviews, quizzes, exams, and classroom video), came from the first year of the NEXUS/Physics course (spring 2012). The classroom and interview data in chapter 4, and all the data in chapter 6 (interview, recitation, and classroom video), came from the second year of the course (2012-13).

Chapter 4: Chemical energy in an introductory physics course for the life sciences[2]

4.1 Introduction

Energy is a central concept in all of the scientific disciplines, universally useful for describing and explaining a range of phenomena (Quinn et al., 2012). However, energetic frameworks are applied variably across the science disciplines, each utilizing aspects of the concept most relevant to the phenomena of interest: falling objects, chemical reactions, or ecosystem dynamics. In science instruction, different disciplines tend to present these frameworks in isolation (Cooper & Klymkowsky, 2013), which can make the teaching and learning of energy concepts appear fragmented rather than unified (Dreyfus et al., 2012).

To build connections among physics, biology, and chemistry (Meredith & Redish, 2013), an interdisciplinary understanding of energy is necessary. The discipline-based education research literatures on energy largely fail to talk to each other across disciplinary boundaries (Dreyfus, Geller, Meltzer, et al., under review), but these conversations become more essential as the sciences themselves become more interdisciplinary. Cooper and Klymkowsky (2013) write "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." This chapter presents one such approach to substantive curricular change that begins to make these explicit connections across disciplines.

In traditional introductory physics courses, the focus of the "energy" portion of the course is on mechanical energy to the exclusion of other energy. If it is mentioned at all, "chemical energy" is treated as a black box, a "miscellaneous" form of energy whose role is to account for discrepancies when mechanical energy is not conserved, but it is not explored at a deeper level. Introductory physics for the life sciences (IPLS) courses are aimed at providing the tools to explain the physics principles that underlie complex phenomena in biology and chemistry. For students in the life sciences, there is a need to understand how chemical energy transformations at the molecular level connect with organism and ecosystem level flows. Because of the central role of chemical energy in biology, building a coherent framework of energy that connects physics to biology requires integrating ideas about chemical

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[2] A version of this chapter has been published in the *American Journal of Physics* (Dreyfus, Gouvea, et al., 2014).

energy with the more canonical treatments of energy from physics. We conceptualize the concept of chemical energy as existing throughout the course as a recurring conceptual "thread." We describe our intentions in developing the chemical energy thread and present some examples of curriculum materials and student data that illustrate our approach.

In Section 4.2, we provide background on the interdisciplinary course context in which our course materials were developed. In Section 4.3, we explain the role of the chemical energy "thread" in the course and how it interacts with other threads. Section 4.4 discusses the conceptual connections within the thread, and the motivations behind them. Section 4.5 describes some examples of the tasks that comprise the thread. In Section 4.6, we present some qualitative data illustrating preliminary student outcomes. While the course materials included in this chapter are a limited selection, a larger selection is included in the Appendix, and the full set of materials is freely available at the thread website ("NEXUS/Physics").

4.2 Background to the course

The IPLS course (Redish et al., 2014) in which our materials are developed and used is part of the National Experiment in Undergraduate Science Education (NEXUS) (Thompson et al., 2013), and represents the results of an interdisciplinary collaboration (Redish & Cooke, 2013) bringing together perspectives from physics, biology, biophysics, chemistry, and education research. The NEXUS/Physics course is a two-semester course intended for life sciences majors. The course is structured as 150 minutes per week of lecture (using Peer Instruction and other interactive techniques) along with 1 hour of recitation (used for group problem solving) and 2 hours of lab (K. Moore et al., 2014). While calculus is a formal prerequisite (as it is required anyway for biology majors at Maryland), the use of calculus in the chemical energy thread is primarily conceptual, and these materials could be used in an algebra-based course with little modification. The prerequisites also include a year of biology and a semester of chemistry, and therefore we design the curriculum in a way that builds on students' prior experiences in biology and chemistry coursework (Redish et al., 2014).

This thread relies on highly simplified models of atomic and molecular interactions, in order to enable qualitative sense-making around much more complex processes and reactions that are discussed in the biology and chemistry courses. Therefore, there is no requirement for the physics instructor teaching this course to have sophisticated knowledge of chemistry or biology.

Our data from the course show that our students come in with ideas about energy from biology and chemistry. As an illustrative example, at the beginning of the energy unit in fall 2012, the professor asked the class "You talk about energy in your biology classes and your chemistry classes. So I want to know what you think energy is." Two students, Irene and Violet (all names are pseudonyms), simultaneously responded "ATP!" and then one cheered "Yeah!" They were talking about adenosine triphosphate, the molecule that Irene referred to in an interview as "the biological form of energy." The professor probed further about what they meant when they said that energy is ATP, and Sonia responded, “In biology it's the chemical bonds which hold energy.” Sonia was using language about chemical bonds in a manner that is common in introductory biology courses (Novick, 1976), and which has been noted as problematic in the biology and chemistry education literature (Boo, 1998; Gayford, 1986; Storey, 1992; Teichert & Stacy, 2002b). This brief episode makes it clear that teaching about energy to this student population, in a way that builds from their existing knowledge, must engage with chemical bonds and ATP, which are salient in these students’ incoming understandings of energy.

4.3 Structure of the chemical energy thread

The NEXUS/Physics (Redish et al., 2014) course has multiple components: a wikibook with readings, interactive lectures with clicker questions, weekly group problem-solving sessions, homework problems, and labs. Chemical energy is included in the course as an instructional “thread” that runs through and links many aspects of the course and is not merely an independent unit. The goal of the chemical energy thread is to help students make stronger connections, both within physics and between physics and other disciplines. Conceptualizing the curriculum as threadlike has helped us support this goal in several ways.

Threads represent a structuring of the curriculum that builds expertise over time. Students need to encounter ideas and reasoning strategies many times in different contexts in order to develop expertise (Bruner, 1960). They don’t have to “get it” in an all-or-nothing way the first time they see something. For example, we do not expect students to fully understand potential energy when they first grapple with it in the context of near-earth gravitational free-fall scenarios. Nor do we expect students to fully understand it when they engage in reasoning about charged particles interacting. We want to give students multiple opportunities to reason about potential energy across a variety of situations and support them in coordinating these understandings. A thread is more than just a conceptual sequence. It also must include opportunities for students to examine the links between concepts.

For this reason some of the problems and activities that comprise the thread are designed to ask students to explicitly consider the ways in which different ideas about energy are connected. Students are given multiple opportunities to connect chemical energy to other relevant descriptions of energy within physics (e.g. kinetic and potential energy; the relationship between energy and force), and to make connections among multiple ways of describing and representing energy (e.g. a focus on transfer of energy in and out of a system vs. a focus on energy transformations within a system vs. a focus on the energy of an object as a function of position), facilitating links to ideas about energy from chemistry and biology. Accomplishing all of this would be more difficult if chemical energy were simply added to the existing course as an isolated module.

Our curricular thread on chemical energy comprises a series of instructional tasks including clicker questions, homework problems, recitation group problem-solving activities, quiz and exam questions designed to help students develop coherence along the particular dimension of topical understanding of chemical energy. However, the tasks that constitute this thread are also components of other threads designed, for example, to develop productive stances on the nature of knowledge in the sciences, or competence in interpreting and creating representations. Figure 4.1 shows a few examples of how these threads intersect.

Our intention is for the multiple interacting threads to simultaneously work to develop different dimensions of scientific expertise. Attempting to influence one dimension of expertise may be facilitated by attention to other dimensions of scientific expertise. For example, developing a robust conceptual framework for ideas about energy can be facilitated by simultaneously developing the ability to understand and translate among different representational forms (graphical, diagrammatic, symbolic, and verbal). A third interacting component of expertise involves asking students to consider and evaluate differences in the ways physics, chemistry, and biology use models of energy in order to make sense of different kinds of phenomena. This epistemological thread engages students in evaluating what they know and determining the realm of applicability for particular models of energy.

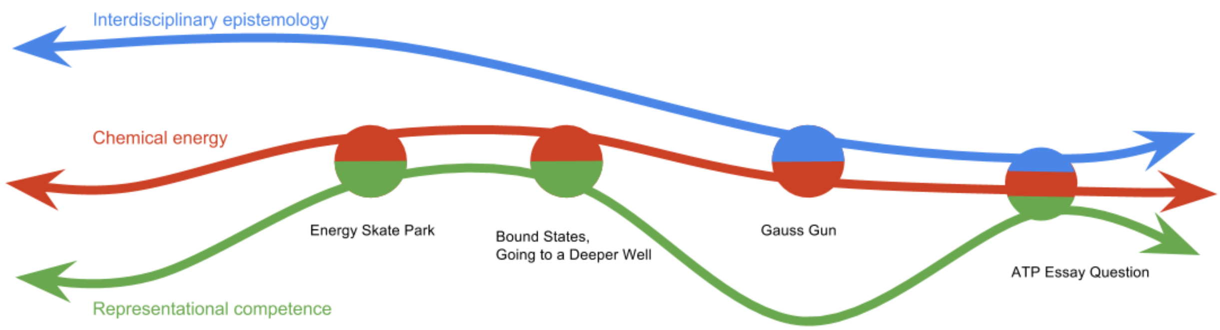

Figure 4.1. A small section of the chemical energy thread and how it intersects with two other threads we are developing in the NEXUS/Physics course. The circles represent a few example tasks (homework, exam problems, etc.) that were designed to help students build up the ideas and connections in this thread. Split circles represent tasks that develop competence across multiple threads.

4.4 Content of the chemical energy thread

Building across these curricular tasks to develop an understanding of chemical energy requires combining concepts traditionally covered in introductory physics courses with ideas that are more commonly taught in chemistry and biology. The nodes in Figure 4.2 represent the way we have built up the conceptual components of this thread in our course. Our thread asks students to explicitly reflect on the links between the canonical physics contexts and other disciplinary contexts. These important links are represented as the arrows in Figure 4.2. The chemical energy thread comprises a particular sequence of tasks that aims to support students in understanding and coordinating among these concepts. Our purpose in this chapter is not to prescribe this particular sequence of tasks, but to articulate connections that should be scaffolded in developing a more complete model of chemical energy that will serve students across disciplinary contexts (Table 4.1). In this section we identify the connections that the chemical energy thread is intended to highlight, and in section 4.5 we discuss how the specific example tasks support building these connections. The claims in these section about the ideas that students bring in are based on the intuitions that the NEXUS/Physics research team has built up based on their teaching and research experiences in this context.

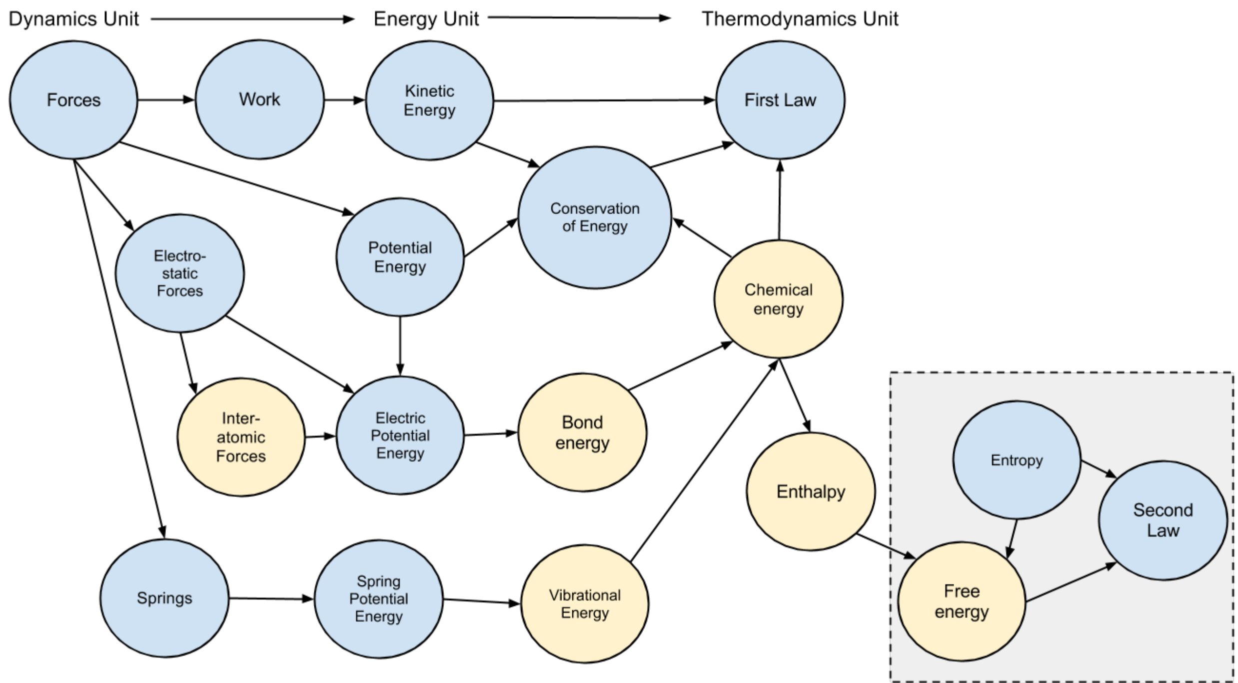

Figure 4.2. The nodes represent conceptual components of the chemical energy thread, and the arrows represent links between these concepts. The darker-colored nodes (color online) represent content typically included in introductory physics. The lighter nodes represent content added in service of building up an integrated treatment of chemical energy (see also Table 4.1). (The gray box at the lower right shows connections to a separate thread on entropy and randomness.)

Thread Component	Motivation for inclusion
Introduce electrostatic forces in force unit	Emphasizes the forces that are most relevant at cellular and molecular scales, and sets the stage for electric potential energy
Include electric potential energy as one type of potential energy	Emphasizes that this energy is not fundamentally different from mechanical energy
Build up a model for chemical bonds using Lennard-Jones (L-J) potential	Models "chemical energy" associated with the formation and breaking of bonds in terms of potential and kinetic energies
Apply L-J model to chemical reactions	Links changes in chemical energy to changes in potential and kinetic energy at the molecular scale
Include chemical energy as component of internal energy	Connects First Law to chemical reactions

Table 4.1. Selected content from the chemical energy thread, with the motivations for including it.

The thread starts at the very beginning of the course with the kinematics unit, which includes examples of motion at the microscopic scale. Students analyze the motion of cell-sized objects in homework and in lab (K. Moore et al., 2014), which establishes the idea that the models of mechanics in the course are valid at scales from macroscopic to molecular (Chabay & Sherwood, 2007). The specifics of these tasks are less relevant here than the general stage-setting for applying common reasoning across physical scales. The course moves some of the electrostatics material (traditionally covered in the second semester) to the first semester, to emphasize forces that are most relevant at cellular and molecular scales. The force unit introduces Coulomb's Law and electrostatic forces, including a careful treatment of charge polarization, showing how a neutral object can experience a net electric force as a result of the separation of charges, a crucial element in understanding atomic and molecular interactions.

When potential energy is introduced, electric potential energy is included as an integral part of the energy unit of the course rather than in a separate electricity unit, emphasizing that this energy is not fundamentally different from mechanical energy. This sets the stage for a model of chemical bond energy. To build up a mostly classical model for chemical bonds, we follow existing curricula (Cooper & Klymkowsky, n.d.; Knight, 2008; Potter et al., 2014) in using the Lennard-Jones potential (Jones, 1924) (Figure 4.3a), which approximates the potential energy associated with the interaction of two atoms with an attractive term proportional to $1/r^6$ and a repulsive term proportional to $1/r^{12}$, where r is the distance between the nuclei.

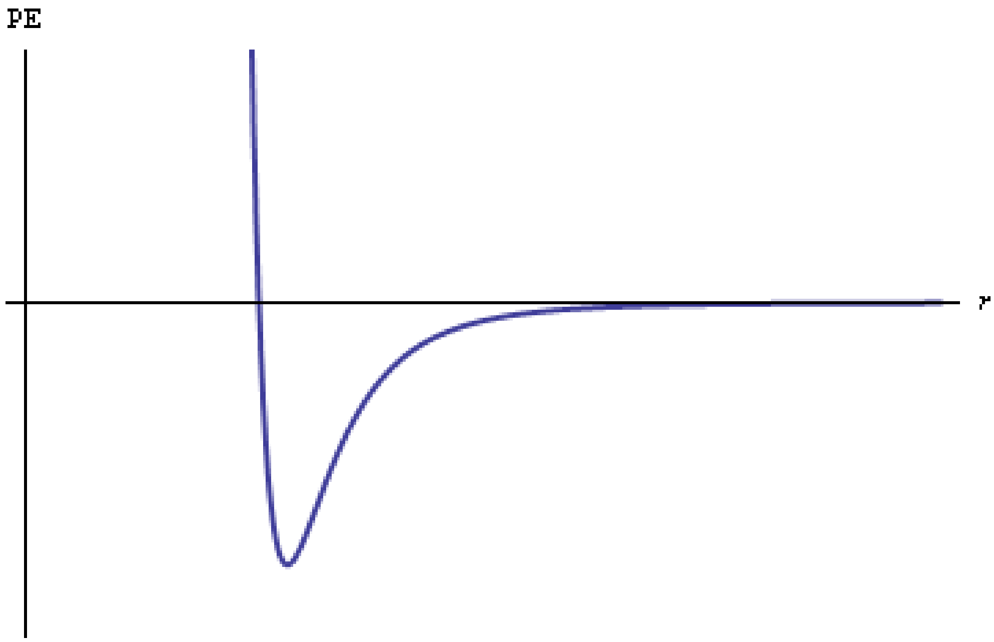

Figure 4.3a. The Lennard-Jones potential, approximating the potential energy associated with the interaction of two atoms, as a function of the distance (*r*) between the atoms.

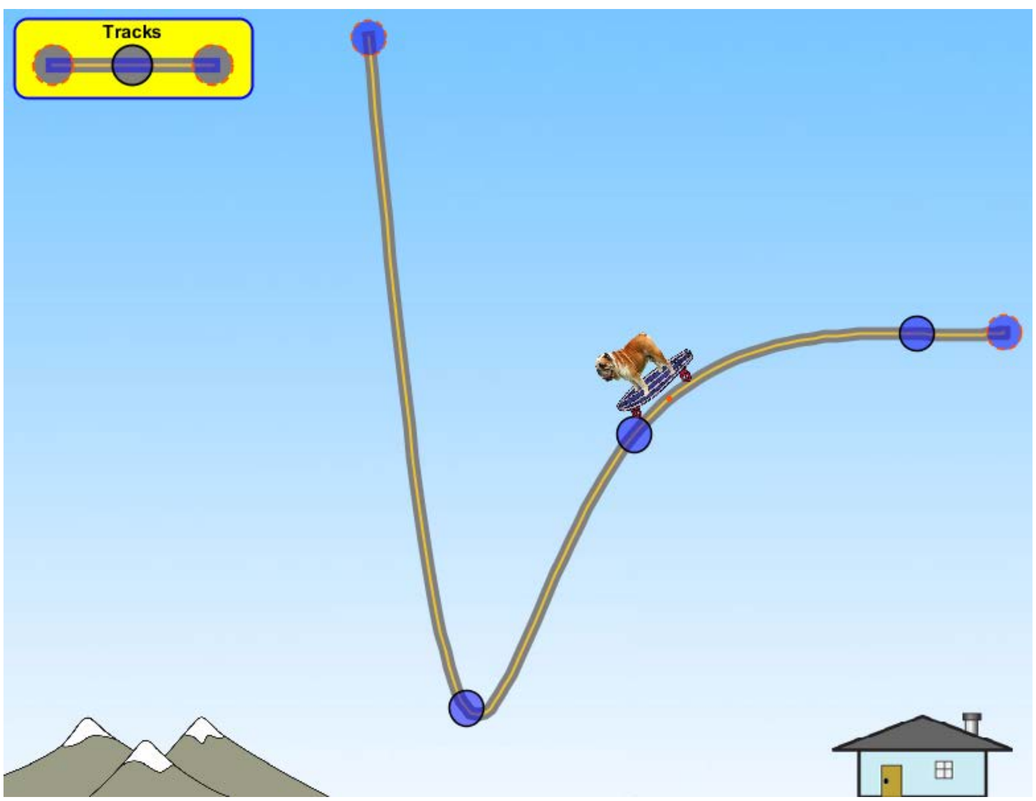

Figure 4.3b. The *Energy Skate Park* simulation("Energy Skate Park," 2006) is a jumping-off point for analogies between chemical bonds and students' experiences with gravitational potential energy.

The shape of the Lennard-Jones potential is justified to the students using primarily qualitative arguments. Building on traditional demonstrations like sticking a charged balloon to the wall ("Balloons and Static Electricity," 2006), a charged particle can induce a dipole in a neutral atom. This leads to a force of attraction between the charged particle and the atom, though this attraction falls off more quickly with distance than the Coulomb force between two charges. Furthermore, a dipole (even a temporary dipole created by random fluctuations of the electron distribution in a neutral atom) can induce a dipole in another neutral atom and attract it, but this attraction is even weaker than the charge-dipole interaction. This is the Van der Waals force that our students have encountered in their chemistry classes. Without getting into the math, the $1/r^6$ dependence is plausible, since the Van der Waals attraction is many degrees weaker than the $1/r$ Coulomb potential except at very short distances. At large r, this attractive potential gives the expected qualitative result: the potential is relatively flat, indicating no significant interaction between neutral atoms at large separation. However, as r decreases, this term suggests that the attraction continues to get stronger. Our students are familiar from chemistry with the Pauli exclusion principle, which prevents atoms from getting too close. Qualitatively, we expect this repulsion to be very strong at short distances (sufficient to overcome the $1/r^6$ attractive term) and to fall off quickly at longer distances (so that the attraction dominates), so a $1/r^{12}$ dependence is plausible.

Putting the two terms together, there is a minimum in the potential energy function that corresponds to an equilibrium (about which the system can oscillate if kinetic energy is present). The r at which this minimum occurs is the bond length for two bound atoms, and this bound state corresponds to a chemical bond. The relevant qualitative features of a chemical bond on which we want to focus emerge from this model: the bound state has a stable equilibrium[3] with negative potential energy (relative to the zero of potential energy set when the atoms are separated by a large distance), so an input of energy is needed to separate two bound atoms (*i.e.*, to break the bond). Conversely, when two unbound atoms become bound, their potential energy decreases, and so conservation of energy dictates an increase of energy elsewhere ("energy is released"). Thus the "chemical energy" associated with the formation and breaking of bonds is explicitly modeled in terms of potential and kinetic energies. (For an example, see the "Bound states" task in Section 4.5.)

The next step is to build up multiple bond-breaking and bond-formation events into a chemical reaction. A reaction is either exothermic or endothermic, depending on the overall sign after adding together all the energy changes associated with bond breaking and bond formation. These overall changes in "chemical energy"

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[3] We recognize that the words "stable" and "equilibrium" have different common meanings in physics and in chemistry. Here we use these words with their usual physics meanings: an equilibrium point is a point at which the net force is zero, and a stable equilibrium means that if the system is perturbed a small distance from the equilibrium, it will return to the equilibrium.

in chemical reactions are now linked to kinetic and potential energy at the molecular scale.

The thread extends later into the course as well, beyond the "energy" section. When the course moves into the laws of thermodynamics, it continues to include chemical energy among the types of energy that are considered. In a traditional introductory physics course, the First Law of Thermodynamics is used primarily in the context of ideal gases, and therefore the "internal energy" term is equated with thermal energy, energy that depends only on the temperature of the gas. In the NEXUS/Physics course, internal energy includes not only thermal energy but also chemical energy. Thus, changes in the internal energy of a system may be manifested not only as temperature changes but also as chemical reactions. This is more consistent with the First Law as it is taught in biology courses, where chemical reactions are central and temperature changes are not. This means that the total internal energy is undefined, since the total chemical energy (which includes potential energy) is undefined, and the zero of potential energy can be placed anywhere. This is a departure from the approach in a traditional introductory course, which may include an explicit expression for internal energy. However, this is not a problem, because only **changes** in internal energy have physical significance.

The chemical energy thread continues with links to enthalpy and free energy. Those topics are beyond the scope of this dissertation, but are discussed elsewhere (Geller et al., 2014). Those links are essential to enabling students to make full connections to ideas about energy from their biology and chemistry courses, since biology and chemistry courses typically formulate reaction energies in terms of enthalpy (along with using Gibbs free energy to determine the spontaneity of reactions).

4.5 Example tasks for students

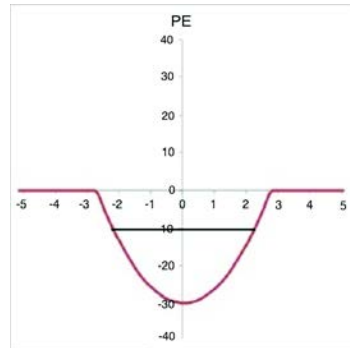
In this section, we present illustrative examples of the kinds of tasks and problems that comprise the thread and support our intention to make connections among concepts and among disciplines. These tasks are available on the NEXUS/Physics course website ("NEXUS/Physics").

Prior to any explicit instruction on chemical energy, but after the Work-Energy Theorem has been introduced, the students do a group problem-solving task on protein folding. This task has been discussed at length, including the process of revising it to support interdisciplinary learning, in Gouvea et al. (2013). The protein folding task asks students to reason about the relationship between force, work, and energy in the context of an optical tweezer, an experimental apparatus that uses laser beams to trap and manipulate individual protein molecules. (The data obtained from this manipulation reveals information about the structure of the protein and the force required to unfold it.) It also asks students to connect these relationships from physics with the biological question of what it means for a protein to be in a stable state, which is relevant because a protein's biological function is often related to its shape when it is in its most stable configuration. Students come in with the idea from biology that a molecule at a lower energy state is "more stable," and so they are asked to coordinate this framework of energy as stability with the force/work/energy framework from mechanics. This task is intended to prime students for the rest of the chemical energy thread by having them think about force and energy on the scale of biomolecules, using the same physical principles that apply at the macroscopic scale. Question prompts include comparing the naturally occurring version of a protein with a version that has undergone a small mutation, both in terms of stability and in terms of the work it would take to unfold them. Students are asked to use two different representations: a graph of energy vs. reaction coordinate[4] that represents the "energy landscape" of a folding protein, and a graph of force vs. extension that shows data from when a protein is stretched with an optical tweezer (Cecconi, 2005).

Another group problem-solving task involves the *Energy Skate Park* simulation ("Energy Skate Park," 2006) from the PhET project. This simulation has a skateboarder on an editable track, and uses multiple representations to keep track of kinetic, (gravitational) potential, thermal, and total energy. The shape of the track itself doubles as a potential energy vs. position graph, since gravitational potential energy is proportional to height. The NEXUS/Physics course then uses *Energy Skate Park* as the foundation for a series of homework problems on chemical energy. An excerpt from one of these problems is given in Figure 4.4. In these problems, students use their physical intuitions about the relationships between energy, force, and motion, based on experience with gravity, and they extend this reasoning to cases where the relevant potential energy is not gravitational, but where a vertical location metaphor (e.g. "potential well" (Brookes & Etkina, 2007)) is still useful. Thus the skateboarder becomes an analogy for two interacting atoms, and the track is an analogy for their potential energy function (as in Figures 4.3a and 4.3b).

[4] The reaction coordinate is a loosely defined coordinate that corresponds to the progress of a chemical reaction, and may or may not correspond to a single physical parameter. Though this description is not explicitly discussed in our physics course, students are familiar with the technique from use in their chemistry and biology classes.

B. Now suppose that the skateboarder starts *inside the well* at a zero velocity -- say at point x = -2.5 units with a total energy as shown by the heavy solid line.

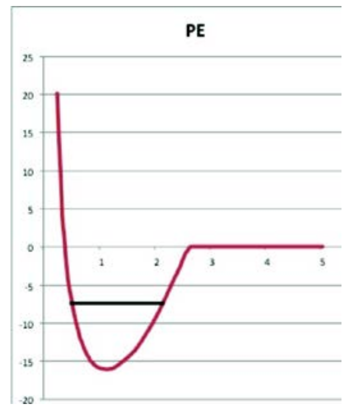


Describe the motion of the skateboarder and how her potential and kinetic energies change as she moves through the well.

C. Her total energy is shown is the figure as -10 units. How can this be? Is it reasonable for the total mechanical energy to be negative?

D. If she wants to climb out of the well and be at 0 kinetic energy at the point x = 3 units, how much energy would she need to gain?

E. The skateboarder is actually just an analogy for the cases we are interested in, which are interacting atoms. The potential energy of the interaction looks like the figure at the right.



If the atoms have the energy of -7.5 units as shown by the solid line in the figure, describe their motion and how their potential and kinetic energies change as they move in the well.

F. If the atoms have an energy of -7.5 units as shown by the solid line in the figure, would you have to put energy in to separate the atoms or by separating them would you gain energy? How much? Explain why you think so.

Figure 4.4. Excerpts from the "Bound states" problem.

Later in the series, the students are given a potential with multiple wells of different depths. This is used as an analogy for chemical reactions that involve going from one bound state to another, and helps students reconcile how it is that breaking a bond (such as in ATP (Dreyfus, Geller, Sawtelle, et al., 2013)) can lead to the release of energy (because other stronger bonds are formed). Unlike the single well (as in Figure 4.3a), where the horizontal axis represents the distance between two atoms, the multiple-well situation is more complicated, in that the independent variable on the graph does not correspond to a single physical parameter. While we recognize the limitations of this toy model (and encourage the students to explore these limitations), we believe that using this representation (among others) can be pedagogically useful because it provides a mechanical analogy that can help students bridge to their macroscopic intuitions, and because it can bridge to the reaction coordinate diagrams that students are familiar with from chemistry and biology courses (in which the reaction coordinate is also not rigorously defined in terms of physical parameters).

A demonstration and homework problem on the Gauss gun (Kagan, 2004) make a similar point, asking students to reason about the Gauss gun as an analogy for an exothermic chemical reaction. The Gauss gun is a device consisting of a magnet and several metal spheres (Figure 4.5). The sphere closest to the magnet (sphere 1 in the figure) is most strongly bound. When a new sphere (sphere 0 in the figure) is released from rest and sticks to the magnet, sphere 3 is ejected at high speed, so that the final kinetic energy of the system is greater than the initial kinetic energy. Students are asked, “Where did the energy come from?” This is a mechanical analog of an exothermic chemical reaction, in which a stronger bond is formed and a weaker bond is broken, resulting in the release of energy.

Figure 4.5. The Gauss gun.

Several tasks then ask students to apply physical models for chemical energy to biological scenarios. In a homework problem, students are given data (Kodama & Woledge, 1979) for the energy changes in the various steps of the ATP hydrolysis reaction catalyzed by myosin, which takes place in muscle cells to make muscle contraction possible. Students are asked to use what they know about chemical bonding from both the physics class and their prior chemistry experiences to explain the sign of the energy change at each step. Specifically, if the energy change is negative (corresponding to energy leaving the system), then bonds are being formed; if it is positive, bonds are being broken.

A second group problem-solving task, on temperature regulation, has the students reason about the signs of heat, work, and the change in internal energy of a system using the First Law of Thermodynamics, in a style similar to traditional physics problems (G. S. M. Moore, 1993). However, the situations are biological, dealing with temperature regulation in mammals and other animals and leveraging students’ knowledge of physiology (e.g. the difference between mammals, which maintain a constant internal temperature, and animals whose body temperatures depend on external conditions; the effects of metabolic reactions on thermal and chemical energy), and students are explicitly asked to separately analyze changes in thermal energy and chemical energy. For example, a warm-blooded animal’s body temperature is generally higher than the temperature of the surrounding air, so there is heat conduction from the body to the outside, resulting in a decrease in the body’s total energy. To maintain a constant temperature, the body’s thermal energy must be constant, so there must be a conversion of chemical energy to thermal energy.

A third group problem-solving task deals with kinesin, a motor protein that “walks” (Yildiz, 2004) along microtubules to transport cargo within cells. This active transport (which requires an energy input, in contrast to passive transport, which results from diffusion alone) is powered by the hydrolysis of ATP. Students are given a "frame-by-frame" description of the kinesin's motion (Figure 4.6), and in their groups produce energy bar charts (Van Heuvelen & Zou, 2001) that account for the bonding between the kinesin and the microtubule, between the kinesin and the ATP, and the ATP hydrolysis reaction itself. This leads up to having the students discuss what it means to say that a cell "uses ATP to fuel molecular movement," producing more detailed explanations for phenomena they have encountered in biology on a more general level. The task is formulated in an open-ended way, and therefore there are many possible approaches the students can take in creating their energy bar charts (and we have in fact observed multiple approaches). They are explicitly asked to define their system, and are not told which objects to include as part of the system. They are also not told which energies to include in their bar charts, so student groups have taken different approaches about whether to use "chemical energy" or "potential energy," and whether to consider the chemical/potential energy "of" particular molecules, or of interactions among them. However, we would expect a correct solution to be internally consistent, with the total energy conserved in each frame (depending on the choice of system), and the correct signs for the changes in energy associated with the formation and breaking of bonds. In many solution pathways, this means keeping track of energy conservation involving positive and negative energies (see Chapter 6).

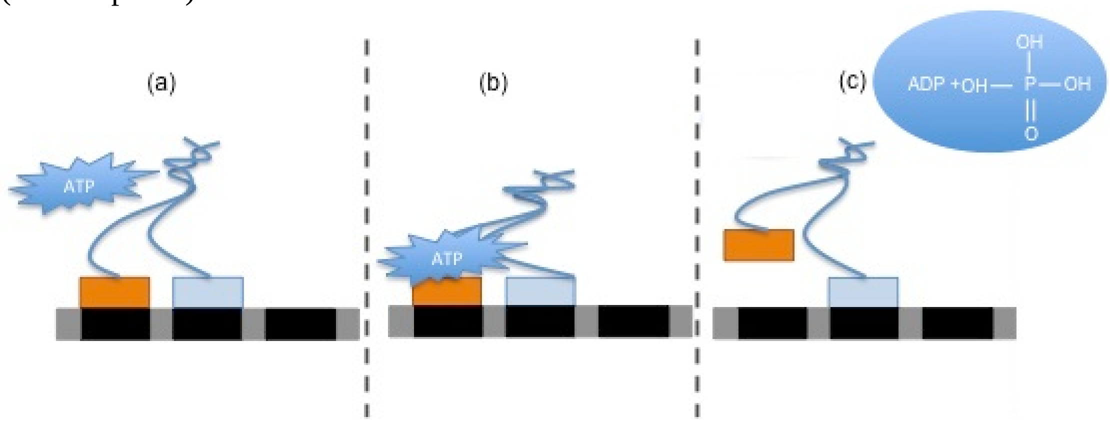
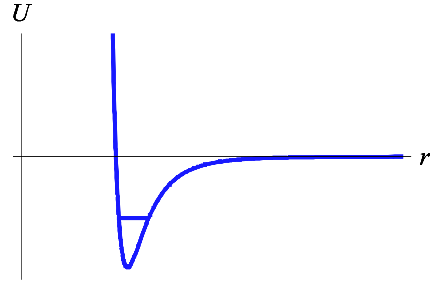


Figure 4.6. The picture given to students in the kinesin task, along with a description of what is happening in each frame: In frame (a) both motor heads are bound to the microtubule. Then, in frame (b) an ATP molecule binds with one of the heads of the kinesin, causing strain on the motor protein (like a compressed spring). In frame (c) ATP is hydrolyzed and the protein moves in the forward direction.

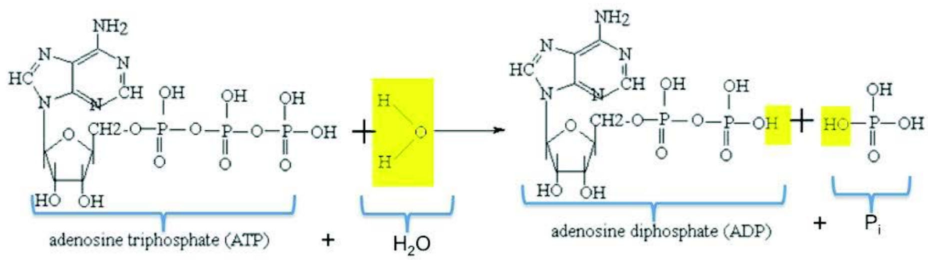
A culminating task for the chemical energy thread is an essay question (originally given on a midterm exam), shown in Figure 4.7, that has students engage in interdisciplinary reconciliation around ATP hydrolysis (see Chapter 5). As shown in the figure, the students are given two different representations: a potential energy diagram for a general chemical bond, and a chemical equation for this reaction showing the structure of each molecule. Students are asked to reconcile the idea (useful in biology) that the O-P bond in ATP is called a "high-energy bond" (Lipmann, 1941) because a large amount of energy is released when ATP is hydrolyzed, with the idea (based on modeling chemical bonds with potential energy) that an input of energy is required to break the bond. Successful reconciliation involves recognizing that both ideas are correct: the reaction includes both the breaking and formation of bonds, and the net effect is the release of energy.

Two students discussing the process of ATP hydrolysis (ATP + H_2O → ADP + P_i) make the following comments:

Justin: "The O-P bond in ATP is called a 'high -energy bond' because the energy *released* when ATP is hydrolyzed is large. That released energy can be used to do useful things in the body that require energy, like making a muscle contract."



Kim: "I thought chemical bonds like the O-P bond in ATP could be modeled by a potential energy curve like this (she draws the picture at the right), where *r* is the distance between the O and the P. If that's the case, then breaking the O-P bond in ATP would require me to *input* energy. I might not have to input *much* energy to break it, if that O-P happens to be a weak bond, but shouldn't I have to input at least *some* energy?"



How did Kim infer from the PE graph that breaking the O-P bond requires an input of energy? Who's right? Or can you reconcile their statements? (The chemical structures of this process are given if you find that useful.)

Note: This is an essay question. Your answer will be judged not solely on its correctness, but for its depth, coherence, and clarity.

Figure 4.7. The interdisciplinary reconciliation essay question on ATP hydrolysis.

4.6 Examples of student outcomes

Our evaluation of students developing ideas about chemical energy has been primarily qualitative and includes analyses of written student work, whole-class and small-group video data, and 48 semi-structured interviews with 23 students during the first two years of the NEXUS/Physics course. By focusing on qualitative descriptions of student thinking across the chemical energy thread we have begun to develop a picture of what an integrated understanding of chemical energy looks like. In this section we present examples of student data that illustrate the interdisciplinary reasoning about energy that is the intended outcome of the chemical energy thread. We then demonstrate how this descriptive data can be used to develop quantitative course-level assessments.

When the ATP essay question shown in Figure 4.7 was given on an exam, students were asked to assess and reconcile the statements of “Justin,” who says that energy is released when ATP is hydrolyzed, and “Kim,” who claims based on a potential energy diagram that energy is required to break the phosphate bond in ATP. We present two exemplary student responses, from Jasper and Anya.

> ***Jasper:*** *Kim is right in her fundamental idea that it takes an input of energy to break bonds, even a weak one like the O-P bond. She inferred this from her PE graph based on the fact that if molecules are in the PE well, they are in a bound state. To escape the well, they must be “pushed out”, which would require an input of energy. Justin is still right in the fact that hydrolyzing ATP releases energy, but this is because there are bonds being formed as well in the reaction, which acts to release energy. This is seen a bit easier in the molecule diagrams. What helps me think about PE problems is thinking of the gravitational analogy. A ball at the edge of a table may have lots of PE, and if rolled off onto the ground, the PE converts to KE. The same is true for a bond. When a bond is formed, it is in a negative PE well, and KE must be released. To get bond out of the negative well back to 0, and positive input of KE is necessary to do so, hence why breaking bonds require and [sic] input of energy. The two's ideas can be reconciled, as they are both right.*

> ***Anya:*** *Kim inferred this based on the fact that the bound state (the lowest point on the PE graph) has the point of lowest PE, and moving toward a non-bound state (aka, larger r/eventually breaking the O-P bond) corresponds to an increase in energy. This energy increase must come from somewhere according to the conservation of energy (can’t just make it from nothing). In the end, both statements are correct – while it does require energy to sever the O-P bond, it is not much, and the ensuing energetic stability of the resulting ADP and P_i molecules is much greater than when they were bound, resulting in a large energy release, much greater than the energy input required to break the bond.*

Both Jasper and Anya are able to employ “physics” concepts about energy (e.g. conservation of energy, kinetic and potential energy) to explain this biochemical scenario. Jasper’s response shows an ability to link bond energy and gravitational energy through an analogy as well as a coordinated use of representations (the PE graph and the molecule diagrams) to support his reasoning. Anya’s response shows an ability to draw attention to the principle of conservation of energy in her discussion of bond breaking. While not all of the students made these connections (and while Anya’s response is not complete since it is not clear from this response that new bonds are formed), these are the kinds of connections among energy concepts, representational forms, and epistemological frameworks that represent a desired outcome.

Analysis of interview data revealed students making connections beyond the specific prompts in the course. Betsy began an interview by spontaneously explaining an instance in which she saw the NEXUS/Physics course as helping her resolve an apparent contradiction between what she was learning in her chemistry and biology classes. In chemistry, she had learned that "it takes energy to break bonds, and when you form bonds you get energy back." Meanwhile, in her biology class, she had studied the difference between anabolic reactions, in which smaller molecules are built up into larger molecules, and catabolic reactions, in which larger molecules are broken down. Specifically, she had learned that catabolic reactions are needed in order to make anabolic reactions go, yet based on chemistry, she would have expected that anabolic reactions would release energy and catabolic reactions would require energy. Betsy began the process of reconciling these two principles with the specific case of ATP hydrolysis, which was supported by the chemical energy thread in the NEXUS/Physics course. As far as we can tell, Betsy made these connections on her own, since there was no explicit discussion of catabolic and anabolic reactions in the NEXUS/Physics course. While Betsy had not fully resolved this issue at the time of this interview, she demonstrated that she had identified a set of seemingly contradictory ideas and had begun to seek reconciliation. In addition to the specific content, Betsy experienced the physics class as creating opportunities to seek interdisciplinary coherence. She introduced the explanation of the chemical bond conundrum by reporting that "it feels like all of my classes are contradicting each other all the time, but the physics is kind of helping me pull it all together and understand that different things apply at different times." Betsy's ability to recognize variation in disciplinary frameworks and her desire to seek conceptual consistency across these frameworks illustrates the kind of outcome we hope this thread-based integrated curriculum can support.

We have drawn on this qualitative data to develop a strategy for evaluating students' evolving understanding of chemical energy at the class level. For a subset of tasks in the chemical energy thread we have developed formal rubrics ("NEXUS/Physics"). This evaluation strategy gives us feedback about how students overall are understanding and linking the components of the thread. For example, the rubric we developed for analyzing the ATP essay question in Figure 4.7 assesses student responses along six dimensions: defining the reaction, energy in breaking/forming bonds, balance of energy, spontaneously generating connections between the potential energy curve and a physical picture, spontaneously generating connections to other concepts outside the problem, and coherence. (This goes beyond the standards by which students were graded on the actual exam; the "spontaneous" connections are those that were not explicitly required by the problem statement.) In the first year of the NEXUS/Physics course, we found that around half of the students (N=19) met or exceeded expectations on this question. While this result suggests that there is still work to be done, we cite this result to show that the examples from the interviews above are not outliers.

Our students have shown us that they are both interested and capable of coordinating ideas across their science courses, but it remains an ongoing challenge to design assessments that can both measure this development and productively inform new iterations of our curriculum. Our current approach, which is still in development, is to conduct a coordinated analysis of student progress across multiple rubrics and along multiple threads. This approach reflects our understanding of scientific expertise as involving integration and fluency of knowledge, not merely presence or absence of specific concepts.

4.7 Conclusion

A focus on chemical energy in the introductory physics course can help serve the needs of life sciences students by serving as a bridge between physics approaches to energy and the energy contexts most relevant to biology (Potter et al., 2014). Unpacking chemical bond energy provides students with opportunities to reconcile seemingly contradictory ideas from the disciplines, and with a more coherent view of energy at different scales. Conceptualizing chemical energy as a thread means building up students' understanding of chemical energy by making explicit the links between different disciplinary ideas throughout the course.

The description of the chemical energy thread presented in this chapter is a starting point, and will continue to be revised iteratively based on how students engage with it. Future directions include integrating chemical energy with our ongoing work on entropy and free energy (Geller et al., 2014), building conceptual links to coupled biochemical reactions (in which energy is not simply "released," but makes another reaction possible), and connecting chemical energy to optics through modeling photosynthesis. We invite the reader not to see our materials as a finished product that can be used anywhere, but to continue adapting them for new student populations and instructional settings. We also welcome the development of additional materials in this area and of other threads that support interdisciplinary connections.

Chapter 5: A vision of interdisciplinary education: Students' reasoning about "high-energy bonds" and ATP[5]

5.1 Introduction

It is well-established that physics students can compartmentalize their understanding of the physical world (Lising & Elby, 2005; McDermott, 1991). The ideas about physical phenomena and about the nature of knowledge that students bring to bear in physics class settings are often different from the ideas that the same students bring to bear in "everyday" settings. Previous work has focused on developing opportunities for students to reconcile canonical physics concepts with their everyday experience (Elby, Scherr, Goertzen, & Conlin, 2008; Elby, 2001; Goldberg, Otero, & Robinson, 2010; Redish & Hammer, 2009). This does not mean learning to discount everyday intuitions, but rather, learning to build coherent connections between the "physics" domain and the "everyday" domain.

In this chapter, we turn our attention to a related yet distinct type of compartmentalization, into compartments that have been referred to as "disciplinary silos." Students take physics, biology, and chemistry courses, but rarely have opportunities to bring the ideas of each discipline into direct contact, and disciplinary experts often have limited contact with the other science disciplines. In an age of increased emphasis on interdisciplinary connections among the sciences, we seek to understand the reconciliation of ideas from different science disciplines, with an eye toward clarifying the goals of interdisciplinary science education. While related, interdisciplinary reconciliation is qualitatively different from the reconciliation between "physics" and "everyday" ideas, because it involves reconciling multiple sets of "expert" scientific ideas.

Our investigation has a theoretical goal and draws heavily on case-study data of an introductory physics course for undergraduate life science students, in the context of reasoning about energy and ATP (adenosine triphosphate). We pursue one central research question: How can we characterize interdisciplinary reconciliation in the context of existing frameworks for reconciliation of ideas? In this chapter, we explore two specific subquestions in the context of learning about chemical energy as a way to address the more general question: 1) What does successful interdisciplinary reconciliation look like in the context of energy? 2) When biology students encounter

[5] A version of this chapter has been accepted for publication (Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014).

ATP in a physics course, how do they negotiate disciplinary differences between biology and physics in this instructional context?

5.2 Theoretical framework

The guiding theoretical perspective for our analysis is the resources framework, which we now briefly overview. The consensus view in physics education research is constructivism: the idea that learners are not blank slates, but all new knowledge is built on existing knowledge (Driver et al., 1994). In order to understand how students learn, PER across the board strongly focuses on understanding the ideas they enter with. However, there are two major ways of characterizing these ideas. Under the misconceptions model (McCloskey, 1983; Posner et al., 1982; Vosniadou, 1994), students possess strongly held, stable, and unitary beliefs, which differ from expert conceptions. That is, if a student holds a misconception, we would expect that student to exhibit that misconception consistently across multiple contexts. In this model, the goal of instruction is to confront and replace misconceptions, or the underlying presuppositions.

In contrast, the resources framework (Hammer, 1996, 2000; Redish, 2003), which has its roots in the knowledge-in-pieces framework (diSessa, 1993; Smith et al., 1994), sees students' knowledge as more dynamic, with the possibility of being fragmented. Rather than a single coherent theory that differs from expert understanding, students possess a variety of resources that can be activated differentially in different contexts. For example, a student might apply the conception that "motion is caused by a force" in the context of reasoning about pushing an object across the floor, but not in the context of an object moving freely in space (Hammer, 1996). Students might access particular resources in ways that lead them to incorrect conclusions. The goal of instruction is not to eliminate these resources, which have both productive and unproductive applications, but to help students use their resources productively and refine their sense of when those resources are most useful. Resources can be both conceptual (resources for understanding the content of physical phenomena) and epistemological (Hammer & Elby, 2002; Hammer, 1994a, 2000) (beliefs about the nature of knowledge and learning). The resources framework also allows for the possibility of stable patterns of resource activation. However, in this framework, stability is one possible description of a set of resources rather than the default assumption, and multiple stabilities can coexist in a student's cognitive ecology and be activated at different times (Gupta & Elby, 2011).

The resources framework is based in physics education research but is spreading into other science disciplines (Danielak, 2014; Maskiewicz & Lineback, 2013), and we extend it here to interdisciplinary reasoning. Our analysis involves concepts (in this case, chemical bond energy) that students encounter in multiple contexts associated with multiple disciplines, and so we draw on research on the context dependence of student reasoning. Our objective is to understand how ideas from different disciplines are coordinated in a new context, a phenomenon that falls under the broad class of phenomena often described as "transfer." Hammer et al. (2005) argue that transfer phenomena can be understood as the context-dependent activation of cognitive resources. What looks like transferring ideas from one context to another is the activation of similar sets of resources through the generation of similar framings, across different contexts.

Framing is a concept from sociolinguistics (Goffman, 1997; Tannen & Wallat, 1993; Tannen, 1993) that describes an individual's understanding in a given situation of "What's going on here?" Specifically, *epistemological* framing is an individual's expectations or interpretation of "What kinds of knowledge or approaches are appropriate here?"(Kuo, 2013) Hammer et al. use the concept of framing to refer to the activation of locally coherent sets of resources. Student reasoning influences and is influenced by the context (Finkelstein, 2005); this leads to an understanding of framing as emergent from the interaction between the student and the context. Along these lines, Engle et al. define framing as "the metacommunicative act of characterizing what is happening in a given context and how different people are participating in it" (Engle, Lam, Meyer, & Nix, 2012). This definition of framing gives emphasis to both the physical setting and the social interactions that build up reality in a moment.

As we discuss in greater depth in section 5.6, the framework of context-dependent activation of resources is relevant to understanding reasoning across disciplines because disciplinary contexts influence (and are influenced by) the conceptual and epistemological resources that students draw on. Furthermore, in addition to the disciplinary context, there are aspects of the instructional context (messages from the instructor that suggest how following messages should be framed, and other elements of the "hidden curriculum") that may contribute to students' framing. Therefore, we also highlight those aspects in our data in order to present a more complete picture of the context in which the reasoning takes place.

5.3 Setting for the case study

5.3.1 Energy is an ideal context for studying interdisciplinary reconciliation

There have been many calls for interdisciplinary science education in recent history (AAAS, 2011; AAMC/HHMI, 2009; National Research Council, 2003) and attempts at integrating the disciplines in the last several decades (Stevens, Wineburg, Herrenkohl, & Bell, 2005). However, bringing the disciplines together in a meaningful way is not a trivial process (Gouvea et al., 2013; Redish & Cooke, 2013). At the University of Maryland, we have been involved in creating an Introductory Physics for the Life Sciences course (Redish et al., 2014), which at its core attempts to aid students in building connections across the disciplines of physics and biology. One area of focus for creating these connections resides in topical areas that span the disciplines such as energy, thermodynamics, and light (i.e., constructs that are central to each discipline independently). However, we start from the perspective that overlapping content topics alone are insufficient for making meaningful interdisciplinary connections. It is also necessary to attend to how knowledge is structured in and among the disciplines by instructors and by students. A number of other physics courses (Christensen et al., 2013; Meredith & Bolker, 2012; O'Shea et al., 2013; Potter et al., n.d.) and curricula (Benedek & Villars, 2000; Nelson, 2007) have incorporated strong connections to biology content, and research on some of these courses has evaluated students' conceptual understanding and attitudes (often through assessments developed for conventional physics courses). Still, research that explicitly addresses how students connect ideas from multiple disciplines in those courses is limited. This chapter is situated in the context of energy, one of these cross-disciplinary topics, and uses this context for a broader examination of interdisciplinary science education and the reconciliation of concepts between physics and biology.

Understanding the role of energy in biological processes requires understanding ATP (adenosine triphosphate), a molecule that biology students know as "the energy currency of the cell." However, the treatment of energy in the traditional introductory physics curriculum (including the courses taken by most biology students) focuses on mechanical energy, and does not make a clear connection to the energy transformations most relevant to biological systems at the cellular and molecular levels (Cooper & Klymkowsky, 2013). Developing a physics curriculum for life sciences students that is intended to build cross-disciplinary coherence requires engaging with energy concepts as they are understood and leveraged in biology and chemistry. A major component of supporting this cross-disciplinary coherence requires attending to the energy associated with chemical bonds, and especially ATP.

ATP is produced during cellular respiration and photosynthesis. In the ATP hydrolysis reaction, which takes place in aqueous solution within the cell, a bond is broken to remove the terminal phosphate group from the ATP molecule, leaving ADP (adenosine diphosphate). Breaking this bond (like any bond) requires an input of energy. Both products (ADP and inorganic phosphate) form other bonds as a result of their interaction with water. These new stronger bonds are associated with a greater total bond energy (equivalently, they are represented by a deeper potential well), resulting in a net release of energy.[6] This energy is used to power various cellular processes, by coupling ATP hydrolysis to other reactions. As a shorthand, many biology texts and instructors refer to the phosphate bond in ATP as a "high-energy bond" (Lipmann, 1941). This terminology may be understood to imply that there is energy "in" this bond that is released when the bond is broken, even though the breaking of this bond itself is not what releases the energy.

Students' conceptual difficulties with ATP and bond energy are well-documented in the biology and chemistry education literatures. In biology, Novick

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[6] In this case, the qualitative description at this level of detail would be identical if we were discussing Gibbs free energy (which is often the more relevant quantity in many biochemical contexts) rather than energy. For the remainder of the chapter, we talk only about energy and not free energy, because the distinction is immaterial here (though we are aware that this distinction is significant in other situations).

and Gayford both write about student confusion about "energy stored in bonds" and the misleading terminology of "high-energy bonds," particularly in regard to ATP (Gayford, 1986; Novick, 1976). Storey identifies biology textbooks as perpetuating this confusion.(Storey, 1992) In chemistry, Boo documents students' "alternative conception" that bond making requires energy input (even in non-biological reactions), as an alternative to the idea that bond making releases energy (Boo, 1998). Galley also documents "exothermic bond breaking" (Galley, 2004) in student reasoning, as we will discuss at greater length in sections 5.4 and 5.5. Teichert and Stacy show that students (when discussing ATP) can simultaneously express the idea that energy is released when a bond is formed, and that energy is released when a bond is broken (Teichert & Stacy, 2002b).

This literature does not clearly establish what good interdisciplinary reasoning should look like in the context of ATP. In our approach, our understanding of "good" reasoning emerged from a careful examination and articulation of exemplary student reasoning. This chapter further explores conceptions about ATP, presents evidence of students' reconciliation of these ideas in a manner that may be unique to interdisciplinary concepts, and explores how an interdisciplinary instructional context supported this reconciliation.

5.3.2 Course setting

The context of this study was the pilot year of a new introductory physics course[7] for undergraduate biology students (Redish et al., 2014). The course is part of the National Experiment in Undergraduate Science Education (NEXUS), a project that is producing competency-based curricula for life science students (Thompson et al., 2013). It represents the results of an interdisciplinary collaboration (Redish & Cooke, 2013) bringing together perspectives from physics, biology, biophysics, chemistry, and education research. This course is unusual in that biology and chemistry are required as prerequisites, and students are therefore expected and encouraged to draw on their knowledge from these other disciplines. The course spent substantially more time on energy and thermodynamics than the typical introductory physics course, because these topics are also central to chemistry and biology, and they provide opportunities to build coherence across the disciplines.

Structurally, the course ran as a typical introductory physics course at the university level with three 50-minute lectures per week, accompanied by one 2-hour lab section and one 50-minute discussion section. In contrast to a typical introductory physics course, the class meetings and discussion sections involved extensive group problem-solving tasks that were designed to build connections between chemistry, biology, and physics. In this first pilot year, approximately 20 students were enrolled

[7] See http://nexusphysics.umd.edu

in the course each semester. One of the authors (Redish) served as the instructor in the course.

Our previous research (Dreyfus et al., 2012) shows that some students perceive a disconnect between energy in physics and energy in biology, even to the point of thinking about energy in the two disciplines as two separate entities (related only by analogy). One student we interviewed saw this distinction as corresponding to spatial scale, with physics primarily concerned with mechanical (kinetic and potential) energy at the macroscopic scale, and biology concerned with chemical energy at the cellular and molecular scales. Other recent work (Donovan et al., 2013; Hartley et al., 2012) has contrasted the curricular treatment of energy in physics and biology using data from curricula and faculty.

To bridge these various uses of energy, our course included an extensive thread on chemical bond energy (Dreyfus, Gouvea, et al., 2014), emphasizing that the energy associated with chemical bonds is potential and kinetic energy and is included in the overall conservation of energy. The course readings developed the Lennard-Jones potential (mostly qualitatively) as a way to describe the chemical bond in terms of electric potential energy and other constructs "native" to physics courses. Students were given a series of tasks in which they were to model chemical bonds with potential energy graphs (displaying potential energy as a function of position), and to use reasoning similar to conventional conservation-of-mechanical-energy problems. (One homework problem paired a question about interacting atoms with a question about a skateboarder skating down a hill.) Students also used computer simulations from the CLUE curriculum (Cooper & Klymkowsky, n.d.) that illustrated the formation of bonds using graphical representations of potential energy. This model of chemical bonds was intended to provide a stronger conceptual foundation for the principle that breaking a bond requires an energy input (and conversely, that forming a bond releases energy), by recognizing that climbing out of a potential well requires an input of energy and represents the breaking of a bond.

5.4 Case study methodology

5.4.1 Data collection

This chapter explores a case of interdisciplinary reconciliation in the context of ATP and bond energy through four complementary data sources: 1) quantitative student response data from a multiple-choice quiz question to obtain a baseline for the class as a whole, 2) qualitative data from interviews to examine individual students' thinking in greater detail, 3) in-class video data from the day the quiz was handed back to illustrate how students and the instructor framed the task in that moment, and 4) a capstone essay exam question to investigate whether and how students reconciled conflicting ideas at the end of the relevant unit of the course. We examine these data sources to develop an initial model of interdisciplinary reconciliation in the context of ATP and chemical bond energy.

5.4.1.1 Multiple-choice quiz question

Early in the second semester of the course, the students were given a quiz that included two multiple-choice questions taken directly from Galley (2004) (given originally at the beginning of a physical chemistry course), for comparison. Here, we look at one of those questions:

> *An O-P bond in ATP is referred to as a "high-energy phosphate bond" because:*
> *A. The bond is a particularly stable bond.*
> *B. The bond is a relatively weak bond.*
> *C. Breaking the bond releases a significant quantity of energy.*
> *D. A relatively small quantity of energy is required to break the bond.*

Students were instructed to "put the letters corresponding to all the correct answers;" this is slightly different from Galley's students, who were given a limited set of choices ("A and C," "B and C," etc.). In both our class and Galley's class, choices B and D were considered the correct responses. The intent was that students would recognize that energy is released because a relatively strong bond was formed after a relatively weak bond was broken, and that no energy is released by the actual breaking of the bond.[8]

5.4.1.2 Interviews

Over the course of the year, the research team conducted 22 semi-structured interviews with 11 students on various topics related to the course. Some of these interviews were designed as case studies to investigate how students were developing over time in this interdisciplinary course. In an effort to build in opportunities for triangulation with other data sources, these interviews often focused on specific course tasks. Semi-structured protocols were developed primarily to guide the interviewer in a set of research directions. A standard initial prompt was, "Have you encountered biology so far in this course? In what contexts?" These prompts were followed with probing questions to fully explore the contexts the students raised. At times this meant that a single prompt from the protocol guided the entire 45-minute interview.

[8] The question, as written, may have been misleading because it asks about the reason for using a term that is itself misleading. Because of this, we believe the question is more valuable as a formative task than as an assessment, and we focus on how the students subsequently thought through the question in interviews.

Two of these interviews, with two pre-medical students, included explicit discussion of the ATP quiz question. The first interview, with Gregor[9], took place immediately after class on the day that the quizzes were handed back, and was the first interview completed with Gregor as a case study. Gregor brought up the quiz spontaneously in response to the prompt described above about the role of biology in the physics course. The second interview, with Wylie, was three weeks later and was the second interview completed with him as a case study. In the second interview, more time was spent on specific task prompts from the course. By this time, the research team had seen the Gregor interview data, so the interviewer prompted Wylie more directly about the ATP quiz question to explore how his reasoning compared with Gregor's.

5.4.1.3 In-class video

We collected video of the course for the entire year (embedding microphones with two student groups seated in different parts of the classroom). To investigate what contextual features of the pedagogy and curriculum may have supported reconciliation, we examine the directions that the instructor gave the students regarding the quiz, and a conversation between Gregor and the instructor immediately after the quizzes were handed back. These video data provide additional information on the larger classroom context, enabling us to understand the features of the course context that may have supported interdisciplinary reconciliation.

5.4.1.4 Exam essay question

Using the data from the quiz, interviews, and in-class video we developed an essay question that would capture the ideas that students were grappling with in considering the energy in ATP. At the end of the thermodynamics unit, we administered this capstone essay question on a midterm exam, with the goal of observing and assessing interdisciplinary reconciliation for the whole class. All exams were scanned before returning them to the students, which allowed for further analysis after the exams had been handed back. A rubric for evaluating the ideas in the essay question was developed by a team of chemistry, biology, and physics faculty. We discussed this rubric in chapter 4, but do not use it in detail in this chapter, because the rubric was developed for multiple purposes and does not necessarily assess the construct of interdisciplinary reconciliation as formulated in this chapter. The details of the question are discussed in section 5.5.3.

[9] All names are pseudonyms.

5.4.2 Data analysis

We use the four data sources in an interweaving way to address our research question. The fairly sparse multiple-choice data provided a baseline for how students were understanding ATP and chemical energy. Results from the multiple choice question and the in-class discussion inspired deeper probing of individual student reasoning through interviews. Finally, we spiraled back to understanding interdisciplinary reconciliation at the class level by developing an essay question reflecting the views from the individual student interviews. Similarly, understanding how we can characterize interdisciplinary reconciliation as building upon existing theoretical frameworks leverages the details of reasoning in both the student interviews and the all-class essay question.

There are at least three classification schemes that we could use to identify ideas articulated by students as belonging to particular disciplines: 1) the past experiences the students would have encountered (e.g. analysis of textbooks in the disciplines), 2) the ways in which disciplinary experts discuss the concepts, or 3) how the students themselves describe ideas as belonging to the disciplines. In this chapter, we have chosen to examine interdisciplinary reasoning through the ways students label the disciplines, and as such we primarily focus on the ideas the students describe as belonging to physics and/or biology. We have shared these characterizations with our disciplinary colleagues to confirm that these descriptions are consonant with their disciplinary experiences, though we do not explicitly leverage these data in this work.

A significant component of our methodology in analyzing the data involves attending to the reasoning of individual students. In some sense, this limits the claims that we can make from the data, relative to a larger-N study. We do not claim that the results are directly generalizable to the entire student population. However, the case-study methodology allows us to examine the dynamics of individual student reasoning in ways that would be difficult to measure over a larger population (Lising & Elby, 2005). In analyzing student reasoning, we focus our attention on the disciplinary context-dependence of students' modeling choices and on the process of reconciling apparently contradictory models associated with different disciplines. This focus is consistent with our theoretical framework, which allows for context-dependent reasoning and multiple stabilities.

5.5 Results

5.5.1 Quiz and classroom data

On the quiz question, 79% of the class (N=19) selected choice C (breaking the bond releases energy) as a correct answer. Our sample size is too small to draw meaningful conclusions from a more detailed breakdown of the quantitative data. We bring up this result primarily to show that our class is broadly comparable to Galley's results, in which 87% of students chose C. Galley interprets this as a sign of a "persistent misconception." However, the qualitative data (which are the focus of the rest of this chapter) illustrate that the picture is more complex than the multiple choice results suggest, and that our students are engaged in reconciling multiple disciplinary ideas, whether on their own or supported by the instructional context.

For initial insight into how disciplinary ideas are being reconciled, we look at interactions between the instructor and the students during lecture. This was the first quiz of the semester, and while the majority of the students in the class had been in the first semester of the sequence (with the same instructor), several students (including Gregor and Wylie) were new to the course. The instructor made a number of verbal moves, while administering the quiz and while returning it to the students, to attempt to reframe the meaning of the "quiz" activity in this course. While the quiz was being administered, the instructor emphasized the multiple-choice multiple-response format, in which students have to consider each answer option separately (rather than jumping to one "correct" choice as on a conventional multiple-choice question). During the quiz, he explicitly articulated his motivation for giving the students this format of questions: "Anything that I can do to undermine test-taking strategies and replace them with actual thinking, I will do." This may serve to communicate to students that they are intended to be thinking deeply about these questions, and not expected to quickly recognize or simply recall the correct answer.

On the next class day, when the quizzes were handed back, the instructor began the discussion by noting how little the quiz grades would contribute to the overall course grade. He explained that "the point of the quizzes is to get you thinking about stuff, and not so much as an evaluation of how well you are doing." Here, he attempted to renegotiate the purpose of "quizzes" with the students, explicitly describing them as formative opportunities to practice thinking, rather than as summative measures of students' success.

The instructor introduced the notion that students can argue for why a given quiz answer (which was marked wrong) should be considered correct. Discussing the ATP question, he said:

> *"The results were that 79% of you picked C. That's almost everybody. If you want to make an argument why you think that should be accepted as an answer, I will accept this as a regrade and consider, so write on the back, say 'I gave C, and I think you want to accept this as an answer because of the following.' If you have a good thoughtful answer … I don't know how they use the language in chemistry and biology, and if they talk about it as C, you might have a case. If you feel you can make it, do so. I'm perfectly willing to listen. That, by the way, is standard procedure here."*

Here we see the instructor describing how "correctness" on quizzes will be established. He shares with students that he will carefully listen to the arguments that they make and consider regrades based on the substance and sensibility of those arguments. Additionally, he acknowledges that different scientific disciplines may talk about these ideas in different ways. He also elaborates on these descriptions, and situates them as “normal” for the rest of the course.

There was some amount of discussion that followed the instructor’s description of the quiz results. Gregor directly engaged with the instructor about how he (and, he surmises, other students in the class) were interpreting the question. This demonstrates that at least one student orients to the framing of the quizzes as an opportunity to engage about plausible interpretations of the quiz questions and answers:

> **Gregor:** *So I, and I guess probably a lot of other people, were assuming something that was not part of the question, that was that a more stable bond would be formed by breaking that bond, which would—*
> **Instructor:** *Write it up! Write it up. That's your justification.*
> **Gregor:** *But that's the assumption that we were making, is that—*
> **Instructor:** *Yes. And because you had some context that you were assuming that wasn't specified, or because this always happens in some context when you use it in biology that I wouldn't know about it, let me know. And if you convince me, I'll give you a point.*

In this interaction the instructor opens the door to other answers as being reasonable within a particular set of assumptions and says that, with those assumptions articulated and explained, he could be convinced that it is a reasonable answer. We also see here that the instructor points to the fact that these unarticulated assumptions may be associated with commonly used disciplinary contexts in biology. This conversation may have contributed to what Gregor then says in his interview.

5.5.2 Interview data

Gregor had selected B, C, and D as correct answers on the quiz, and lost a point for choice C. In the interview immediately following the class when the quizzes were returned, Gregor responds to a prompt about the role of biology in the physics course, and explains why he chose C (though this retrospective explanation may or may not represent exactly what he was thinking while taking the quiz):

> *“I put that when the bond's broken that's energy releasing. Even though I know, if I really think about it, that obviously that's not an energy-releasing mechanism. Because like, you can't break a bond and release energy, like you always need to put energy in, even if it's like a really small amount of energy to break a bond. Yeah, but like. I guess that's the difference between like how a biologist is trained to think, in like a larger context and how physicists just focus on sort of one little thing. Whereas like, so I answered that it releases energy, but it releases energy because when an interaction with other molecules, like water, primarily, and then it creates like*

an inorganic phosphate molecule that has a lot of resonance. And is much more stable than the original ATP molecule. So like, in the end releases a lot of energy, but it does require like a really small input of energy to break that bond. So I was thinking that larger context of this reaction releases energy. Because I know what the reaction is, ya know? So, um, not, does the bond breaking release energy."

Gregor demonstrates a sophisticated understanding of the ATP hydrolysis reaction, and makes clear that his justification for choosing C on the quiz does not correspond to the standard "misconception" that bond breaking releases energy. He displays understanding of the intended resolution of the apparent paradox: energy is released not by the breaking of a bond but by the formation of other more stable bonds. In thinking back over the question, Gregor stands by his answer, but also recognizes the correctness of the quiz answer key. He attributes the discrepancy to differing interpretations of what the question is asking (and even assigns this reasoning to the other students who answered the question the same way):

"When I was taking the test, I guess I was thinking breaking this bond then leads to these other reactions inevitably. That result in an energy release … I don't [argue] that breaking a bond releases energy, but just like in a larger biological context, that reaction does release energy. So that's what me and apparently like 80% of the class was thinking."

Gregor then, following up on a thread that begins above, ties these differences in perspective to differences between the disciplines:

"Because I guess like in biology it's not as important to think about like breaking this bond doesn't release energy and then all these other things that happen do release a lot of energy. So, we're, I've just been taught like for a long time that like ATP going to ADP equals like a release of energy. … I guess that's just the difference between physics and chemistry and biology. … It's just your scale. Like, physic[ists] really love to think about things in vacuums, and like without context, in a lot of senses. So, you just think about like whatever small system you're—isolated system you're looking at, and I guess chemist or biologists thinking about more of like an overall context, that like wherever a reaction or process is happening, like that's important to what's going on."

Gregor and his classmates have biology backgrounds, and their experience talking about ATP and bond breaking is in biology and chemistry courses; those experiences inform how he frames the context of the quiz question. Gregor now believes he is seeing a different perspective in a physics course, one in which the phenomenon of

ATP hydrolysis is more narrowly conceived.[10] He sees the boundary of the phenomenon under consideration as a salient difference between the disciplines.[11] When Gregor says "scale," he is not talking about physical scale, but about whether we are looking at the breaking of a bond on its own (which requires an input of energy) or the ATP hydrolysis reaction as a whole (which releases energy).

Wylie also answered B, C, and D on the quiz. Like Gregor, both his multiple-choice responses on the quiz and his responses in the interview were consistent with holding two pictures simultaneously. However, Wylie apparently had not reconciled these two pictures prior to the interview to the same extent that Gregor had. The interviewer begins by handing Wylie a blank copy of the quiz on which the ATP question appeared. Wylie immediately affirms that he recalls the quiz from class and that he "picked something wrong," asserting that he answered option C, "for sure." As he is considering the other answers he had originally given on the quiz, the interviewer prompts him to say aloud what he is thinking. In the 10 minutes of discussion around the quiz question that follow, Wylie demonstrates awareness that he still has reconciliation to do. In thinking back over the question, he says "there's obviously a conflict" between breaking bonds (in ATP) releasing energy and forming bonds (in general) releasing energy. Wylie explains that he answered C because "the result of ATP hydrolysis is ADP, which is much more stable, because I know this from chemistry. … And we have energy released. So obviously you're going from an unstable state to a more stable state." He also justifies his choice of D ("a relatively small quantity of energy is required to break the bond"), "because if something is really unstable, if something is really highly charged, then all it needs is a little push, and that's it, it just goes downhill." Putting it together, Wylie says:

> *"If I were to rationalize [the physics professor's] model, then I would have to say ATP breaks down into ADP plus something. There's a bond formed between the phosphate and something that makes it more stable. And this part is the part that releases the energy. … It's not the breaking of the bond that's releasing the energy. Because when, in breaking of the bond, you actually require energy, but the result of the breaking of the bond is that you get energy."*

Even though Wylie does this reconciliation, possibly in real time during the interview, to explain why C was deemed incorrect, he remains unsatisfied with this

[10] Of course, Gregor does not know that this quiz question originated in a chemistry education paper; perhaps his reaction would have been different if he, like Galley's students, had encountered the question in a chemistry course.

[11] Gregor's and other students' views on the relationships between the disciplines are explored further in Geller, Dreyfus, Sawtelle, et al. (2013).

conclusion. Like Gregor, Wylie ultimately connects the discrepancy to disciplinary differences:

> **Wylie:** *If … that same question was in a biology course, and I picked C, I would get points.*
> **Interviewer:** *Why do you think that is?*
> **Wylie:** *Because I think in the biology course, the focus of the question would be on the significant quantity of energy, not necessarily breaking the bond. … Breaking the bond in ATP gives you energy. That's what a biologist might think. … But this is more specific. This is going into, you know, exact details.*

Wylie, too, distinguishes between a "biology" approach, in which the focus is on the entire reaction that releases energy, and the "more specific" approach that he associates with the physics class, which focuses on the "exact details."

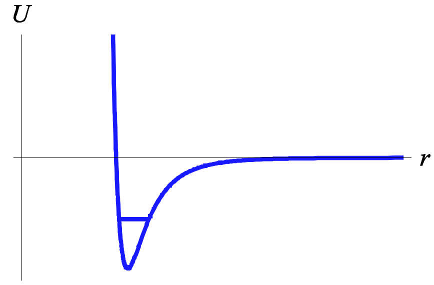
At the end of the day, Wylie has not gone all the way in building a coherent model and knows that he has further to go:

> *"But … I keep thinking that there have to be things that, you know, just like ATP, you know they are macromolecules. They're not as stable together, but when they break down they're more stable separately...what do you do with that? How would you release energy in that sense? I don't know. I'm really just kind of unclear on that."*

5.5.3 Exam essay question

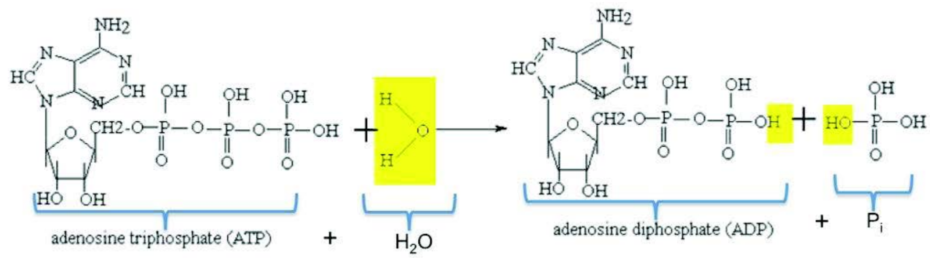
In reviewing the interview data from Gregor and Wylie we see the two sets of ideas around ATP being clearly articulated, but with distinctions in disciplinary ideas being drawn between them. We used the clear articulation of these ideas from the interviews to form a capstone assessment question. This question drew students' attention to the difference between focusing exclusively on the breaking of the O-P bond in the ATP molecule and allowing the system under consideration to include the forming of bonds with the H_2O molecules surrounding the ATP, just as Gregor and Wylie have articulated. The capstone assessment was given as an essay question on the first exam in the second semester of the course. The essay question (shown in Figure 5.1) presents two contrasting arguments, allowing for other students in the class to demonstrate their understanding of the reconciliation of these ideas. Based on the ways that students associate the disciplines with these arguments in interviews, we see the focus exclusively on breaking the O-P bonds as associated in the students' views with "physics" and the focus on the entire ATP hydrolysis process as associated with "biology."

Two students discussing the process of ATP hydrolysis ($ATP + H_2O \rightarrow ADP + P_i$) make the following comments:



Justin: “The O-P bond in ATP is called a ‘high -energy bond’ because the energy *released* when ATP is hydrolyzed is large. That released energy can be used to do useful things in the body that require energy, like making a muscle contract.”

Kim: “I thought chemical bonds like the O-P bond in ATP could be modeled by a potential energy curve like this (she draws the picture at the right), where *r* is the distance between the O and the P. If that’s the case, then breaking the O-P bond in ATP would require me to *input* energy. I might not have to input *much* energy to break it, if that O-P happens to be a weak bond, but shouldn’t I have to input at least *some* energy?”



How did Kim infer from the PE graph that breaking the O-P bond requires an input of energy? Who’s right? Or can you reconcile their statements? (The chemical structures of this process are given if you find that useful.)

Note: This is an essay question. Your answer will be judged not solely on its correctness, but for its depth, coherence, and clarity.

Figure 5.1. The reconciliation essay question given to students on the midterm exam.

In the essay question Justin articulates that hydrolyzing ATP releases a large quantity of energy, which is why the O-P bond in ATP is typically called a “high-energy bond.” In contrast, Kim describes the O-P bond with a potential-energy curve that shows a negative energy. Kim reasons that getting out of this negative energy well (which represents the O and P moving far apart from each other) would require an input of energy. The essay question explicitly asks students to make sense of the potential-energy curve and use it to explain why Kim’s response makes sense. Then the essay prompts students to take a position as to whether Justin or Kim is correct, or to reconcile the two statements.

Kim’s and Justin’s statements were juxtaposed in this essay question to explicitly draw attention to the differences in reasoning. Students in the class were accustomed to this type of essay question, in which two ideas are presented and the expectation is that the students take up one side or the other of the argument. However, in the case of this prompt, both Kim and Justin are explaining correct ideas. The intention with this capstone assessment was to examine the extent to which the students in the class attempted to reconcile these perspectives and to examine the form of that interdisciplinary reconciliation.

Student responses to the essay question varied widely, from some who said plainly that Justin’s idea about energy being released when ATP is hydrolyzed is wrong, to others explaining quite articulately why the reasoning from both Justin and

Kim are correct. Essays from Sameer and Sebastian represent what we consider to be exemplary responses demonstrating interdisciplinary reconciliation.

> **Sameer:** *In general, Kim is correct. Justin is correct in that ATP is a vital source of energy for biological reactions, but he's confusing the energy of ATP hydrolysis with the energy of the bond. By the principles of thermodynamics (illustrated by the chart above), atoms do want to be bound together, as it represents the lowest potential energy level. Due to their attractive forces, it requires energy to break the bond – the stronger the bond, the lower the energy state, and the greater the amount of energy required to break the bond.*
>
> *With ATP, the O-P bond has a higher energy state, and does not require as much energy to leave the bound state. When new bonds form, though, they are at a much lower energy state than the O-P bond (deeper well), so large amounts of energy are released to the environment. It is not the bond breakage that releases energy, but rather the formation of new bonds, and this is where the confusion lies.*
>
> **Sebastian:** *They are both right. On the graph, at z* [z is indicated on the PE curve at the location of the horizontal line showing total energy] *the atoms are bonded and they are at a lower potential energy which is where they want to be. In order to increase r (the distance b/w the atoms) you would have to put in energy to increase the energy. Makes sense. So Kim is right that even though it is a weak bond you still have to put in some energy. Justin is also right because the formation of ADP releases more energy than required to break the initial O-P bond. Therefore there is a net release of energy. Just like in the graph you lose PE when the molecules come together rather, it is released. Justin is right too.*

In Sameer's and Sebastian's responses we see evidence that the students see the correct ideas within the two apparently contradictory statements that breaking the O-P bond requires an input of energy and that ATP hydrolysis results in a net output of energy. Both Sameer and Sebastian emphasize the formation of new bonds in describing the hydrolysis process and Sameer even goes so far as to explain that "this is where the confusion lies."

This is not to say that all the students in the class demonstrated this understanding of the reconciliation this task afforded for students. Ava and Zeke demonstrate an alternative but relatively common response to the question, which favors the reasoning from Kim:

> **Ava:** *Kim says that breaking the O-P-bond requires an input of energy because as shown at the black line, that is the total energy that the O-P bond has, since they are bound together. Being in a bound state means that you are at a lower potential energy, such as the dip in the graph. Therefore, to break the bond, or to get out of that dip, you would need to input the amount of energy that is ≥ than the negative total energy that the molecule has. Therefore, Kim is right. Breaking a bond needs at least some energy because the O-P bond <u>is</u> a weak bond. Justin is not right because energy is <u>not</u> released when ATP is hydrolyzed. He is mistaking the phrase "high energy" in that there is no high energy in the bonds.*

> **Zeke:** *I think Kim is right. The energy released when the O-P bond broken is NOT large like Justin says (when ATP is hydrolyzed). It's called a high energy bond because it's a weak bond and relatively easy to break. Kim inferred that energy is required to break the bond since the potential energy is negative when the O-P are in a bound state. So she feels that she must input that amount of energy to make them unbound. I think Kim is right and her graph makes sense. You would need to put in the amount of energy that is shown as –U on the graph to break the bond. Justin is right in saying that the energy that is then released can be used to do useful work. So you have to input energy to break it, but more useful energy is released by breaking it.*

In both Ava's and Zeke's responses we see an emphasis on describing how Kim is right because breaking the O-P bond requires an input of energy in order to get out of the potential energy well. However, in Ava's response we see an explicit reference to Justin's ideas being incorrect because she concludes (incorrectly) that energy is not released when ATP is hydrolyzed. In Zeke's response there is evidence of the reconciliation not quite being worked out. He clearly describes the O-P bond requiring energy to break, though it is a relatively weak bond. However, when he describes Justin being right, it is unclear whether he thinks both that it requires energy to break the bond and that breaking the bond releases energy.

We note a difference between the multiple-choice quiz question discussed in the interviews and this exam essay question: Both Justin and Kim in the essay question present scientifically correct ideas. It does require energy to break the O-P bond and to move out of the negative potential-energy well. At the same time, ATP hydrolysis, which involves the breaking of the O-P bond as well as the forming of new bonds between the phosphate molecule and the water surrounding the molecule, does result in a net energy release. This is different from the more common type of reconciliation task, asking students to abandon an "incorrect" idea in favor of the more scientifically "correct" one, which is what is required by the quiz question presented earlier.

We believe that the essay question provided students with the opportunity to reconcile these ideas, as nearly half of our 19 students in response to this prompt discussed both the forming and the breaking of bonds, which have different implications for the net energy effects. We claim that these students demonstrate recognition that both of these ideas hold some value to making sense of the language of "high-energy bond" surrounding ATP hydrolysis, and that by examining the essay responses in detail we have gained insight into how students reconcile these ideas. When students seek consistency between Kim's and Justin's ideas, we see them as grappling with the relationship between disciplinary perspectives. Though not all of the students tagged the disciplines explicitly in their responses (as Gregor and Wylie did in their interviews), they were still seeking consistency between ideas presented in connection to different disciplines, and affirming the correctness of both ideas while explicating the conceptual bridges between them.

5.6 Discussion

5.6.1 Interdisciplinary reconciliation

In this chapter we have developed a model for the process of interdisciplinary reconciliation (IDR) that draws from classroom supports, student reasoning in interview contexts, and student essay responses. We draw attention in this initial model to both the endpoint that Gregor exemplifies in the interview setting as well as the groundwork for this target in the instructional supports.

Under the framework of interdisciplinary reconciliation, we include both a model of student thinking and an instructional approach. We detail both aspects of IDR in the rest of this section, and we summarize the key elements here. As a model of student thinking, IDR includes 1) fluency in the language and models of each discipline in its local context, 2) understanding how the disciplinary models connect to one another, and 3) the tools to decide when each disciplinary approach is productive. As an instructional approach, IDR includes 1) opportunities to bring ideas from different disciplines into contact, 2) explicit attention to disciplinary similarities and differences, and 3) the recognition of multiple "correct" answers to the same or similar questions depending on context.

5.6.1.1 The target endpoint for IDR

Gregor's interview response represents what we see as an exemplary aspect of interdisciplinary reconciliation:

> *Physic[ists] really love to think about things in vacuums, and like without context, in a lot of senses. So, you just think about like whatever small system you're—isolated system you're looking at, and I guess chemist or biologists thinking about more of like an*

overall context, that like wherever a reaction or process is happening, like that's important to what's going on.

In Gregor's words we see a sophisticated understanding of the modeling choices he has encountered in physics and biology. In the interview, Gregor ties these choices to the reasoning behind the different answers about the O-P bond in ATP. He connects his answers about the energy released in ATP hydrolysis to the kinds of questions one might ask in the different disciplines and the different ways the disciplines define the boundaries of systems. We see in Gregor's response a compelling example of the place where students get to through interdisciplinary reconciliation. At the time of his interview, Wylie represents a point on the way to this place: he acknowledges the different ideas associated with physics and biology and the circumstances in which one or the other set of ideas might be more appropriate, and is still in the process of reconciling how these ideas fit together coherently.

In interdisciplinary reconciliation (IDR), both disciplines represent locally coherent sets of canonically correct scientific ideas that can be activated for different purposes. While some biologists would take issue with Gregor and Wylie's "biology" statements, our conversations with biologists have corroborated Wylie's claim that his answer would be considered correct in many biology instructional contexts. More importantly, the idea that ATP hydrolysis results in a net release of energy is particularly useful for reasoning in biological contexts. The goal, then, is for students to understand the connections between disciplinary ideas while maintaining each one in its appropriate context.

In addition to achieving conceptual reconciliation, an important outcome of interdisciplinary reconciliation is that students will subsequently be able to activate the appropriate disciplinary idea(s) depending on the context. Therefore, part of the reconciliation is developing the resources to distinguish contexts, to establish the appropriate framing in each context, and to understand why an approach is most productive in a given context.

5.6.1.2 Instructional components of IDR

In addition to the endpoints displayed in the interview and essay data, we also consider the elements of the instructional environment that contributed to the process of IDR. In the classroom video data, the instructor continually attempted to engage students in rethinking the purpose of activities, encouraging them to think carefully and consider all the options available to them, which may have included disciplinary ideas. The instructor set up quiz questions as multiple-choice multiple-response, which is in direct contrast with common multiple-choice questions where there is only a single correct answer. Multiple-choice, multiple-response questions allow students to consider the possibility that there can be multiple ideas that are correct. This style of quiz lends itself to exploring disciplinary ideas, which may have different languages and assumptions associated with similar (correct) ideas.

The instructor in discussions and other elements of the course also tried to communicate that disciplinary language and starting assumptions might not be transparent, and that students could help in clarifying these disciplinary ideas. As mentioned in section 5.3.2, the course was structured to encourage students to bring in ideas from the various scientific disciplines. One example can be seen in the prompts students encountered in the class. Both the quiz prompt and the essay question described above explicitly bring up ATP and ideas of stability and weakness of the O-P bond. These ideas are more commonly encountered in biology or biochemistry classes, and by situating them within a physics classroom we encourage students to examine the differences in the disciplinary descriptions of these ideas.

Similarly, when the instructor discussed the quiz results with the students, he directly referenced the potentially different uses of language in chemistry and biology, and encouraged students to consider that language when making arguments about points deserved on the quiz. Further, the instructor acknowledged that particular assumptions and ways of bounding the system that the students might be using are more common in biology contexts. Through the explicit references to scientific disciplines and traditional disciplinary ideas, the course and the instructor communicated to students that some ways of reasoning through the phenomenon might be discipline-specific and not unique.

We conjecture that the reasoning displayed by the students in the interviews and in their responses to the essay question was encouraged by these supports from the course and instructor. In identifying a model for IDR we draw attention to these instructional moves as important aspects of the process of reconciling disciplinary ideas.

5.6.2 IDR and other frameworks for reconciliation of ideas

Our primary research question asks how existing theoretical frameworks can help characterize interdisciplinary reconciliation. In this section and the next, we compare and contrast IDR to existing frameworks.

An essential part of understanding student learning with a focus on conceptual ideas is having a model of what happens when students change their ideas. In particular, research on learning and conceptual change has focused on what students do with two sets of ideas that on the outset appear to be in direct conflict with one another. We focus on two ways of creating instructional activities to deal with this situation that have received attention in the physics education research literature: *elicit-confront-resolve* (*e-c-r)* and *Elby pairs*.

Both of these processes for reconciliation begin with the same basic step: elicit commonly held student beliefs that are typically in conflict with widely held scientific concepts. The second step centers around confronting those beliefs with experimental data that is in conflict with the originally elicited belief. The difference in the two methods lies in the process of reconciliation. We describe each of these methods in more detail below.

5.6.2.1 Elicit-confront-resolve

The *e-c-r* method focuses on replacing an old unscientific idea with a new one that is more aligned with those that are held to be scientifically correct. The University of Washington Physics Education Group has spent a large part of their efforts identifying and documenting "student difficulties": sets of conceptual ideas that students bring to an introductory physics environment that can be reliably activated with a particular set of contexts and questions (McDermott, 1991; Shaffer & McDermott, 1992). In developing highly successful curricular reforms, they have identified a process they call *elicit-confront-resolve*. The strategy begins with a well-structured question that elicits students' commonly held beliefs. Next, that belief is confronted with contradictory experimental evidence that the student observes individually. Finally, in the *resolve* step of the process, students practice applying physics rules in carefully structured examples that help them to overcome their tendency to apply commonly held beliefs, and replace them with the scientifically correct conceptions.

While the *elicit-confront-resolve* framework has been highly successful in achieving student understanding of complex ideas within physics, one of the fundamental requirements of this instructional strategy is the idea of replacing the student's naïve conception with a new scientifically correct conception. This replacement is problematic when the conflicting ideas to be resolved are those from different disciplines, and neither is more "correct" than the other. In the *elicit-confront-resolve* framework, we can easily imagine many students giving similar reasoning to Ava's exam response where she says clearly, "Justin is not right because energy is <u>not</u> released when ATP is hydrolyzed." From all of her biology experience, Ava must know that the hydrolysis of ATP does release energy, but here we see her going past the point of reconciliation. Indeed she appears to have resolved the conflict, but in doing so has abandoned her (correct) biology knowledge in favor of using correct physics reasoning about breaking bonds. This kind of reconciliation is not consistent with our goals for an interdisciplinary environment.

5.6.2.2 Elby pairs

An alternative pathway has been proposed by Elby (2001), reasoning from the resources framework. The framework, as we described in section II, allows for students holding multiple ideas at the same time, and for the activation of particular ideas to be related to the context at hand. Elby pairs (a term coined by Redish (2003) to describe a reconciliation process outlined by Elby (2001)), are a set of two questions that ask the same question in two different ways. The first way is designed to elicit the common idea in a similar way as the *elicit* component of the *e-c-r* process. However, the second question is designed to match the students' correct intuition about the situation. The classic example given in both (Elby, 2001) and (Redish, 2003) centers around Newton's third law. One question in the Elby pair elicits students' intuition that when a truck collides with a car, the truck exerts a larger force on the car than the car does on the truck. The second question activates students' correct sense that the momentum changes of the interacting objects are balanced. Reconciling their answers to the pair of questions leads students to conclude that the car **accelerates** more than the truck, but also has a smaller mass, so their intuition that the car is affected more than the truck is in fact consistent with Newton's third law.

The key difference between the Elby pairs version of reconciliation and the *e-c-r* version is that the Elby pairs are designed to invite students to see the pair of questions as refinements of the same raw intuition. Thus the Elby pairs version of reconciliation does not ask students to replace one idea with the other, but rather to recognize how their initial ideas need to be refined in order to be aligned with the scientifically correct assumptions. In so doing, students are not asked to abandon their initial set of ideas, but rather to modify them in order to resolve the conflict.

Seeking to support students in refining their raw intuition to develop an understanding of how their intuition can be productive in a physics class is a positive and encouraging goal. However, in an interdisciplinary environment, we are not dealing with students who need to refine a raw intuition into a more scientifically correct conception. Instead, these students may already have productive ideas that have come from scientifically correct ideas in biology and chemistry contexts. Our goals for reconciliation should then be to encourage maintaining both sets of conceptions with a deep understanding of the assumptions that underlie them and the context of their utility: a vision that was reached through careful examination of exemplary student reasoning.

5.6.2.3 Interdisciplinary reconciliation

We argue that the model of interdisciplinary reconciliation that we present in this chapter is different from both the *e-c-r* and Elby pairs types of reconciliation. As discussed above, both disciplines involved in IDR represent locally coherent sets of canonically correct scientific ideas. Therefore, the goal of IDR is not to arrive at one refined idea (a common goal of both *e-c-r* and Elby pairs), but to refine both ideas to the point where students can understand how the two disciplinary ideas fit together. In Elby pairs, both explanations are shown to be based in the same raw intuition; in IDR, the two disciplinary ideas may come from different places, and the role of reconciliation is to bring them into coherence.

While much of the previous work on context-dependent activation of resources can be interpreted as operating under the assumption that one pattern of resource activation is correct in answering a given question, we take the position for interdisciplinary questions that disciplinary context-dependence is productive and is one of the goals of IDR.

Of course, it is not always the case that when students are reconciling multiple ideas, both ideas are correct. Therefore, the other approaches to reconciliation are still appropriate in many circumstances. We describe IDR as appropriate in a limited set of cases, when the ideas to be reconciled are correct ideas from different disciplines, but this set of cases is increasingly significant with the development of more interdisciplinary curricula.

5.6.3 Misconceptions and resources, revisited

We introduced the misconceptions and resources frameworks in section 5.2, and we now apply them to our data to compare our approach with previous work on student learning of the same scientific phenomena. In analyzing student difficulties with ATP, both Novick (1976) and Galley (2004) invoke the misconceptions model. Novick writes, "many students conceive chemical energy as stored in something called a chemical bond … Now this is obviously a serious scientific misconception." To remedy this, he suggests eliminating the energy storage language from textbooks. Galley writes that students "adhere to the belief that energy is obtained when chemical bonds are broken," and attributes this primarily to "misinformation" in biology courses. He concludes, "[i]f students are alerted to the confusion and misinformation about bond making and bond breaking that they were likely exposed to, coupled with a review of the correct picture of bond rupture and formation, the problem is largely resolved. Students then recognize the misconceptions that they encounter." In both cases, the model of students is that they hold only one view about chemical bonds, and if the source of this incorrect view is eliminated or confronted, then students will replace it with the correct picture.

We can make some predictions from a misconceptions model. If students have a unitary belief that energy is stored in bonds, we would then expect them to say that a stronger bond is a bond that stores more energy (so that more energy is released when such a bond is broken), and to reject the idea that an input of energy is required to break bonds. After they are convinced of the correct view of bond breaking and bond formation, we would expect them to abandon their previously held incorrect view. The misconceptions perspective would suggest a vision for interdisciplinary education in which one view is eliminated and one specific view is maintained.

Instead, our data are more consistent with the resources framework. On the ATP quiz question, several students answered both C and D: that breaking the O-P bond releases a significant quantity of energy and that breaking the bond requires a small amount of energy. Other students answered both B and C: that the bond is relatively weak and that it releases a large quantity of energy. Many instructors would see these combined responses as mutually inconsistent, suggesting that breaking the O-P bond both requires an input of energy and releases energy or that the bond is weak and releases a large amount of energy. The fact that many students did supply these two apparently inconsistent ideas is difficult to explain using a unitary "misconceptions" view. However, from a resources perspective we can view these apparently contradictory ideas as being sets of activated resources.

Our interview data with Gregor and Wylie suggest that the disciplinary context has a key role in determining which resources are activated. When Gregor explains his reasoning,

> *I guess that's the difference between like how a biologist is trained to think, in like a larger context and how physicists just focus on sort of one little thing. Whereas like, so I answered that it releases energy, but it releases energy because when an interaction with*

> *other molecules, like water, primarily, and then it creates like an inorganic phosphate molecule that has a lot of resonance…. So like, in the end releases a lot of energy, but it does require like a really small input of energy to break that bond.*

he explains how his biology training encouraged him to consider the ATP molecule's interaction with other molecules around it, such as water. This explanation suggests that Gregor has access to both the resource that says energy is required to break the O-P bond and the resource that explains the large amount of energy released from ATP hydrolysis, and the disciplinary context created the framing that activated the set of resources he used to answer the question. Furthermore, Gregor demonstrates an awareness of his access to these different resources, suggesting that one of them is not more likely to be accessed than the other unless prompted by a disciplinary context. Wylie makes an explicit reference to the disciplinary context deciding which resource is the most appropriate to bring to bear when he says,

> *Because I think in the biology course, the focus of the question would be on the significant quantity of energy, not necessarily breaking the bond. … Breaking the bond in ATP gives you energy. That's what a biologist might think.*

We do not mean to suggest that all students may be as self-aware as Gregor and Wylie in articulating the connection between the sets of ideas that should be brought to bear and the disciplines. However, we do believe that the responses from Gregor and Wylie highlight the advantages of a resources framework over a misconceptions view in explaining these data. The dynamic view of the resources framework allows us to make sense of how students could be articulating apparently contradictory ideas within the same set of responses, as well as how the disciplinary context may change which ideas students bring to bear.

5.7 Conclusions

In this chapter, we demonstrate that when biology students encounter ATP in a physics course, reasoning about chemical bond energy in an interdisciplinary context is a complex process requiring students to manage ideas that may seem contradictory on the surface. We provide examples of what interdisciplinary reconciliation looks like in the context of ATP hydrolysis and highlight the seemingly contradictory scientifically correct ideas that students must learn to navigate. We explain this reasoning process within a resources view of student cognition, in which students' ideas are not unitary and coherent, but can be fragmented and dynamic. This model of student learning helps us build an understanding of how students can display coherent reasoning with two seemingly contradictory ideas, and how those ideas may be encouraged through disciplinary contexts. We present an alternative view of reconciling student ideas that embraces disciplinary differences, and encourages students to make explicit the assumptions that may be behind particular disciplinary reasoning. Finally, we point to particular instructor and course supports that may have encouraged the interdisciplinary reconciliation process.

The *Vision and Change* report calls for future biologists to develop expertise in another scientific discipline and to "develop the vocabulary of both disciplines and an ability to think independently and creatively in each as well" (AAAS, 2011). We share this vision of interdisciplinary education, which does not suggest eradicating disciplinary differences. Instead, this vision emphasizes being able to reason **within** each discipline, using its own native tools, in ways that are informed by and coherent with the other disciplines.

We want our students to be able to make choices about how to model a system or phenomenon based on the questions that they are trying to answer. In some circumstances, it is appropriate to consider the individual steps of the ATP hydrolysis reaction mechanism and keep track of which bonds are broken and which bonds are formed, or to track the energy transformations and transfers that take place within this reaction. In other circumstances, the aqueous environment is backgrounded. The relevant features of the reaction are that ATP is broken into ADP and phosphate and that energy is released, and this relatively black-boxed picture is a useful way to think about the reaction in its larger biological context. Interdisciplinary competency in physics, biology, and chemistry incorporates both of these models, as well as the flexibility to move coherently among the models. In this disciplinary context-dependence we see the roots of productive interdisciplinary reasoning.

Future directions for research include applying the interdisciplinary reconciliation framework outlined in this chapter to other content areas. This work has begun with an analysis of students' interdisciplinary reasoning about entropy, free energy, and spontaneity (Geller et al., 2014). We have also identified cases in which "interdisciplinary" reconciliation is appropriate even within a single discipline, when different conceptual and epistemological resources are called for in different subfields. For example, at the level of professional physics, the modeling choices made in condensed matter physics and in particle physics are very different. In the standard introductory physics course, the simplifying assumptions made about energy are very different when energy is encountered in the contexts of mechanics and thermodynamics. A future analysis can explore the similarities and differences between this sort of intradisciplinary reconciliation and the interdisciplinary reconciliation discussed in this chapter.

Chapter 6: Ontological metaphors for negative energy in an interdisciplinary context[12]

6.1 Introduction

Energy is a central concept in physics, chemistry, and biology, and has been widely promoted (National Research Council, 2003) as a way to connect physics and chemistry to biology. Yet the concept of energy can be fractured for students along disciplinary lines (Dreyfus et al., 2012; Dreyfus, Geller, Sawtelle, et al., 2013). Chemical energy (energy changes associated with chemical bonds and reactions) is essential in biology and chemistry (Cooper & Klymkowsky, 2013), and rarely has a central role in introductory physics courses. However, introductory physics courses that seek deeper interdisciplinary coherence with chemistry and biology are now integrating chemical energy into their treatment of energy (see chapter 4). We argue below that one element of building this interdisciplinary coherence around chemical energy is reasoning about negative energy. However, we note that this would be less essential in other introductory physics curricula.

Negative energy has been documented as an area of difficulty for students (Lindsey, 2014; Stephanik & Shaffer, 2012). In this chapter, we draw on an ontological metaphor perspective to suggest why this concept is difficult, and use a dynamic ontologies model to illustrate ways that experts and students can reason productively about negative energy.

In section 6.2, we explain the ontological metaphor theoretical framework and review the PER literature on ontological metaphors, particularly as applied to energy. We focus on two metaphors for energy: substance and location. In section 6.3, we discuss the concept of negative energy: why it is pedagogically necessary for our interdisciplinary context, and how it has been a source of confusion. In section 6.4, we argue that the exclusive use of the substance metaphor for energy is untenable for an interdisciplinary context that relies on negative energy, and present examples of the productive use of a blended substance/location ontology. In section 6.5, we present a case study of one group problem-solving task on energy at molecular scales, and analyze student reasoning about negative energy with a focus on ontological metaphors. In section 6.6, we discuss the implications for research and for instruction, including suggesting the instructional value of coordinating multiple ontologies, and proposing future directions for research beyond this chapter's narrow context.

Our approach is primarily theoretical, but supplemented by qualitative case-study data. Thus, the central argument on blending the substance and location ontologies for energy (in sections 6.3 and 6.4) is one where the theory comes first, followed by

[12] This chapter has been submitted for publication (Dreyfus et al., under review).

empirical proofs of concept. However, in section 6.5, the case studies provide new directions for refinement of the theory.

6.2 Theoretical framework

6.2.1 Ontologies and conceptual metaphors in physics education

Our analysis is based in the conceptual metaphor theory developed by Lakoff and Johnson (2008). This theory elucidates the metaphors we use, based in our physical experiences in the world, when we think and talk about abstract ideas. These include ontological metaphors, which Lakoff and Johnson define as “ways of viewing events, activities, emotions, ideas, etc., as entities and substances.” For example, “He cracked under pressure” is an instance of the *The Mind Is A Brittle Object* metaphor.

Another relevant strand of research is based in the work of Chi and colleagues (Chi, Slotta, & de Leeuw, 1994; Chi & Slotta, 1993; Chi, 2005; Slotta, Chi, & Joram, 1995). They build on the theory of Keil (1979), which posits that all entities in the world can be placed into a hierarchy of ontological categories, and apply this theory to science concepts, using Matter, Processes, and Mental States as the primary ontological categories. According to Chi et al.’s theory, each physical entity has a correct ontology, and many robust physics misconceptions are the result of attributing an incorrect ontology to a concept. While we do not share this theoretical perspective, we draw on Chi et al.’s methodology of identifying ontologies that students (and experts) use by analyzing the predicates that they use: words, phrases, or ideas that are taken to reflect an underlying ontological attribute (Slotta et al., 1995). For example, saying that a physical entity is “stored” is evidence that that entity is being talked about as a material substance.

Brookes and Etkina (2007) synthesize the conceptual metaphor framework and the ontological categories framework. They follow Chi et al. in placing each physics concept into an ontological category based on expert understanding of physics (a lexical ontology), but they also identify instances when a grammatical analysis indicates that students and experts invoke other ontologies for a given concept. When these ontologies do not match the lexical ontology, they identify this as a metaphor.

Gupta et al. (2010) respond to Chi et al.’s “static ontologies” model (which they label as such because it requires that each entity belongs to a single stable ontological category), and show that both novices and experts can place the same physics entity in multiple ontological categories, and that this ontological categorization is context-dependent. They show furthermore that using multiple complementary ontologies for the same concept in different contexts can be productive. We extend this dynamic ontologies model to cases in which multiple ontological categories are used for the same entity within the same episode.

6.2.2 Ontological metaphors for energy

In recent years, a popular theme in the physics education research literature has been the use of ontological metaphors for energy: conceptual metaphors that express "what kind of thing energy is" (Scherr, Close, McKagan, et al., 2012).

Scherr et al. (Scherr, Close, McKagan, et al., 2012) identify three ontologies for energy found in student and expert discourse:

- *Substance:* energy as "stuff" contained **in** objects
- *Stimulus:* energy **acts on** objects
- *Vertical location*: objects are **at** higher or lower energies, by analogy to gravitational energy.

They note that "the stimulus metaphor is not common in expert physicists' discourse about energy," and likewise here we focus primarily on the substance and vertical location metaphors, both of which are commonly used by expert physicists.

All three of these ontologies are used metaphorically according to Brookes and Etkina's definition (Brookes & Etkina, 2007): Energy is an abstract concept that is not "actually" a substance or a location according to canonical physics understanding. Therefore, in this particular domain, we are justified in referring to "ontologies" and "metaphors" largely interchangeably in this chapter (in keeping with other literature in this area), even if they are not always equivalent in other cases.

We should clarify here the distinction between the substance and location ontologies for energy. Amin's (2009) conceptual metaphor analysis of energy identifies attributes of energy with elements of Lakoff and Johnson's (1999) Object Event-Structure and Location Event-Structure metaphors. Both of these fundamental metaphors create spatial mappings for events, but the Location Event-Structure metaphor identifies events with locations (e.g. "He went into a depression"), and the Object Event-Structure metaphor identifies events with objects (e.g. "I have a headache"). It may appear that these metaphors correspond to the substance and location ontologies respectively, but this correspondence is not accurate, because our focus is on what the metaphors imply about what energy is, rather than about the metaphors themselves.

The Object Event-Structure metaphor does indeed correspond to the energy-as-substance ontology; this includes possession language about "having" energy. However, different uses of the Location Event-Structure metaphor may correspond to either the substance or the location ontology for energy. As one example of the Location Event-Structure metaphor, Amin includes energy being "in" some form. We would still classify this as the substance ontology, because the energy is "in" the metaphorical "location" (and being at a location is a predicate associated with a substance) rather than the energy itself being the location. In another context, Amin writes "Here again we find the Location Event Structure conceptual metaphor, but now with a figure/ground reversal. Energy transformation was construed in terms of this metaphor. In that case, energy was construed as an object moving from one location to another. Here, in contrast, we find that energy state is the location and objects move with respect to *it*." This is the context that we identify as the energy-as-location ontology, which includes atoms **in** the **lowest** energy state, and accelerating electrons **to high** energies.

When we discuss the location ontology, we are also not referring to situations where the energy of an object depends on the object's spatial location. In those situations, the location of the object is not a metaphor, but a physical property. While the energy may depend on the location, the energy is independently described by some ontology, which may or may not also be the location ontology. (This can be a source of confusion for both students and researchers in understanding potential-energy-vs.-position graphs, because the horizontal axis on those graphs represents spatial location, while the vertical axis, representing energy, can be interpreted as a metaphorical location. As we discuss below, this can also help activate productive conceptual resources.)

After describing three common ontologies for energy, Scherr et al. (Scherr, Close, McKagan, et al., 2012) go on to focus on the substance ontology, making the case for its pedagogical advantages and detailing how it can be used in instruction. Brewe (2011) takes a similar approach, also focusing on the energy-as-substance metaphor as a central framework for an introductory physics curriculum. Lancor (2012) examines the use of conceptual metaphors for energy in all three disciplines, and also focuses on the substance metaphor in its various manifestations.

All of these recent papers share a theoretical commitment to dynamic ontologies (Gupta et al., 2010). This stands in contrast to the "static ontologies" view (Chi & Slotta, 1993) that there is one correct ontological category corresponding to each entity, and misconceptions arise from ontological miscategorizations. Thus, when Scherr et al. and Brewe advocate for emphasizing the substance ontology in instruction, they are not claiming that the substance ontology is the "correct" ontology for energy; rather, their claims are based on the pedagogical affordances of this metaphor. These affordances include supporting the ideas that energy is conserved, can be located in objects, is transferred among objects (Scherr, Close, McKagan, et al., 2012), and is unitary (i.e., there is only one type of energy) (Brewe, 2011) and/or can change form (Lancor, 2012).

However, they concede that one place where the substance metaphor encounters difficulties is the representation of negative energy, since a substance cannot ordinarily be negative. Scherr et al. resolve this concern with "the realization that potential energy depends not only on the system of mutually interacting objects but also on a reference point." In other words, it is possible to choose a reference point such that the potential energy of the system of interest is always positive, enabling the use of the substance metaphor. In Brewe's Modeling Instruction course, energy is first visually represented with pie charts, which emphasize conservation and unitarity. This representation breaks down when attempting to incorporate negative energy, and this provides the motivation to replace pie charts with bar charts (Van Heuvelen & Zou, 2001), which can represent negative energy. However, it is less clear that bar charts embody the substance metaphor in the way that pie charts do, or how negative bars fit into the structure of this metaphor. The case study in section 6.5 will present examples of students reasoning about positive and negative energies with the bar chart representation, and illustrate that they are not necessarily stably associated with a single metaphor. In sections 6.3 and 6.4 we will discuss the negative energy issue and suggest a solution consistent with student and expert data and with the dynamic ontologies perspective.

6.3 Interdisciplinarity and negative energy

Our research in this area is in the context of developing and studying the NEXUS/Physics course (Redish et al., 2014; Thompson et al., 2013), an introductory physics course[13] for undergraduate biology students that is focused on building interdisciplinary coherence between physics, biology, and chemistry. In a traditional introductory physics course, the energy curricular unit focuses on mechanical energy: kinetic energy and macroscopically detectable potential energies (usually gravitational and elastic). “Chemical energy” (i.e., energy changes associated with chemical bonds and chemical reactions) is most typically treated as a black box (to account for where the missing mechanical energy went) if at all (Cooper & Klymkowsky, 2013). This approach comes up short for biology students, because most energy relevant in biological systems is chemical energy, and so the traditional physics sequence does not give them the appropriate tools to analyze energy in biological situations. These students encounter energy in each of their science classes, but can end up with a fragmented picture of energy when the different science disciplines treat energy in disconnected ways (Dreyfus et al., 2012; Hartley et al., 2012).

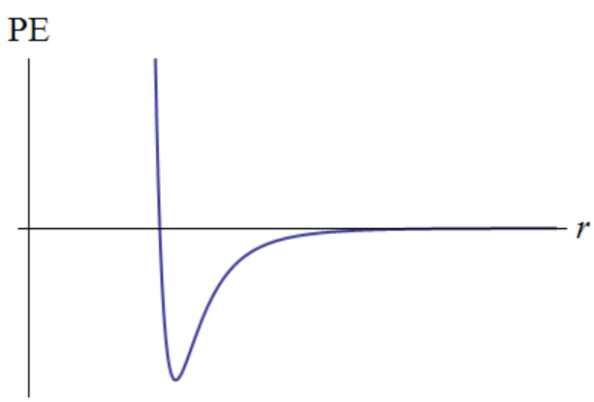


Figure 6.1. The Lennard-Jones potential, approximating the interaction between two atoms.

Therefore, chemical energy is a core component of the NEXUS/Physics course’s treatment of energy (see chapter 4), following other physics courses for the life sciences (Potter et al., 2014). Electric forces and electric potential energy are moved

[13] See http://nexusphysics.umd.edu .

up to the first semester and used to model (qualitatively) the potential for a system of two interacting atoms (Figure 6.1). This leads to a description of chemical bonds in terms of electric potential energy and other constructs that connect to the overall conceptual framework of physics. This approach is intended to help students build coherent models of energy that connect physics, biology, and chemistry: it addresses the energy phenomena that are essential to biology and chemistry, but from a physics perspective.

The concept of negative energy is essential to modeling chemical bonds in terms of electric potential energy. When two atoms are bound, their energy is less than the energy of the same atoms if they were unbound. If the energy of unbound atoms is taken to be zero, then the energy of the bound atoms is negative. Unlike models of gravitational potential energy (*mgh*) that are common in introductory physics courses, the “zero” point of potential energy in this model is not arbitrary. Zero potential energy has a specific physical meaning here: the energy when the atoms are far enough apart that they are not interacting. Shifting the zero point below the strongest bond in the system to make all energies positive (in order to preserve the substance ontology) would mean that adding new molecules to the system (which have the capacity to form additional bonds) would require shifting the zero again, with no limit. Modeling bound atoms with negative energy contributes substantial conceptual clarity by allowing for a common “zero” point in the absence of interaction. Therefore, when chemical energy is a central piece of the overall energy picture, the representational tools in use need to be set up so that negative energy is accessible from the beginning.

While there are sound conceptual reasons for the use of negative energy to model chemical bonds in this context, we know that negative energy has also been shown to be a subject of confusion for students. Stephanik and Shaffer (2012) document the belief that potential energy cannot be negative, as well as the belief that kinetic energy cannot exceed total energy. (This latter belief may also have roots in the substance ontology; if the total energy is a pie, it is inconceivable that one slice of the pie could be larger than the entire pie.) Lindsey (2014) shows a tendency to look only at the magnitude of the potential energy, and therefore to conclude that a system of two (electrostatically or gravitationally) attracting objects has greater potential energy when the objects are closer together. While these concerns may weigh against the instructional use of negative energy, they may be mitigated by ontological choices in reasoning about energy. Specifically, as we will discuss in the next section, reasoning about negative energy with the location ontology may bypass these difficulties.

6.4 Blending the ontologies

6.4.1 Theoretical argument

While other authors operating in different instructional contexts have argued for the primary use of the energy-as-substance ontology, our student population and curricular goals lead us to a different cost-benefit analysis. Scherr et al. (Scherr, Close, McKagan, et al., 2012) are exploring these questions in the context of a professional development program for K-12 teachers, and Brewe's (2011) Modeling Instruction course is for undergraduates from all the science and engineering majors. Neither context demands the same special concerns that are occasioned by our interdisciplinary context that attempts to form deep connections between physics and biology. The centrality of negative energy in modeling bonding and chemical reactions means that an exclusive substance ontology for energy is untenable. (Paradoxically, it is not only straight "physics" contexts that are able to sufficiently black-box chemical energy to treat it as a positive substance. Straight biology contexts frequently do the same. It is the interaction between physics and biology, and the use of physics constructs to describe phenomena relevant to biology, that necessitates opening up this black box and engaging with negative energy.)

The energy-as-vertical-location metaphor is better suited for energies that can be positive or negative: Extending the substance ontology to negative quantities requires complicated maneuvering (e.g. defining a negative substance that cancels out when it combines with the positive substance). However, it is no more conceptually difficult to be at a location "below" zero than at a location "above" zero. The location ontology for energy is also in common usage among expert physicists, such as in the potential well metaphor (Brookes & Etkina, 2007).

However, it is hard to imagine a comprehensive picture of energy that is based exclusively on the location ontology. The location metaphor succeeds at capturing some important aspects of energy: energy is a state function (i.e., the energy of a system is independent of the path that the system took to reach that state); energy can be positive or negative; changes in potential energy are more physically meaningful than the actual value of potential energy (not obvious in the substance metaphor, in which the value of potential energy appears to have physical meaning); intuitions based on gravitational potential energy about the relationship between energy and force (and embodied experience about up and down) can be applied to other non-gravitational energies. But there are other aspects that the location metaphor represents less effectively: interactions and energy transfer among objects in a system; energy is conserved.

The use of these two metaphors for negative numbers is explored extensively in the mathematics education literature, though not in the same language we use here. Ball (1993) writes about teaching negative numbers to elementary students, and uses two primary models: a building with floors above and below ground (analogous to the vertical location metaphor), and money and debt (analogous to the substance metaphor). The students in Ball's study had greater difficulty with the money and debt representation. Streefland (1996) and Linchevski and Williams (1999) contrast substance metaphors for negative numbers (positive and negative cubes) with thinking about positive and negative numbers as processes or changes in some other quantity (people getting on and off a bus).

Though neither the substance nor the location ontology for energy is adequate on its own for the reasons outlined above, combining the two addresses these shortcomings. We suggest that the framework of conceptual blending (Fauconnier &

Turner, 2002) is appropriate to describe this combination of ontologies. The authors are currently developing a more rigorous analysis of why this constitutes blending the ontologies (rather than switching between two distinct ontologies) which will appear in a future publication.

6.4.2 Empirical proof of concept

We have begun a theoretical argument in favor of blending the substance and location ontologies for energy, and we now present empirical examples. These examples illustrate what this ontological blending looks like in practice, and make a plausibility case that both experts and students are able to do it productively (in response to the argument that expert-like reasoning is characterized by the use of a single ontology).

As part of a larger research project on the NEXUS/Physics course, we collected video recordings of each class for the first two iterations of the course. We analyze the transcript data by coding for predicates (Slotta et al., 1995) associated with the substance and location ontologies. Slotta et al.'s taxonomy of predicates includes a list of substance predicates, but does not include location as a category. However, for the reasons we have discussed, we believe the energy-as-location metaphor is sufficiently different from the energy-as-substance metaphor that we analyze it separately.

Substance predicates include all language that describes energy as a material substance, such as "put in," "release," and "store." Location predicates include all language describing a location or movement, such as "here," "go," "up," and "down," but only when the energy **is** the location where some physical object or system is located. (If the energy is described as being **at** a location, this is considered a substance predicate.) In the transcripts below, the use of the energy-as-substance metaphor is <u>underlined</u>, and the use of the energy-as-location metaphor is in **bold**. This coding excludes language (such as "get them back apart") that refers to the *spatial* location of the atoms, since that location is literal and is not a metaphor for energy.

First, we claim that the blended substance/location ontology for energy is common among expert physicists. This is illustrated by the following classroom transcript from a physics professor teaching the NEXUS/Physics course.

> *If the two atoms are apart and form a bond, they* ***drop down to here*** *and <u>release that much energy</u>. And because that's* ***where they are, at that negative energy****, that's equal to <u>the energy you have to put in</u> to get them back apart. So it's just about* ***where you're going****, that when you're forming a bond, you're* ***dropping down****, and if you come in* ***at this energy*** *you <u>gotta get rid of this much</u>. But if* ***you're down here*** *and you want to* ***get back up to here****, <u>you gotta put in this much</u>.*

Here, the substance and location ontologies are combined in a productive way, and the professor fluidly moves between these metaphors within a single sentence. The blended ontology is consistent: the energy of the system of atoms is described as a vertical location, and changes in the energy of the system are described as a substance (that enters or leaves the system). There is nothing extraordinary about this quotation; it illustrates a standard way that expert physicists talk about energy, especially in atomic and molecular contexts. Another typical example is found in *The Feynman Lectures on Physics* (Feynman, Leighton, & Sands, 2011b): "If an atom is initially **in one of these 'excited states,'** … sooner or later **it drops to a lower state** and <u>radiates energy in the form of light</u>."

This blending can also be productive for students. A well-documented issue in biology and chemistry education is the student difficulties around "energy stored in bonds" (see chapter 5). The causes of this problem can be traced to multiple sources, but the inappropriate application of a substance ontology for energy may be partially responsible. The substance ontology supports a metaphor in which a bond is a piñata containing "stuff," and the stuff (energy) is released when the bond is broken. One student, Anita[14], explained in class that she used to think about bonds this way: *"whenever chemistry taught us like exothermic, endothermic, … I always imagined like the breaking of the bonds has like these little molecules that float out."* She was using this metaphor *"until I drew … the potential energy diagram, and that's when I realized, to break it you have to put in energy."* In a follow-up interview in which she was reflecting on this specific discussion in class, Anita said that she now had "*a better way to visualize the breaking and formation of a bond*" and explained her use of the potential energy graph (with the substance and location predicates once again coded in the transcript):

> *What I imagine it is, to get it to break, you need to <u>put in energy</u>. So to **get up the hill**, you need to <u>input energy</u> … Say that you're **bicycling up the hill**. You <u>need energy to put it in</u>, that's what breaks the bond, but to bring them back together, it's <u>released</u>. So I just think of—when you're **falling down**, if you're **going down a hill with a bike**, you're not <u>putting in energy</u> to the pedals, but yet your pedals keep going so there's <u>energy released</u>.*

According to Anita's self-report, her initial exclusive use of the substance metaphor led her to claim incorrectly that energy is released when bonds are broken. In this interview clip, we see Anita using the location metaphor to leverage intuitions about gravity in a non-gravitational context. Even though the location language that she uses does not directly refer to energy in the same manner as the instructor's language above ("you come in at this energy"), and instead could be interpreted as referring to a literal hill, Anita makes clear several times during the interview segment that she is using the bicycle on the hill as an extended metaphor for the energy associated with chemical bonds. She says "*I just picture a hill, even though this potential[?] diagram is telling me the potential energies of each stage of the atoms, of the two atoms as they're colliding*." (If Anita were actually talking about

[14] All names are pseudonyms.

bicycling up a hill, rather than using bicycling up a hill as an analogy, then we would not code her location language as the energy-as-location metaphor.) Thus, Anita now describes herself as visualizing energy in terms of a hill, rather than as "little molecules that float out" (though in her description of the hill analogy, she continues to use substance predicates for energy as well). Switching to a blended substance/location ontology has helped her develop a more correct understanding of chemical bond energy.

The data in this section are "clean" examples of blending the substance and location ontologies for energy, representing a way of thinking about energy that a student or expert has already found productive. In the next section we examine some "messier" examples, in which this blend arises in the midst of trying out other ideas while reasoning about a new situation. The case study data in the next section give us the opportunity to consider the factors that can make the blend more or less successful.

6.5 Case study: How a kinesin walks

6.5.1 The kinesin task

In this section we analyze, through the lens of ontological metaphors for energy, one group problem-solving task that asks students to reason about chemical bond energy, and students' work on this task in groups. The kinesin problem was used in both of the two pilot years (2011-13) of the NEXUS/Physics course (with some revisions between the two years) during the weekly discussion section where students work on problems in groups of four. We collected video recordings of two groups during the first year and four groups during the second year; the examples that we analyze here are from the second year.

Kinesin is a motor protein that "walks" (Yildiz, 2004) along microtubules to transport cargo within cells. This active transport is powered by the hydrolysis of ATP (see chapter 5). In the kinesin task, students are given a "frame-by-frame" description of the kinesin's motion (Figure 6.2), and are asked to produce energy bar charts to keep track of the energy transformations that take place during this process. They are asked to account for energy conservation in each frame, and are finally asked to discuss what it means to say that a cell "uses ATP to fuel molecular movement" (a statement they might see in a biology class).

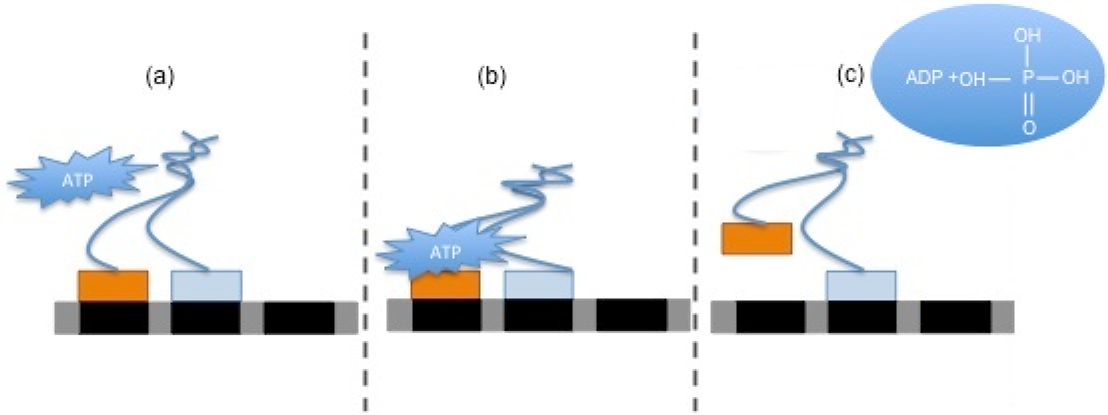


Figure 6.2. The picture given to students in the kinesin task, along with a description of the kinesin's motion.

The task was formulated in an open-ended way, and therefore there were many possible approaches the students could have taken (and did take) in creating their energy bar charts. They were explicitly asked to define their system, and were not told which objects to include as part of the system. They were also not told which energies to include in their bar charts, so student groups took different approaches about whether to use chemical energy or potential energy[15], and whether to consider the chemical/potential energy "of" particular molecules, or of interactions among them.

Though the kinesin task was used only for group discussion and was not graded, we would consider a complete solution to be one that accounted for the kinetic energy of the kinesin, and the changes in chemical (or potential) energy associated with the bonding between the kinesin and the microtubule, between the kinesin and the ATP, and the ATP hydrolysis reaction itself. We would also expect a correct solution to incorporate the correct sign for the changes in energy associated with the formation and breaking of bonds (breaking a bond requires energy to be taken away from some other part of the system). However, the students were not instructed on what level of detail they needed to include. Therefore, it was possible to complete the task in an internally consistent way (at a relatively coarse grain size) by treating all chemical energies as positive (as is done in other settings that use substance-based representations for chemical energy (Scherr, Close, Close, & Vokos, 2012)). Nothing internal to the task would necessarily lead the students to reconsider this and shift their representations to using negative energy. This was an unintended consequence of the open-ended task design; while this task was not intended specifically to motivate the need for negative energy, we also expected that students would use

[15] We understand "chemical energy" and "potential energy" to be largely interchangeable when referring to potential energy associated with chemical bonds; however, the students may or may not understand these terms in that way.

negative energy in their bar charts. Some groups did spontaneously use negative energy; others did so only after a suggestion from the TA (and these groups varied in their stances on whether this was something they should have been doing or whether it was a pointless hoop to jump through). Here we examine some of the video data from student groups that were modeling negative energy under these various circumstances.

The kinesin task was selected for analysis because it provides opportunities for the students to reason about negative energy. The specific episodes below were selected because they include explicit discussion of the negative sign of energy and we were able to identify ontological metaphors for energy in the student discourse that seem to be coupled to key aspects of students' reasoning. (There are many other cases where ontological metaphors for energy are used in fleeting ways.) As we discuss below, these two episodes represent different ways of combining the substance and location ontologies for energy that are associated with different results in reasoning about the conservation of energy. The sample size from this task is small, and the approaches varied, which makes it difficult to determine whether these particular examples were typical or outliers. We include them as examples that are in the set of possible responses. Though our argument is primarily theoretical, this case study helps us to refine some of the specific implications.

6.5.2 Phillip's group: Confusion about negative energy

We look first at Phillip's group, working on the energy bar charts portion of the kinesin task. This is their first substantive group discussion during this task, after running quickly through the first parts. They initially draw all of the bars (including those representing the "chemical energy" associated with the bonds) as positive. The language they use around energy suggests that they are talking about it as a positive substance that can be divided up into smaller pieces. For example, Phillip says "This is like the total energy of the system. It's all chemical right now." Later, when an instructor asks "What's the potential energy here?" Phillip says "100%," and Otis clarifies "Like all of it." (If any of the energies can be negative, it does not make sense to say that "all" of the energy is a particular form, since the kinetic energy could be greater than the total energy as in Figure 6.3, or the total energy could be zero or negative.) In addition to the "all" language, Phillip uses "container" predicates that also suggest a substance ontology: "all the energy's in chemical;" "all of it's in ATP, the bonds;" "ATP itself has lots of energy within its bonds."

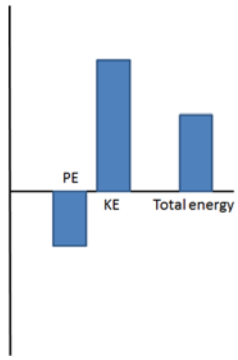


Figure 6.3. An example of an energy bar chart in which the kinetic energy is greater than the total energy.

A learning assistant (LA) reminds the group of the potential energy graph that they have seen for chemical bonds, and gets them to say that the energies representing the chemical bonds should be negative. However, they are not entirely convinced that changing their bar graph to include negative bars is necessary. When the TA comes over later and asks them about their decision to make all the bars positive, Phillip responds:

Phillip: *We said absolute value, like the magnitude of the energy.*
TA: *Why did you decide to take the absolute value?*
Phillip: *Because it doesn't really matter later on, because everything else, like this potential, whatever, it just matters where you put the zero.*

Phillip is avoiding negative energy (despite a suggestion to consider it) by making all the energies positive, which is a valid move under some circumstances (possibly including the kinesin task itself). However, he confuses two different methods of making negative quantities positive: translating all the potential energies by a constant amount (moving the zero), and taking the absolute value. While the former method preserves conservation of energy, the latter does not.[16] In other words, rather than moving the zero so that it is below the lowest energy in the system (making all the bars positive), Phillip's strategy is to flip all of the negative bars upside down (also making all the bars positive).

In the mathematics education context, Ball (1993) writes that "comparing magnitudes becomes complicated. There is a sense in which −5 is more than −1 and

[16] To illustrate this with a numerical example: Suppose the initial potential energy is −2 and the initial kinetic energy is 5, and the final potential and kinetic energies are −4 and 7. Then the initial and final total energies are both 3, so energy is conserved. Now, if we move the zero of potential energy by 12 so that the initial potential energy is 10, then the final potential energy is 8 (thus all the energies are positive), and the initial and final total energies are both 15, so energy is still conserved. However, if we instead take the absolute value of potential energy, then the initial total energy is 2+5 = 7, and the final total energy is 4+7 = 11, and energy is not conserved.

equal to 5, even though, conventionally, the 'right' answer is that −5 is less than both −1 and 5. … Simultaneously understanding that −5 is, in one sense, more than −1 and, in another sense, less than −1 is at the heart of understanding negative numbers."

Similar issues arise in physics, particularly in our interdisciplinary context. In most cases when we talk about negative energy, the "magnitude" is a distraction with no physical significance, since the zero point for potential energy is an arbitrary choice. In those cases, it is obvious that −5 is less than −1 (albeit not always obvious to students). However, in the context of chemical bonds, there is also a sense in which −5 is "more" than 1. A chemical bond with a deeper potential well, associated with a lower (more negative) potential energy, can also be described as a "stronger bond" or "more stable." In chemistry contexts, chemical binding energies are typically reported as positive quantities (absolute values).

Phillip may be activating two different "negative energy can be treated as positive" resources: 1) potential energy is relative, so the zero point can be placed anywhere, 2) "There is a sense in which −5 is more than −1." Each of these resources can be individually useful, but the combination (in the context of energy conservation) leads Phillip and the group to inappropriate reasoning (which will lead to internal inconsistency when they try to keep track of energy conservation) and to resistance to the instructors' interventions.

The "potential energy is relative" resource is situated more in the energy-as-location ontology, as we see in Phillip's utterance "where you put the zero." The "−5 is more than −1" resource belongs more to the energy-as-substance ontology: larger negative stuff is more than smaller negative stuff. Thus, this example represents a mixing of substance and location predicates in a way that leads to confusion. This confusion can be manifested both in canonically incorrect results and in internal incoherence.

6.5.3 Peter's group: Productive blending of the substance and location ontologies

Another group working on the same problem starts out talking about energy "stored in the bond," and is unbothered by this idea. As they work through the task and draw their bar charts, they treat all energies as positive, and talk about energy stored in ATP, e.g. "ATP has all the potential energy." But after they overhear the TA saying to another group "…the idea that bound stuff has a negative energy," they quickly reconsider their approach and start incorporating negative energy into their model. When the TA comes over to their group, Peter asks "Would you represent something like the energy that this [kinesin] has while bound to the microtubule as negative energy, 'cause it's like an energy barrier that has to be overcome via the ATP to make it come off?" Tiffany later explains this as "the negative is when energy has to be input to break the bond."

The group classifies which of the energy bars should be positive and negative, and then tries to figure out how to make sure energy is still conserved. They have this discussion, looking at bar charts similar to Figure 6.4:

Peter: *So what does this have to sum up to?*
Tiffany: *Whatever it starts off at–*
Peter: *Just whatever it started off, ok.*
Tiffany: *Yeah, whatever it starts out at the beginning.*
Zara: *I think it would be negative. The total is [inaudible].*
Peter: *So essentially the well, the net well of the ATP and the bond to microtubule* <u>*has to equal one big well*</u> *from the ADP.*
Tiffany: *'Cause at the end we'll be left with two things. We had the kinetic and the–*
Peter: *But kinetic's up.*
Tiffany: *Yeah.*
Peter: *And the ADP is down. So the ADP has to be* ***so low*** *that it's equal to the initial two gaps put together, plus wherever* (**Zara:** *yeah*) *the velocity goes. So, ok, so ADP is like* ***waaaaay down****. Essentially.*
Zara: *Yeah.*
Peter: *Ok. Got it.*

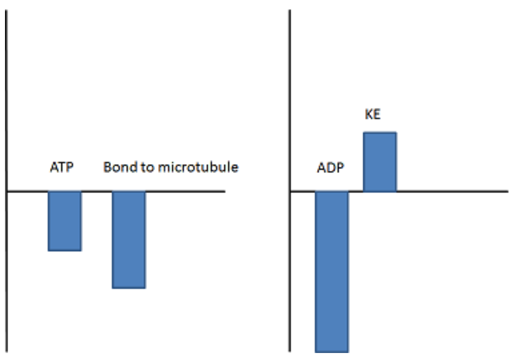


Figure 6.4. A reconstruction of the bar graphs drawn by Peter's group.

Peter is doing qualitative arithmetic with the energy bar charts, using positive and negative bars. The bar chart representation is intended to illustrate the conservation of energy by showing that all the bars add up to the same total. But this is only visually obvious when all the bars are positive, so that the total area of all the bars is constant in each frame. In Figure 6.4, even when the lengths of the bars are adjusted (as the group is negotiating in the transcript clip) so that energy is conserved, the total area of the bars in each frame will not be equal, because some bars represent positive quantities and some represent negative quantities. Therefore, an exclusive substance metaphor (which maps the amount of energy to the amount of bar "stuff") does not work here.

We suggest that Peter is combining the substance and location ontologies for energy, though this is more subtle than in the examples in section 6.4. When Peter talks about the two wells adding up to one big well, we code this as an energy-as-substance metaphor (even though the "substance" here represents a negative quantity); he is describing the size of a well as “stuff.” But when he says the ADP is “so low” and “waaaaay down,” he describes the ADP as being at a vertical location.[17] Finally, the logic that “it’s equal to the initial two gaps put together, plus wherever the velocity goes” does not seem to be obviously based in either metaphor; rather, Peter seems to be doing (qualitative) algebra in his head, and mapping it back onto the bar chart representation.

Peter’s blended ontology, though it contains the same ingredients, is different from the professor’s blended ontology in section 6.4. There, the professor consistently used the vertical location metaphor for the energy of the system, and the substance metaphor for changes in the energy of the system. Here, it is more difficult to isolate when each metaphor is used: does ADP **have** a well, or is it **in** a well? It is possible that the use of the metaphors is determined by the type of operation that is being performed: addition of negative numbers is simple enough that it can be visualized with a substance ontology (in the same manner as addition of positive numbers, of which it is just the mirror image), but other operations such as subtraction involving both positive and negative numbers require the location ontology. There are not enough data here to reach a strong conclusion about the exact nature of the blended ontology that Peter uses here. However, he uses this combination of metaphors in this moment to make progress on this energy task. This progress is evident in that he is able to account for the conservation of energy in a way that both matches the canonically correct process and is internally coherent (in contrast to Phillip’s group, which struggles to reach this coherence).

Unlike Phillip, who uses a resource associated with one ontology when a resource associated with another ontology would be warranted, Peter uses the two ontologies in complementary ways. In the episodes that we have focused on, Peter’s approach is more successful, suggesting that combining the substance and location ontologies is insufficient; the blended ontology needs to have a structure within which the two metaphors can complement each other. Even though both ontologies are in use, they do not collide.

6.6 Implications and future directions

Interdisciplinary contexts for teaching physics are becoming more widespread and essential as physics becomes more integrated with the other sciences at both the professional and the educational level. Teaching energy in physics-for-life-sciences

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[17] It is also possible that Peter is using “ADP” as metonymy for “the ADP well” or “the ADP bar.” In this alternate interpretation, Peter is not referring here to the “location” (i.e. the energy) of the ADP molecule itself, but to the bar chart representation. We think that this distinction is not substantial, because the representation is closely coordinated with the verbal use of ontological metaphors. Even if Peter is primarily referring to the bar chart, the general claim about coordinating the substance and location ontologies still stands. Talking about the ADP bar as “so low” and “way down” is giving it a location meaning, which differs from the substance interpretation of looking at the size of the bar.

contexts, in which chemical reactions are a central phenomenon of study, implies a more primary role for the concept of negative energy in introductory courses.

Negative energy furthers the goal of bridging canonical physics models of potential energy (e.g. electrostatic interactions based on Coulomb's Law) with canonical chemistry and biology models of bonding and chemical reactions (e.g. attending to overall energy changes in a reaction (see chapter 5)). We have argued here that this goal changes the pedagogical considerations and conclusions regarding ontological metaphors for energy that are supported in the instructional context. Instead of focusing on a single ontology for energy, capturing all the relevant characteristics of energy for building this bridge requires a blended ontology.

In the same way that coordinating multiple representations (Van Heuvelen & Zou, 2001) has been shown to be useful in building expertise in both energy and other domains, we suggest that coordinating multiple ontological metaphors can accomplish similar goals in moving towards expertise. We see this productive coordination of ontological metaphors in the data, with examples from experts as well as students who are displaying reasoning that is expert-like to varying degrees. Experts have developed a coherent blended ontology; when students access multiple ontological resources, they have the possibility of coordinating them coherently, or of getting them confused. When the ontologies are mixed haphazardly, this may lead to confusion, but if the blended ontology has a governing structure, it can be productive. Our case studies illustrate both possibilities: both Peter's group and Anita were successful in coordinating the substance and location ontologies to reason about chemical energy, while Phillip's group had difficulties tied to the failure to coordinate these ontologies.

The possibility of confusion has motivated other authors to call for the primary use of the substance ontology in instruction, but in our interdisciplinary context, we call for instructional approaches that help students achieve coherent coordination of ontological metaphors. This may not be necessary or the most effective use of effort in all pedagogical contexts, but in interdisciplinary physics contexts that foreground chemical energy, attention to blended ontologies for energy is worthwhile.

Going forward with this agenda raises a number of practical and theoretical questions, which provide directions for future work. To what extent can student difficulties with the ontology of negative energy be attributed to the specific context of energy, and to what extent do they represent more general difficulties with negative numbers (as documented in the math education literature)? How can the coherent blending of ontological metaphors for energy be explicitly taught? Others (Brewe, 2011; Scherr, Close, Close, et al., 2012; Scherr, Close, McKagan, et al., 2012; Scherr et al., 2013) have developed representations and activities that can comprise an energy curriculum based on the substance metaphor. Are there representations that can support blending (Podolefsky & Finkelstein, 2006)? Or is ontological blending best supported by the coordination of multiple representations, each associated with a single ontological metaphor? The coherent coordination of ontologies requires the development of epistemological resources to determine when it is appropriate to use each metaphor; what pedagogical approaches can support this development?

These issues around ontologies for physical concepts are complicated, and the ontologies that students use are dynamic and arise from multiple sources. Therefore, advising educators to be careful about the metaphors they use in their own speech (Veiga, Costa Pereira, & Maskill, 1989) is neither feasible nor likely to be effective. Conversely, even if experts already use blended ontological metaphors in their speech, we would not expect that their continuing to do so would be sufficient to help students develop blended ontologies, since mere exposure to multiple ontologies is not sufficient to build them into a coherent structure. What are the ways that educators can model blended metaphors effectively for students?

The existing work on ontological metaphors for energy has focused on introductory courses, and we have shared that focus, albeit in a specific interdisciplinary course context. However, the "expert" examples that we have presented suggest that blended ontologies for energy may be productive for physicists even in the absence of the interdisciplinary considerations that motivate us. A new direction to explore is the role of blended ontologies for energy in (not necessarily interdisciplinary) physics courses beyond the introductory level.

Implications for researchers include an illustration of the use of the dynamic ontologies framework for making sense of students' reasoning. When this framework is applied to a complex interdisciplinary issue, we see a phenomenon that had not previously been documented within this framework: the productive coordinated use of multiple ontologies in service of a single explanation of a physical phenomenon (as distinct from the ability to access multiple ontologies for the same entity in different situations). This opens up a research agenda to explore ontological blending beyond the energy contexts, both in its general aspects and as applied to other physical phenomena.

Chapter 7: Discussion and Conclusion

7.1 Summary and synthesis

This thesis has described three different aspects of the problem of interdisciplinary coherence about energy: topical connections (chemical energy), interdisciplinary reconciliation, and ontological metaphors. Each of these aspects corresponds to the central theme of one of the three body chapters (4–6), but each one is also a thread that runs through all three chapters. In this section, we synthesize each thread, one by one. For each thread, we begin by summarizing the chapter that is most focused on that thread, then explain how that thread is also present in the other two body chapters.

7.1.1 Topical connections: chemical energy

Chapter 4 presents a curricular approach to promoting interdisciplinary connections about energy in a physics course. We distill the key points of this approach here:

- Chemical energy is a nexus for connections among physics, biology, and chemistry
- Chemical energy is treated as a core element of the general treatment of energy in the course
- Chemical energy is understood in terms of potential and kinetic energy at the molecular scale
- Microscopic and macroscopic pictures of energy can be connected both directly (macroscopic interactions are the aggregate of many microscopic interactions, and energy is conserved at all scales) and by analogy (microscopic interactions can be understood by analogy to more familiar macroscopic interactions)
- Students should come away with the epistemological belief that it is possible to connect biological, chemical, and physical phenomena even if they do not have all the conceptual tools to complete all of these bridges.

Chapter 5 points to a particular subtopic that an interdisciplinary energy curriculum should give students the tools to understand: ATP (with central importance to biology) and chemical bonds (with central importance to chemistry). If a student is able to explain the “high-energy bond” in ATP in a way that acknowledges the biological significance and accounts for the relevant chemical reactions and physical mechanisms, that student has achieved a goal of interdisciplinary coherence around energy.

Chapter 6 argues for the importance of negative energy in modeling chemical bonds in order to develop a coherent picture that includes both atomic and molecular energies and mechanical energy. Negative energy is therefore a conceptual component of the curriculum detailed in chapter 4.

7.1.2 Interdisciplinary reconciliation

In chapter 5, we developed a model for interdisciplinary reconciliation. We want students to be fluent in the language of each discipline, to understand the conceptual relationships between the ideas in the various disciplines, and to make and justify modeling choices about which set of constructs to apply in a given situation. In the context of the theoretical framework described in chapter 2, we understand this as the context-dependent activation of resources, in which the dependence on disciplinary context, with multiple local coherences, is valuable in learning to be fluent in multiple disciplinary languages. We observed students engaging in this interdisciplinary reconciliation, in a course context that made it possible.

The chemical energy thread described in chapter 4 is intended to enable interdisciplinary reconciliation, by introducing students to the language and models of physics, and giving them opportunities to connect these to models from biology and chemistry. In that chapter, we documented further instances in which students sought out opportunities for reconciliation.

The challenges that we grapple with in chapter 6, on ontological metaphors for negative energy, are sparked by the interdisciplinary context designed to promote reconciliation. In both introductory biology and some introductory physics settings, it is possible to treat energy as a positive quantity and rely primarily on the substance metaphor. Negative energy becomes central when the disciplines interact and chemical bonds are described with physics-based models. Furthermore, the ontological blending discussed in chapter 6 has structural similarities to interdisciplinary reconciliation, in that they both involve the context-dependent activation of resources, decisions about which resources to activate in a given context, and intentionally building coherent connections between those resources.

7.1.3 Ontological metaphors

In chapter 6 we discussed the substance and location metaphors for energy, and argued that a blended substance-location ontology can be productive in reasoning about negative energy. We showed evidence of students and experts blending the substance and location ontologies productively to reason about chemical bonds and chemical energy, in both a general chemical context and a biological context. We compared instances in which the combination of the two ontologies was productive and unproductive, and suggest that a more systematic use of the two ontological metaphors (which experts may do unconsciously) may be necessary in order for the blend to be successful.

The chemical energy thread in chapter 4 is strongly coupled to a thread on representational competence. A goal of the chemical energy thread is that students will learn to use and coordinate multiple representations for energy. Many of these representations contain embedded ontological metaphors for what energy is, and so the skill of coordinating representations for energy overlaps with and contributes to the skill of coordinating ontologies. This includes the skill of determining which representation (or ontology) is appropriate for modeling a particular phenomenon or answering a particular question.

The interdisciplinary reconciliation in chapter 5 can involve reconciling different ontological metaphors for energy used in the different disciplines. In the specific case of ATP discussed there, the language of "energy stored in the bond" associated with biology reflects a substance ontology for energy. The student data in chapter 5 involve students reconciling this model with language such as "higher energy level" and "well" that reflects a vertical location ontology.

7.2 Implications for instruction

For educators, the chemical energy thread represents an approach to incorporating chemical energy into an introductory physics course for the life sciences and to bringing the disciplines into closer contact. We hope that these materials will continue to be adapted, and that other threads that support interdisciplinary connections will be developed.

The interdisciplinary reconciliation paradigm can inform the development of tasks that address disciplinary differences. Implications of this paradigm for task design include explicit awareness of differences in disciplinary languages, assumptions, and modeling choices. Interdisciplinary reconciliation can be supported by a course environment that encourages students to bring in ideas from other disciplines and to think of multiple ideas and perspectives as potentially being simultaneously correct.

In the same way that coordinating multiple representations (for energy and other concepts) can be useful in building conceptual understanding and expertise, coordinating multiple ontological metaphors can be similarly useful. We suggest that curriculum and task designers take ontology into account, with an eye toward coordinating multiple ontologies, whether within a single blended representation or through the coordination of multiple representations.

7.3 Implications for research

This dissertation is an early contribution to the emerging field of interdisciplinary science education research. Though there is little work so far on how students understand ideas across disciplines (Stevens et al., 2005), this is an area that will undoubtedly grow, as there is growing interest in interdisciplinarity among educators and researchers. Our work suggests to future interdisciplinary education researchers that we cannot expect to reuse all of our theoretical and methodological principles from physics education research without alteration. While the similarities across the disciplines mean that many of these principles still apply, we can expect that there will need to be some modifications because of epistemological differences among the disciplines, and between disciplinary and interdisciplinary approaches to learning.

In chapter 5 we found that existing approaches within physics education to the reconciliation of ideas are not always appropriate when the ideas to be reconciled are associated with different disciplines. The existing approaches in physics assume one stable equilibrium of expert knowledge on a given topic, while interdisciplinary reconciliation works with multiple local coherences even at the expert level. While this approach may also find applications within individual disciplines, it is the interdisciplinary setting that first highlighted the need for it.

In chapter 6 we followed up on other work in PER that had focused on the primary use of the substance ontology in physics education. We found that the balance of interests was different in our interdisciplinary setting, and that the interdisciplinary setting called instead for blended ontologies. This opens up a number of future research questions at both the theoretical and empirical levels: Is a blended ontology in fact "blended" in the sense of conceptual blending (Fauconnier & Turner, 2002), or is it composed of separate ontologies that remain distinct (though one can move fluidly between them)? How can the coordination of multiple ontological metaphors be explicitly taught? What representations can support ontological blending? Again, while there may be applications within physics (or biology or chemistry), the interdisciplinary context made the need clear.

7.4 Future directions

This dissertation sets out to explore students' interdisciplinary reasoning about energy. While much has been learned, we have only scratched the surface of this rich and complex issue, leaving many more questions to investigate.

7.4.1 Additional research on NEXUS/Physics

We presented the chemical energy curricular thread from the NEXUS/Physics course along with some example illustrations of student outcomes, and now that the course has been scaled up, we can evaluate its success for a larger student population.[18] One type of potential evaluation might be a multiple-choice concept inventory on chemical energy or on interdisciplinary ideas about energy. This type of assessment has the advantages of being easy to administer, and easy to compare scores across multiple course settings. However, it would only be able to assess a limited slice of the questions we are interested in (as discussed in chapter 3), and a multi-year investigation would be needed to confirm reliability and validity before the survey instrument could be used to make meaningful comparisons. Even then, it is not clear what the appropriate control group would be, since the chemical energy thread includes content that is generally not addressed in introductory physics courses.

[18] The course itself may change in the scaling-up process, and may not simply be the same as the pilot course with more students added. Many other parameters are changing aside from the number of students. This process is itself a potential subject of future research.

In the meantime, the NEXUS/Physics research team is conducting other assessments on the scaled-up course. On the conceptual side, some of the free-response homework and exam problems that comprise the chemical energy thread have been selected to be scored with research-oriented rubrics, including the ATP reconciliation question discussed in chapters 4 and 5. This may enable researchers to document progress through the interdisciplinary reconciliation process, across many students. On the epistemological side, the students have taken a Perceptions of Interdisciplinary Bridges (PIB) pilot survey at several points during the year, assessing students' attitudes about the relationships between disciplines. The timing may make it possible to assess the impact of the chemical energy thread (along with the related entropy and free energy thread) on these perceptions.

A full model of energy that connects physics to biology and chemistry needs to include entropy, free energy, and other concepts related to the Second Law of Thermodynamics. Free energy is the preferred measure used in many biology contexts to describe the energy of reactions, and also matches students' intuitions about energy being "used up" (Geller et al., 2014). Another dissertation from the NEXUS/Physics research group that addresses these issues is in preparation.

7.4.2 Intradisciplinary reconciliation

Our context for this work has been interdisciplinary, and the interaction between physics and biology has been fruitful for raising and investigating our research questions. However, there are also intradisciplinary contexts in which the same issues are relevant, and another direction for future research is identifying those contexts and applying our results there. We have described a model of "interdisciplinary" reconciliation that involves understanding the language of two different "disciplines" independently and building coherence that connects them. But this model could apply equally when the "disciplines" are two different subfields of physics. This is certainly true at the professional physics level, where, e.g., particle physics and condensed-matter physics make different modeling assumptions (though they both deal with electrons). It can also be true in an introductory physics course, where the model of energy in the mechanics unit might only account for center-of-mass motion, and the model of energy in the thermodynamics unit might account for everything **except** center-of-mass motion.

Similarly, the arguments for the use of negative energy in modeling chemical bonds are context-dependent, and this context dependence is not on disciplinary lines, but there are different contexts within physics that can lead to different modeling choices. In chapter 6 we showed that negative energy is appropriate for modeling chemical bonds in a context where we are interested in the formation and breaking of bonds and in the electrostatic and other atomic interactions that are responsible for bonding. In that context, it is natural to set the zero of potential energy to the configuration in which the atoms are far apart and not interacting (as is standard for electrostatics) and to treat chemical bonds as negative energy. However, this year in the NEXUS/Physics course we encountered a different situation: modeling temperature at the molecular level. When temperature is modeled using the equipartition theorem, there is an equal energy (proportional to the temperature) associated with each degree of freedom of the system. This applies to both kinetic and potential energies, and therefore is only possible if all energies are positive. In that model, the zero of potential energy has to correspond to the state of the system at absolute zero temperature. For an individual chemical bond within the system, this means the zero is at the “bottom of the well” rather than the top of the well. In that situation, it may be the case that the vertical location metaphor for energy contributes nothing useful, and an exclusive substance metaphor may be most productive. (The substance metaphor is invoked by the term “equipartition” itself, which suggests dividing up a substance into many equal pieces.) We want students to be able to reason within each of these models, and it would be a laudable goal for students to connect them coherently. That reconciliation would not be interdisciplinary per se, but similar principles would still apply.

7.4.3 Theoretical work on ontological blending

When we raised the issue of blended ontologies in chapter 6, we noted that there was still more theoretical work to do to place this phenomenon within the framework of conceptual blending (Fauconnier & Turner, 2002). We plan to do this analysis in an upcoming paper, along with empirical investigation of whether the ontologies are in fact “blended” or whether they remain separate (and the speaker is simply switching rapidly between them). To investigate this question, we plan to employ methods of knowledge analysis (diSessa, 1993) and gesture analysis (Scherr, 2008) alongside the predicate analysis (Slotta et al., 1995) that we used in chapter 6. Along with the NEXUS/Physics data, we will bring in another corpus of data, interviews with physics graduate students reasoning about phase transitions.

7.4.4 Extension to other student populations

The student population addressed in this dissertation, and in the NEXUS project as a whole, is undergraduates, and specifically undergraduate biology majors. There are different ways that the relationship between physics and biology can be framed in that setting, and we have advocated for an approach that respects the integrity and authenticity of each discipline. Still, in this setting, the relationship between the disciplines will never be fully symmetric. The students have primary identities as biology majors, and they are taking physics because it is deemed to be valuable for understanding biology. A future project is exporting the results of this work (and the rest of NEXUS/Physics) to other student populations where the relationship between the disciplines is different.

There is already a body of research on student learning of energy concepts in the K-8 setting, where science is not sharply subdivided into disciplines (as discussed in chapter 2). However, in the same way that research on interdisciplinary reasoning about energy was sparse in the undergraduate setting, it is also sparse in the high school setting. In most high schools, the disciplinary divisions exist; students take science courses that are labeled with the disciplines. As in college, there is often fragmentation, and the different science courses do not build on each other's content. (This is what the Next Generation Science Standards (Quinn et al., 2012) attempt to address with "crosscutting concepts.") There is a clear need for stronger interdisciplinary connections in the high school science curriculum. But this would necessarily look different from how it looks in the undergraduate curriculum. In the United States, high school students do not have "majors." Students take biology, chemistry, and physics courses, but do not do so identifying as biology students or as physics students. Any adaptation of the NEXUS/Physics curriculum (or other IPLS curricula) for high school would need to be reframed so that it is not physics "for" the life sciences, but still builds bridges between physics and the life sciences. Because most high schools only have one science department (unlike universities, with a department for each science discipline), this removes one institutional barrier to interdisciplinary cooperation.

Another student population that may benefit from some adaptation of the NEXUS/Physics curriculum and the associated research is undergraduate physics and engineering majors. One way to think about applying this work to that population is at the level of specific content. These students are generally not required to take any biology courses for their majors, but as biophysics and bioengineering become more prominent subfields in the 21st century, it will be appropriate to redesign introductory physics courses, even for physics and engineering majors, to enable stronger conceptual connections to biology. Furthermore, beyond the specific biologically relevant content, there have been more general lessons learned about interdisciplinary education that can be applied at other disciplinary interfaces. In the same way that developing the NEXUS/Physics course involved negotiations among physicists, biologists, and chemists, and an understanding of the ideas and background that biology students are bringing in, a transformed physics curriculum for engineering students (and vice versa) might involve physicists and engineers carefully listening to one another and to their students. The physics/biology interface is both similar to and different from the physics/engineering interface in important ways, so these discussions will need to take those similarities and differences into account.

Appendix: Selected Materials from the Chemical Energy Thread

This appendix includes static versions of selected materials from the NEXUS/Physics chemical energy thread that are referenced elsewhere in the dissertation, provided for reference purposes. The curriculum continues to evolve, and updated versions can be found at http://nexusphysics.umd.edu , at the chemical energy thread page. These materials are by Benjamin W. Dreyfus, Benjamin D. Geller, Julia Gouvea, Edward F. Redish, Vashti Sawtelle, and Chandra Turpen.

A.1 Group Problem-Solving Tasks

A.1.1 Investigating Protein Stability with the Optical Tweezer

I. Introduction. Various experimental and computational techniques have been developed to study the process by which proteins go from a linear sequence of amino acids to a precise three-dimensional structure.* The process is often represented by a "protein folding landscape," which shows the energetic peaks and valleys that an amino acid strand traverses as it goes from it's unfolded (U) to folded (F) state. There are usually local intermediate valleys in the landscape where "misfolded" (M) proteins live.

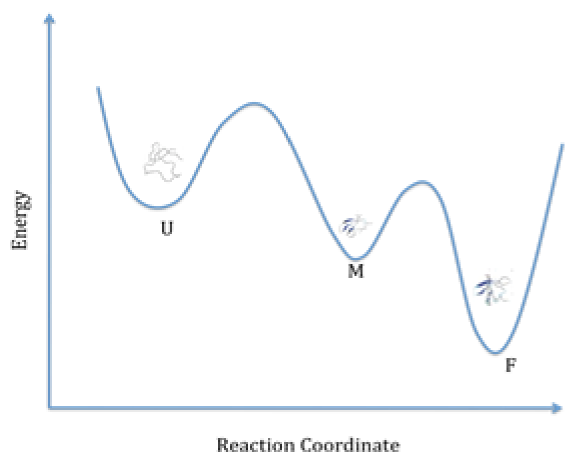


Figure 1. Protein Folding Landscape

Prompt 1: Which of the protein forms depicted in Figure 1 is the most stable? Describe changes to a protein or its surroundings that would stabilize it. Describe changes that would destabilize it.

That three-dimensional structure determines the protein's ability to function within a cellular environment, such that even slight changes to the structure can have catastrophic effects on an organism's ability to survive. The general problem of predicting a folded protein structure given only its linear sequence of amino acids is called the "protein folding problem" and is of the most important unsolved problems in molecular biology. Experiments of the sort described in this exercise do not "solve" the protein folding problem. However, by performing such experiments under a whole host of conditions and with a whole host of differently mutated protein species, it is possible to learn a tremendous amount about the pathway that particular proteins take in going back and forth between linear amino acid sequence and folded tertiary structure. A number of interesting papers describing this work can be found here, for anyone interested: http://zebra.berkeley.edu/publications.php

Experimental Set-up. Studying protein stability in a test tube involves studying millions of protein molecules at once. If one wants to study protein stability one molecule at a time, to search for idiosyncratic behavior that might not be evident in a test tube, one needs to devise some pretty clever technology. The optical tweezer set-up that we mentioned earlier in the course when studying the spring-like properties of DNA is a good way to do it. The APPENDIX to this recitation reviews that problem – go read that before continuing if you'd like a refresher! Now imagine that we have two such DNA springs, each acting as a "linker" or "handle," and that the protein RNase H is placed between the two, as shown in Figure 2.

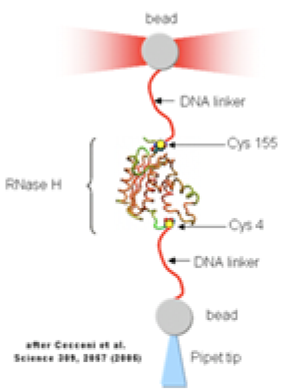


Figure 2. Optical tweezer set-up for protein folding experiments.

The polystyrene beads to which the DNA linkers are attached are held in place, one by a laser beam and the other (in this case) by the suction of a pipette tip. The protein RNase H is chemically attached to the DNA linkers via bonds involving cysteine amino acids at the two termini of the protein. Under normal physiological conditions, and under the conditions of this experiment, RNase H spends most of its time in its folded form, the form illustrated in the figure. By moving the focus of the laser beam slightly, we can begin to exert small forces on the DNA, and in turn on the protein to which it is attached, eventually supplying enough force to "unfold" the protein.

II. Making Predictions. Imagine that we mutate the amino acid sequence of RNase H, so that one alanine somewhere in its sequence is replaced by a lysine. This change, while seemingly small, serves to *destabilize* the folded protein structure, i.e., it makes its folder form *higher* in energy than the un-mutated species. Let's think for a moment about how that destabilized, mutated protein will behave under the conditions imposed by the optical tweezer.

Prompt 2: Do you expect the work required of the tweezers to unfold the mutated RNase H to be less or more than that required to unfold the wild-type RNase H. Why?

Prompt 3: Do you expect the force at which the unfolding occurs to be smaller or larger in the mutated case than it is in the wild-type (un-mutated) RNase H?

(BONUS! Do you think it is possible to mutate the RNase H in a way that <u>stabilizes</u> the protein relative to its wild-type form, i.e., in a way which <u>lowers</u> its energy?)

Prompt 4: If one does work on a protein with the tweezers, where does the added energy go?

<u>III. Looking at the Data</u>. The data obtained when force is applied to the system shown in Figure 2 is given in Figure 3 below.

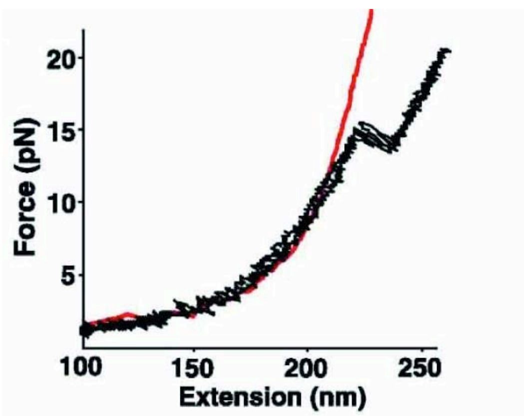


Figure 3. Data obtained when RNase H is explored via the optical tweezer set-up described above.

The "extension" in Figure 3 refers to the distance between the two beads in the experimental set-up, and the red line represents a *theoretical* prediction of what would be seen if no protein were present. Focus on the black curve, which shows what happens *experimentally* when RNase H is attached to the DNA linkers as in Figure 2.

Prompt 5: Focusing on the black curve in Figure 2, draw a physical picture that represents what might be happening to the protein and its DNA handles (a) when the applied force is between 0 and 15 pN, (b) when the applied force is about 15 pN, and (c) when the applied force is greater than 15 pN. Explain how your pictures correspond to the different regions on the plot.

The really interesting behavior occurs when the tweezer has applied a force of about 15 pN. Here, we see a sudden increase in the distance between the two beads, and we interpret that event to be the "unfolding" of the RNase H protein. Protein unfolding events often occur in multiple steps and can be far more complicated than the single-step unfolding process shown in Figure 3.

Prompt 6: Draw a protein folding energy landscape for RNase H that is consistent with the force-vs-extension data shown in Figure 3.

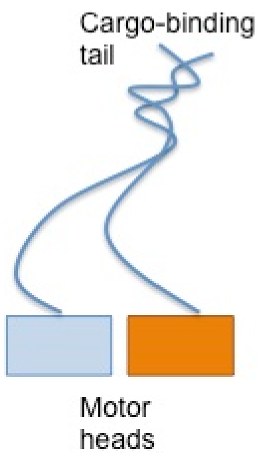
Prompt 7: How could you use the data in Figure 3 to quantify the amount by which the unfolded RNase H is destabilized relative to the folded form? Where is this value represented on the protein folding energy landscape?

Prompt 8: Draw a Force-vs-Extension curve that one would expect to see if one used the optical tweezers to pull on the protein represented by the protein folding landscape depicted in Figure 1.

A.1.2 How a Kinesin Walks

We know a lot of movement takes place within cells. In order to function properly, cells need to move things - ions, molecules, even whole organelles. But what drives this movement? Active transport can move stuff in cells over long distances much more quickly than through diffusion alone, but it requires energy. But how exactly is ATP used to generate movement? Let's look at a kinesin as an example of active transport and use your understanding of energy transformations to explain what it means to say that a cell "uses ATP to fuel molecular movement."

A kinesin is a molecular motor protein with two motor head domains and a tail where the cargo binds. It looks something like this:



Scientists have found that the kinesin moves in a hand-over-hand fashion, similar to how humans walk, as shown in the following frames (the grey and black track represents the microtubule the kinesin walks along). The exact mechanism is still controversial, but according to one model, we can break the movement down into the following steps: In frame (a) both motor heads are bound to the microtubule. Then, in frame (b) an ATP molecule binds with one of the heads of the kinesin, causing strain on the motor protein (like a compressed spring). In frame (c) ATP is hydrolyzed and the protein moves in the forward direction.

1) Act out a movie (with your body or hands) of how the kinesin walks along the track so you can get a feel for describing the movement.

2) In order to make sense of the role ATP is playing you will need to keep track of the energy transformations that take place during this process. First, define the system.

That is, identify the component parts and the associated forms of energy that you think are important. Then, for each frame of the process, use energy bar charts and the principle of conservation of energy to keep track of changes in energy.

3) Where does the energy that allows the kinesin to move forward come from? Make sure your bar charts are consistent with your answer.

4) In Q2 & Q3, has the energy conservation principle been satisfied? If not, how can you modify the definition of your system in each frame so that it is? If you make that change, what happens to your energy bar charts?

5) The energy released by ATP hydrolysis is around 50 kJ/mol. Each "step" the kinesin moves the cargo approximately 8.5 nm. If each step of the kinesin requires one ATP, how much energy does it take to move a vesicle all the way down your leg?

6) Finally, discuss with your group what it means to say that a cell "uses ATP to fuel molecular movement".

A.1.3 Temperature regulation

For each of these situations, answer questions 1-7 below.

A) Normal human body temperature is 37°C. Room temperature is more like 25°C. So unless it's **really** hot out, there is always a temperature difference between your body and its surroundings. What's going on?

B) You get too cold, and need to warm up. What happens?

C) You get too warm, and need to cool down. What happens?

D) Now answer parts A, B, and C for the ectothermic (i.e. what is popularly and inaccurately known as "cold-blooded") animal (e.g. reptile) of your choice!

1) What's happening? Explain what's going on qualitatively, and feel free to bring in outside knowledge.

2) What object or set of objects is the most useful for you to define as "the system"? (There are a large number of possible correct answers to this! But this is an important choice you must make.)

3) Draw a system schema for your system (which you can continue updating as you answer the rest of the questions).

4) During the process described, what is the change in the total energy of the system? (Positive, negative, or zero?)

5) Same question as 4, for the chemical energy in the system.

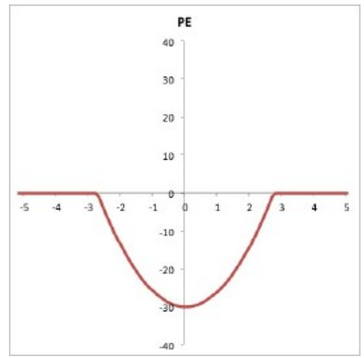
6) Same question as 4, for the thermal energy in the system.

7) Does any energy enter or leave the system? If so, by what process (heat, work, etc.)?

A.2 Homework Problems

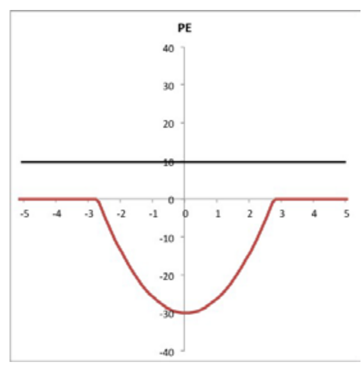
A.2.1 Bound states

One of the challenging ideas of using energy at the atomic and the molecular level is the idea of *bound states*. What this means is that you might start with two objects that have essentially zero kinetic energy, they get close and interact strongly in an attractive way. They find some way to emit energy into another form and wind up being stuck together -- bound. You have to put energy in -- do work on them -- in order to get them apart. Let's work through the language of potential energy to see how to talk about this.



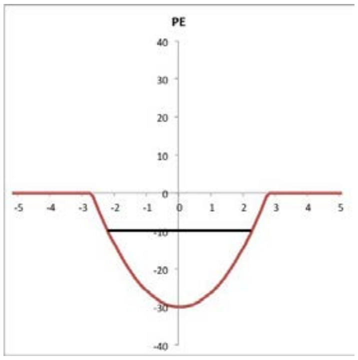
A. Let's first talk about a simple problem that you have now had some practice with -- the motion of a skateboarder on a track. Suppose the track looks like a dip in the ground as shown in the figure. A potential shape like this is often referred to as a *potential well*, since it looks like a dug-out area for a well.

Now suppose that the skateboarder approaches the dip from the left traveling with a positive kinetic energy. The figure at the right shows the skateboarder's total mechanical energy as a solid black line at a PE of 10 units (units unspecified).



Describe the motion of the skateboarder and how her potential and kinetic energies change as she moves through the well.

B. Now suppose that she starts *inside the well* at a zero velocity -- say at point x = -2.5 units with a total energy as shown by the heavy solid line.

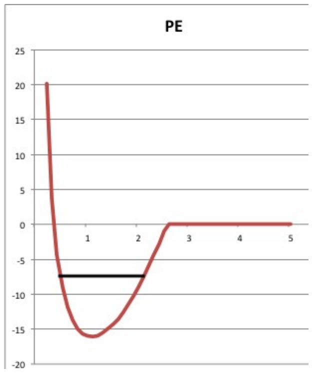


Describe the motion of the skateboarder and how her potential and kinetic energies change as she moves through the well.

C. Her total energy is shown is the figure as -10 units. How can this be? Is it reasonable for the total mechanical energy to be negative?

D. If she wants to climb out of the well and be at 0 kinetic energy at the point x = 3 units, how much energy would she need to gain?

E. The skateboarder is actually just an analogy for the cases we are interested in, which are interacting atoms. This is really too simple a model: the atoms are impenetrable and will repel if pushed too close together. Instead of the simple well shown above, the atom-atom potential looks more like the one shown in the figure at the right. When the atoms are far apart there is little to no interaction. When they are closer, they are attracted and pulled together. If they get too close they are pushed apart. The potential energy of the interaction looks like the figure at the right.

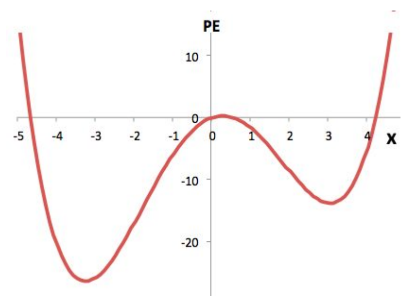


If the atoms have the energy of -7.5 units as shown by the solid line in the figure, describe their motion and how their potential and kinetic energies change as they move in the well.

F. If the atoms have an energy of -7.5 units as shown by the solid line in the figure, would you have to put energy in to separate the atoms or by separating them would you gain energy? How much? Explain why you think so.

A.2.2 Going to a deeper well

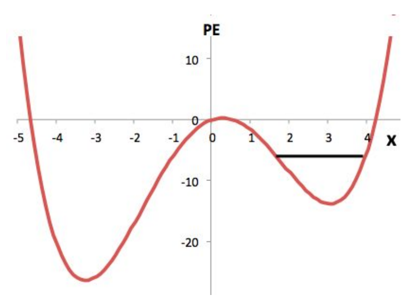
In the figure at the right is shown the potential energy for an object moving in response to conservative forces from a number of other objects that can be treated as fixed, so we can pretend this is the PE of a single object. Never mind the units of either position or PE for now. We can think of this as about a skateboarded rolling back and forth on a curved track.



A.Suppose the skateboarder starts with 0 kinetic energy at the point -5 and starts to roll. Describe the motion she will go through assuming that whatever resistive forces are acting can be neglected. Describe one full cycle of the motion.

B. The PE curve is shown as going to negative values. Is this a problem? Explain.

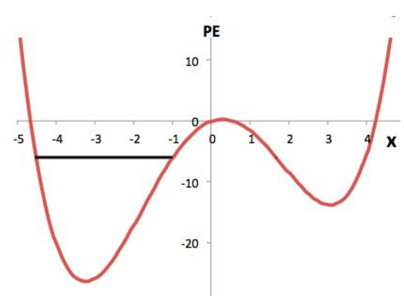
C. Now assume that she starts instead at the point x = 4 at the point where the black line intersects the red PE curve (at PE = -5). Now describe one cycle of her motion.



D. The solid black line is supposed to represent her total mechanical energy -- kinetic plus potential. This is negative. Is this a problem? Explain.

E. The black line only is shown on the right suggesting that she can't get to the left side given the energy she has. Is this correct? Explain your reasoning.

F. Now assume that she is as in part C, oscillating back and forth between the points 1.5 and 4 when suddenly, she is flipped to the point -1 by some bit of magical hand-waving -- without changing her total mechanical energy. Describe her motion. Will she be going faster or slower than she was on the right?



This kind of "magical hand-waving" transition is actually possible on the atomic scale, thanks to the laws of quantum physics.

A.2.3 Muscle contraction

The molecular process that makes muscle contraction possible is that ATP binds to myosin, which releases the energy needed to make the muscle contract. In this problem, we will examine the quantities of energy involved in this process.

Part 1

The reaction of ATP hydrolysis catalyzed by myosin (M) occurs in several steps*:

1) M + ATP → M·ATP

2) M·ATP → M·ADP·P_i

3) M·ADP·P_i → M·ADP + P_i (*aq*)

4) M·ADP → M + ADP

* T. Kodama & R.C. Woledge, "Enthalpy Changes for Intermediate Steps of the ATP Hydrolysis Catalyzed by Myosin Subfragment-1", *J. Biol. Chem.* 254(14), 6382-6836

According to experimental data, the heats of reaction for these four reactions are –90 kJ/mol, +83 kJ/mol, –88 kJ/mol, and +72 kJ/mol.

a) Based on what you know about chemical bonding (from this class, from chemistry, and from anywhere else), explain the positive and negative signs for each of these four reactions. What does a positive and a negative sign mean, and why is a positive (or negative) sign expected in each case?

b) Find the total energy released (in kJ/mol) in the overall ATP hydrolysis reaction.

Part 2

The energy released by this reaction in each muscle fiber, multiplied by a huge number of muscle fibers, results in the kinetic energy of your muscles moving.

c) Estimate the kinetic energy of your leg when you are walking at a normal pace.

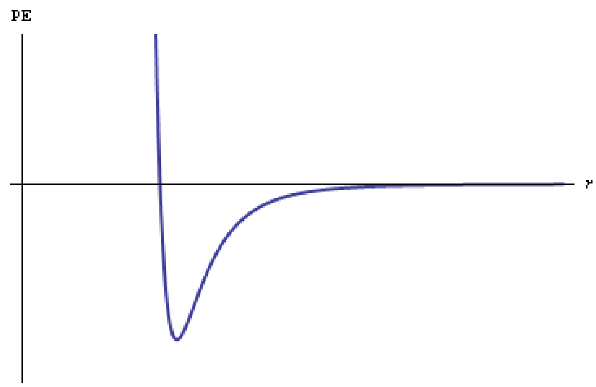
d) Using the data from Part 1, estimate the total energy released by ATP-myosin reactions throughout your entire leg. Explain how you arrived at this estimate.

Some possibly useful information: Muscle fibers (cells) are composed of many myofibrils, tubular components measuring 1-2 micrometers in diameter. Each myofibril is divided along its length into sarcomeres (the basic unit of a muscle, with a single myosin filament), each of which is about 2 micrometers long. Remember that "kJ/mol" means kilojoules for every $6.02x10^{23}$ myosin molecules.

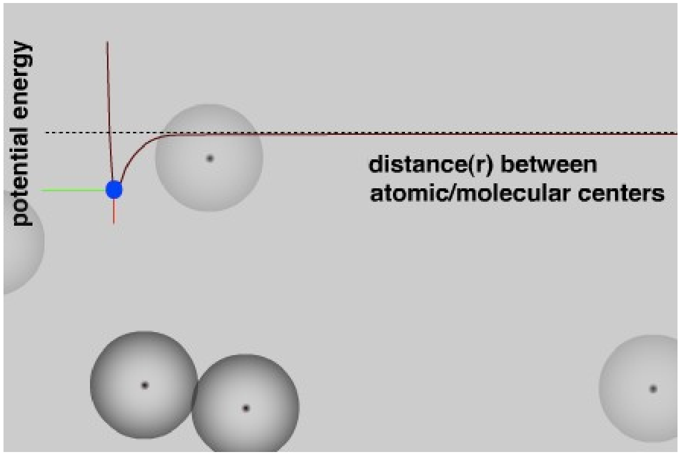
e) Are the results from parts c and d similar? If not, what are some possible ways to account for the discrepancy?

A.2.4 Thermal to chemical energy transfer

When two atoms are bound in a molecule, the interaction between them can sometimes be modeled by a force that is attractive at long distance and repulsive at short. This interaction can be described by a potential well that looks like the figure at the right. The horizontal axis in this graphs represents the distance between the atoms' centers. When the atoms are in a bound state, the point on the graph representing the relative position of the atoms will be near the bottom of the well. The higher up it is, the more that atoms will oscillate around their stable point (the minimum of the potential well).

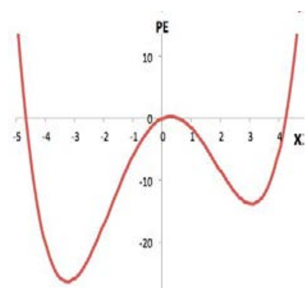


A. The CLUE simulation of molecular collisions shows the potential energy between two bound atoms moving in a gas with other atoms. When the simulation starts, the two bound atoms (shown darker than the others) are bound with a relative energy near the bottom of the potential well describing the interaction between them. As they move around, they may collide with other atoms or molecules and some of the kinetic energy of the other atom may be transferred through the collision into the relative motion of the two bound atoms, setting them oscillating.



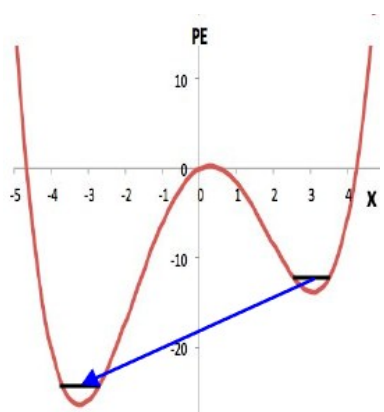
Consider two situations: one in which the collision adds not enough energy to the relative motion of the two bound atoms to separate them and one in which it adds more than enough to separate them. For both cases, tell the story of what is happening to the relative motion of the two atoms and describe how that motion and change in motion would be represented on the potential energy graph of the relative motion of the two bound (at first) atoms.

B. In the problem, Going to a deeper well, we considered what it might mean for a system moving in a double potential-energy well like the one shown at the right. For atomic/molecular physics, this kind of a potential energy curve might represent the potential energy of a more complex molecule of atoms in two different arrangements. The variable "x" now does not just represent the distance between two atoms, but may be a more complex combination of coordinates (a "reaction coordinate") that describes not only the separation of the atoms but their arrangement. Here, we will consider positive values of x to represent one arrangement and negative values a different one.



In which arrangement -- the bottom of the x positive well or the bottom of the x negative well-- is the set of atoms more strongly bound? Explain why you think so.

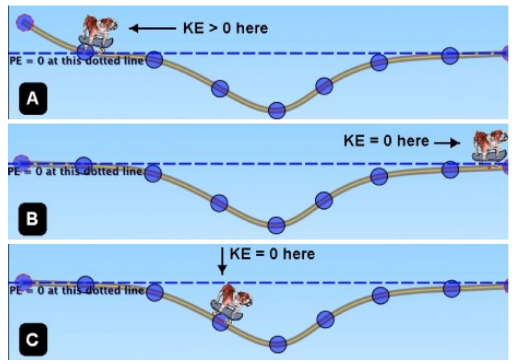
C. Now suppose that the molecular system starts in the arrangement represented by the well at the right (positive x) as shown by the solid black horizontal line in that well. Then suppose that as a result of a collision with an atom, the molecule makes a rearrangement to the state shown by the black horizontal line in the well at the left (negative x). The transition is indicated by a blue arrow.



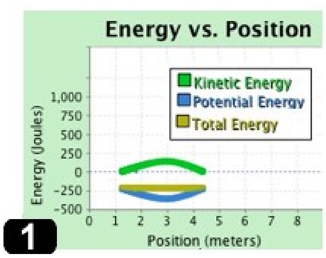
Given that total energy (potential plus kinetic) of the entire system (molecule plus atom) is conserved, do you think that the atom would leave the collision with this molecule going faster than when it came into the collision, slower, or going at the same speed? Explain why you think so.

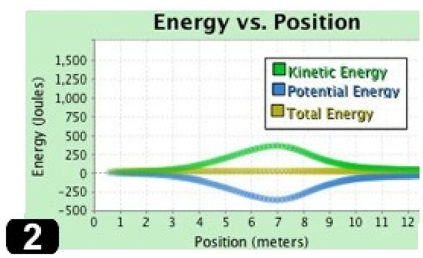
A.2.5 The bulldog on the skateboard

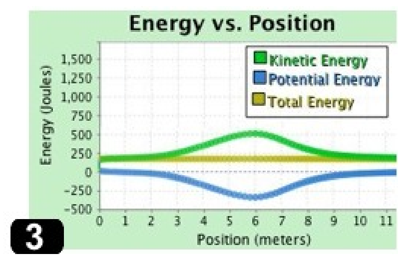
In the three figures labeled A, B, and C at the right are shown three situations in which a bulldog on a skateboard traverses a dip in the ground. (The dips are all the same.) In A, the bulldog enters the dip traveling at a non-0 kinetic energy (KE). In B, when he leaves the dip, he has 0 KE. In C, he begins in the dip (at the position indicated) at a KE of 0. Since he is riding a skateboard, friction may be ignored.



A. In the figures below are shown graphs of the KE, gravitational PE, and total energy as a function of position. In situation 1, the total energy is negative; in situation 2, the total energy is 0; and in situation 3, the total energy is positive. Match which situation goes with which graph and put the letter of the situation to the left of the corresponding graph







B. The bulldog and skateboard have a combined mass of 20 kg. In case B (the middle of the three pictures of the bulldog and the well), the bulldog and skateboard have a KE of 380 J when they roll past the bottom of the well. How deep is the well?

C. In case 1 (the left one of the three graphs) it says the KE is positive but the total energy is negative. How is this possible? Explain what it means for the total energy to be negative.

D. In case 3, the total energy is 200 J. How fast is the bulldog when he passes the bottom of the well?

A.2.6 What's conserved

Although we know that the total energy in the entire universe is always conserved, the value of understanding energy conservation is figuring out where energy flows from one part of the universe to another and in what form. To do this, it is essential to clearly identify a subset of the universe -- a ***system*** -- that we are considering.

For convenience of discussion, we divide energy into a variety of types:

- kinetic (coherent energy of motion of an object -- associated with an object's momentum)
- potential (gravitational, spring, and electric -- associated with some of an object's interactions)
- thermal (energy associated with the chaotic and random motion of an object's molecules)
- chemical (energy that is internal to an object's molecules)

We refer to the combination of an object's coherent kinetic energy of motion and its potential energy arising from interactions with other objects as its *mechanical energy*. In this problem, we will select a set of extremely simple (unrealistic) situations that allow us to see the basic mechanism of energy transformation most clearly. In realistic situations (in both physics and biology), things become more complicated, but being able to track the energy will be extremely valuable.

A. Briefly state and describe the law of conservation of mechanical energy for a macroscopic object, being careful to define any terms or symbols you use and state the circumstances under which it holds. Describe how the law is related to Newton's laws.

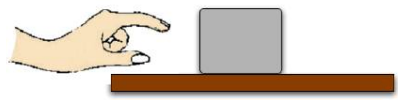
B. For the macroscopic objects or set of objects described in the numbered list below, complete the following:

- For each object in the system, draw a free-body diagram identifying the forces acting on the object.
- For each force in your free-body diagram, identify whether the force is internal or external to the system. (A force is internal if both the objects causing the force and feeling the force are a member of the system.)
- For each force in your free-body diagram, identify whether the force is conservative or non-conservative. (A force is non-conservative if the changes it causes in the energies of the objects it acts on are not reversible.)
- Identify whether the objects in your system can be considered to conserve mechanical energy for the time interval described.

- If mechanical energy of the system is NOT conserved, indicate where the energy has gone (into what objects and forms).

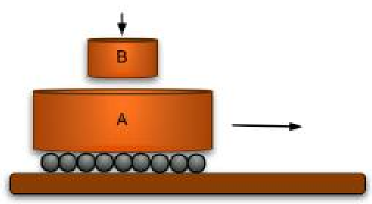
1. System = ball. The ball has been thrown straight upward. Consider the object after it has left the hand but may be rising or falling but has not yet been caught. Ignore the effect of air resistance.

2. System = block. The block is sliding on a smooth table after being pushed but before it comes to a stop. (Smooth ≠ frictionless!)



3. System = a car and a truck. Both are in neutral and can roll freely. The truck rolls into the car and smashes into it, doing damage to both vehicles. Friction with the ground can be neglected. Consider from just before the objects collide to just after they collide.

4. System = two cylinders marked A and B. A heavy cylinder (A) with frictionless wheels rolling along on a horizontal table top and a lighter cylinder (B) that is lightly dropped onto the moving cylinder. Consider the time from just before B lands on A until a bit later when they are rolling together, both at the same speed.

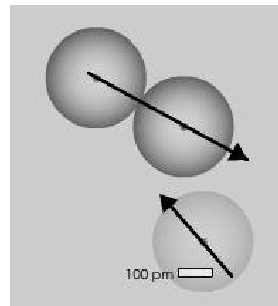


For a system consisting of a small number of microscopic objects -- atoms and molecules -- we will talk about the *mechanical energy* of the atoms and molecules as being their kinetic energy and any potential energies they have while they retain their identities. When they react chemically and change the internal energies associated with their arrangements, we will refer to that as *chemical energy*.

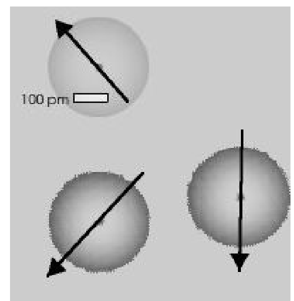
C. For the two systems below, ignore the effects of gravity.

- Identify whether the objects in your system can be considered to conserve mechanical energy for the time interval described.
- If mechanical energy of the system is NOT conserved, indicate whether the mechanical energy has increased or decreased and where (if it has increased) it came from, and where (if it decreased) it has gone (into what objects and forms).

1. System = Two atoms bound together in a molecule and a single atom. These collide with each other but the state of the molecule is not changed (AB + C → AB + C). Consider the time from a bit before the collision to a bit after.



2. System = same. But this time when they collide, the two atoms previously bound are broken apart (AB + C → A + B + C). Consider the time from a bit before the collision (when it looks something like the picture in 1) to a bit after (when it looks something like the picture at the right).



A.2.7 The Gauss gun

One of the most important energy transforming processes in biology is that of chemical reactions. The storage of energy in chemical structures and the extraction of that energy that results from transforming bound atoms from one structure to another is found in the most basic processes of life such as photosynthesis to respiration.

In this problem we'll explore how to think about this storage of energy conceptually and, through the use of a mechanical metaphor, we'll see how it relates to our macroscopically developed energy concepts: kinetic energy, potential energy, and work. These are related by the work-energy theorem, which says that the change in the kinetic plus potential energy of a system is equal to the work done on the system by outside forces.

$$\Delta(K+U) = \int \vec{F} \cdot d\vec{r}$$

In a molecule, the atoms are bound together by interactions whose effect is described by a potential energy. As a model of this we consider "four atoms bound together" -- a magnet and three steel spheres, shown in the figure at the right. The magnet exerts an attractive force on each of the steel spheres that falls off rapidly as a function of distance (i.e., the attraction is stronger when the sphere is closer).

A. Just looking at the system consisting of the strong magnet and the steel spheres labeled 1, 2, and 3, I would conjecture that "sphere 1 is the most strongly bound, sphere 2 is less strongly bound, and sphere 3 is weakly bound." Discuss to what extent this is a good description of the situation, how you might test it if you had the apparatus in front of you, and why it might be a misleading description (especially for spheres 1 and 2).

B. If an external metal sphere (labeled "0" collides with this molecule, it is strongly attracted. Watch the video of what happens below.

If we think of this as a collision between the two mechanical objects, it is a *super-elastic collision*, that is, the kinetic energy of the two objects after the collision is greater than the kinetic energy of the two objects before the collision. Where did the energy come from? Tell the story of the collision, walking us through what happens describing carefully the forces and energies involved so that we understand the source of the kinetic energy of ball 3 at the end of the video.

C. To what extent do you think that this is a decent analogy for an exothermic chemical reaction -- one in which some energy is made available to do other things as a result of the reaction? Explain why you think so.

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