# CONNECTING CHEMISTRY AND BIOLOGY: EXPLORING STUDENTS' PERCEPTIONS OF COLLEGE COURSES

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ABSTRACT

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Despite the number of university students who take courses in multiple science disciplines, little is known about how they perceive common concepts from different disciplinary perspectives and to what extent they recognize connections among their courses. This dissertation explores students' perceptions of their chemistry and biology courses through the lens of two crosscutting concepts, energy and the relationship between structure, properties, and function. Energy underlies all scientific phenomena. Structure-property and structure-function relationships have long been considered important explanatory concepts in the disciplines of chemistry and biology, respectively. As such, these crosscutting concepts provide an interesting context in which to investigate student connections and misconnections across disciplines.

Funded by the Association for American Universities' STEM Education Initiative, a multi-year interdisciplinary effort was underway to transform the introductory biology, chemistry, and physics courses using the lens of three-dimensional learning. To inform cross-disciplinary discussions on the improvement of undergraduate education, a series of studies using interview data were conducted. An initial set of twenty-two interviews explored a diverse group of undergraduate students' perceptions across all three dimensions (i.e. disciplinary core ideas, crosscutting concepts, and science practices). However, this resulted in a large and diverse dataset lacking sufficient depth to richly describe student experiences.

This work led to three more targeted studies with a revised interview protocol focusing on the crosscutting concepts of energy and the relationship between structure, properties, and function. An additional fourteen university students concurrently enrolled in general chemistry and introductory cell

and molecular biology were interviewed. Findings suggest that, while students believed energy to be important to the scientific world and to the disciplines of biology and chemistry, the extent to which it was considered central to success in their courses varied. Differences were also apparent in students' descriptions of the molecular-level mechanisms by which energy transfer occurs, revealing a disconnect between how energy is understood and used in introductory science course work.

These interviews also explored students perceptions regarding (1) the meaning of structure, properties, and function, (2) the presentation of these concepts in their courses, and (3) how these concepts might be related. While the concepts of structure and properties were interpreted similarly between chemistry and biology, only three students were able to consider function productively in chemistry. Additionally, students more closely associated structure-property relationships with their chemistry courses and structure-function with biology. Despite receiving little in the way of instructional support, nine students proposed a coherent conceptual relationship, indicating that structure determines properties, which determine function, and described ways in which they connected and benefited from their understanding across both courses.

The final study follows Laura, a Genomics and Molecular Genetics major, across three years of chemistry and biology coursework, including general and organic chemistry, honors cell & molecular biology, and a two-semester biochemistry course sequence. Across her four interviews, Laura consistently recognized the utility of thinking about the relationship between structure, properties, and function. However, her ability to discuss energy diminished over time. Despite describing energy to be a central and crosscutting concept in Year 1, she rarely considered it in Year 2; and, during her final interview, she noted having had a deeper conceptual understanding of energy in the past.

Though some students were successful in making connections across their chemistry and biology courses, this work uncovers a need for cross-disciplinary conversations among instructors to understand the shared goals and disciplinary distinctions regarding these important concepts.

To all the people, opportunities, and interactions that have led me to this moment.
I did not and could not have planned the path I took, but I am a better person for it.

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## KEY TO ABBREVIATIONS

| | |
|---|---|
| AAAS | American Association for the Advancement of Science |
| AAU | Association of American Universities |
| ADP | adenosine diphosphate |
| AP | advanced placement |
| ATP | adenosine triphosphate |
| B1 | introductory biology 1 |
| CC | crosscutting concepts |
| CLUE | *Chemistry, Life, the Universe, and Everything* |
| DBER | discipline-based education research |
| DCI | disciplinary core ideas |
| GC1 | general chemistry 1 |
| GC2 | general chemistry 2 |
| HB1 | honors introductory biology 1 |
| NRC | National Research Council |
| SEP | science and engineering practices |
| SPF | structure, properties, and function |
| STEM | science, technology, engineering, and mathematics |

# CHAPTER 1: INTRODUCTION

The world we live in, made up of both natural and built systems, is governed by a set of unifying scientific laws. And, as our knowledge of these systems advances, the disciplines and subdisciplines of science, engineering, technology, and mathematics (STEM) are becoming more integrated. During their college years, students make the pivotal decision to focus their energy and attention on a major program that will shape their future. In turn, these programs provide direction and requirements intended to help students achieve their academic goals. Such requirements often include course pre-requisites spanning multiple departments. This would suggest that some courses require scaffolded knowledge provided in other disciplines. However, university research and teaching communities are often described as being disciplinarily siloed, with individual communities of practice having little interaction with one another. Students navigate their academic careers constantly moving between courses where different disciplinary assumptions and expectations are at play. And who is to say that they are able to integrate, extend, and apply their knowledge across real and perceived disciplinary boundaries.

There have been few research studies that explore undergraduate students' understanding in different disciplinary contexts (Chapter 2). Instead, many have theorized the benefits of integrated learning experiences that blend and synthesize different disciplinary knowledge and perspectives (Bainbridge & Roco, 2016; Czerniak & Johnson, 2014; Gibbs, 2017). Those that have been described in the literature vary widely in their implementation and often provide little in the way of evidence on student learning gains (e.g. Gentile *et al.*, 2012; Johnson & Graves, 2017; Vogel Taylor, Mitchell, & Drennan, 2009). The report *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering* (NRC, 2012b), confirmed this gap in the research literature, recommending that interdisciplinary studies on crosscutting concepts be conducted.

> Interdisciplinary studies could help to increase the coherence of students' learning experience across disciplines by uncovering areas of overlap and gaps in content coverage, and could

> facilitate an understanding of how to promote the transfer of knowledge from one setting to another. (2012b, p. 202)

To help fill this gap and to inform cross-disciplinary discussions on the improvement of undergraduate education, I conducted a series of studies using interview data to explore how students perceive the conceptual relationship between their chemistry and biology courses. These studies were done in the context of a multi-year introductory course transformation initiative at Michigan State University (Chapter 3). Funded by the Association for American Universities' STEM Education Initiative, an interdisciplinary effort was underway to transform the introductory biology, chemistry, and physics courses using the lens of three-dimensional learning (Cooper *et al.*, 2015; Laverty *et al.*, 2016; NRC, 2012a). In Chapter 3, the design of the original study and subsequent revisions are discussed. While the original protocol explored a diverse group of students' perceptions across all three dimensions (i.e. disciplinary core ideas, crosscutting concepts, and science practices; 2012a), this resulted in a large and diverse dataset lacking sufficient depth to richly describe student experiences. However, this work led to three more targeted studies focusing on the crosscutting concepts of energy and the relationship between structure, properties, and function using a revised interview protocol (Chapters 4-6).

Crosscutting concepts are central to understanding the disciplines of science and engineering; and they have the potential to help students make cross-disciplinary connections, serving as lenses for considering varied phenomena (Rivet, Weiser, Lyu, Li, & Rojas-Perilla, 2016). Using the revised protocol, a second group of students, co-enrolled in general chemistry and introductory cell and molecular biology, were interviewed. Chapter 4 describes how these students compared the presentation of energy in their introductory chemistry and biology courses, particularly regarding mechanisms of potential and kinetic energy transfer (Kohn, Underwood, & Cooper, 2018). Similarly, Chapter 5 presents how these same students understood the concepts of structure, properties and function, and the relationship between them. The disciplines of chemistry and biology emphasize structure-property and structure-function relationships, respectively (American Association for the Advancement of Science, 2011; College Board, 2014, 2015; NRC, 2012a). As such, I explored students' perception of the presentation in their introductory courses and whether they interpreted a connection between them (Kohn, Underwood, & Cooper, in press). The third project, discussed in Chapter 6, follows Laura, a Genomics and Molecular Genetics major, across three years of chemistry and biology coursework, including: general and organic chemistry, honors cell & molecular biology, and a two-semester biochemistry course sequence. Laura's perspective on learning and her ability to discuss the crosscutting concepts of energy and the relationship between structure, properties, and function are considered with particular attention given to changes that occurred over time. Finally, Chapter 7 summarizes and synthesizes the findings presented in Chapter 4-6 and discusses implications for teaching and future research.

## CHAPTER 2: THEORETICAL FRAMEWORK AND A REVIEW OF THE LITERATURE

### Introduction

University science students are required to take multiple, introductory science courses outside of their major discipline before continuing to advanced course work, presumably because these experiences are expected to expose students to the requisite prior knowledge needed to develop a sophisticated understanding of their chosen field. For example, life sciences and preprofessional majors are commonly required to take two years of chemistry course work early in their degree. And yet, it is not clear that these students recognize how deeply connected the disciplines of chemistry and biology are, and that their knowledge of one can inform or bring context to that of the other. The extent to which a learner can integrate their conceptual understanding across multiple science disciplines has largely gone unstudied. Furthermore, the bodies of literature that could inform such work (e.g. knowledge transfer, convergence, and interdisciplinary learning experiences) tend to focus on integration of knowledge at a level either too fine-grained or too broad to be useful. For example, while the history of research on knowledge transfer is long and varied, much of the work has concerned students' ability to "carry over" predefined pieces of information or strategies to solve a narrowly defined problem (Barnett & Ceci, 2002; Bransford & Schwartz, 1999; Carraher & Schliemann, 2002; Lobato, 2006). In comparison, theoretical perspectives such as convergence and transdisciplinary learning focus on preparing students to work in interdisciplinary teams through effective communication and engagement in authentic research experiences (Bainbridge & Roco, 2016; Gibbs, 2017); and proponents of integrated and interdisciplinary learning experiences often advocate problem-based learning or themed curricula (Czerniak & Johnson, 2014; Spelt, Biemans, Tobi, Luning, & Mulder, 2009). As such, much of this work is predicated on the restructuring of students' learning experiences.

This dissertation is different in that it explores how students concurrently enrolled in traditionally-defined disciplinary courses in chemistry and biology perceive those experiences and any recognizable connections (or lack thereof) that exist between them. Disciplines are a common organizing principle used in academia. And so, it is only pragmatic to consider their effect on university students' understanding of science. The students who participated in this study were taught disciplinary subject matter by disciplinary experts associated with their respective disciplinary departments. However, the introductory chemistry and biology courses that provided the context for much of the work described in this dissertation were undergoing curricular transformations influenced by *A Framework for K-12 Science Education* (NRC, 2012a), which puts forth a vision of science education that promotes three-dimensional learning as "the kind of thinking and understanding science education should foster" through the integration of scientific and engineering practices (SEP), disciplinary core ideas (DCI), and crosscutting concepts (CC). In this way, the *Framework* (2012a) describes not only the disciplinary content students should know but also what they should be able to do with that knowledge and conceptual threads that cut across disciplines. While written for a K-12 audience, these values have been extended to the university context, and have framed the interdisciplinary discussion that surrounded the aforementioned transformation efforts (Cooper *et al.*, 2015; Laverty *et al.*, 2016). In particular, the DCI and CC have guided the design and analysis of this study to focus on students' understanding of energy concepts and the relationship between structure, properties, and function (Kohn *et al.*, in press, 2018).

**Meaningful learning**

In 1963, David Ausubel proposed a cognitive theory describing the process of acquisition and retention of knowledge through meaningful learning (as opposed to rote learning; 1963, 1968, 2000). This distinction hinges on the extent to which the learner integrates their new and prior knowledge (Ausubel, 2000). Meaningful learning occurs through the construction of substantive connections which make possible "the understanding of various kinds of significant (e.g., derivative, qualifying, correlative) relationships." (Ausubel, 1963, p. 23). In comparison, the products of rote learning are generally of limited but practical utility with peripheral and arbitrary connections to a learner's cognitive structure (Ausubel, 2000, p. x). The commonly used example is the memorization of telephone numbers. In comparison, for meaningful learning to occur, students must choose to engage with the learning material in a meaningful way that is, with the intention of making nonarbitrary connections to their prior knowledge. However, to do so, students must possess some relevant prior knowledge, and they must perceive that which they are tasked with learning to be both important and relatable to that prior knowledge (Ausubel, 1968; Novak, 1998). And so, while the extent to which meaningful learning occurs depends on the choices and past learning experiences of the student, instructors can promote and facilitate more meaningful learning through careful consideration of how curricula are organized and by making clear and explicit connections among related ideas (Ausubel, 1960, 1968; Novak, 1977). And so, by exploring students perceptions of their chemistry and biology courses, I can investigate the extent to which they were to meaningfully connect the concepts discussed and how we might better support them in this process. To develop a coherent understanding of science, university students must be able to integrate, extend, and apply their knowledge across the perceived disciplinary boundaries, often reinforced by the organizational structures in academia.

### Integration, transdisciplinary, and convergence learning

Conceptually, disciplines are both structured and amorphous, intuitive and difficult to define. They are represented by bodies of literature, communities of practice, and characteristic patterns of discourse. They influence the questions asked, the assumptions made, and the methods that are applied. And yet, what separates one discipline from another is difficult to describe and these boundaries are constantly shifting. What was once considered a sub-discipline or an intersection between disciplines may later be described as a discipline in its own right. Still, disciplines are a defining organizational structure in academia and undoubtedly influence students' educational experiences.

Many have theorized the superiority of interdisciplinary educational experiences in improving students' ability to explore complex problems or socioscientific issues (e.g. global climate change), develop deep understanding, and engage in authentic science practice (Broggy, O'Reilly, & Erduran, 2017; Czerniak & Johnson, 2014; Nagle, 2013; Spelt *et al.*, 2009). These experiences are often defined based on the extent to which disciplinary components are integrated (Czerniak & Johnson, 2014; Huutoniemi, Klein, Bruun, & Hukkinen, 2010). Whereas multidisciplinary education includes the presentation of various disciplinary knowledge and perspectives, integrated and interdisciplinary curricula are expected to facilitate their synthesis (Spelt *et al.*, 2009). An assortment of course transformations and novel curricula have been described in the literature as either integrated or interdisciplinary in nature (e.g., Abdella, Walczak, Kandl, & Schwinefus, 2011; Copp, Black, & Gould, 2012; Gentile *et al.*, 2012; Lega, Buxner, Blonder, & Tama, 2014; Schaller, Graham, & Jakubowski, 2017). For example, while Vogel and coworkers (2009) describe little more than the inclusion of biology-related examples into an introductory chemistry course, Johnson and Graves (2017) took a more novel and integrative approach, which they termed the Chemistry-Genetics Course Collaborative. Students enrolled in introductory chemistry for nonscience majors were cotaught with those taking human genetics for nonbiology majors, collaborating on various activities. The incorporation of chemistry and biology content vary drastically between these two courses, reflecting a disconnect between the theoretical connotations of the term and how practitioners choose to use it. Additionally, course evaluation is often limited to student and faculty self-report data, as opposed to providing evidence of an improvement in students' conceptual understanding, despite research on the assessment of interdisciplinary problem solving and communication (Mansilla & Duraising, 2007; Mansilla, Duraisingh, Wolfe, & Haynes, 2009; Shen, Sung, & Zhang, 2015; Zhang & Shen, 2015).

Proponents of convergence (Bainbridge & Roco, 2016) and transdisciplinary learning (Gibbs, 2017) believe educational experiences should be even more expansive, going beyond integration across disciplines. Transdisciplinary learning, as described by McGregor (2017), includes integration with the experiences and understanding of societal members and organizations (e.g. government, industry); by considering both disciplinary and stakeholders' knowledge, students are expected to collaboratively address socially relevant issues. For convergence learning, integration is expected along four dimensions that is, integration over time, across disciplines, across settings and methodologies, and via crosscutting societal and economic relevance (Chang, Shanahang, & Hsu, 2016). While similar to transdisciplinary learning in many ways, in convergence learning there is an increased emphasis on "learning anytime, anywhere" and becoming a lifelong learner (Singer, 2016). Both theoretical perspectives describe how the context and goals of students' educational experiences can more authentically parallel their future engagement in real world problems. However, they do little to inform the exploration of the more representative university learning environments, situated in disciplinary-based organizational units.

Many of the discussions surrounding integrated learning (whether it be multidisciplinary, interdisciplinary, transdisciplinary, or convergent) are predicated on the restructuring of educational experiences, from the creation of thematic curricula to the use of problem-based learning. In comparison, crosscutting concepts are an acknowledgement of the universal themes underlying science content across disciplines (NRC, 2012a). Through awareness, discussion, and assessment of these themes, in concert with what students should know (DCI) and be able to do with that knowledge (SEP), existing courses can become more three-dimensional (Cooper *et al.*, 2015; Laverty *et al.*, 2016; NRC, 2012a).

**Crosscutting concepts: Spanning the disciplines of chemistry and biology**

The NRC's *A Framework for K-12 Science Education* (the *Framework*; 2012a) promotes a vision for science education that fosters three-dimensional learning through the integration of scientific and engineering practices (SEP), crosscutting concepts (CC), and disciplinary core ideas (DCI). From this perspective, meaningful science education not only emphasizes what students should know (DCI), but also what they should be able to do with their knowledge (SEP), while highlighting thematic concepts that span disciplines (CC). Although the *Framework* was developed to inform K-12 education, describing what students should know and be able to do by the end of grades 2, 5, 8, and 12, the underlying principles have been extended to undergraduate education (Cooper *et al.*, 2015; Cooper, Posey, & Underwood, 2017; Laverty *et al.*, 2016; Stowe & Cooper, 2017; Underwood, Posey, Herrington, Carmel, & Cooper, 2017). At Michigan State University, three-dimensional learning has guided an interdisciplinary initiative to transform the introductory biology, chemistry, and physics courses. These interdisciplinary conversations inspired the research described herein and informed the interview protocols used. Additionally, the research participants were enrolled in introductory chemistry and biology courses that were directly impacted by the transformation effort (see Chapter 3).

**Table 2.1 Three-dimensional learning**

| Scientific Practices [1] | Crosscutting Concepts | Disciplinary Core Ideas [2] |
|---|---|---|
| Asking questions and defining problems | Patterns | (PS1) Matter and its interactions |
| Developing and using models | Cause and effect: mechanisms and explanation | (PS2) Motion and stability: forces and interactions |
| Planning and carrying out investigations | Scale, proportion, and quantity | (PS3) Energy |
| Analyzing and interpreting data | Systems and system models | (PS4) Waves and their applications in technologies for information transfer |
| Using mathematics and computational thinking | Energy and matter: flows, cycles, and conservation | (LS1) From molecules to organisms: structures and processes |
| Constructing explanations and designing solutions | Structure and function | (LS2) Ecosystems: interactions, energy, and dynamics |
| Engaging in argument from evidence | Stability and change | (LS3) Heredity: inheritance and variation of traits |
| Obtaining, evaluating, and communicating information | | (LS4) Biological evolution: unity and diversity |

[1] For simplicity, the engineering practices have not been included.
[2] The disciplinary core ideas (DCI) for physical science (PS) and life science (LS) are provided as examples since they are most pertinent to the work presented herein. DCI for earth sciences and engineering have not been included.

Of the three dimensions, crosscutting concepts have arguably been the least explored in the research literature. Additionally, despite their inclusion in the education reform and standards documents of the last few decades (generally referred to as unifying themes or common concepts;

American Association for the Advancement of Science, 1994; College Board, 2009; NRC, 1996), “they have rarely been taught or have not been taught in a way that fosters understanding of their cross-disciplinary utility and importance” (NRC, 2014, pp. 2–3). The CC described in the *Framework* were chosen based on their explanatory value across all areas of science and engineering. Through their application in multiple contexts across K-12 education, they can serve as “common and familiar touchstones” for students (NRC, 2012a). Further, they are viewed both as topics for learning and “ways of thinking,” or “tools” to consider unfamiliar problems (Laverty *et al.*, 2016; NRC, 2014).

However, the CC have been described as “the most difficult dimension to discuss and develop shared understanding” (Rivet *et al.*, 2016). Through an analysis of the language used to describe CC in the *Framework* (as well as the NGSS and supporting documents), Rivet and coworkers (2016) identified a set of four conceptual metaphors which can inform the incorporation of CC into instruction (summarized in Table 2.2). These metaphors can be applied depending on the goals of instruction; for example, to encourage students to consider a problem from a new perspective (using CC as lenses) or recognize similarities across various systems (using CC as bridges). Further, these metaphors show the diversity and flexibility with which CC can be applied and assessed in the classroom.

**Table 2.2 Conceptual metaphors for the NRC’s crosscutting concepts**

| CC as... | Through this conceptual metaphor... |
|---|---|
| lenses | CC encourage students to consider “features of a phenomenon or problem that they may have previously found insignificant.” |
| bridges | CC allow students to recognize “conceptual relationships between phenomena” |
| tools | CC help students “engage with [SEP] in more meaningful and effective ways” and can use “their existing understandings to construct complex explanations and resolve practical problems.” |
| rules | CC can “provide order and structure to students’ potential understandings of a complex (and often chaotic) world.” |

Four conceptual metaphors used to describe crosscutting concepts in the Framework and supporting documents as presented in Rivet A.E., Weiser G., Lyu X., Li Y., & Rojas-Perilla D., 2016.

In this work, I focus on student understanding of two CC, *Energy and matter: Flows, cycles, and conservation* and *Structure and function*, chosen because of the prevalence with which they are discussed in the chemistry and biology education literature, in commonly used curricular materials (Freeman *et al.*, 2017; Mason, Johnson, Losos, & Singer, 2015; Reece *et al.*, 2014; Shane & Bodner, 2006), and most notably in the introductory courses at Michigan State University (Chapter 3).

**Understanding energy in chemistry and biology**

*"Energy and matter: Flows, cycles, and conservation. Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations." (NRC, 2012a, p. 84)*

Energy is undoubtedly considered a central and explanatory concept across all science disciplines (American Association for the Advancement of Science, 2011; Chen *et al.*, 2014; College Board, 2014, 2015; Cooper, Klymkowsky, & Becker, 2014; Holme & Murphy, 2012; Nordine, 2015). In particular, the *Framework* (2012a) calls out energy as a lens through which phenomena can be considered, and notes that attending to the conservation and transfer of energy (and matter) is vital for characterizing and modeling systems. Across calls for curricular reform, a clear emphasis on integration between the science disciplines with regard to energy can be noted (AAMC-HHMI Committee, 2009; American Association for the Advancement of Science, 2011; College Board, 2014, 2015; NRC, 2012a). However, even within the context of a single discipline, developing a coherent and sophisticated understanding of energy is notoriously difficult (Barker & Millar, 2000; Batiza *et al.*, 2013; Becker & Cooper, 2014; Cooper & Klymkowsky, 2013b; Nordine, 2015; Teichert & Stacy, 2002). Many of the scientific terms used to discuss concepts of energy have different connotations when used in colloquial language and "when classroom instruction seems to conflict with – rather than clarify – their intuitive ideas about energy, students struggle to develop a strong and self-consistent understanding of the energy concept" (Nordine, 2015, p. 4). Additionally, students are likely to encounter variations in symbology between the science disciplines, even when discussing the same concept (e.g. U, V, and $E_p$

are used to represent potential energy depending on the context). These and other difficulties (e.g. the abstract nature of the concept and debates among experts regarding constructs such as the use of forms-of-energy language; Kaper & Goedhart, 2002; Papadouris, Constantinou, & Kyratsi, 2008) make developing a coherent and sophisticated understanding of energy problematic.

An extensive area of research in K-12 education has been on examining how energy is discussed with respect to various characteristics; namely, concepts of energy conservation, transformation of energy into different forms, transfer of energy between components of a system, and energy degradation (i.e. the decrease of energy available for further use in a system) are considered important for understanding energy across contexts (Duit & Haeussler, 2012; Hecht, 2007; Trumper, 1990a). Additionally, some researchers have included energy source, given the utility of this idea for understanding the flow of energy through ecosystems (Lee & Liu, 2010; Liu & McKeough, 2005; Neumann, Viering, Boone, & Fischer, 2013). Using metaphor theory as a lens to describe how the science education literature, disciplinary textbooks, and students in both disciplinary and interdisciplinary courses at the undergraduate level talk about energy, Lancor (2013, 2014b, 2015) has identified six conceptual metaphors summarizing "specific instances of metaphorical language or explicit analogies identified in discourse" (2015, p. 882). Metaphors highlight some characteristics of energy while obscuring others, which may be problematic if students are not made aware of limitations regarding their utility (Lancor, 2015). How we discuss and consider energy is context-dependent and varies by discipline. In the context of physics education for life sciences majors, Dreyfus and coworkers (2015) found that an instructor and their student both used a blended metaphor (combining energy as a substance and energy as a vertical location) to reason about topics such as chemical bonding and ATP metabolism. As Lancor notes, "The value in each conceptual metaphor is that it helps to explain the role of energy in its application to a particular context; energy cannot be defined out of context or outside of a system." (2015, p. 886)

**Energy and chemistry**

At the introductory college level, discussions of energy tend to be concentrated in two discrete chapters on thermochemistry and thermodynamics (College Board, 2014; Holme, Luxford, & Murphy, 2015). Therefore, it is not surprising that most of the research on university students' understanding of energy focuses on thermodynamics. A review of this literature by Bain and coworkers (2014) found that the largest proportion of studies examined student conceptions regarding the laws of thermodynamics, spontaneity, and equilibrium (Banerjee, 1995; Carson & Watson, 1999, 2002; Greenbowe & Meltzer, 2003; Hadfield & Wieman, 2010; Nilsson & Niedderer, 2012, 2014). Carson and Watson (1999) found that general chemistry students thought enthalpy, entropy, internal energy, and activation energy were forms of energy. Additionally, they found that students had difficulty differentiating between heat, work and internal energy (Greenbowe & Meltzer, 2003).

Research on student understanding of potential energy, a concept critical to understanding bonding and interactions (Cooper & Klymkowsky, 2013b), has been considerably less prevalent. Becker and Cooper (Becker & Cooper, 2014) found that undergraduate chemistry students enrolled in general chemistry, organic chemistry and upper division courses generally described potential energy at the atomic-molecular level in three ways (i.e. energy storage, capability, and stability). They note that each of these ideas could be used productively to reason about atomic and molecular interactions, but more often students provided intuitive or incorrect interpretations rather than scientifically accurate ones. Similar interpretations have been noted among students in physics courses, although usually in the context of gravitational potential energy (e.g. the view that potential energy is the property of a single object rather than the configuration of objects in a system; (Jewett Jr, 2008b, 2008a; Lindsey, Heron, & Shaffer, 2012).

Furthermore, the idea that breaking bonds releases energy is a commonly held alternative conception among both high school and undergraduate students (Barker & Millar, 2000; Galley, 2004;

Storey, 1992; Teichert & Stacy, 2002) and has even been noted even among chemistry graduate students (Gonzales, 2011). Some students even hold seemingly contradictory ideas, such as simultaneously believing that both breaking and forming bonds releases energy (Boo, 1998; Teichert & Stacy, 2002), indicating that few students have a coherent and consistent understanding of the energy changes involved. These problematic ideas may stem from students' early experiences with energy in everyday life (e.g. energy content in food) and later be reinforced in courses where energy is discussed as being stored in molecules (Cooper & Klymkowsky, 2013b; Storey, 1992). This persistent misconception is a profound example of why it is so necessary that we address energy with a coherent, interdisciplinary perspective.

**Energy and biology**

Biology instructors and researchers have long been concerned with students' ability to understand and integrate their knowledge of energy in biology with what they learn in physical science classrooms (Barak, Gorodetsky, & Chipman, 1997; Chabalengula, Sanders, & Mumba, 2012; Gayford, 1986). Chabalengula and coworkers (2012) asked first-year students in college biology (n=90) to "explain what energy is in a biological context." However, they found that approximately half of the students situated their response in another context, particularly favoring a physics-oriented perspective (e.g. discussing energy in the context of mechanics). On a second task, over half of the students agreed that "living organisms have a kind of energy which is different from the energy we learn about in physical science." Such beliefs are problematic, especially when students are expected to apply their knowledge of energy from courses taught from other disciplinary perspectives. Understanding the energy transfers involved in cellular respiration and photosynthesis are considered particularly difficult for both teachers and students (Batiza *et al.*, 2013; Brown & Schwartz, 2009; Parker *et al.*, 2012; Wilson *et al.*, 2006), arguably because students must have a solid understanding of physical science principles such as atomic structure, electrostatic attractions, and the aforementioned relationship between energy and bonding to grasp “what gets electrons moving, the paths they follow, and the work done as they move” (Batiza *et al.*, 2013, p. 288). Energy is an important component to developing a deep conceptual understanding of both chemical and biological systems. Moreover, it is vital that students recognize that the energy discussed in their various science courses is one and the same. It is for these reasons that energy was chosen as one of the crosscutting concepts explored in this study.

### The relationship between structure, properties, and function

*“Structure and function. The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.” (NRC, 2012, p. 84).*

Regardless of scale, it is possible to discuss systems in terms of the relevant structure, properties, and functions present, but it is through an understanding of the relationships between these that allows us to make predictions and construct explanations. For example, knowledge of molecular level structures and properties can be used to design organic semiconducting materials for use in electronic devices (Shirota & Kageyama, 2007), information regarding the mineral density and flexibility of primate mandibular bones has been used to hypothesize the adaptive functionality of these structures (Ray *et al.*, 2015), and terrestrial biosphere models can be informed by the inclusion of characteristic properties and functional dynamics of plant root systems (Warren *et al.*, 2015). In the *Framework* (NRC, 2012a), it is the relationship between structure and function that is called out as a central and crosscutting concept that spans the disciplines of science and engineering. However, despite the labeling, properties are identified as a component of this relationship; and many education reform documents include discussions of structure, properties, *and* function (American Association for the Advancement of Science, 2011; College Board, 2009, 2014, 2015; National Academy of Engineering and National Research Council, 2009; National Research Council, 1996, 2012a).

While biologists often emphasize the relationship between structure and function (American Association for the Advancement of Science, 2011; College Board, 2015; Tansey *et al.*, 2013), in chemistry, there is more commonly a focus on the relationship between structure and properties, considered fundamental to the discipline (College Board, 2014; Cooper *et al.*, 2017; DeFever, Bruce, & Bhattacharyya, 2015; Talanquer, 2017; Underwood, Reyes-Gastelum, & Cooper, 2016). The connection between molecular level structure and the emergent, chemical and physical properties of a substance is not a simple one to make, especially when considering macroscopic properties such as boiling point and malleability (Cooper, Corley, & Underwood, 2013; DeFever *et al.*, 2015; Shane & Bodner, 2006; Talanquer, 2008). Moreover, many students do not recognize the extent to which properties can be predicted from structural information, even after taking a semester of organic chemistry (Cooper, Underwood, & Hilley, 2012; Underwood, Reyes-Gastelum, & Cooper, 2015; Underwood *et al.*, 2016). However, students enrolled in the reformed general chemistry curriculum Chemistry, Life, the Universe, and Everything (CLUE; Cooper & Klymkowsky, 2013a) have been shown to recognize these connections earlier than students taking more traditional courses (Underwood *et al.*, 2016).

In biology education research, it is common to find the relationship between structure and function as part of the context for a study, but it is rare for student understanding of this central concept to be the subject of study (e.g. Bednarski, Elgin, & Pakrasi, 2005; Mulnix, 2003). Function appears to be so embedded in the history of biological study (Allen, Bekoff, & Lauder, 1998; Coleman, 1971; Moulyn, 1957) that an understanding of its meaning has been taken for granted. While many biology courses introduce structure and function to students early on, they often do so without providing a general working definition that students can apply across varied and unfamiliar examples (e.g. Mason *et al.*, 2015; Reece *et al.*, 2014).

Despite differences in disciplinary emphasis, the concepts of structure, properties, *and* function are clearly related (American Association for the Advancement of Science, 2011; NRC, 2012a). However, little is known about how students perceive these three concepts and the relationships between them, and whether those perceptions are disciplinary specific. This subject is further explored in Chapter 5.

# CHAPTER 3: THE EARLY INTERVIEWS

## The MSU AAU project: Developing a coherent gateway for STEM teaching and learning

At large, research institutions, faculty are often rewarded for successes in groundbreaking and lucrative research. However, despite the large number of students who are being taught at these institutions, the support and reward systems for promoting effective teaching practices are often lacking (President's Council of Advisors on Science and Technology, 2012). And for years, reports have described low retention rates in science, technology, engineering, and mathematics (STEM) major programs as students switch to non-STEM majors after taking introductory STEM courses (NRC, 2015; President's Council of Advisors on Science and Technology, 2012; Singer, S. R, 2007). In 2011, the Association of American Universities (AAU) launched the Undergraduate STEM Education Initiative which aims to investigate and overcome barriers to implementation of evidence-based teaching practices in STEM courses at research institutions.

One of eight project sites, Michigan State University (MSU) received funding as part of this initiative to transform the introductory science courses across chemistry, biology, and physics using the lens of three-dimensional learning (Cooper *et al.*, 2015). The NRC's *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (2012a; see Chapter 2 for more detail) describes not only what disciplinary and crosscutting concepts should be taught, but also how students should be able to apply that understanding. While the *Framework* was written in the context of the K-12 education system, these principles can be extended to undergraduate STEM classrooms (Cooper *et al.*, 2015, 2017; Laverty *et al.*, 2016). The MSU AAU project was committed to leading a transformation effort that would be sustained well past the duration of the project itself, through engaging faculty external to the project in a variety of activities, including tasking disciplinary groups with coming to a consensus regarding the core ideas of their discipline (Cooper *et al.*, 2015). Additionally, long- and short-term professional development programs were developed to support instructors in creating instructional materials and assessments that align with the project goals, and to collaborate across disciplines. These activities, in addition to the cross-disciplinary conversations occurring within the MSU AAU project group, spawned the research presented in this dissertation.

Universities are often described as consisting of disciplinary silos, highlighting the lack of communication and collaboration across disciplinary groups. The MSU AAU project, however, was generating a network of education researchers and instructors across campus who were thinking about effective, evidence-based teaching and learning (Cooper *et al.*, 2015, 2017; Laverty *et al.*, 2016). Furthermore, the use of three-dimensional learning as a collective framework was bringing the introductory science courses into closer contact, providing a unique opportunity to explore student experiences and perceptions regarding connections between their courses.

**The early interviews: Cohort 1**

To characterize the unique context presented by the MSU AAU project, an expansive interview protocol (Appendix A) was designed in collaboration with Dr. Sonia Underwood, who was employed as a post-doctoral researcher at the time. At the end of the Spring 2014 semester, exploratory interviews were conducted with students who had taken General Chemistry 1 (GC1) and Introductory Biology 1: Cells and Molecules (B1) in the most recent academic year. The 22 students interviewed (17 of which were in their first year of college) were largely life sciences and pre-professional majors. However, their course experiences were varied (Table 3.1). All 22 students interviewed had taken GC1 in the Fall semester, and most (17 of 22) took both GC2 and B1 in the Spring semester.

That year GC1/GC2 was taught using two curricula, one traditional and one transformed, that differed completely. The transformed curriculum, *Chemistry, Life, the Universe, and Everything* (CLUE), focused on a reduced number of concepts taught in greater depth with an emphasis on facilitating student construction of representations and explanations (Cooper & Klymkowsky, 2013a; Cooper *et al.*, 2017). In comparison, the traditional general chemistry course attempted to cover 17 textbook chapters subdivided into 66 units and used exclusively forced-choice and calculation-based assessments. Of the 22 students interviewed, 14 took CLUE GC1/GC2, and 5 took traditional GC1/GC2. The three students who did not take GC2 were enrolled in traditional sections of GC1.

The first introductory biology course (B1) is taken primarily by STEM majors. During the Spring 2014 semester, five lecture sections of B1 were offered ranging in size from 150-350 students. While these sections covered the same content, and used a common textbook and homework system, they varied by pedagogical style, formative, and summative assessments. Some sections presented the course material in terms of big ideas and actively engaged their students in group work, while others were more traditionally organized. Additionally, one student (Laura) was enrolled in the honors introductory biology course (HB1; denoted by the asterisk in Table 3.1).

**Table 3.1 Interview Participants – Cohort 1**

| Course | Fall 2013 | Spring 2014 | Total |
|---|---|---|---|
| Intro Bio 1: Cells and Molecules | 2 | 20[a] | **22** |
| Intro Bio 2: Organisms and Populations | 0 | 2 | **2** |
| **Total:** | **2** | **22** | |
| | | | **Total** |
| General Chemistry 1 | 22 | 0 | **22** |
| General Chemistry 2 | 0 | 19 | **19** |
| Survey Organic Chemistry | 0 | 1 | **1** |
| Organic Chemistry 1 | 0 | 1 | **1** |
| **Total:** | **22** | **21** | |

a. Laura was enrolled in the honors version of this course (HB1). Her experiences are discussed in more detail in Chapter 6.

**Interview protocol**

Aligning with the theoretical perspectives of MSU AAU project, three-dimensional learning, as described in the *Framework* (2012a), was applied as an organizational and analytical lens for the interviews. As such, the protocol was divided into three main sections – disciplinary core ideas, crosscutting concepts, and scientific practices. To develop a rapport, the interviews began with conversational questions regarding students' experience in college, their academic goals, and their background in science. From there, students were asked a series of questions on each of their courses individually, culminating in a discussion of the disciplinary core ideas (referred to as big ideas during the interview). This process began by asking students to describe their general experience having taken the course. They were then prompted to brainstorm a list of things they had learned. This provided students time to reflect on the academic year. And by asking them to create a written list, they were given a reference; notes that could be referred to as necessary throughout their interview. These activities were intended to diminish the cognitive load required to describe cross-disciplinary connections. With their list in hand, students were asked to relate the items on their list and to group them into categories. They were then asked to consider what the big ideas for the course had been, with an emphasis on their perspective as opposed to concepts that had been promoted by the instructor. This series of questions was designed to help students think about big ideas as high-level concepts central to their courses, rather than describing organizational headings (e.g. units or chapters).

The second section of the protocol asked students to think about concepts that spanned the disciplines of chemistry and biology (i.e. crosscutting concepts; also referred to as themes). Students were first given an opportunity to express their own ideas before being asked about two in particular – energy and the relationship between structure and function (or structure and properties). Student generated crosscutting concepts were only discussed in more detail if they were closely related to those listed in the *Framework* (2012a). For each crosscutting concept, *s*tudents were prompted to describe how their chemistry and biology courses presented the idea, as well as, any similarities or differences they perceived between those presentations.

The purpose of the final section, on scientific practices, was to explore how students were being asked to use their conceptual understanding in the context of their chemistry and biology courses. This was approached in several ways—from asking students to discuss their formative and summative assessments to considering the types of things scientists do on a daily basis. The goal of these questions was to provide students with an opportunity to lead the discussion of scientific practices based on their perspective on the courses. However, it was generally most productive to ask students about scientific practices outright, namely constructing explanations and using models. Even then, early interviews revealed that students responded differently depending on how each practice was described. As such, each prompt was phrased in several ways (Table 3.2) to encourage students to think about various types of scientific representations and types of evidence, many of which are used in the *Framework* (2012a).

**Table 3.2 Scientific Practices - variations in phrasing**

| **Constructing Explanations** |
| --- |
| Using evidence to explain an observation or phenomena<br>Using data to explain what we see<br>Using pieces of information to support an explanation |
| **Using Models** |
| Using pictures to help predict and explain phenomena<br>- Also referred to as representations, graphs, diagrams, and models |

The intent of these interviews was not to assess conceptual understanding but to see how a varied group of students reflected on their experiences. Interviews with this protocol ranged greatly (23-150 minutes) based on the amount of information students wished to impart, with the average interview lasting approximately 80 minutes. Preliminary analysis was conducted using open coding (Corbin & Strauss, 2008). However, the dataset proved to be difficult to analyze for a variety of reasons. Most notably, the scope of the protocol was broad, and the sample of students interviewed was diverse. As such, the dataset included many interesting and unique viewpoints but insufficient information to richly characterize student experiences in any general sense. Ultimately, this dataset was most influential in that it inspired me to initiate three, more targeted projects using a revised protocol.

### Protocol revisions

The variation in students' academic experiences and the breadth of the interview protocol led to a large and diverse dataset. However, during the early stages of analysis, it became clear that additional interviews, narrower in scope, would be required. It was particularly difficult to meaningfully describe how students in the initial dataset characterized the relationship between their chemistry and biology courses without a common conceptual theme around which to frame their discussions. For this reason, I decided to delve more deeply into the crosscutting concepts, specifically energy and the relationship between structure, properties, and function (Chapters 4 & 5). These crosscutting concepts were unique in that they were valued by educators at both a national and local level, as seen by their inclusion in the *Framework* (2012a) and in course syllabi.

For this reason, the crosscutting concepts section was expanded to probe students' disciplinary perspectives more deeply and to characterize how those perspectives were similar or different. Energy is a notoriously difficult concept for both students and instructors (Barak *et al.*, 1997; Carson & Watson, 2002; Chen *et al.*, 2014; Galley, 2004; Nordine, 2015). The vocabulary and symbology used to describe energy, the assumptions made, and the representations presented vary by discipline. To help students make connections to their disciplinary content knowledge, questions prompting discussion of energy transfer and the conservation of energy were included, in addition to the more general prompts from the original protocol. Transfer and conservation were central concepts in the CLUE curriculum[1], discussed regularly across the two-semester course sequence (Cooper, Klymkowsky, *et al.*, 2014). Further, these concepts were commonly discussed in the education literature as central characteristics of energy (College Board, 2014, 2015; Lancor, 2014a; Liu & McKeough, 2005; NRC, 2012a).

[1] Subsequent interview participants would be enrolled in the CLUE general chemistry course as it was in the process of replacing the traditional curriculum at MSU.

For the second crosscutting concept, the relationship between structure, properties, and function, the revised protocol was modified to introduce all three concepts simultaneously. The original protocol reflected much of the literature in both science and science education, which tends to refer to discussions as either that of structure-property or structure-function relationships, often depending on the disciplinary ties of the authors (Cooper *et al.*, 2013; Hmelo-Silver & Pfeffer, 2004; Huang, Patil, Li, & Mann, 2014; Meijer, Bulte, & Pilot, 2013; Nowinski, Sun, White, Keefe, & Jiang, 2012; Tansey *et al.*, 2013; Underwood *et al.*, 2016). However, the *Framework* (2012a) and many other education reform documents discuss the concepts of structure, properties, and function relative to one another, though the labels do not always reflect that choice (American Association for the Advancement of Science, 2011; College Board, 2014, 2015; NRC, 2012a). By removing the constraints of pre-defined relationships, students had greater opportunity to describe how they understood and related the concepts of structure, properties, and function.

Finally, additional questions were included that prompted students to compare the presentation of each crosscutting concept in their courses and how they perceived those as having impacted their understanding (Table 3.3). In this way, students were asked to assess the value of discussing these concepts in their individual courses and how they believed those discussions affected their understanding moving forward.

**Table 3.3 Comparing Energy in Chemistry and Biology**

| |
|---|
| Do you think that your understanding of energy was more important for one course over the other or equally important for both? |
| Do you think that most of what you learned about energy came from one particular course or did they work together to improve your understanding? |
| Were you able to use what you learned about energy in one course to help understand your other course? |

In narrowing the scope of the interviews, the section on scientific practices was removed from the revised protocol. Further, the disciplinary core ideas (or big ideas) section was heavily edited as the original protocol encouraged too lengthy a discussion on each of the individual courses prior to making connections between them. That being said, I still deemed the disciplinary core ideas section necessary as I believed it would reduce the cognitive load of subsequent sections (as discussed above). Additionally, I anticipated that allowing students time for self-paced reflection would limit their reliance on their most recent experiences and allow them to draw examples from across the academic year. For this reason, the revised protocol still asked students to brainstorm and then discuss a list of things they had learned, and then to consider what the big ideas for the course had been. However, questions intended to scaffold that process through categorization and connection-making were eliminated. Additionally, the language in the revised protocol was refined to focus on application of concepts across courses as opposed to content that overlapped, and on instances in which discussions of common content had led to confusion or had seemed contradictory as opposed to difficult to connect. In summary, the disciplinary core ideas section became more focused and purposefully adjusted such that the time spent was in service to subsequent discussions of the crosscutting concepts.

## Summary of the resulting research projects

Using the revised protocol, fourteen additional interviews were conducted at the end of the Spring 2015 semester. The students interviewed had been enrolled in GC1 during the Fall 2014 semester, and both GC2 and B1 in the Spring of 2015. Additionally, they all experienced the same course environments, that is, CLUE general chemistry and a select B1 lecture section, which reflected the move toward introductory courses structured around big ideas. Students' shared experiences and the more focused protocol allowed for a more thematic description of student connections regarding the crosscutting concepts of energy (Chapter 4) and the relationship between structure, properties, and function (Chapter 5).

A third project, following a single student from Cohort 1, Laura, is presented in Chapter 6. As a Genomics and Molecular Genetics major, Laura was required to take additional, more advanced courses in both chemistry and biology. To explore how her understanding of the intersection between chemistry and biology changed over time, she participated in three additional interviews: at the end of her second year and twice during her third year. For the three follow-up interviews, the revised protocol was used to explore how her understanding of energy and the relationship between structure, properties, and function changed as she took more advanced chemistry and biology coursework culminating in a two-semester biochemistry course sequence.

# CHAPTER 4: ENERGY CONNECTIONS AND MISCONNECTIONS ACROSS CHEMISTRY AND BIOLOGY

## Introduction

Energy has long been identified as central to a robust understanding of science. In *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (referred to as the *Framework*), it is referred to as both a disciplinary core idea in the physical and life sciences and a crosscutting concept (NRC, 2012a). However, energy is an elusive concept not easily defined by experts, let alone students. As Richard Feynman famously wrote, "It is important to realize that in physics today, we have no knowledge what energy is" (Feynman, Leighton, & Sands, 1977, p. 4.1 What is energy? section, para. 5). But from an early age, students hear the word "energy" used in colloquial language, and the intuitive ideas they develop are not always productive for constructing a meaningful and useful scientific framework (Barak *et al.*, 1997; Chen *et al.*, 2014; Goldring & Osborne, 1994; Nordine, 2015; Papadouris *et al.*, 2008; Watts, 1983). This is particularly problematic, because understanding energy is vital to developing a robust understanding of concepts both within and across science disciplines. In chemistry, all processes are associated with changes in energy, from the macroscopic observations in a lab to the molecular-level interactions that underpin them. Likewise, all biological systems rely on large inputs of energy to maintain order and function, and students are taught to trace this energy through ecosystems and the mechanisms by which it is captured, processed, and stored in organisms.

No matter the disciplinary context, the underlying energy concepts should be the same. However, the ways in which energy is approached in introductory biology and chemistry courses may seem (at best) superficially similar to students. Variations in scale (e.g., macroscopic vs. molecular), disciplinary system (e.g., organismal vs. solutions chemistry), and perspective (e.g., thermodynamic vs. kinetic) may mask the similarities that underlie these disciplinary approaches and hinder students' ability to transfer their understanding between courses. To facilitate the meaningful learning of energy concepts and the transfer of such learning across disciplinary boundaries, students need to be given scaffolded opportunities to recognize the similarities and reconcile the differences between how we talk about energy in different disciplines and contexts. In this chapter, we investigate how students who are concurrently enrolled in both introductory chemistry and biology courses at the university level perceive the integration of energy within each discipline and across the two disciplines, and how they attempt to accommodate and reconcile different disciplinary approaches to energy, for the purpose of informing future, interdisciplinary course reform.

## Meaningful learning and knowledge transfer

Arguably, one of the goals of education is for students to develop a coherent and connected body of knowledge that can be applied in new contexts. To do so, students must engage in meaningful learning (as opposed to rote learning) through the integration of new knowledge with that which they have already learned (Ausubel, 1968; Novak, 1977, 2002). This requires the learner to “consciously and deliberately choose to relate new knowledge to relevant knowledge the learner already knows in some nontrivial way” (Novak, 1998, p. 23). However, for this to occur, the student must already possess appropriate, relevant prior knowledge and perceive the new material as both important and connected to that prior knowledge (Ausubel, 1968; Novak, 1998). Meaningful learning and knowledge transfer are similar, in that they both consider “the impact of prior experience upon current learning” (Ausubel, 1968, p. 129).

The mainstream cognitive perspective on knowledge transfer has traditionally assessed whether the learner can carry over a predetermined piece of knowledge from a learning task to a transfer task (Anderson, Reder, & Simon, 1996; Lobato, 2006; Singley & Anderson, 1989; Wagner, 2010). Education researchers are particularly interested in situations of far transfer, that is, where the transfer task is situated in a new and different context from the learning task. However, the term “far transfer” has been arguably ill-defined, resulting in a body of literature in which researchers have come to a variety of conclusions regarding whether and when knowledge transfer occurs (Barnett & Ceci, 2002; Detterman, 1993; Halpern, 1998).

Lobato (2006) has argued that, while some have approached this as a methodological or organizational problem (Barnett & Ceci, 2002; Butterfield & Nelson, 1991; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Mayer, 1999; Novick, 1988; Perkins & Salomon, 1988), such solutions do not address critiques regarding the traditional conceptualization of transfer as a passive application of knowledge (Beach, 1999, 2003; Bransford & Schwartz, 1999; Greeno, 1997; Lave, 1988; Lobato, 2003; Packer, 2001; Tuomi-Gröhn & Engeström, 2003). Carraher and Schliemann have argued that transfer should be abandoned as a research construct, because “if we endorse the idea of transfer, we subscribe to questionable beliefs about knowledge” (2002, p. 22). However, other researchers have attempted to redefine knowledge transfer to align with accepted theories of learning. Two such alternative perspectives on knowledge transfer are actor-oriented transfer (Lobato, 2003, 2012) and preparation for future learning (Bransford & Schwartz, 1999; D. L. Schwartz & Martin, 2004). Rather than assessing whether a predefined strategy or principle is transferred between two tasks that the researcher views as structurally similar, these perspectives consider any ways in which learners’ prior experiences shape their engagement in the transfer task (Lobato, 2006; Marton, 2006). Additionally, preparation for future learning considers how a past learning experience may enhance a student’s ability to engage with and learn from a future one (Bransford & Schwartz, 1999; D. L. Schwartz & Martin, 2004).

Chi and VanLehn (2012) have hypothesized that the results of many of the early two-problem transfer studies could be better explained by a lack of deep initial learning rather than a failure to transfer. Similarly, meaningful learning emphasizes that the “quantity and quality” of existing knowledge structures (Novak, 2002, p. 522) and “such organizational properties of the learner’s subject matter knowledge as clarity, stability, generalizability, inclusiveness, cohesiveness, and discriminability” (Ausubel, 1968, p. 129) will determine transfer success.

The conditions of meaningful learning indicate ways in which instructional practices can encourage deep learning experiences such that students can more successfully transfer their knowledge to new contexts (Ausubel, 1968; Novak, 2002). While the extent to which meaningful learning occurs depends on the choices and past learning experiences of the student, instructors can promote and facilitate more meaningful learning through careful consideration of how curricula are organized and by making clear and explicit connections among related ideas (Ausubel, 1960, 1968; Novak, 1977). Further, assessment practices can encourage students to learn meaningfully by limiting their ability to be successful through memorization alone (Novak, 1977). While meaningful learning and knowledge transfer are often considered within the context of a single course or discipline, we believe that such theories can be broadened to consideration of course sequences.

There is little work on how students transfer knowledge from one discipline to another (which we might certainly characterize as far transfer). As such, the goal of the following study was to characterize the current state of alignment between the introductory biology and chemistry courses from the learner's perspective in an effort to facilitate future, interdisciplinary course reforms that support meaningful learning and the transfer of said learning across disciplinary boundaries.

**Defining and discussing energy: A review of the literature**

For decades, instructors and researchers have considered how best to improve the teaching and learning of energy. Early research at the K–12 level focused on describing the intuitive ideas and alternative conceptions of students (Barak *et al.*, 1997; Goldring & Osborne, 1994; Papadouris *et al.*, 2008; Watts, 1983). More recently, focus has shifted to proposing and evaluating new teaching approaches (Batiza *et al.*, 2013; Fortus, Sutherland Adams, Krajcik, & Reiser, 2015; Pintó, Couso, & Gutierrez, 2005) and describing how scientific understanding develops across grade levels through research on learning progressions (Jin & Anderson, 2012; Lee & Liu, 2010; Liu & McKeough, 2005; Neumann *et al.*, 2013). At the high school and undergraduate levels, as students' science course work begins to become more discipline specific, the scope of the research narrows. Studies explore student conceptions surrounding discrete topics such as enthalpy (Carson & Watson, 1999; Nilsson & Niedderer, 2014) or photosynthesis (Brown & Schwartz, 2009; Parker *et al.*, 2012), as we will discuss in more detail later. Recent approaches to the development of more coherent curricula have not only brought the concept of energy to the forefront of science education, elevating it from an isolated topic to a core idea that forms the foundation for understanding many different phenomena, but have also emphasized the interdisciplinary role it plays as a lens through which all science topics can be considered (American Association for the Advancement of Science, 2011; NRC, 2012a).

**The interdisciplinary nature of energy**

The *Framework* (2012a) designates energy as one of four disciplinary core ideas for physical science; it also appears as part of the ecosystems disciplinary core idea for life sciences and is a crosscutting concept: “energy and matter: flows, cycles, and conservation”. There is no other idea that transcends disciplinary boundaries in this way. However, the ways that energy is integrated into each discipline are different because of the nature of the discipline, the history and culture under which it arose, and perhaps most importantly, a lack of interdisciplinary understanding about how energy might be integrated in a more coherent manner.

Consider the complexity of navigating various definitions of energy encountered in multiple science contexts. Terminology and symbology can vary between disciplines even when referring to the same concept (e.g., U, V, and $E_p$ are used to represent potential energy in various contexts). Many of the scientific terms we use (e.g., energy, heat, potential, and work) have strikingly similar and yet significantly different meanings when encountered in everyday speech (Nordine, 2015). One of the most common definitions, energy as the capacity to do work (“Energy,” 2000) is problematic for several reasons. For one, it relies on circular reasoning, as work is commonly accepted to be one of the means through which energy is transferred (Hecht, 2007; Lehrman, 1973; Sexl, 1981; Trumper, 1990a, 1990b, 1991). In physics texts, this definition is almost exclusively associated with mechanical energy, which does not provide students with a satisfactory connection to topics involving thermal and radiant energy (Sexl, 1981). To make matters worse, chemistry and biology textbooks often use this definition without even defining work (Lancor, 2014b) and despite the fact that mechanical energy is rarely useful in the context of these courses (Gayford, 1986; Kaper & Goedhart, 2002).

The situation is even further complicated by the many “forms” of energy introduced to students over the course of their education. In this chapter so far, we have mentioned mechanical, thermal, radiant, and potential energy. Instead of this multiplicity of different types of energy, the *Framework* (2012a) lays out a coherent approach in which energy can be considered as either that of motion (kinetic energy) or stored in fields (potential energy), which gives educators a way to help students construct an understanding of energy that is consistent and transferable across disciplines. For example, mechanical energy means little in chemistry or biology, and chemical energy rarely makes an appearance in physics courses, but kinetic and potential energy can be used to understand all the forms of energy that are typically presented to students. In addition, this coherent approach provides a way to describe the mechanisms of energy transfer via molecular-level collisions and reaction coupling.

While it may seem obvious to experts that the energy discussed in one course is no different from the energy discussed in any other, this is not always apparent to students (Cooper & Klymkowsky, 2013b; Jewett Jr, 2008b). How we talk and think about energy is context dependent. Energy is an analytical tool that is applied differently depending on the scale we are exploring and to answer different disciplinary questions (Nordine, 2015). In one of the few studies to explore energy in multiple disciplines at the university level, Park and Liu (2016) developed an instrument of two-tiered questions (multiple choice followed by short-answer justification) to assess students’ conceptions of energy in four disciplines (i.e., biology, chemistry, environmental science, and physics). The authors found that students who understood energy in one disciplinary context were more likely to understand it in another, but the study did not address how understanding of energy transferred between disciplines. Lancor (2014b) found that students from chemistry, biology, and physics courses used the same underlying metaphors (e.g., energy as a substance that can be carried) and that choice of metaphor was more dependent on attributes of the context (e.g., scale) rather than the disciplinary setting. Both studies addressed student understanding of energy in multiple disciplines, but not how that understanding is transferred and used.

Another area of research has been situated in the context of interdisciplinary courses such as the NEXXUS/Physics project, which redesigned introductory physics for biologists (Dreyfus, 2014; Dreyfus *et al.*, 2014; Geller, 2014; Geller *et al.*, 2014; Redish *et al.*, 2014). Geller (2014) reports that some NEXXUS/ Physics students described physics and biology being in a hierarchical relationship based on scale, complexity, or level of abstraction. One student described the order in terms of increasing system complexity from physics to chemistry to biology. This student believed the jump from physics to biology to be too large and felt that she lacked the connections between physics and chemistry that were needed along the way.

**Energy and biology**

Before considering energy as it pertains to biological systems, we must first define the scope of our study. Biologists can study anything from the replication of DNA to the biodiversity of the entire planet. Because the students who are the focus of this study were enrolled in a cell and molecular biology course, we will focus on the cell and molecular level, the components and processes of which are strongly tied to chemical structure and mechanism.

Biology instructors and researchers have long been concerned with students' ability (or lack thereof) to understand and integrate their knowledge of energy in biology with what they learn in physical science classrooms (Barak *et al.*, 1997; Chabalengula *et al.*, 2012; Gayford, 1986). Understanding the energy transfers involved in cellular respiration and photosynthesis is particularly difficult for both teachers and students (Batiza *et al.*, 2013; Brown & Schwartz, 2009; Parker *et al.*, 2012; Wilson *et al.*, 2006). Batiza and coworkers (2013) argues that this is because learners must have a solid understanding of physical science principles such as atomic structure, electrostatic attractions, and the energy changes associated with the formation and breaking of bonds and interactions—a concept that is notoriously problematic for students, as discussed later (Barker & Millar, 2000; Boo, 1998; Galley, 2004; Storey, 1992). On a related note, Garvin-Doxas and Klymkowsky (2008) found that many student difficulties in cell and molecular biology could be traced to problematic understanding of the stochastic nature of biological processes. Few students recognize the relevance of random molecular motion and energy transfer via collisions, which has widespread consequences in all science disciplines (Garvin-Doxas & Klymkowsky, 2008). It is the perpetual motion of atoms and molecules that leads to the necessary collisions that allow energy transfer and change to occur. However, little research has explored student understanding of stochasticity in biology despite the disciplinary relevance. This may be due to the instructional emphasis on Gibbs free energy and reaction coupling in introductory cell and molecular biology courses.

**Energy and chemistry**

The concept of energy is also fundamental to developing an understanding of chemical phenomena. However, it should be noted that, in most college-level chemistry courses, the idea of energy as an overarching concept may not be explicit. For example, to understand diverse phenomena such as bonding and intermolecular forces, ionization energy, phases changes, and solution formation, one must consider the associated energy changes. And yet, at the introductory college level, discussions of energy tend to be concentrated in two discrete chapters on thermochemistry and thermodynamics, and even the national-level transformation efforts (College Board, 2014; Holme *et al.*, 2015) appear to limit discussion of energy to these two topics. Therefore, it is not surprising that most of the research on student understanding of energy at the college level focuses on thermodynamics. A review of the thermodynamics education literature by Bain and coworkers (2014) found that most studies focused on student conceptions, particularly relating to spontaneity, equilibrium, and the laws of thermodynamics (Banerjee, 1995; Carson & Watson, 1999, 2002; Greenbowe & Meltzer, 2003; Hadfield & Wieman, 2010; Nilsson & Niedderer, 2012, 2014).

**Making and breaking bonds: Chemical potential energy**

While most of the research on energy in chemistry is focused on thermochemical ideas, it is in fact an understanding of potential energy that is necessary for students to understand chemical bonding. Despite this, there is considerably less research on how students understand potential energy in the context of chemistry. Becker and Cooper (2014) identified three ideas (i.e., energy storage, capability, and stability) that chemistry students use to describe potential energy at the atomic–molecular level. While each of these ideas could be productively applied to reason about atomic and molecular interactions, more often students offered intuitive or incorrect interpretations rather than scientifically accurate ones. Only approximately 10% of students in a general chemistry course could provide appropriate, useful ideas about potential energy.

Understanding potential energy is crucial, as it is central to the relationship between energy and bond breaking and formation. While students are often able to identify whether a process requires or releases energy at the macroscopic level from the resultant temperature change (i.e., thermochemistry), the underlying mechanism of this energy change is fraught with difficulty for students. The idea that breaking bonds releases energy is a commonly held alternative conception among both high school and undergraduate students (Barker & Millar, 2000; Boo, 1998; Galley, 2004; Storey, 1992; Teichert & Stacy, 2002) and has even been noted among chemistry graduate students (Gonzales, 2011). These problematic ideas may stem from students' early experiences with energy in everyday life (e.g., energy content in food) and later be reinforced in courses in which energy is discussed as being stored in molecules (Cooper & Klymkowsky, 2013b; Storey, 1992). Indeed, there are a number of instructional materials that describe ATP as having “high-energy bonds” (“Cell energy and cell functions,” n.d.), even though many instructors and researchers have argued that this is misleading and can cause confusion when students attempt to make connections between what is taught in the physical and life sciences (Galley, 2004; Gayford, 1986; Storey, 1992). Villafañe and coworkers (2011) have shown that this misconception persists into biochemistry and found that 74% of students were able to correctly answer all three bond energy questions during a posttest assessment (as opposed to 4% on the pretest), which they attributed to the use of a process-oriented guided-inquiry learning activity on high-energy compounds (Loertscher & Minderhout, 2010). These promising results suggest that students at all education levels could benefit from explicit consideration of energy topics. Nevertheless, the persistence of confusions about bond energies, is a profound example of why it is so necessary that we address energy with a coherent, interdisciplinary perspective.

**Purpose of the study**

Typically, more than half of the students who take two semesters of general chemistry are life science or pre-professional majors, and chemistry is often listed as a prerequisite (or at least a co-requisite) for introductory biology, presumably so students can use their knowledge of chemical reactions and molecular interactions to think about biological systems. Little is known about how students use and transfer knowledge across disciplinary boundaries, and therefore, to inform future, interdisciplinary reform, this study was designed to characterize the current alignment of the introductory chemistry and biology courses from the learner’s perspective by investigating whether students do in fact recognize connections between the content and to determine whether they believe the connections to be useful. When this study began, the introductory science courses were at various stages of a collaborative transformation process (Cooper *et al.*, 2015). Therefore, the data we present should be considered in the context of courses that were attempting to develop a coherent approach across the disciplines. The ultimate goal of the study described herein was to identify opportunities for stronger connections between the courses and to understand potential barriers in developing those connections in an effort to facilitate course reform focusing on making explicit interdisciplinary connections.

## Methods

### Setting and participants

This study was set at a large, public research university in the Midwest where the average student had an ACT composite score of 24–29. The student body includes 18.7% students from underrepresented groups and 14.4% international students. At this university, general chemistry for science, technology, engineering, and mathematics (STEM) students is taught as a two-semester sequence (GC1 and GC2). Lecture sections are 350–450 students in size and include a required 1-hour recitation section. About 35% of students who take GC1 go on to GC2 at this institution, with most of these students pursuing majors related to the biological sciences. Only students who had taken both GC1 and GC2, in the Fall 2014 and Spring 2015 semesters, respectively, were included in this study, because we wanted them to share a recent experience that would allow them to provide informed commentary.

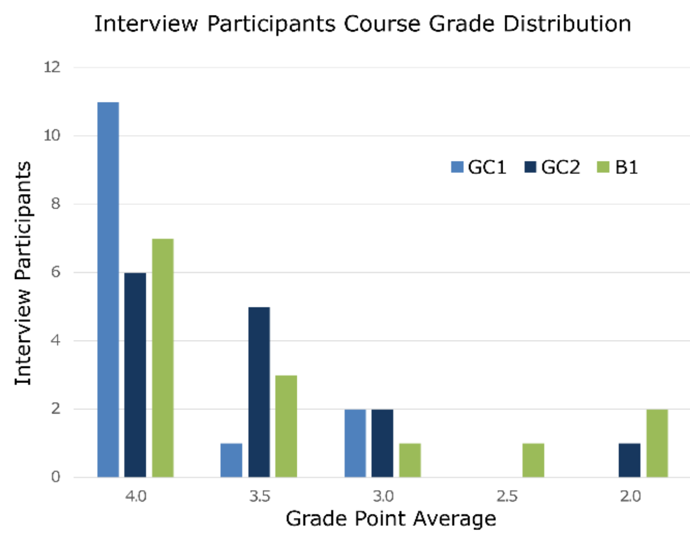
It is important to note that these students were taught using a transformed general chemistry curriculum—*Chemistry, Life, the Universe, and Everything* (CLUE)—designed to help students build a more sophisticated and cohesive understanding of four core ideas, one of which is energy (Cooper & Klymkowsky, 2013a, 2013b). It is intended to address the needs of the majority of general chemistry students including life science and pre-professional majors and uses biological phenomena to illustrate the underlying chemistry content. Over time, the energy progression within the curriculum has been iteratively improved to help students connect to their prior knowledge of forces and energy by starting with potential and kinetic energy in the context of atomic interactions explicitly discussing the relevance of collisions and the energy changes associated with bond breaking/formation (Cooper & Klymkowsky, 2013b; Cooper, Klymkowsky, *et al.*, 2014). This course plays an integral role in the context of this study.

The first introductory biology course (B1), taken primarily by STEM majors, focuses on cell and molecular biology. While students can take this course concurrently with GC1, it is not common for students to do so. Lecture sections range from 150 to 250 students and present seven core ideas that were negotiated by the faculty, using *Vision and Change* (AAAS, 2011), a call for undergraduate biology curriculum reform, as the starting point, which are introduced at the beginning of the semester. One of these core ideas is matter and energy. At the beginning of each unit, the applicable core ideas are described again in the context of the upcoming material. All lecture sections of B1 use a commercial textbook and homework system (Mason *et al.*, 2015) to provide a common resource and approach. The students who participated in this study were enrolled in the same lecture section of B1, the instructor of which was aware of this study and provided helpful guidance to the researchers to contextualize the information being taught. One of the authors attended lectures of both this course and the chemistry course from which participants were selected.

A call for participants was made in the GC2 courses during the last 2 weeks of the Spring 2015 semester, offering a small amount of extra credit as compensation for participation. The first 14 volunteers who met the qualifications were included in the study. That is, they had taken GC1 in Fall 2014 and both GC2 and B1 in Spring 2015, were in CLUE lecture sections for both GC1 and GC2 and had taken the preselected B1 lecture section. The other 385 volunteers were given an alternate activity to complete for extra credit. Of the 14 participants, nine were female and five were male; all were interested in pursuing careers related to biological science or the health professions. Twelve of the students were finishing their first year; the other two were finishing their second year. Of the 14 students, eight earned a 3.5 or above in GC1, GC2, and B1. On average, the interview participants earned a 3.8 GPA in GC1, 3.5 in GC2, and 3.4 in B1. The complete student grade data are presented in

Figure 4.1. All student data presented were gathered with institutional review board approval. Students were notified of their rights as research participants and provided informed consent before participating in the study.

**Figure 4.1 Interview Participants Course Grade Distribution**




GC1 – general chemistry 1; GC2 – general chemistry 2; B1 – introductory biology 1

**Interview protocol**

The work presented here was part of a larger interview protocol that probed student perceptions regarding connections between their course content more generally (Appendix B). Because we were asking students to discuss and connect an entire year of science course work, we designed the protocol to allow time for reflection and discussion of each course before having the students attempt to make connections. Therefore, the protocol began by asking students to brainstorm a list of things they had learned in general chemistry and consider what the big ideas or take-home messages were for the course. GC1 and GC2 were treated as a single course sequence throughout the interviews. While instructors had defined core ideas in both GC1/GC2 and B1, students regularly provided their own. After repeating this process for B1, the students were asked to discuss any connections they felt existed between the courses and what, if any, conflicts they perceived between the material discussed.

The second half of the protocol was inspired by the crosscutting concepts of the *Framework* (referred to as "themes that span chemistry and biology" in the interviews; 2012a). Students were given the opportunity to generate their own themes before being asked about two in particular—energy and the relationship between structure, properties, and function. Students were asked to describe why energy would be considered a theme, how it was discussed in each of their courses, and to describe the relative emphasis and importance of energy in each course. Concepts of energy transfer and energy conservation were explicitly discussed.

**Data collection and analysis**

The 14 interviews varied in length from 70 to 150 minutes depending on the amount of information provided by the students, who were told that they could terminate the interview at any time. However, all participants had a great deal of information to impart and willingly stayed longer than we had anticipated. Students used a *Livescribe* pen to create lists of ideas and enhance their descriptions with diagrams and drawings that allowed the audio data to be collected in conjunction with their constructed responses. Additionally, a digital recorder was used as a backup audio source. Data collection and analysis were undertaken from a phenomenographic perspective, as our intention was not to categorize what students do or do not know, but instead to provide a rich description of the various ways that students related their experiences taking introductory chemistry and biology.

The audio data were transcribed verbatim by a professional transcription service. I then reviewed and edited the transcripts for both accuracy and completeness. To gain a holistic understanding of each student interview, the entirety of the transcript was read, and summary notes were taken. However, due to the length and depth of the interviews, all references to energy or topics considered by students to relate to energy were excerpted with both context and analysis notes interspersed. The excerpts were then coded by context (i.e., chemistry or biology) and topic (e.g., references to potential or kinetic energy, bonding, cell metabolism). Each topic and context code was treated as a subsection of data and open coded. This allowed the researchers to identify what course topics were being discussed and how discussion of those topics varied by context and by student. The interview protocol followed three lines of questioning: discussion of energy generally within the courses and with respect to the conservation of energy and energy transfer. Ultimately, student discussions of the conservation of energy were found to contain little more than a restatement of the first law of thermodynamics. Therefore, the findings presented herein are limited to discussions of energy (general) and energy transfer. The data were reviewed and discussed iteratively by myself and Dr. Cooper to ensure that these areas of discussion were accurately represented by the chosen quotes. While most of the data herein are from the portions of the interviews during which energy was the focus, all discussions of energy were used to inform our analysis. To improve readability, vocal fillers have been removed from the transcript excerpts presented here.

## Findings

Within the two main areas of discussion, we found that 1) students held differing opinions about whether energy would be considered a core idea in their courses, despite describing it as generally important to the scientific world, and 2) descriptions of energy transfer (and particularly the molecular-level mechanisms by which it occurs) were highly context dependent. As students elaborated on their understanding of energy transfer in chemistry and biology, it became clear that many were unaware or confused about how to make connections between their courses, particularly when discussing ideas such as reaction coupling, the relationship between energy and bond breaking and forming, and molecular-level collisions. Additionally, while it was common for the terms “kinetic” and “potential” energy to be discussed in the context of chemistry, this terminology was infrequently used in the context of biology. Together, student discussion of these ideas and the relative necessity of energy within their courses reveal a substantial disconnect between how energy was understood and used in their course work.

**Energy as a core idea in chemistry and biology**

As noted previously, both the *Framework* (NRC, 2012a) and *Vision and Change* (AAAS, 2011) regard energy as a core concept, central to a robust understanding of science. Students also recognized the importance of energy to the physical and natural world, stating that energy "gets things started," "drives reactions," or as John put it, "Everything requires energy." These statements are reminiscent of conceptions taught in early science classes, describing energy as a causal necessity, a notion that is at the very least incomplete (Lancor, 2014b; Ogborn, 1986, 1990). However, despite their belief in the general importance of energy, opinions varied regarding the relative importance of energy in the general chemistry (GC1/GC2) and cell and molecular biology (B1) courses they were co-enrolled in. One of the final energy questions during the interviews was, "Do you think that understanding energy was more important for one course over the other or equally important for both?" Four students felt that understanding energy was equally important in both courses. Nine believed that understanding energy was more important in chemistry. The remaining student, Lida, clarified that energy was "not necessarily less important in bio, but less apparent." In comparison, she said that, in chemistry, "Literally everything that you do I feel like energy is somehow incorporated." Three of the nine students (Daniel, Natalie, and Joseph) went so far as to state that understanding energy was not necessary to their success in B1.

> Natalie: I think you can still do well on any biology test that I've taken without really understanding energy and its properties, and I think you would not do well at all if you had no understanding of energy and its properties on any of those chemistry tests—or just in understanding chemistry in general.

Natalie believed that she needed to understand energy not just to be successful in GC1/GC2, but also to develop a strong understanding of the content. However, she believed that she could do well on her biology exams without such understanding of energy. It is important to remember that these students were comparing their biology course with a transformed chemistry curriculum that was designed to explicitly focus on four core ideas (one being energy). This is made evident by Daniel's description of energy in GC1/GC2. He recognized that subsequent ideas were built upon energy concepts they had already learned and were therefore more important to understand.

> Daniel: In chemistry, in order to succeed and learn the next idea, big concept or whatever you need to know, that you need to know about energy. I think in biology the way we learned it, we didn't necessarily need to, know about energy. I would have liked to, because I think I would have understood it better, but in order to succeed I really don't think we needed it as much in the course.

While Daniel felt that having a better understanding of energy would improve his comprehension of the biology material, he too felt that it was not necessary for the course. As noted earlier, even though energy has been designated as a core idea in B1, the commercial textbook does not explicitly connect the core ideas for students. Differences between how explicitly energy was discussed and connected to other ideas within the two courses led students to believe it was more important for GC1/GC2, as evidenced by Louanne.

> K. Kohn: Do you think that your understanding of energy was more important for one of your courses over the other? Or equally important in both?
>
> Louanne: In chemistry, it just keeps coming up again, and again, and again. So I feel like it's used for more things … yeah definitely more in chem, over biology. Just based on the fact that it's brought up more, and I feel like I personally use it, the idea of it more.

In fact, five of the 14 students went on to describe the discussion of energy in B1 as being limited to the metabolism unit. While Lida recognized that ATP was being used as a placeholder, a reference to the energy involved in biological processes, Louanne did not.

> Louanne: I know we use energy for the different cycles and stuff like that. But now that we're out of the cycles, we're into DNA replication, and we're not talking about energy anymore.
>
> Lida: When they're talking about DNA synthesis they don't really talk about where the energy comes from to do that, or where the energy goes to do that, it's more so, "Oh, just ATP." Everything just goes back to ATP.

These references to ATP (and therefore, energy) made throughout B1 were not sufficiently explicit for Louanne. And so, because she could more easily recognize the role of energy in GC1/GC2, she believed it to be more important in that course.

We also found that students described various ways in which they could use their understanding of energy in chemistry, such as constructing reaction diagrams and other graphs of Gibbs free energy, or determining the enthalpy of a reaction; however, we did not find any description of how students used their understanding of energy in biology. Instead, students focused on describing metabolic processes and cataloguing the inputs and outputs of those reactions (e.g., the number of ATP molecules required for and produced during glycolysis). Discussions of energy largely occurred at the molecular level, as one might expect from students co-enrolled in chemistry and cell and molecular biology. This was particularly apparent when students were discussing energy transfer.

**Molecular-level descriptions of energy transfer**

**Energy transfer in biology: Reaction coupling** The coupling of ATP hydrolysis to an unfavorable reaction is a vital component of energy transfer in biology. While it is not the only example of reaction coupling in biological systems, it is the most commonly discussed example in introductory biology courses. However, only two students (Ruth and Natalie) discussed reaction coupling in any detail.

Ruth: Energy transfer in biology, I feel like I think more of something being phosphorylated, and how that sort of transfers energy, as opposed to two things colliding … when you transfer a phosphate group, and that gives off a lot of energy… It can be used as activation energy for something else, and a coupled reaction.

Natalie: It's also hard to understand how the glucose can be converted into ATP if you don't really understand chemistry. And so obviously a lot goes into it, but basically it's like a coupled reaction … so you need an exergonic reaction in order to have the energy to allow the endergonic reaction to overcome the activation energy.

The ideas that these students are struggling with are complex and often counterintuitive. Natalie implies that the coupling provides energy to overcome the activation energy barrier; in fact, coupling acts to produce a more reactive phosphorylated species so the barrier to reaction is lower. Ruth expanded on this idea by including the transfer of a phosphate group, but neither student could give a coherent explanation of this mechanism.

The level of insight that both Ruth and Natalie provided was unusual. Of the 13 students who discussed ATP, eight indicated that they were unsure about how it worked. In fact, it was not uncommon for students to have incorrect notions about ATP and its role in biological processes. Five students referred to ATP as energy or a form of energy.

> Daniel: ATP is a form of energy that, can help a reaction take place… And the way that we were briefly described in biology was that, it was like harnessed energy, and when the bonds were broken, it released energy.

Daniel's description includes an alternative conception (i.e., breaking bonds releases energy) that has been well documented among students at varying stages in their education (Barker & Millar, 2000; Boo, 1998; Galley, 2004). While not uncommon among students interviewed for this study, it was exclusively mentioned in the context of their biology content. Of the 12 students who discussed the relationship between energy and the breaking and forming of bonds, every one of them did so correctly in the context of chemistry (i.e., energy is required to break a bond and energy is released when a bond is formed). This is possibly because these concepts are emphasized in the transformed chemistry curriculum. Reports of students in more traditional chemistry curricula indicate more confusion around this topic (Teichert & Stacy, 2002). Unfortunately, this understanding did not seem to transfer well to their studies in biology. Only eight students discussed the energy changes associated with bond breaking/formation in the context of biology; of these students, five felt there was a conflict between what they had learned in chemistry and what they perceived to be the correct relationship in biology. Clarice seemed to recognize this conflict for the first time during her interview.

> Clarice: I'm starting to think about this as I was trying to explain it to you because ATP, when the bond's broken, energy is released … when one of the phosphates is broken off, it releases energy. That's, I think, what's getting me. Because when the bond's broken, it should absorb energy. So I'm getting very confused.

When trying to explain how ATP could provide energy to a reaction, she realized that she was contradicting what she had learned in chemistry. Although she was comfortable with the ideas she had learned in her respective courses, she was unsure how to reconcile them, having never considered it before.

Lida recognized the conflict in the process of studying with a group of friends who were co-enrolled in chemistry and biology. Someone proposed a practice question about ATP to which she (and her friends) believed the correct answer would have been different depending on the course she was taking the test in. She found her inability to reconcile these two ideas frustrating.

> Lida: I just learned something in two opposite ways… I actually still don't really understand it, to be honest. I don't really know which one's right, if it's ATP produces energy or the phosphate group from the ATP produces the energy when bound to—I think it's the second one, but I'm not really sure… Because I know that everybody who I'm friends with who's in bio and chemistry all knows the same thing, in bio this is right, in chemistry this is right. But then we don't actually know which one's right.

Lida got to the root of the problem without even realizing it. Without an understanding of the setting in which ATP hydrolysis occurs, the only noticeable change is that a phosphate group is broken off. This is because the new bonds being formed are often left out. Daniel also indicated that a lack of context left him unsure of how ATP works.

> Daniel: So in glycolysis we said, "Oh, it releases ATP and that gives energy." I know that, okay, ATP, energy. But I'm just not entirely sure how that whole process happens … the way that we were briefly described in biology was that, [ATP] was like harnessed energy, and when the bonds were broken, it released energy … in the back of my head I know that that's probably not exactly how ATP works. There has to be something else that's going on, because clearly that's the opposite of what we had learned [in chem].

Daniel was confident in his understanding of the energy change associated with bond breaking and formation based on what he had learned in GC1/GC2: breaking bonds requires energy. This allowed him to recognize that the brief discussions of ATP in biology were missing something. Throughout his interview, he expressed the desire to better understand ATP and how it relates to energy.

If we consider Natalie's explanation of ATP, the potential for misunderstanding seems quite clear. "[ATP is] divided into ADP and phosphate and then that division provides energy for your body since that's an exergonic reaction." Indeed, ATP hydrolysis is an exergonic (thermodynamically favorable) reaction. And students are told that there is a net release of energy that can allow thermodynamically unfavorable reactions to occur through reaction coupling. However, when this reaction is described superficially, as Natalie did (and as is shown in some educational materials; “Cell energy and cell functions,” n.d.)), it is the breaking of the phosphate bond that is most apparent. Given these two pieces of information, the conclusion that breaking bonds releases energy seems quite logical and self-consistent. Though frustrated and confused, those who recognized the conflict did not believe that B1 was negatively impacted. Daniel described it as a “minor detail” in biology, and the other four students knew what would be considered the correct answer in each course. Consider Priyah:

> Priyah: I feel like I can ration [*sic*] it out both ways, so then, I understand why someone would say either/or, but then I know for biology what [the instructor] wants us to say and then for chemistry what we have to say.

Unable to determine which was correct, Priyah would tailor her response to the course she was in. Despite feeling that they could successfully answer the question for each course, both Lida and Priyah expressed dissatisfaction with their understanding.

In summary, only two students (Ruth and Natalie) mentioned reaction coupling as a mechanism of energy transfer. More commonly, students simply described ATP hydrolysis as providing energy, though they did not know how this happened. Some students could do little more than equate ATP with energy. For instance, Louanne used an analogy to describe how biological processes occur, “Well, we talk about [ATP or GTP] as … I think of it as coins, at an arcade. You have to put so many in to get the system going.” While such an analogy serves to impress upon students that ATP is important and associated with energy input, it is an example of how discussing ATP hydrolysis and reaction coupling only briefly can leave students feeling as Daniel did, that the only takeaway is that ATP has something to do with energy.

It is interesting to note that the term “potential energy,” or even “chemical energy” (which is often described as a type of potential energy by instructional materials), was not used by students when describing biological systems at the molecular level. While two students mentioned learning about potential energy in biology, only one student applied the term in context.

> Simon: We know that energy comes from the things that we eat, the potential energy in food… And we know that the cells can then use that chemical potential energy to create things like kinetic energy or chemical energy to do the things that they need to do.

While Simon's discussion of potential and kinetic energy is almost certainly prior knowledge, he did not go on to use it in the context of the courses he was taking.

In contrast, most of the students interviewed (11 of 14) mentioned learning about potential energy in the context of chemistry, often referencing the potential energy curve that was discussed extensively at the beginning of GC1. Simon: "I just remember drawing the potential energy curve 100,000 times." The simulation[2] showed how the kinetic and potential energy changed as the distance between two atoms changes.

> Aaron: We talk about energy between atoms, coming together. Like if two helium atoms are coming together, we talk about the kinetic energy versus the potential energy of the atoms, like depending on where they're at—if they're close or if they're far. We talk a lot about energy all the time.

The multiple lecture periods spent discussing potential energy and the chance for students to interact with the situation in a variety of ways may have led to a number of the connections students made to other concepts (e.g., stability, energy transformation, conservation of energy). Clarice and Shelly describe features of the simulation that show energy being added or removed from the system through the collision of a third atom.

> Clarice: Because in the beginning we talked about the potential energy curve or whatever, and how … when it was in a stable bond and you put that extra molecule in, it broke up the bond because it was giving it its energy.

> Shelly: […] and the potential energy curve, and they would come together and they would come apart, and then, they would come together, and then something would come collide and take the energy, and they'd stay together.

These descriptions illustrate the relationship between energy and the breaking and forming of bonds. However, both potential and kinetic energy are implicit in these descriptions, through discussion of the stable bond and collisions, respectively. And when explicitly discussing reactions and bonding (topics that were discussed at a later time in GC1/GC2), students favored terms like "Gibbs free energy" or simply "energy." While it is clear that the students interviewed were aware of potential energy in chemistry, they did not appear to be connecting and applying this concept to other ideas in either chemistry or biology.

**Kinetic energy and collisions: The initiation of energy transfer** While reaction coupling is the mode of energy transfer most commonly mentioned in introductory biology courses, a reaction would never be initiated if the reactants did not first collide (a mechanism of kinetic energy transfer). However, use of the term "kinetic energy" was absent from students' descriptions of energy transfer in biological systems. This is not entirely surprising, as few biology (or even chemistry) courses discuss the role of collisions in detail. In this way, the CLUE curriculum is different, emphasizing the importance of collisions as the mechanism of kinetic energy transfer throughout the entirety of the course. Most students in this study (10 out of 14) discussed the collisions of atoms and molecules in the context of energy transfer. There were examples of students describing collisions in the context of phenomena (e.g., phase changes) and using them to explain why breaking a bond requires energy. Three students (Natalie, Joseph, and John) went so far as to call collisions a "big idea" of GC1/GC2. While Natalie did not feel that collisions were discussed to the same extent in the second semester, she asserted that they were still at the core of the concepts being discussed (e.g., kinetics, equilibrium):

> Natalie: [Collisions are] the underlying reason for a lot of things. So we'll just say, "Okay, well when temperature increases more collisions and therefore that's why this happens," … that's why the reaction will go faster and that's why it will go in this direction or that direction. So I feel like it still is a huge part of what we're learning … it's always kind of there in the back of your mind.

Natalie recognized that, even if collisions were not being discussed in detail, they were fundamental to the causal mechanism underlying changes in the direction or rate of a reaction. She was not alone in emphasizing the importance of collisions. Joseph referred to them as the "answer to everything" and

Ruth stated that “in order for every action to occur, [the] molecules need to collide and they need to transfer energy to each other.” Despite this confidence in their ability to describe the role of collisions within chemistry, only three students (Joseph, Serina, and John) immediately made the connection to biological systems. Consider Louanne’s description of energy transfer in biology as compared with chemistry:

> Louanne: The transfer of energy? Well, I know we talk about it in chemistry a lot… You have two atoms, and then you add another one. And they collide, and it transfers energy to break it out of that system. Or heating things up, where you have a container of something and you heat the outside. So the atoms are going to start colliding faster and transferring that energy around. In biology, the transfer of energy—I don’t know… I know for sure I can relate it to chemistry. But biology, eh, not so much.

While she could discuss collisions when considering the energy transfer involved both in a single interaction and with respect to changes in the macroscopic properties of a material, she was unsure of how to think about energy transfer in biology. When asked to consider it further, Louanne stated that they were more focused on “the breaking down of energy and then building it back up.” When encouraged to think about how her understanding of energy transfer in chemistry might relate to biology, she seemed to be at a loss.

> Louanne: I don’t know if things happen the same way. Just because when I think of energy transferring in chemistry, I’m thinking of atoms colliding. And just because biology’s just at a little bit bigger scale than the atoms colliding… I’m sure that in some way they do relate. Because, I mean the cells are made of atoms… So [pause] I think in some way that you could, but I don’t know if I have.

Because biological systems are typically discussed at a larger scale than in chemistry, she had not considered the relevance of collisions in biology. While she recognized that the systems discussed in GC1/GC2 and B1 were related, it was not immediately apparent to her how to make those connections. Similarly, Evelyn could predict how collisions applied to biological systems, but she had not needed to make those connections for B1.

> Evelyn: I might be wrong since we haven’t talked about it, but I think it is collisions and things that make the process run. From step to step to step. We just kind of memorized the steps, what’s formed in each step, and what’s made in each step, or what’s broken.

While in fact, her biology instructor did *not* require her to memorize the metabolic pathways, Evelyn chose to do so anyway. Her course did not consider the molecular-level interactions that allowed these reactions to occur, and she was unprepared to make those connections on her own without considerable prompting.

Opinions varied as to whether understanding the collisions associated with energy transfer would be helpful in biology. Some felt that energy transfer via collisions would be an unproductive addition to an already detailed course, or even that collisions were not applicable in biology. Others believed it might provide additional insight into how energy transfer occurs. Natalie was interested in trying to make connections between her courses but recognized it would be difficult.

> Natalie: I think it would confuse me… Because in biology … the systems of harvesting energy, it's a very long process. It's not just a collision … you have a glucose molecule and it goes through this and then it goes through this and then it goes through this and then finally energy. You know, it's not just like, "Okay, two things collide and then your body interacts." So I think … yeah, it would be an interesting thing to try to transfer over to my understanding of biology but I think it would be confusing at first.

Natalie believed that understanding energy transfer via collisions in the context of biology would be difficult by comparison, because there would be more than one collision to consider. Her implication being that, in chemistry, the focus is often on a single collision or within simple systems. While descriptions of a single collision were common in the context of disrupting or forming a stable interaction, there were also discussions of multiple, simultaneous collisions in the context of heating a container or in changes to the kinetics or equilibrium of a reaction (described earlier by both Louanne and Natalie). Despite this, Natalie still felt that the gap in complexity would be a difficult one to bridge on her own.

John felt that understanding energy transfer via collisions would not have helped him on his biology exams. However, he did value the time spent discussing energy transfer in chemistry, as it was something "you have to understand." When questioned about his ability to apply what he learned about energy transfer from chemistry to biology, John stated: "If I had to I could but I don't—there's no reason to… Because you don't go into the depth of it." In biology, only the presence of energy was mentioned, whereas they had discussed "how the energy would play a role in the reaction" in his chemistry course. So while he believed that he could apply his understanding of energy transfer to biology, he had not needed to do so. Despite this, John had faith that one day he would.

> John: I imagine I'm going to have to at some point in time… I could see where it would be very important to understand energy and how it's transferred [in biology] because … when you're talking about energy so much, you need to understand where it's coming from and where it's going. You can't just assume there's just energy floating out there and [it] just magically goes into something and then something happens… You have to understand why that energy's needed and how it's used.

John recognized the value of understanding energy transfer at the molecular level. Without it, he felt that you might take for granted energy's role in reactions, believing it just "magically" occurs. John was able to acknowledge these potential misconceptions because of his understanding of energy transfer from GC1/GC2.

> John: I think you can understand biology without a chem background, but it's definitely nice to have a mix of all the chem stuff in there … because the chem is just real in detail and like bio doesn't go into that much detail in like the chemistry side… So if you have the prior knowledge [from chemistry], you can apply that to what's going on in biology. But if you don't have the prior knowledge, you can't—you have nothing to work with.

John did believe that biology could be understood without a chemistry background, but he recognized that it would be a different depth of understanding. Ultimately, John represents a best-case scenario. He developed an understanding of the transfer of kinetic energy via collisions in GC1/GC2. And, even though it was not necessary for him to apply this understanding in B1, he believed that it was valuable information that would someday be necessary for him to think about in a biological context. Additionally, John was able to consider what might have happened if he had not understood the molecular-level mechanism of energy transfer; that he might have taken energy for granted and never considered why things occurred. He believed that, without the prior knowledge that he had built in chemistry, he would have had "nothing to work with" when attempting to understand the underlying molecular-level mechanism. Students' prior understanding of collisions was not well connected to their knowledge of energy in biology, resulting in a missed opportunity to make stronger connections between disciplines. Only John appears to have fully recognized the potential of making such a connection.

**The dynamic nature of biological systems** Student descriptions of biological systems in the context of energy contain few references to the dynamic nature of the molecular-level and the kinetic energy transfers involved. In fact, not a single student explicitly referenced kinetic energy in the context of biology. The potential consequences of these descriptions are made most apparent by Clarice and Aaron who, when attempting to discuss the metabolic cycles, used neither reaction coupling nor collisions to describe a molecular-level mechanistic explanation.

Clarice associated energy transfer with the breaking and forming of bonds in a chemical reaction. However, when asked how energy transfer related to B1 she was tentative in her response, considering as she spoke.

> Clarice: [It's] different than in chemistry … the energy released in the one spot eventually I guess works itself down. You use ATP in glycolysis and it—that energy gets moved to the Krebs cycle … and like gets transferred I guess, from everywhere… In biology I guess I think it has—when I think about it, it has [an] effect on a lot of different parts not just … like in chemistry where I think of it as just having an effect on this one reaction.

Clarice was focused on describing the order of events (i.e., from glycolysis to the Krebs cycle) and the increased complexity of biological systems in comparison with the ones discussed in chemistry. Her focus on the differences between the systems may have resulted in her belief that energy transfer was different depending on the disciplinary context. When asked to describe how the energy transfer in biology occurs, her response focused on biological pathways.

> Clarice: In bio, and I think it's because the one energy released, it goes down the chain of events. I know it goes from this cycle to this cycle to this cycle, that's the natural occurrence. So I think the energy just flows through.

Clarice has been taught the metabolic pathways in a particular order and how the products of one pathway feed into the next. However, her description indicates that she has taken this process for granted as the “natural occurrence.” Clarice was unable to describe how this occurred, instead stating that she was just told that it happened. This is in direct contrast to her identification of an explicit, molecular-level description of how kinetic (though not potential) energy transfers in chemistry: “through [atoms] hitting each other.” She went on to state that this idea of atoms or molecules colliding to transfer energy does not apply to biology. In this way, Clarice’s understanding of bond energies and collisions does not appear to have been connected to her understanding of energy in biological systems.

Similarly, Aaron brought up collisions as something he learned in GC1/GC2. However, he did not give the same attention to the molecular level when discussing biological systems. Instead, he too described energy transfer between metabolic cycles. “If energy is given off by some system … it somehow needs to get the energy back. I think of it more as a cycle thing in bio, because a lot of the processes are repetitive within your body.” Aaron’s regular use of the term “cycle” and his statement that the energy lost will need to be renewed would suggest that he understands that energy must be consistently added to metabolic processes, but later he contradicts this view.

> Aaron: I see bio as more of a cycled aspect of energy. I think if something is continuously going around and around and around … the system is not going to lose energy and it’s not going to gain energy. It’s just going to keep going on what it has.

Aaron’s description of energy in the context of biological systems was certainly inconsistent, and while it is unlikely that he really does think that the energy is continuously being recycled without being gained or lost, he goes on to state that he does not need to worry about energy transfer, because the energy is already there.

> Aaron: We know that these processes happen. And I think of energy as a more continuous cycle, so you don’t need to worry about energy being transferred at all… That’s just how I think about it, how it’s cycled through. I think of it more as it already has energy. Energy is being transferred, but I already see it as it’s already there… I don’t care where it’s coming from.

His matter-of-fact view of these processes allowed him to believe that energy transfer was unimportant and that he could take it for granted, that energy would be present whenever needed. And yet, when asked to consider his understanding of energy in both courses, Aaron asserted that he could apply what he learned about energy in chemistry to biological systems.

> Aaron: I can make sense of it through chemistry. I know that this energy came from somewhere; it didn't just come out of nowhere. I know that it's continuously being transferred. Like I said in the earlier questions, the fact that I learned it here [in chemistry] makes me better understand it here [in biology].

Having discussed energy transfer and the conservation of energy in GC1/GC2, Aaron recognized that these same principles apply to biological systems. However, it was not clear that he could appropriately discuss or use them. Although Clarice recognized that energy transfer could occur via collisions, neither Aaron nor Clarice provided a description of energy transferring via collisions or reaction coupling in biological systems. Instead, both students appear complacent with their level of understanding of energy in biology. However, as John stated, "You can't just assume there's just energy floating out there and [it] just magically goes into something and then something happens… You have to understand why that energy's needed and how it's used."

## Discussion

What stands out most dramatically is the context dependence of students' descriptions of energy. While students recognized the general importance of energy to the scientific world, nine felt that energy was more important to understand in GC1/GC2 than B1. We found that student discussions of ATP were often oversimplified (i.e., five students referred to ATP as energy or a form of energy) and eight students expressed confusion as to how ATP works. Additionally, reaction coupling was only discussed by two students. In comparison, most students were able to discuss the foundational energy topics that had been presented in GC1/GC2, such as potential energy (11 of 14), the relationship between energy and the breaking and forming of bonds (12 of 14), and kinetic energy transfer via collisions (10 of 14). However, in many cases, this approach to understanding energy transfer and bond breaking/forming did not appear to be useful to students in B1. Five students believed there to be a conflict between how their courses presented the relationship between energy and the breaking/forming of bonds. Only two students discussed potential energy in the context of biology. And opinions on the relevance of collisions to their biology content ranged widely. Together, students' discussions of the perceived importance of energy within their courses, the various mechanisms of energy transfer discussed, and their own understanding of the relationship between energy and the breaking/ forming of bonds reveal a profound difference between how energy was presented and used in their course work, and their perceptions of what was or was not important clearly factored into whether they chose to use their prior knowledge.

In chemistry, energy was embedded in the progression of topics, necessary for building understanding throughout the course. As Daniel said, "In chemistry, in order to succeed and learn the next idea, big concept or whatever you need to know, that you need to know about energy." In biology, energy was also considered fundamental; life could not exist without it. And yet, students felt that the discussion of energy was limited to metabolic cycles and did not recognize it as a lens through which many of the ideas they were learning could be considered. Generally, students perceived energy to be more important in GC1/GC2, necessary for success and to achieve a strong understanding of the material. Whereas in biology, this was not the case; Natalie even went so far as to note that "I think you can still do well on any biology test that I've taken without really understanding energy and its properties." This idea that course assessments tend to drive what students focus on has been noted on many occasions (Crooks, 1988; Entwistle, 1991; Momsen *et al.*, 2013; K. Scouller, 1998; K. M. Scouller & Prosser, 1994; Snyder, 1970) and is consistent with one of the tenets of meaningful learning—that is, students have to choose to incorporate new knowledge into existing cognitive structures (Ausubel, 1968; Novak, 1998). If assessment practices do not encourage such behavior, students may not see the value of putting in the effort to learn meaningfully. GC1/GC2 and B1 both acknowledged the importance of energy, each explicitly identifying it as a core idea. However, the core ideas were incorporated into these courses differently. While GC1/GC2 was redesigned from the ground up to help students understand and connect the core ideas throughout the course (Cooper & Klymkowsky, 2013a; Cooper *et al.*, 2017), efforts to transform B1 were still in the early stages. The core ideas, negotiated by the B1 instructors, were explicitly incorporated into lecture, but the commercial textbook and homework system did not appear to reinforce them, instead focusing on particular topics around which the units were organized. And so, it is unsurprising that students recognized these differences.

Students' ideas about energy transfer and the energy associated with bond breaking/forming were more confidently expressed in the context of GC1/GC2. Of the 14 students interviewed, all 12 who discussed the relationship between energy and the breaking/forming of bonds in the context of chemistry did so correctly (i.e., that breaking bonds requires energy and forming bonds releases energy) but did not explicitly connect this to potential energy transfer. Collisions were described as the mechanism of energy transfer learned in chemistry by 10 of the 14 students. Both ideas were discussed extensively and explicitly throughout the two-semester general chemistry course sequence. And yet, some students did not see the need to apply their ideas to B1 (e.g., John), and others explicitly stated that their courses were providing conflicting information about the relationship between energy and the breaking/forming of bonds. For Lida and Priyah, this dichotomy resulted in the pragmatic decision to provide the "correct" (expected) answer in each course. However, others (like Daniel) expressed a desire for stronger connections to be made between their courses. Students with an interest and intellectual curiosity about science were certainly not being satisfied by the explanations provided. Indeed, even those pragmatists who could "play the game" and return what was expected were being provided with the antithesis of a scientific message. While there are certainly differences in the ways that chemistry and biology (and other STEM disciplines) approach energy concepts, it should give us all pause to think about the messages we send when we do not address those differences. Ausubel (1968) discussed a similarly problematic practice among textbook writers that involved the compartmentalization of common concepts into topical chapters and the subsequent assumption that students were capable of and would chose to perform the necessary "cross-referencing" to make meaningful connections. As he pointed out, if "little serious effort is made explicitly to explore relationships between these ideas, to point out significant similarities and differences, and to reconcile real or apparent inconsistencies," students may be driven to rote learning, and "artificial barriers" may obscure common features (Ausubel, 1968, p. 155). Students (e.g., Lida and Priyah) who chose to memorize the correct answer in each course may have been driven to such rote learning by the "cognitive strain and confusion" associated with making the necessary connections between their chemistry and biology understanding on their own (Ausubel, 1968; Cooper *et al.*, 2017).

When considering the learning objectives of both courses, it is clear that there is a common goal—to develop a useful and transferable understanding of energy. And yet, neither course appeared to provide students with appropriate activities, knowledge, and explanations to meet these expectations. When discussing chemical systems, those interviewed could describe collisions transferring kinetic energy in the context of a phase change or the breaking/forming of bonds. However, these same students were not able to provide coherent explanations about how potential energy is transferred via coupled reactions. In biological systems students described energy as ATP, cycling through metabolic pathways. However, they were not clear about the mechanism by which energy transfer was occurring. In fact, as Aaron seemed to indicate, there was no need to consider such a mechanism: "We know that these processes happen. And I think of energy as a more continuous cycle, so you don't need to worry about energy being transferred at all."

While students appeared to have a grasp of how kinetic energy is transferred in chemistry, these ideas were simply not applied in the context of biology. And the mechanism by which potential energy is transferred was less clear both in chemistry and biology. As the K–12 system continues to be transformed in the context of the *Next Generation Science Standards* (NGSS Lead States, 2013), students will be entering college with an understanding of potential and kinetic energy as the two forms of energy. It will be important for them to be able to extend these ideas to how energy is transferred at the molecular level, both by collisions (kinetic energy) and the formation of stronger bonds replacing weaker ones, in the context of coupled reactions (potential energy). Indeed, it is clear that we are not providing a coherent and universally applicable description of the mechanisms by which energy is transferred in either course. Students who have been educated using the vision of the *Framework* will have been exposed to crosscutting concepts such as "cause and effect: mechanism and explanation" (NRC, 2012a). If we open the door to mechanistic thinking, we need to be prepared to respond. We must recognize that compatible mechanistic explanations of kinetic and potential energy transfer must transcend common disciplinary practices (or shortcuts).

The literature has clearly shown that the belief that breaking bonds releases energy is problematic and resistant to change (Barker & Millar, 2000; Boo, 1998; Galley, 2004; Storey, 1992; Teichert & Stacy, 2002). Our work demonstrates that even students with a strong understanding of the relationship between energy and the breaking/forming bonds in one discipline have difficulty transferring that understanding in a coherent manner when situated in the context of another. While these students theoretically might have been prepared for future learning (Bransford & Schwartz, 1999), in this situation, they certainly were unable to activate this knowledge. Providing a description of the hydrolysis of ATP as the source of energy can lead students to believe that they are being told by their instructor that breaking bonds releases energy, which may give the impression that their instructors are presenting contradictory information. Not only is this confusing to students, but it reinforces the idea that the science disciplines are separate and that their understanding should be compartmentalized. This is in direct conflict with our goal of helping students develop a consistent, useful, and transferable set of knowledge and skills. To this end, it is the responsibility of both chemistry and biology instructors to address the mechanisms of energy transfer such that students can develop a coherent understanding that can be applied across disciplinary contexts.

Some may argue that such an explanation is rightfully addressed in more advanced biology courses (e.g., biochemistry), when students are expected to have sufficient prior knowledge in reaction kinetics and thermodynamics to engage with this explanation at a conceptual level. However, this would require students to recall information taught in a chemistry course 2 years prior (in many cases) and transfer that understanding to a biological context that they may or may not recognize as similar. Additionally, those who do not take upper-level courses may end up leaving college with a confused understanding of energy in biological systems (Villafañe *et al.*, 2011).

**Implications for teaching**

It is unsurprising that students' experiences with energy differed between these two courses (disciplines), given that each has different objectives and considers systems of vastly different complexities and characteristics. GC1/GC2 is a service course meant to help students with many academic backgrounds develop an understanding of chemistry that can serve as the foundation for more advanced science courses in various disciplines. In comparison, a substantial portion of the students who take B1 are biology or pre–professional majors with the intention of taking more advanced biology course work for which this course must prepare them. Additionally, chemical systems begin at a distinct moment and move toward a stable equilibrium, whereas biological systems have an origin in the distant past, have a history, and maintain a nonequilibrium state. Based on these differences in both course goals and disciplinary perspectives, the significance of particular concepts (such as energy) are likely to change. A typical biology course may never explicitly consider the role of energy inputs in terms of molecular synthesis and associated repair and replacement mechanisms or macroscopic phenomena such as movement and growth. It is for this reason that it is critical that students' introductory science instructors work together to build and connect student understanding into a coherent whole. To do so effectively, especially in the case of a concept so important and yet perpetually confusing as energy, we must consider not just the perspective and goals of our own discipline, but those of the other sciences. As students are often enrolled in introductory chemistry courses before cell and molecular biology, it is the responsibility of chemistry instructors to effectively prepare students to understand energy in biological systems. Chi and VanLehn (2012) suggest that, in some cases, it may not be that knowledge transfer has failed to occur but that students have not sufficiently learned the material in the first place. That being said, our findings show that students' conceptual understanding of energy in one context does not automatically translate to other disciplinary contexts. In this case, we believe that students did not perceive a need to use their prior knowledge in the context of biology, and therefore were unable to use energy ideas in appropriate ways. One thing is clear, if we are to provide learning environments in which students are able make these connections, instructors must collaborate across disciplines to negotiate long-term learning goals for the students enrolled in their courses.

There are a number of potential approaches that could provide the basis for these conversations. One school of thought is that introductory biology instructors focus on thermodynamic connections between the courses. Rather than addressing the mechanism by which reaction coupling occurs, they would use thermodynamic factors such as Gibbs free energy change to indicate overall Gibbs energy changes for coupled reactions. To pursue this approach, instructors will need to consider how best to ensure that students have sufficient conceptual understanding of thermodynamics to engage with such a discussion in biological systems, particularly in light of the nonstandard conditions found in living systems. This does remove the requirement for any discussion of molecular-level events, but for many molecular biology introductory courses that purposefully include molecular-level mechanistic reasoning, this approach may not be a satisfactory solution.

Another potential approach is to restructure the introductory chemistry and biology courses around common themes, such as energy or the relationship between structure, properties, and function. Certainly, this is ambitious and may not be an option for all who wish to do so, as it would require significant buy-in across multiple departments and instructors. There are few examples of thematic reforms of chemistry and biology courses (Goldey *et al.*, 2012; Hunt, 2017; Schaller *et al.*, 2014), and while integrated courses that cross disciplinary boundaries do exist (Copp *et al.*, 2012; Gentile *et al.*, 2012; Johnson & Graves, 2017; Lega *et al.*, 2014), the designs of such courses range widely, and the evidence of improved learning is sparse. Such courses provide an intriguing opportunity for education research, and we look forward to future studies on the effectiveness of such approaches for improving students' understanding of interdisciplinary concepts and their ability to make substantive connections across disciplines.

Given the findings presented here, our experience reforming how energy is taught in general chemistry (Becker, Noyes, & Cooper, 2016; Cooper, 2015; Cooper & Klymkowsky, 2013b), and our interdisciplinary conversations about connections between chemistry and biology (Cooper *et al.*, 2015; Klymkowsky, Rentsch, Begovic, & Cooper, 2016), we advocate the potential of a third approach that builds on the approach developed in the *Framework* and involves treating energy as either potential or kinetic energy. We believe that a common discussion of kinetic and potential energy transfer via molecular-level collisions and reaction coupling, respectively, can serve as a bridge between the disciplines and allow students to make the connections that are so important. We provide a longer description of this approach and the ways in which both kinetic and potential energy transfer could be discussed in Appendices C and D.

Regardless of the approach that is taken, without constructive conversations across the disciplines, it is unlikely that students will leave their introductory science courses with a coherent and productive understanding of energy. By negotiating long-term learning goals and understanding the constraints and perspectives at play, instructors can work toward fostering a more cohesive, interdisciplinary learning environment. It will be important for both biology and chemistry instructors to understand what resources students are bringing with them from chemistry to support the relevant parts of the biology curriculum. For example, closer communication might allow instructors to explicitly ask students to connect ideas across disciplines. If courses are restructured to emphasize core ideas and crosscutting concepts, then students can be helped to make these connections. This is especially important in instances in which such connections are not immediately obvious—and it is clear that these connections are particularly problematic for students attempting to understand energy. One way that this could be undertaken is by scaffolding activities to require students to think about content and examples learned in other courses. In chemistry courses, this may be through the inclusion of systems that introductory biology instructors will teach in more detail. For biology instructors, this may be the inclusion of prompts asking students what prior knowledge they may bring to bear on the problem. Such activities could also be used to assess whether and how well students are able to bring in relevant concepts learned in other contexts. Certainly, it is likely that different learning environments (e.g., based on class size or students' academic backgrounds and goals) will require different approaches. Therefore, we strongly encourage those considering such reforms to collect evidence on the efficacy of their approaches.

## Limitations of the study

The students who were interviewed in this study were concurrently enrolled in chemistry and biology courses that had been transformed in light of the education research literature. As previously noted, these courses were not at the same stage of transformation, but nevertheless, both courses were undergoing transformation efforts. These contextual details may have influenced student understanding and descriptions of energy in chemical and biological systems. And therefore, students situated in other, more traditional learning environments would likely not respond in the same ways. It is not our intention to infer that these students’ experiences could be generalized to other science classrooms. However, it is notable that, even in situations in which transformational efforts have been made to improve student understanding of energy, more work needs to be done to help students make connections across disciplinary boundaries.

# CHAPTER 5: CONNECTING STRUCTURE-PROPERTY AND STRUCTURE-FUNCTION RELATIONSHIPS ACROSS THE DISCIPLINES OF CHEMISTRY AND BIOLOGY: EXPLORING STUDENT PERCEPTIONS

## Introduction

The relationship between structure and function is widely recognized as a central and crosscutting concept in science and engineering (American Association for the Advancement of Science, 2011; College Board, 2009; National Academy of Engineering and National Research Council, 2009; National Research Council, 1996, 2012a; Tansey et al., 2013); Table 5.1; Appendix E). Indeed, many authors, curriculum documents and standards explicitly include "structure and function" as a central concept. For example, in biology, *Vision and Change* (AAAS, 2011) describes six core competencies and five core biological concepts (of which *Structure and Function* is one) that can "serve as the basis for any undergraduate biology course." The concept that "basic units of structure define the function of all living things" is applicable across organizational scales and contributes to a foundational understanding of

**Table 5.1 Structure and Function as Described in Curriculum Reform Documents**

| | |
|---|---|
| *Vision & Change in Undergraduate Biology Education* (AAAS, 2011) | **Core Concept** - Structure & Function (p. 12)<br>*Basic units of structure define the function of all living things.*<br>Structural complexity, together with the information it provides, is built upon combinations of subunits that drive increasingly diverse and dynamic physiological responses in living organisms. |
| *A Framework for K-12 Science Education* (NRC, 2012) | **Crosscutting Concept** - Structure & Function (p. 84)<br>The way in which an object or living thing is shaped and its substructure determine many of its properties and functions. |
| "Anchoring Concepts Content Map for General Chemistry" (Holme & Murphy, 2012) | **Anchoring Concept** - Structure & Function (p. 6)<br>Chemical compounds have geometric structures that influence their chemical and physical behaviors. |

biology for majors and non-majors alike (AAAS, 2011). However, this fundamental concept extends beyond life sciences education. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (referred to here as *Framework*) identifies "structure and function" as a crosscutting concept and notes that "the functioning of natural and built systems alike depends on the shapes and relationships of certain key parts as well as on the properties of the materials from which they are made"(2012a, p. 96). This deceptively simple idea is foundational to understanding natural systems ranging from those at the atomic-molecular scale to ecosystems, and is inherent to the engineering of products, buildings, and even organizations. Furthermore, as the *Framework* states, students well versed in this idea should be able to apply their understanding "when investigating phenomena that are unfamiliar to them" and "as critical elements of successful designs" (2012a, p. 98).

In chemistry however, discussions of structure and function are not as clearly defined. Although the American Chemical Society Examinations Institute does name "structure and function" as one of 10 general chemistry anchoring concepts, they appear to be using the terms "function", "behavior", and "properties" synonymously (Table 5.2; Holme & Murphy, 2012). While these terms are clearly related, most education reform documents make distinctions between them. For example, in the *Framework's* definition of "structure" and "function," both concepts are discussed: "the way in which an object or living thing is shaped and its substructure determine many of its properties and functions" (2012a, p. 84). Furthermore, "structure and properties of matter" and "structure and function" are listed as components of disciplinary core ideas in the physical and life sciences, respectively. Similarly, the curricular frameworks for AP Chemistry (College Board, 2014) and AP Biology (College Board, 2015) discuss structure, properties, and function alongside one another without implying that they are the same (Table 5.2). The relationship between structure and properties has long been considered fundamental to the discipline of chemistry (College Board, 2014; Cooper *et al.*, 2017; DeFever *et al.*, 2015; Underwood *et al.*, 2016) and there has been considerable focus among chemistry education

**Table 5.2 Structure-Properties and Structure-Function in Curriculum Reform Documents**

| | |
|---|---|
| *A Framework for K-12 Science Education* (NRC, 2012) | **Crosscutting Concept** - Structure & Function (p. 84)<br>The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.<br>**Core Ideas PS1**: Matter and its interactions<br>(A) Structure and Properties of Matter (p.106)<br>**Core Ideas LS1**: From molecules to organisms: Structure and processes<br>(A) Structure and Function (p.143) |
| "Anchoring Concepts Content Map for General Chemistry" (Holme and Murphy, 2012) | **Anchoring Concept** - Structure & Function (p. 6)<br>Chemical compounds have geometric structures that influence their chemical and physical behaviors.<br>(A) Atoms combine to form new compounds that have new properties based on structural and electronic features.<br>(E) Three-dimensional structures may give rise to chirality, which can play an important role in observed chemical and physical properties<br>(F) Reactions of molecules can often be understood in terms of subsets of atoms, called functional groups.<br>(G) Periodic trends among elements can be used to organize the understanding of structure and function for related chemical compounds.<br>(H) Many solid state, extended systems exist, and geometric structures play an important role in understanding the properties of these systems. |
| AP Chemistry Curriculum Framework (College Board, 2015) | **Big Idea 2** - Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules, and the forces between them. (p. 19)<br>Essential Knowledge 2.B.3.e (p.27) - The structure and function of many biological systems depend on the strength and nature of the various Coulombic forces.<br>Big Idea 5 –<br>Essential Knowledge 5.D.3.b (p. 62) - The functionality and properties of molecules depend strongly on the shape of the molecule, which is largely dictated by noncovalent interactions. |
| AP Biology Curriculum Framework (College Board, 2015) | **Big Idea 4** (p. 78) - Biological systems interact, and these systems and their interactions possess complex properties.<br>Enduring Understanding 4.A: Interactions within biological systems lead to complex properties.<br>Essential Knowledge 4.A.1: The subcomponents of biological molecules and their sequence determine the properties of that molecule.<br>Essential Knowledge 4.A.2: The structure and function of subcellular components, and their interactions, provide essential cellular processes.<br>Essential Knowledge 4.A.4: Organisms exhibit complex properties due to interactions between their constituent parts.<br>Enduring Understanding 4.B: Competition and cooperation are important aspects of biological systems.<br>Essential Knowledge 4.B.1: Interaction between molecules affect their structure and function |

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esearchers on students' understanding of this relationship (Cooper *et al.*, 2013; Cooper, Underwood, & Hilley, 2012; DeFever *et al.*, 2015; Meijer *et al.*, 2013; Shane & Bodner, 2006; Underwood *et al.*, 2015, 2016). While discussions of structure and function do exist in the chemistry research literature (e.g., Aussignargues *et al.*, 2016; Huang, Patil, Li, & Mann, 2014; Melo *et al.*, 2017; Nowinski, Sun, White, Keefe, & Jiang, 2012; Schwartz *et al.*, 2016; Shirota & Kageyama, 2007; Wang *et al.*, 2017), the functions to which they are referring are biological in nature or the researchers are studying the properties of molecular materials to facilitate a desired macroscopic function. As such, we would argue that while an understanding of function can help contextualize examples in chemistry classrooms, it is the relationship between structure and properties that is foundational to chemistry (Talanquer, 2017). Additionally, function can be applied in both natural and built systems (as noted in the *Framework*, 2012a), but such uses have distinct implications about the system origins, as we will discuss further.

We will move forward with the understanding that structure, properties, and function are closely interconnected concepts, but that they can be defined independent of one another (despite the fact that some sources appear to be rather unclear about the differences between them). To understand *structure*, one must consider the components of the substance and their arrangement and orientation in space. A substance or category of substances (e.g., solids, metals) has a given set of descriptive characteristics which are termed *properties*. Finally, *Merriam-Webster* defines "function" as "the action for which a person or thing is specially fitted or used or for which a thing exists: purpose" ("Function," n.d.). While unproblematic when considering built systems designed to function in a particular way, such a definition is not directly applicable to natural systems such as those discussed in biology.

Early conceptions of biological function were colored by the teleological[2] arguments of the time (based on the belief in a divine creator), the implications of which philosophers of biology have since

[2] Teleology, according to the *Encyclopedia Britannica*, is "explanation by reference to some purpose, end, goal, or function" ("Teleology | philosophy," 2016)

attempted to overcome (Coleman, 1971; Rosenberg & McShea, 2008). Among philosophers, biological function can be interpreted from two, potentially complementary, perspectives—selected effect and causal role (Rosenberg & McShea, 2008). The selected effect interpretation of function suggests that function and adaptation are synonymous, and so it is an understanding of the evolutionary origins that determines a structure's function (Amundson & Lauder, 1994; Millikan, 1989; Neander, 1991; Rosenberg & McShea, 2008). Alternatively, the causal role interpretation of function is based on the idea that the object under consideration is a part of larger system to which it makes a causal contribution (Amundson & Lauder, 1994; Rosenberg & McShea, 2008). In this way, the causal role perspective allows function to be applied in both biological and non-biological systems. This is reflected in a second definition of function as "any of a group of related actions contributing to a larger action; especially: the normal and specific contribution of a bodily part to the economy of a living organism" ("Function," n.d.).

Despite widespread use of the concept and considerable emphasis on the connection between structure and function, many textbooks fail to define what is meant by the term function itself. For example, *Understanding Biology* (Mason *et al.*, 2015), the textbook used by the introductory biology course in this study, introduces the relationship between structure and function in the very first chapter as one of seven unifying biological themes. While the authors elaborate on the benefits of understanding such a relationship (e.g., being able to infer the function of a similar structure in different organisms), they do not provide a general definition for either structure or function.

It is more common to find explicit definitions of function in the education research literature where it is typically described as either the *purpose* (Collins & Ferguson, 1993; Dauer & Dauer, 2016; Dauer & Long, 2015; Ferrari & Chi, 1998; Hmelo, Holton, & Kolodner, 2000; Hmelo-Silver & Pfeffer, 2004), *role* (Dauer, Momsen, Bray Speth, Makohon-Moore, & Long, 2013; Golick, Dauer, Lynch, & Ingram, 2017; Hmelo-Silver *et al.*, 2008; Hmelo-Silver, Marathe, & Liu, 2007; Hmelo-Silver & Pfeffer, 2004; Jordan, Brooks, Hmelo-Silver, Eberbach, & Sinha, 2014; Sinha *et al.*, 2013), or *outcome/output*

(Dauer & Long, 2015; Dauer *et al.*, 2013; Golick *et al.*, 2017; Hmelo-Silver *et al.*, 2008, 2007; Jordan *et al.*, 2014; Reinagel & Bray Speth, 2016; Sinha *et al.*, 2013; Yen, Helms, Goel, Tovey, & Weissburg, 2014) of a system or system component. Each of these definitions has implications for how function might be interpreted by students. Purpose suggests intent, role requires the context of a larger system, and outcome indicates that the function is the consequence of some process. One might wonder whether these definitions are equally productive for students or whether the meanings are even compatible, perhaps a question for a future study.

In the biology education literature, there is little research exploring students' conceptual understanding of the relationship between structure and function. However, one use of function has been in the context of structure, behavior, function (SBF) theory. Originating in the disciplines of computer science and engineering (Goel *et al.*, 1996), SBF theory was adapted for biology education research by Hmelo-Silver and coworkers (2000; 2007; 2004), as it considers the causal relationships between structure and function through the identification of mechanisms (i.e., behaviors). More recently, the use of SBF theory has extended into post-secondary education research. The goal of this work was to improve students' ability to connect molecular-level processes to organism- and population-level events (Bray Speth *et al.*, 2014; Dauer & Long, 2015; Dauer *et al.*, 2013; Reinagel & Bray Speth, 2016). It is important to note that SBF theory has been used as a research lens and, especially given its origins in the disciplines of computer science and engineering, is not necessarily representative of how the terms structure, behavior, and function are interpreted by the biology community.

Consideration of function in chemistry is complicated as some practitioners appear to use the term synonymously with properties. Additionally, given that chemistry principles are applied to understand both natural and built systems (e.g., by those studying molecular biology, geology, or materials science), the use of the term function in chemistry may have different implications depending on the context. Furthermore, in chemistry, students may associate the term function with "functional group” and as such, would be closely related to the ways in which groups of atoms behave (i.e, properties such as reactivity). Clearly, the meaning of function is more varied among the science disciplines than that of structure or properties. As such, we felt it necessary to ask students to begin by discussing what such terms meant to them.

## Purpose of the study

Structure-property and structure-function relationships are central to how experts think about chemistry and biology. They can be used as frameworks for connecting conceptual understanding, constructing explanations, or predicting the effect of a change on a system. The purpose of this study was to explore student conceptions of structure, properties, and function (and the relationship between them) after having encountered elements of these frameworks in their introductory chemistry and biology courses. Typically, more than half of the students who take two semesters of general chemistry are life sciences or pre-professional majors; and chemistry is often listed as a prerequisite (or at least a co-requisite) for introductory biology, presumably so students can use their knowledge of chemical reactions and molecular interactions to think about biological systems. When this study began, the introductory science courses were at various stages of a collaborative transformation process (Cooper *et al.*, 2015). Therefore, the data we present should be considered in the context of courses that were attempting to develop a coherent approach across the disciplines. Our study focused on three research questions:

RQ1: How do students co-enrolled in introductory chemistry and biology courses describe the meaning of the terms “structure”, “properties”, and “function”?

RQ2: How do students co-enrolled in introductory chemistry and biology compare their experiences with regard to the presentation of structure, properties, and function (and the relationship between them) in these courses?

RQ3: How do students co-enrolled in introductory chemistry and biology courses describe the relationship between structure, properties, and function?

These research questions are deeply interconnected, as students' interpretation of the meaning of the component terms would likely affect their understanding of the relationships presented in their courses and vice versa. Together, this understanding of the terms in context and the presentation of the relationships between them would likely affect how and whether they develop a coherent understanding that spans the disciplines.

## Methods

### Setting and participants

This study was set at a large, public research university in the Midwest. The student body was predominantly made up of domestic students who self-identified as Caucasian. The student body was approximately composed of 51.7% women, 18.7% students of color, and 14.4% international students. The middle 50% of students entering the university had an ACT composite score of 24-29.

**General chemistry** At this university, general chemistry for STEM students is taught as a two-semester sequence (General Chemistry 1 [GC1] and General Chemistry 2 [GC2]). Lecture sections are 350-450 students in size and include a required 1-hour recitation section in addition to the 3 hours a week in lecture. About 35% of students who take GC1 are also required to take GC2, and the majority of these students pursue life sciences majors. For the purposes of this study, we did not distinguish between the two semesters and instead treated the course as a single entity (GC1/GC2). At the time, the university was in the process of transitioning from a traditional to a transformed general chemistry curriculum - *Chemistry, Life, the Universe and Everything* (CLUE) - designed to facilitate development of students understanding of four core ideas (one of which is the relationship between structure and properties; Table 5.3) in a scaffolded intertwined progression (Cooper & Klymkowsky, 2013a; Cooper, Underwood, Hilley, & Klymkowsky, 2012). Furthermore, the curriculum was designed to consider the needs of the students enrolled, including life sciences and pre-professional majors, and uses biological phenomena to illustrate the underlying chemistry content. Students complete their homework using beSocratic, a freeform, online assessment platform that allows students to construct representations and explanations, as well as revise their work (Bryfczynski, 2012; Bryfczynski, Pargas, Cooper, & Klymkowsky, 2012; Cooper, Underwood, Bryfczynski, & Klymkowsky, 2014).

**Table 5.3 Course Big Ideas related to Structure, Properties, and Function**

| | |
|---|---|
| CLUE Chemistry (GC1/GC2)[a] | Atomic/Molecular Structure and Properties<br>The macroscopic physical and chemical properties of a substance are determined by the three-dimensional structure, the distribution of electron density, and the nature and extent of the noncovalent interactions between particles. |
| Cell and Molecular Biology (B1)[b] | Structure Determines Function<br>At the molecular level, biology is based on dynamic, three-dimensional chemical and physical interactions.<br>Differences in molecular structures and properties determine molecular and cellular functions. |

a. As presented in Cooper *et al.*, 2017
b. As presented in the Cell and Molecular Biology course syllabus

**Introductory biology** The first introductory biology course (B1), taken primarily by STEM majors, focuses on cell and molecular biology. B1 presents seven core ideas, one of which is "structure determines function," described in the syllabus as the idea that differences in molecular structures and properties determine molecular and cellular functions (Table 5.3). The seven core ideas were determined by the faculty instructors through extensive discourse based on the concepts presented in a variety of curricular reform documents (e.g., AAMC-HHMI Committee, 2009; American Association for the Advancement of Science, 2011; NRC, 2012a). At the beginning of each unit, the applicable core ideas are discussed in the context of that unit's material. Lecture sections range from 150 to 250 students and use a commercial textbook and the associated online homework system (Mason *et al.*, 2015) to provide a common resource for students. All participants attended the same lecture section of B1; the instructor was aware of this study and provided researchers with context about the information being taught. This lecture section incorporated regular in-class exercises, in which students were asked to engage with material being taught and encouraged to work in groups. Furthermore, students participated in five modeling activities throughout the semester, in which students constructed representations of a system and then were required to predict and explain the biological processes involved. I sat in on the lectures for both this course and the chemistry course from which participants were selected. GC1 is listed as a prerequisite or co-requisite for B1. However, less than 25% of students take B1 and GC1 concurrently.

**Study participants** The call for participants was made in the GC2 course during the last 2 weeks of the Spring 2015 semester, with a small amount of extra credit offered as compensation for participation. The first 14 volunteers who met the qualifications were included in the study. Qualifying participants had taken GC1 in Fall 2014 and both GC2 and B1 in Spring 2015, were in CLUE lecture sections for both GC1 and GC2, and had taken the preselected B1 lecture section. These qualifications were selected because we wanted the students to have shared a recent experience that would allow them to provide informed commentary. The other 385 volunteers were given an alternate activity to complete for extra credit. Of the 14 participants, nine were female and five were male; all were interested in pursuing careers related to biological science or a health profession. Twelve of the students were finishing their first year, and two were finishing their second. Of the 14 students, eight earned a 3.5 or above in all three of the relevant courses. And on average, they earned a 3.8 GPA in GC1, 3.5 in GC2, and 3.4 in B1 (see Figure 4.1 for full grade distribution). Students were notified of their rights as research participants and provided informed consent before participation in the study. Students were given pseudonyms to protect their anonymity.

**Interview protocol**

The first half of the interview protocol[3] was inspired by the disciplinary core ideas of the *Framework* (2012a). The goal was for students to discuss any connections they felt existed between the courses and what, if any, conflicts they perceived between the material discussed. Because we asked students to discuss an entire year of science course work, the protocol was designed to allow time for reflection and discussion of each course before having students attempt to compare and make connections between the courses. Beginning with general chemistry (GC1/GC2), students were first asked to brainstorm a list of things they had learned and then to describe what the big ideas[4] or take-home messages were. Notably, while instructors had defined core ideas in both GC1/GC2 and B1, students often came up with their own. After repeating this process for B1, students were prompted to compare their courses and describe how they perceived the concepts to be related.

The second half of the protocol was inspired by the crosscutting concepts of the *Framework* (2012a; described during the interviews as "themes that span chemistry and biology"). Students were given the opportunity to generate their own themes before being asked about two in particular - energy and the relationship between structure, properties, and function. For the purposes of this work, we will refer to the relationship between structure, properties, and function as the SPF relationship. However, it is not meant to imply a single predetermined order, hierarchy, or relationship between these concepts as those were open to interpretation by the students. Additionally, students could (and did) selectively include the concepts that they felt were relevant within a given context.

At the beginning of the SPF relationship portion of the interviews, students were first asked what each term (i.e. structure, properties, and function) meant to them. They were then asked to describe how they believed the terms were related. Once a shared understanding of a student's

[3] The full interview protocol can be found in Appendix A.
[4] Meant to be synonymous with "core ideas" (NRC, 2012a), the term "big ideas" was used to align with the language used by instructors during GC1/GC2 and B1

interpretation of the SPF relationship was established (including instances in which it varied based on the context), he or she was asked why it would be considered a theme, how it was discussed in each of their courses, and to describe the relative emphasis and importance of the relationship in each course.

**Data collection and analysis**

The 14 interviews varied in length from 70 to 150 minutes depending on the amount of information provided by students, who were told that they could terminate the interview at any time. However, all participants had a great deal of information to impart and willingly stayed longer than we had anticipated. Students used a Livescribe pen to create lists of ideas and enhance their descriptions with diagrams and drawings, which allowed audio data to be collected in conjunction with their constructed responses. Additionally, a digital recorder was used as a backup audio source. Data collection and analysis was undertaken from a phenomenographic perspective, as our intention was not to categorize what students do or do not know, but instead to provide a rich description of the various ways that students related their experiences taking introductory chemistry and biology.

The audio data was transcribed verbatim by a professional transcription service. I then reviewed and edited the transcripts for both accuracy and completeness. To gain a holistic understanding of each student interview, the entirety of the transcript was read, and summary notes were taken. However, due to the length and depth of the interviews, all references to the SPF relationship were excerpted for further analysis. While most of the data herein are from the portion of the interviews during which the SPF relationship was the focus, any discussion of the SPF relationship by the student was used to inform our analysis. The SPF relationship excerpts were iteratively open-coded to gain a sense of the breadth of student responses and to identify any emergent areas of discussion. The resulting codes were organized by research question for subsequent analysis. Answering RQ1 was relatively straightforward, as students were directly asked to describe how they think of structure, properties, and function. RQ3 was directly addressed via the following interview prompt: "Can you describe how you see these ideas as being related to each other?" However, students often returned to this idea throughout the interview in response to other prompts. Similarly, students compared their experiences with regard to the presentation of the relationship in their introductory chemistry and biology courses (RQ2) throughout the interviews. For this reason, additional rounds of coding were conducted for each research question, with the specific aim of identifying any variation in opinion or subtleties in students' perceptions. The authors then met to discuss the findings, review contextually situated excerpts, and select representative quotes. Additional quotes can be found in the Appendices. To improve readability, we have removed vocal fillers from the transcript excerpts presented here.

## Findings

The purpose of this study was to explore student conceptions of structure, properties, and function and the relationship between these concepts after having been exposed to structure-property and structure-function relationships in their introductory chemistry and biology courses, respectively. Three closely connected research questions were posited. To understand students' perspectives and the associated context, we wished to explore (RQ1) how students understood the component concepts of structure, properties, and function and (RQ2) how they understood the relationship in each of their courses. RQ1 and RQ2 provided additional insight for our final research question, which asked how students described the relationship between structure, properties, and function (RQ3).

### RQ1: How do students co-enrolled in introductory chemistry and biology courses describe the meaning of the terms "structure", "properties", and "function"?

During the interview, the terms "structure", "properties", and "function" were introduced together as being associated with a theme that spans chemistry and biology. In general, students appeared to have little difficulty describing structure and properties, providing examples that ranged from the atomic-molecular to macroscopic scales and across disciplines (Table 5.4). For function, while some students attempted to provide an example situated in chemistry (e.g., metals being used as wire, compounds acting as medication), most described the concept as more relevant in B1 (Appendix F). As such, most students interpreted structure, properties, and function in ways that were consistent both with each other and with disciplinary expectations.

**Table 5.4 Summary of student definitions and examples[a]**

| | |
|---|---|
| Structure | **Definitions**: what it's made of, how it's set-up, the arrangement<br>**Examples**: atomic structure, molecular structure, cellular structure, 4 levels of protein structure, Lewis structures, *shape, size, type of bonds, interactions polarity*, charge |
| Properties | **Definitions**: characteristics, adjectives<br>**Examples**: *shape, size, types of bonds or interactions, polarity*, electronegativity, reactivity, boiling point, phase, color, malleability, hardness |
| Function | **Definitions**: the purpose, the job, the role it plays, what it is supposed to do, what it does, how it works, why something occurs<br>**Examples[b]**: DNA stores information, mitochondria produce energy, enzymes catalyze reactions; compounds as medication, conductive metals used in wiring |

a. Italicized examples were mentioned during discussions of both structure and properties. See Appendix G
b. More examples of how students attempted to consider function in chemistry can be seen in Appendix F

Structure was generally described based on the underlying components and their arrangement in space. For example, structure was defined broadly as "how something is set-up and what it's made of" (Priyah) and "the arrangement of things in another thing" (Natalie). Students typically mentioned examples that included the word "structure," but these varied by both scale (from the atomic-molecular to the cellular level) and discipline (e.g. Lewis structures vs. the four levels of protein structure). When discussing properties, students tended to provide examples rather than a general definition (Table 5.4). Those who did define the term stated that properties were "characteristics everything has" (Joseph) or "adjectives to describe the structure" (Lida). Again, the examples that students provided were not confined to a particular scale. Properties that could be used to describe a single molecule, such as electronegativity, acidity, and polarity, were common, but macroscopic properties such as phase (i.e.

solid, liquid, or gas), boiling point, and those used for materials (e.g. hardness, malleability) were also mentioned.

It is important to keep in mind, that this was the first time students were asked to discuss these terms (i.e., structure, properties, and function) during the interview, and some appeared to still be in the process of deciding what each meant. For example, Aaron (Appendix K) first indicated that the types of bonds present in a structure would determine its properties. However, he quickly changed his mind, describing the presence of ionic or covalent bonds to be properties themselves. Other concepts (e.g. shape, size, and polarity) were referred to as both structure and properties by various students and in some instances by the same student (e.g., Joseph and John in Appendix G). For John, the ambiguity may have been related to how his courses presented these concepts. In B1, he described structure and properties as having been "grouped together", saying that "We never used the word 'properties' but like how we talked about structure...once you start talking about like if it's polar or nonpolar, I would consider those properties." It may be that students could benefit from an explicit discussion of the difference between structure and properties, and the relationship between them, especially at the molecular level. However, some might argue that these concepts are so closely related that the line can and will occasionally blur and that it is more important that students would be able to describe the causal relationship between these concepts in the context of a particular example.

Of the three component terms, students provided the most varied definitions when describing function (Table 5.4). Six students described function as the purpose or job of a structure. Additionally, Clarice described function as "what each thing is supposed to be doing." These interpretations appear to imply that the role of a structure within a system is both expected and necessary. Function was also characterized as active, as evidenced by Natalie's description of function as "what something does" and Serina's description of function as "how something is going to work". Examples used by students tended to be biological (e.g. proteins can act as catalysts or receptors, DNA stores information); and when asked about function in chemistry, students appeared to have more difficulty (Appendix F), which is unsurprising, given the disciplinary focus on structure-property relationships.

Of the 14 students interviewed, 11 believed function to be more relevant in B1, suggesting a variety of reasons as to why this was the case (Appendix F). As stated by John, the term "function" was not discussed in GC1/GC2. In comparison, "structure determines function" was one of the core ideas presented in B1. Lida's conception of function made it difficult for her to apply the term in chemistry. She defined function as something's purpose, which she described as more applicable in B1. She noted that, in GC1/GC2, there were not "a lot of chemicals that we're actually using to do something with" and that they did not discuss "how this furthers some sort of organism." In this way, Lida appears to assess a thing's purpose based on personal utility or its relevance to the maintenance and support of life, and her conception of "chemicals" does not satisfy these conditions.

Aaron, Daniel, and Joseph expressed no difficulty applying function to chemistry, although this may have been related to a desire to provide a response, rather than having a meaningful understanding of what function might mean. Indeed, only Daniel was able to apply function in a potentially useful way. Daniel described function in GC1/GC2 as having been discussed with respect to interactions between molecules: "In chemistry we talk about [function] as maybe polar and nonpolar structures, how they interact with other polar and nonpolar structures, stuff like that."

Ruth and Priyah proposed ways in which function could be applied in chemistry from a design perspective, even though the connection was not immediately obvious to them. This is particularly apparent in Ruth's discussion of function in chemistry, "it makes me think of— (pause) not much. Maybe I think of like compounds as drugs, or something like that." It is unclear whether Ruth was referring to the molecular-level mechanism of action or the macroscopic effect (e.g., that an analgesic relieves pain) as she did not describe her example in detail. Priyah was also tentative in her response, as if she was still grappling with the concepts.

Priyah: So for metals conducting electricity...that would be their function and— or would that be property? I feel like these are kind of related— well they're all related but these kind of blur together. But they conduct electricity and that relates back to its structure with the electrons and how they can move freely and— I guess the function would be how you could use the metals [for] wires.

Priyah's difficulty distinguishing between properties and function in chemistry is consistent with the fact that many chemists use the terms interchangeably.

The difficulty students had describing function in the context of chemistry was not unexpected. In chemistry, the disciplinary focus is largely on the relationship between structure and properties and, as such, function was not discussed in GC1/GC2. However, chemistry is inherently apart of both natural and built systems, and in the context of those systems, function is relevant. Ruth and Priyah both made such a connection, specifically focusing on designed system functions. They each proposed a possible function based on their chemistry content knowledge. Lida did not attempt to do so, noting that it had not been a topic of discussion in GC1/GC2. The difficulties that these students had are justifiable as they were provided little in the way of support in making such connections.

**RQ2: How do students co-enrolled in introductory chemistry and biology compare their experiences with regard to the presentation of structure, properties, and function (and the relationship between them) in these courses?**

Given the differences in disciplinary focus between chemistry and biology, it is not surprising that students recognized variation between their courses. Students described B1 as having focused on the relationship between structure and function, while GC1/GC2 emphasized structure and properties. The courses were also described as having discussed these concepts differently. The presentation in B1 was seen as being more explicit; students noted that their instructor called out "structure determines function" as a big idea for the course on a regular basis. Generally, students reported that the relationship between structure and properties in the GC1/GC2 courses was less explicit, but the idea was implicit in almost everything the course discussed. Even so, students appeared to be able to make connections between their courses despite these differences.

**Presentation of the structure-function relationship in B1** During the interviews, students were asked to describe what they would consider the big ideas for each of their courses. Notably, of the seven big ideas presented by the B1 instructor, only two were mentioned by more than one student – "structure determines function" (7 of 14) and "the chemical and physical basis of life" (2 of 14). As this portion of the interview was prior to any prompting regarding the relationship between structure, properties, and function, this would suggest that, of all the big ideas discussed in B1, the relationship between structure and function was by far the one most internalized by students. Additionally, four of the seven students who described "structure determines function" as a big idea in B1, also identified it as a crosscutting concept, or theme that spans chemistry and biology. Consider Natalie, who not only recalled both aforementioned big ideas but indicated that they could be related to one another. She was also able to connect these big ideas to chemistry and physics through the inclusion of properties. While she acknowledged that these big ideas had originally been presented by her B1 instructor, she recognized their value, stating that they allowed her to develop an understanding of why things occurred so that she was not required to rely on memorization.

> Natalie: [Our B1 instructor] has a whole list of them [big ideas]...They make sense. And they make it easier to understand. Personally I think it's easier to learn if you can understand why things are happening than just to memorize...if you know kind of the reasons behind it or even just a little bit of the physical or chemical properties that are driving these interactions then you can kind of go back and kind of slowly bring yourself to the same conclusion...I think that structure and function is kind of a theme that spans both biology and chemistry. The way that something is made up affects the way it interacts with other things and the way it functions and what it's meant to do.

Ultimately, 12 of the 14 students spontaneously mentioned having discussed "structure determines function" in B1 at some point during the interview. Even the two students who did not (Lida and Evelyn) displayed familiarity with the component terms and appeared to recognize that a relationship existed between them. Not only was "structure determines function" referred to as big idea in B1, but students described it as being frequently and explicitly discussed in lecture (Table 5.5), though that did not always result in a clear understanding of the causal relationship between these concepts (e.g., Clarice and Daniel in Table 5.5).

**Emphasis on structure-properties in GC1/GC2**. Most students (10 of 14) described GC1/GC2 as having focused on the concepts of structure and properties. As Natalie described it,

> Definitely the idea of different properties kind of came more from chemistry. The properties of different molecules or atoms...And I think that function may be a little bit more we talked about in biology because it's more just applying all of these things that we learned in chemistry about structure and properties.

However, some students continued to include function when talking generally about presentation of the relationship in GC1/GC2. This may be due to the organization of the interview protocol, which asked students to alternate between discussing GC1/GC2 and B1 individually and comparing them. Additionally, students described it as having been more subtly incorporated into GC1/GC2 than B1 (e.g., Louanne; Tables 5.4 and 5.5). Rather than discussing the relationship explicitly, students recognized it as having been incorporated into how the course was organized and the structure of questions on exams and homework assignments (e.g., Lida and Natalie; Table 5.6). Lida noted that describing the relationship between the terms had felt "natural," based on her experiences in GC1/GC2. Conversely, Evelyn (Table 5.6) described the connections between structure and properties as having been more explicit in GC1/GC2, saying that, while both courses focused on structure, her chemistry instructor supported her ability to think about the relationship. Whereas she felt that she was expected to make those connections on her own in B1.

**Making connections between the courses.** The differences in how structure, properties, and function were discussed, and even the apparent focus on structure-properties in GC1/GC2 versus structure-function in B1 did not appear to hinder students' abilities to make connections between what they had learned in each course (Appendix H). Lida described the benefit of learning about structure and properties in GC1/GC2 as a way to develop an understanding of something's function as opposed to just memorizing it (as she had done in high school). Simon found that he would try to follow a process

**Table 5.5 Presentation of the Relationship in B1**

| Structure determines function was discussed frequently and explicitly in B1 |
|---|
| **Aaron**: [Our B1 instructor] literally brings up the big ideas all the time. Let me write one more. *(writes 'structure determines function' at the top of the list)* This is [their] biggest idea probably…[Our B1 instructor] brings this up a lot. Every day [they'll] say that. |
| **Clarice**: Oh [our B1 instructor] goes over this like every day. How structure determines function...Every day. Every day [our instructor] has a slide that's like 'Structure and function is like a big part of what we're talking about today.' But I don't always get what [our instructor], I guess is trying to, portray. |
| **Daniel**: [In B1] we talk about the structure of DNA and how that affects its function. [Our instructor] always says that you know, the structure determines function, structure determines function. And I know in the back of my head that structure does play a role in function, but I'm not entirely sure how, I guess…[Our instructor] definitely does bring it up a lot, that it is a big idea. But sometimes I'm confused, like we were talking about let's say the nucleus, and [our instructor] said, 'Oh, structure determines function,' but I'm not really sure what that means. |
| **Louanne**: I think it's really emphasized in biology, a lot…I just think that it always goes back to it because no matter what we're doing, you have to relate it back to 'why it's doing that?' or 'what makes it able to do that?'...This as a whole we probably talk about a little bit more in biology. It's just more prominent. |
| **Natalie**: [The big ideas] are repeated again and again. You need to know them to do well on the tests...Any time you're not memorizing something [in B1] you're kind of applying that [structure determines function]...I would say that we've done something that has to do with structure and function, at least every unit. Almost every day in lecture. So yeah, all the time. |
| **Serina**: I know we stressed this a lot in biology, how structure determines the function and we, we like revisit that idea every chapter, so that is really important I would say. |

similar to what he had done in chemistry when thinking about structures and interactions in B1. Furthermore, his knowledge of function from B1 allowed him to think about the "bigger picture" in GC1/GC2. For example, why the ability for water to hydrogen bond might be important to "how water functions in the body."

> Simon: [In GC1/GC2] Like when you have water, it's easy for you to say that this water molecule will hydrogen bond with this water molecule and, you know that's the end of it...thinking about that in terms of biology, I can see why it would do that and I can see how that could be important to how water functions in the body. So it just— I guess it helps me understand the bigger picture of what these things really mean.

**Table 5.6 Presentation of the Relationship[a] in GC1/GC2**

| More implicit presentation in GC1/GC2 |
|---|
| **Joseph**: It was a little more underlying in chemistry. It's there, but [our GC1/GC2 instructor] doesn't say it as much as in biology...Because in biology, like I said, it's one thing that we're widely tested on, and same in chemistry even though we may not even realize it. A lot of the questions [our GC1/GC2 instructor will] ask, it will start with draw the Lewis structure, which is definitely important. So it's not something that she says, "Property, structure, and function are important." It's just a given, that you should understand that it's important. |
| **Lida**: I feel like that's the way that [chemistry] has kind of just been taught. So when you asked me those three and asked how they correlated it just seemed natural that that was the answer because I feel like that's how this course has been set up. Even though I don't think that I've been directly told like structure, then properties, then function, it just seems like, 'Oh, well, that just makes sense to me.' |
| **Louanne**: I think in chemistry it's just like, you know that it's there, but it's just a little bit more subtle...So I think in chemistry, just like maybe I understand without having her say like what it is, so maybe that's just like what she thinks everyone is able to do at this point. And I don't mind that. |
| **Natalie**: [In GC1/GC2] I think that it's kind of something that is almost ingrained into your mind so much that you don't really think about it, but I think that if you didn't and if it wasn't really ingrained into my mind through the coursework, then I would need to explicitly think about these things. So I think it's useful in pretty much every different homework assignment...almost every *beSocratic* [homework] assignment kind of asks us, 'Okay draw this Lewis structure. Okay now look at— circle this part. Why does it do this? Or why does this happen?' So I think that while we're being guided to do it all along so that we don't have to do it ourselves, I think it would be very difficult to understand any of the things you learn without being able to relate those three things. |
| **Shelly**: I don't think I do it explicitly, but I feel it's definitely the progression of thought. Because you do, you have to think— like when you're given a problem you have to think, 'Well okay, I have to draw this out.' And then 'Okay, I'm looking at this Lewis structure' and then 'Well now I have to determine how this does this.' So it's not like— I don't think I think like, 'Okay structure to like properties function,' like that's the progression of thought in general, just done in progressive ways of with you doing the material itself. |
| **More explicit presentation in GC1/GC2** |
| **Aaron**: ...it's a little bit less explicit in bio, I think, just a tiny bit. Only because, more often than not [our GC1/GC2 instructor] really wants us to look at the properties because that's the easiest way to go about solving any sort of problem...I think [our GC1/GC2 instructor] comes out and says a lot of the time, 'You need to know this in order to get to this next step.' In bio, it's more self-reliant...In [GC1], I've already been going about solving problems like that. That helps me go about solving problems like that in bio. Because I find myself having to do that a lot... |
| **Evelyn**: The structure part of it was definitely emphasized in both [courses]. We've looked into structures of many things but like, talking about how that structure like gives it the properties that it has, and then what it does, I'd say was definitely emphasized more in chemistry than it was in biology. In biology, it was kind of like you had to put it together yourself. |

a. Students referred to both structure-property and structure-property-function relationships when discussing the presentation in GC1/GC2.

Ruth described her understanding of the causal relationship between structure and properties from GC1/GC2 as something that she could apply when "thinking of structure going from properties and then that really changing the function, in biology." These students recognized the value of the knowledge they had gained in each of their courses and how they could make connections between their courses to better understand chemical and biological systems.

**Consideration of properties in GC1/GC2 and B1** However, some students believed that there were times when it was unnecessary to think about the properties involved (Appendix I). For example, Natalie indicated that the connection between structure and function could be understood without considering the relevant properties. However, this did not appear to diminish her belief that it would be "helpful" to understand the properties involved, with her stating that "you couldn't get really a holistic view of [a structure's] function without knowing its properties."

Clarice and Shelly also noted that information about properties was not always discussed. Shelly indicated that this was dependent on the content or example being discussed (even within a course). With respect to GC1/GC2, she said that "the structure determines what properties it has and then the properties, you can use those to determine what the function would kind of would be." However, she was tentative in her response, appearing to hesitate. When asked why, she replied, "Because I could see structure going to function right away without needing to think about the properties but, I guess it all depends on what you're talking about at the time." She provided an example from B1 regarding the facilitation of protein synthesis by ribosomes (Appendix I). Shelly recalled discussing the structure of ribosomes as having both mRNA and tRNA binding sites and noted the function as: "It allows tRNAs to come in and bind to the codons and it's just the function of it. I don't really know any exact properties of it." The superficial way in which Shelly described her example may indicate that she had memorized this particular example in the context of a structure-function framework. Additionally, if this had been a scaffolded activity (as opposed to an example that just came to mind), she may have been able to discuss how certain properties facilitate or disrupt the mRNA or tRNA binding (e.g., the size and shape of the binding pockets and the strength of the binding interactions) and, therefore, protein synthesis.

Questions about what students can do with their knowledge must be left to a future study, given that these interviews were conducted to explore student perceptions as opposed to eliciting evidence for their understanding of the content.

Clarice was more confident about the relationship between properties and function, stating that "one leads to the other and you kind of have the basis of structure to understand like where the properties come from and then, understand like the properties to get where like the function comes from." However, when discussing how GC1/GC2 and B1 contributed to her understanding of the relationship, she noted that the properties were sometimes overlooked in B1 (Appendix I). She believed that this was possible because they had built up the relationship from structure to properties in GC1/GC2. While Natalie, Shelly, and Clarice each indicated that properties were not always attended to, it did not appear to change how they perceived the causal relationship between structure, properties, and function (see RQ3).

**RQ3: How do students co-enrolled in introductory chemistry and biology courses describe the relationship between structure, properties, and function?**

Given that students' introductory chemistry and biology courses each emphasized a different combination (i.e. structure-properties and structure-function, respectively), we wanted to explore how (or even whether) students integrated these perspectives into a single, coherent framework. And so, having discussed what structure, properties, and function meant to them, students were asked to describe how these terms related to one another.

Nine students described a causal relationship in which structure determines properties, which determines function (S → P → F; Appendix J). As Evelyn said, "If something has a specific structure, that gives it specific properties, which then gives it a specific job or function." Ruth was also able to make connections between her understanding of the relationship with regard to chemistry and biology despite a lack of any significant support in making those connections on the part of her instructors, "I think [the courses] worked together because I took what I learned in chemistry from structure determining properties, and was really able to apply that when I was thinking of structure going from properties and then that really changing the function, in biology.” In comparison, Natalie described a structure-properties connection as well as a structure-function connection but did not immediately relate properties and function.

> Natalie: I’d say structure is the basic thing...I don’t know how I would order properties and function. Because structure definitely determines the function of something but I think it also kind of determines the properties it has. So I don’t know if you could really say something’s— I mean I guess you could say something’s properties determine its function…

Natalie did not have a pre-established framework in which all three terms were related. She was most confident in the connection between structure and function. However, she was not sure how properties should be included. Because Natalie felt that structure could determine properties and that properties could be described as determining function, she settled on the linear progression of S → P → F. It is striking that, even without instructional support, these students were able to recognize how the structure-function relationship from B1 and the structure-properties relationship from GC1/GC2 could be connected.

Notably, Lida and Ruth not only described a causal relationship between structure, properties, and function, but also described their ability to use this relationship as a framework for making predictions. For example, Lida described each component of the SPF relationship as necessary to truly understand the next: “You can’t tell the function without the properties. You can’t tell the properties without the structure.” However, she also noted that one could reason backwards through the relationship to begin thinking about how or why a function might occur. Similarly, Ruth indicated that she could think about the SPF relationship differently based on what information was provided to her. This suggests that, given the appropriate scaffolding, students could be encouraged to think of the SPF relationship as more than just a theme that spans the disciplines, but also as a tool for thinking about unfamiliar systems or for considering how changes to a structure may affect its capacity to perform a given function (as Ruth noted in Appendix H).

**Alternative relationships.** While there was a great deal of consistency in how many of the students described the causal relationship between structure, properties, and function, some students expressed alternative views. For example, three students (Simon, Joseph, and John) indicated that properties determine structure, which determines function (P → S → F). Both Simon and John provided biological examples that crossed multiple levels of structural complexity but did not explicitly acknowledge the presence of the underlying structural elements. For example, Simon described the SPF relationship as follows: "I know that structure determines function and I know that the properties will determine its structure, at least to some degree," going on to explain that three-dimensional protein structure is based on properties of the constituent amino acids such as electronegativity and the ability to form hydrogen bonds (Appendix K). In doing so, Simon described structural aspects of the amino acids themselves (i.e. the types of elements and the ways in which they were bonded) that lead to the properties under consideration. Despite making connections between the underlying structural components, the resulting properties, and higher-level structures (S → P → S'), he chose to define the relationship as having originated with properties. John provided a similar example (Appendix K). But unlike Simon's, his description of the SPF relationship varied throughout the interview. Ultimately, John chose not to put the terms in a specific order, describing the SPF relationship as "structure slash properties to function." While he indicated that this was applicable for both chemistry and biology, in practice, he believed GC1/GC2 was more focused on "structure to properties."

Other students described alternative relationships based on a purposeful choice to combine the component terms or a difficulty in distinguishing between them (Appendix K). Serina had particular difficulty describing a clear relationship between the terms, stating that "the function of something has different properties...the structure has properties and the structure has a function so, I just, those three words are closely related." Ultimately, she decided that structure and properties determine function though she appeared to lack confidence (Appendix K). While John described the relationship similarly (S/P → F), he appears to have done so strategically, to represent different ways that he could apply it.

These various alternative relationships were likely influenced by how structure, properties, and function had been presented in B1 and GC1/GC2 (RQ2) and, in some cases, were foreshadowed when students had difficulty differentiating between the terms (RQ1). For example, Priyah indicated that properties and function "blur" in both GC1/GC2 and B1. John perceived structure and properties as having been "grouped together" in B1, which likely contributed to his choice in identifying the relationship as S/P → F. Additionally while the implicit nature of the discussion of structure-property relationships in chemistry appears to have been sufficient for many students, this may have contributed to other students' inability to distinguish between the component terms and thus influenced their description of the relationship between them.

Nevertheless, most students were able to describe a causal relationship between structure, properties, and function in a way that appears to align with our disciplinary expectations. However, there are clearly students (like Serina, Priyah, and Aaron) that could benefit from more explicit discussion.

**Potential benefits of the SPF relationship**

One outcome of these interviews was the emergence of connections between structure, properties, and function that had not been explicitly emphasized in either the biology or chemistry courses, and the ways in which this relationship might be used. As noted previously, Ruth and Lida described how they could use the SPF relationship as a framework for making predictions, and Simon described how making connection between his courses allowed him to think about his understanding in GC1/GC2 and B1 from a different perspective. Furthermore, Ruth (Appendix H) noted that having discussed the relationship in both courses had made her more attentive to small changes in structure, as those could ultimately lead to important changes in the properties and function. When asked whether she had used her understanding of the relationship in B1, Ruth described an in-class activity on the potential effect of DNA mutation.

> Ruth: We did, a modeling exercise where we were talking about a mutation, and how that caused a change in the DNA sequence, and how it eventually changed the amino acid sequence, and how that completely changed the structure of a protein, and how that ruined the function.

Further, Shelly (Table 5.6) described the relationship as a thought process she used (albeit subconsciously) to work through problems. Similarly, Evelyn described it as a “universal thought process,” stating that it “applies to everything, almost everything at least. Like understanding the basic structure, like that’s the foundation of it. And then from there that determines its properties and function. I feel like that works for many things in both courses. It’s not just one unit.” In fact, Joseph and Aaron (Appendix K) note that they actively applied the relationship to work through problems. Aaron described this as an iterative process that led to a more refined answer.

Unfortunately, while she was able to talk about the relationship between structure, properties, and function during the interview, Evelyn indicated that she had not recognized the benefit of making such connections in either of her courses. When she was studying for GC1/GC2, she said that everything seemed like a “random idea.” Similarly, in biology she “never really put all of the pieces together.” Instead, she would memorize the structure, the properties, and the function individually. “I wouldn’t find the common theme that like that structure leads to that property to that function. I would just memorize rather than find what connects them all.” In both courses, Evelyn appeared to convey that her use of memorization could have been avoided had she recognized the value of understanding the relationship between structure, properties, and function.

## Discussion and implications

The concepts of structure, properties, and function are inherently connected and have the potential to facilitate the development of conceptual understanding that spans the science disciplines. However, chemists and biologists emphasize this content in different ways (i.e., focusing on structure-property and structure-function relationships, respectively). Little is known about how students understand these concepts and the relationship between them, both within and across their courses, despite the fact that many students are taking introductory chemistry and biology concurrently. We explored student understanding from three angles: through (1) their interpretation of the concepts - structure, properties, and function - individually, (2) how they compared the presentation of these concepts in GC1/GC2 and B1, and (3) the connections students described between these concepts.

### Structure, properties, and function…

When considering these concepts individually, students appeared to have little difficulty describing structure or properties in the contexts of both chemistry and biology. However, while able to provide a variety of definitions for function in biology, discussing function as it relates to chemistry was more difficult. Only three students (Joseph, Ruth, and Priyah) were able to consider function productively in the context of chemistry, and even then, two of them expressed uncertainty in doing so. The successes of Priyah and Ruth appear to stem from their consideration of materials designed for a purpose (i.e., conductive wire and pharmaceuticals, respectively). This conception of function is more aligned with an engineering perspective (National Academy of Engineering and National Research Council, 2009; National Research Council, 2012a) and could almost certainly be harnessed by instructors to make stronger connections to a variety of STEM fields (e.g. biomechanical engineering or catalysis design in chemistry). It is important to note that, in these examples, the scientist or engineer plays an active role in the design, working towards a functional objective. In natural systems, there is no grand architect (despite the implications of describing function as a structure's purpose; Coleman, 1971;

Rosenberg & McShea, 2008). Without explicit discussion of these differences, there is likely to be cross-contamination in how students understand function in various contexts. Furthermore, the regularity with which function was discussed from a biological perspective may have made it difficult for students to interpret function from a design perspective.

As chemistry instructors often teach large numbers of both life sciences and engineering students, it would be beneficial to address these different perspectives on function in chemistry classes. To do so successfully will require instructors to engage in cross-disciplinary discussions so that they are aware of the implications the term “function” carries in various contexts. Further, it is important to find a consensus among the disciplines regarding when and how function is discussed. That is not to say that function should be emphasized in chemistry courses to the detriment of developing a coherent and sophisticated understanding of structure-property relationships, but rather that students may benefit from a foreshadowing of how such an understanding can (and will) be applied in future life sciences or engineering courses and, hopefully, be supported in recognizing this understanding as relevant prior knowledge when the time comes for them to apply it (Ausubel, 1968; Novak, 1998). Ultimately, if we do not at least acknowledge the value of learning about aspects of structure, properties, *and* function in both contexts, some students may not recognize this to be a relationship that spans all of science. An informative starting point for such cross-disciplinary discussions is the *Framework* (2012a), as it describes function, in combination with both structure and properties, as a concept that applies to both natural and built systems.

In general, students’ perceptions aligned with their instructors’ intentions (as presented in course syllabi; Table 5.3) regarding the focus of their chemistry and biology courses on structure-property and structure-function relationships, respectively. In general, students described structure-property relationships as having been more subtly incorporated into GC1/GC2 than structure-function had been in B1. And, while properties were included in the syllabus of B1 as a part of the “structure determines function" big idea, they were perceived as being discussed explicitly relatively infrequently. This suggests that, across both courses, attention to properties was less explicit than that of structure or function. And while this appears to have been unproblematic for many students, it may have contributed to other students' inability to distinguish between the component terms (Appendix G). Although it may not be vital that students know whether size and shape should be considered aspects of structure or properties, for those students (like Aaron) who do not recognize that these are two distinct but related concepts, constructing an explanation describing how subtly different structures can have very different properties might prove difficult (Cooper *et al.*, 2013; Cooper, Underwood, Hilley, *et al.*, 2012).

**…and the relationship between them**

Given that GC1/GC2 emphasized structure-property relationships while B1 focused on structure-function, we were not surprised that students had difficulty describing what function in chemistry means or that properties were not always considered in biology. And yet, even without instructional or curricular supports, these students not only made substantive connections between their course work (Appendix H), but nine students converged on a coherent, causal relationship (i.e. structure determines properties, which determine function; Appendix J). This is particularly notable given the difficulty these same students had describing connections between B1 and GC1/GC2 regarding energy (Kohn *et al.*, 2018).

However, even though most students constructed a reasonable framework, it is important to note that there were those who could have benefited from a more coherent and consistent discussion between the courses (e.g. Serina and Joseph). In fact, Evelyn is an example of a student who could clearly describe a causal relationship between structure, properties, and function during the interview, but had not understood the value of considering that relationship during her courses. Instead, she described how she would memorize the individual components without relating them and as such, everything seemed like a “random idea.” Looking back on her courses, she was able to recognize the potential of working to understand the connection between these concepts.

Other students noted ways they benefited from thinking about the SPF relationship. Shelly, Joseph, and Aaron described it as providing a guiding thought process for working through problems (Appendix L) while Lida and Ruth indicated that it could be used as a framework for making predictions. Lida and Ruth also described what we might consider “backward causal reasoning” (i.e. reason “diagnostically from effect to cause”; Sloman & Fernbach, 2017, p. 58). They suggested that, when given a function, they could consider the aspects of structure and properties that might lead to such a result. This type of reasoning is considered to be both more difficult and more time-consuming than reasoning from cause to effect and indicates their ability to think about the SPF relationship from a more sophisticated perspective. It would be ideal if all our students could benefit from the SPF relationship in this way. For this reason, we propose that chemistry and biology instructors work together to make stronger connections between their courses using the relationship between structure, properties, and function.

Ausubel’s theory of meaningful learning (1968) and Engle’s concept of intercontextuality (2006) provide insight regarding how instructors can help students recognize the value of making such connections and promote knowledge transfer between their courses. For meaningful learning to occur (as opposed to rote learning, which depends on memorization), students must “consciously and deliberately choose to relate new knowledge to relevant knowledge the learner already knows in some non-trivial way” (Novak, 1998, p. 23). Logically, this requires that students possess relevant prior knowledge and recognize that such connections are both possible and valuable (Ausubel, 1968; Novak, 1998). This means that chemistry instructors must help students develop a strong understanding of the relationship between structure and properties and that both chemistry and biology instructors need to emphasize the value of applying that understanding to consider biological systems and to the concept of function, including through the use of assessment, as students often use these to direct their focus (Crooks, 1988; Entwistle, 1991; Momsen *et al.*, 2013; K. Scouller, 1998; K. M. Scouller & Prosser, 1994; Snyder, 1970).

We propose that the SPF relationship could help students and instructors frame the content in chemistry and biology courses as being linked, with the ability to build on prior knowledge and extend to future learning (Engle, 2006; Engle, Lam, Meyer, & Nix, 2012; Engle, Nguyen, & Mendelson, 2011). Engle and coworkers (2012) theorize that transfer of knowledge is more likely to occur when there is intercontextuality between the learning and transfer contexts, because students are sent the message that what they are learning will have future relevance and utility. She proposes a number of ways that this can be fostered through an expansive framing of various aspects of the learning environment (e.g., the participants, topics, purposes). By describing the SPF relationship as a common framework that spans chemistry and biology, and by being explicit with students about when and how they can make connections between their courses, instructors can promote intercontextuality. Additionally, the SPF relationship can be presented as a framework for considering unfamiliar phenomena, making predictions, and constructing explanations, as noted by both the *Framework* (2012a) and our interview participants. Finally, we believe that understanding the relationship between structure, properties, and function can support deeper understanding of other disciplinary core ideas and crosscutting concepts (e.g., emergence, cause and effect; American Association for the Advancement of Science, 2011; Cooper *et al.*, 2017; NRC, 2012a). By building up student understanding of the SPF relationship in both chemistry and biology and supporting connection-making between the disciplines, we may be able to help students recognize the value of their prior knowledge and encourage its application.

It is important to note that, while we advocate for more explicit discussion of the SPF relationship in both chemistry and biology classrooms, we recognize that not every system discussed will require an in-depth, causal description. For this reason, instructors should think critically about why their students are learning about a particular system, the learning goals they hope to achieve, and how they might adjust activities and assessments to accomplish these goals.

## Limitations

The perceptions expressed by students in this study regarding the concepts of structure, properties, and function and the relationship between them may not be generalizable to a larger population. These students were enrolled in introductory chemistry and biology courses transformed by instructors who valued structure-property and structure-function relationships, respectively. Furthermore, the students interviewed were largely successful in these courses. Students situated in other, more traditional learning environments or those that were less successful in their science courses may not respond in the same ways. However, the findings presented here suggest an untapped potential for making cross-disciplinary connections between chemistry and biology courses regarding the relationship between structure, properties, and function.

## CHAPTER 6: LAURA: A LONGITUDINAL STUDY

A goal of science education is to support students in developing a sophisticated, coherent understanding of the core concepts and themes that are not only essential to a single discipline but provide a lens for considering phenomena in physical and built systems across all scales (NRC, 2012a). This means that concepts must be integrated into a conceptual framework, as opposed to fragmented pieces of knowledge, that becomes increasingly interconnected as students' progress through their courses. Developing such a framework requires students to engage in meaningful learning that is, the learner must "consciously and deliberately choose to relate new knowledge to relevant knowledge the learner already knows in some non-trivial way" (Novak, 1998, p. 23), which not only requires students to have relevant prior knowledge, but to also recognize the value of making such connections.

Education researchers often assess whether learning of specific content has improved over the span of a single course or course sequence. They may be exploring the efficacy of an intervention or the impact of some underlying student characteristics or feature of the learning environment on educational outcomes. Additionally, most studies focus on a single subject or discipline. However, this is not reflective of the goals or the context of the university students' educational experience. While each student is pursuing a major that can often be described as part of a specific sub-discipline or field, science and engineering programs regularly require course sequences in biology, chemistry, and physics. Ideally, one might expect that prerequisite courses are intended to prepare students for more advanced ones both within and across disciplines. And yet, there are few studies that cross-disciplinary boundaries in this way (Chapter 2). The preceding chapters have explored the perceptions of a group of students as they reflected on their introductory chemistry and biology courses taken concurrently within a single year. This chapter follows one student, Laura, through three years of university chemistry and biology coursework, culminating in a two-semester, majors biochemistry course sequence.

## Methods

### From whence she came

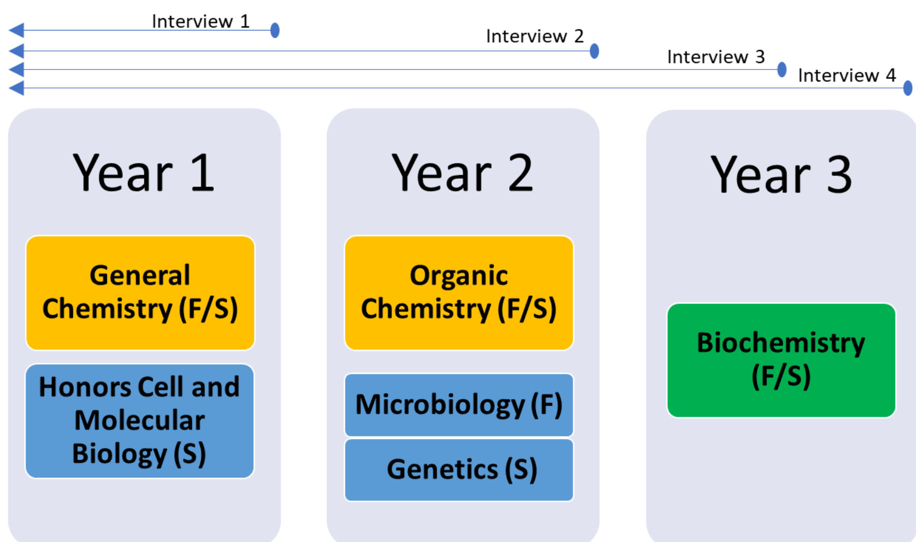
This work began in the context of a larger research study exploring student perceptions of the relationship between their introductory chemistry and biology courses (Chapter 3). At the end of her first year in college, Laura was one of 22 students who volunteered to be interviewed. The protocol, designed based on the *Framework* (NRC, 2012a), asked students to discuss their courses from three perspectives—disciplinary core ideas (referred to as big ideas), crosscutting concepts (or themes that span chemistry and biology), and science practices. In each case, students first reflected on their courses individually before describing perceived relationships between them.

One year later, the 22 participants were contacted regarding their willingness to participate in a follow-up interview. Of the three students who volunteered, Laura's major (genomics and molecular genetics) was most conducive to exploring continued connections between chemistry and biology. That year she had been enrolled in microbiology and genetics, and she was planning to take biochemistry as a junior. In comparison, Sharon was an animal science major who wanted to work as a veterinarian. As such her courses were taught from an animal care perspective and included aspects of animal physiology, nutrition, breeding, and management. Amanda was an interdepartmental bioscience major who intended to pursue a career as a high school science teacher. She was expected to take courses across many biology sub-disciplines to provide her with a broad overview of the biological sciences. Furthermore, both Amanda and Sharon were enrolled in biology courses that focused on more macroscopic biological systems (e.g. organisms and organ systems), which made it more difficult for them to identify and describe connections to chemistry. Given that this project already considered students perceptions of the connections between courses of different disciplines across time, the additional variation in scale and scope added by Sharon and Amanda was determined to be too much for a single project. For this reason, only Laura was asked to participate in the additional interviews.

**Interviews and course experiences**

Over three years, Laura was interviewed four times, at the end of the spring semester of her freshman (Interview 1) and sophomore (Interview 2) years and twice during her junior year, at the end of her fall (Interview 3) and spring (Interview 4) semesters. In Year 3, Laura was interviewed twice to provide ample time for review of her past two years of course work while still allowing for in depth discussion of her biochemistry course. Interviews focused on her chemistry and biology lecture courses (Figure 6.1) though she would sometimes compare or connect these courses to her laboratory experiences.

**Figure 6.1 Laura: Four interviews over three years**




F – fall; S - spring

**Year 1** Even during her first interview, Laura stood out in several ways. She was a highly successful student with an interest in biology at the molecular level. Having taken AP Biology in high school, both semesters of college introductory biology were waived. However, as a genomics and molecular genetics major considering higher education, she decided to enroll in Honors Cell and Molecular Biology (HB1) during the spring semester. In addition to covering the introductory biology content in more detail, the honors course included a laboratory component and required students to present on and discuss research journal articles. Further, the course description stated that organic chemistry experience would be advantageous but was not essential. This course was team taught by two professors.

That year Laura was also enrolled in *Chemistry, Life, the Universe, and Everything* (CLUE), a two-semester transformed general chemistry curriculum. At the time of her interview, this was one of two curricula being used, the other being more traditionally organized and run. CLUE had undergone iterative design cycles since it was first taught in the spring of 2010 (Cooper & Klymkowsky, 2013a; Cooper *et al.*, 2017) and emphasized four core ideas, that of structure and properties, stability and change, forces and interactions, and energy. In addition to considering these central concepts in increasingly sophisticated and interconnected ways, students are required to apply their understanding through construction of representations and explanations using beSocratic, a freeform online assessment platform. Both semesters of the course were taught by a single professor offering additional pedagogical consistency. During Year 1, Laura was also enrolled in the general chemistry laboratory courses at the same time, though these were not considered to be within the scope of the interviews.

**Year 2** As a sophomore Laura took the two-semester organic chemistry lecture course sequence and the associated organic chemistry lab course. Both semesters of the lecture course were taught by a single professor using Klein's *Organic Chemistry* 2$^{nd}$ edition (2015). The lectures largely followed the order of topics presented in the textbook and assessments were described as reflecting the end of chapter problems. As is common among organic chemistry courses, lectures were organized based on structural functional group with an emphasis on knowing large sets of chemical reactions and associated mechanisms.

Laura's microbiology course was taught by a single professor and aimed to provide a broad overview of the diversity, genetics, genomics, and ecology of microbes using the Brock *Biology of Microorganisms* 14$^{th}$ edition (Madigan *et al.*, 2014). Over a quarter of the class was dedicated to pathogenicity, immunology, and infectious diseases. Her genetics course, taught by a single professor using *Genetics: A Conceptual Approach* 5th edition (Pierce, 2013), aimed to provide students with a basic understanding of genetics and the ability to evaluate and apply genetic information. The course included weekly recitations in which students worked through ungraded genetics problems separate from homework assignments with a focus on understanding the logic behind and implications of genetics experiments and being able to predict and interpret experimental outcomes.

**Year 3** Laura took a two-semester biochemistry course sequence designed for students majoring in biochemistry or closely related fields. The instruction team consisted of six professors including one who acted as the course coordinator across both semesters. The course was organized by class of biomolecule with proteins and carbohydrates covered in the first semester and lipids and nucleic acids covered in the second using *Lehninger Principles of Biochemistry* 6th edition (Nelson & Cox, 2008). Weekly recitations were run as review sessions with short presentations followed by an opportunity for students to ask questions.

**Data collection and analysis**

Laura's first interview was conducted using the original protocol and the three subsequent interviews (2-4) followed the revised protocol (Appendices A & B). While the original protocol included three sections, which align with the three dimensions described in the *Framework* (disciplinary core ideas, crosscutting concepts, and practices; 2012a), the length of the interviews and the breadth of the resulting data led to removal of the practices section. The revisions, described in more detail in Chapter 3, allowed for deeper exploration of the crosscutting concepts – energy and the relationship between structure, properties, and function. Across the four interviews, Laura engaged in over 9.5 hours of discussion about her courses. She was an exceptional interview participant, and this work benefited greatly from her willingness to discuss her experiences.

## Findings

From the first, Laura reflected on ways in which her experience in university science courses differed from high school, especially with respect to her ability to make connections between chemistry and biology. She described how her general chemistry course supported her understanding in biology and explicitly discussed energy as a crosscutting concept. She did not immediately recognize the connections between her sophomore year courses. And yet, she maintained the expectation that her biochemistry would bring together her understanding of chemistry and biology.

### A new perspective on learning

Early in her first interview, it became clear that, since leaving high school, Laura had experienced a shift in her perspective on learning. She described her high school chemistry instruction as rather shallow and fragmented. In comparison, she felt that she could reason through unfamiliar problems after having taken CLUE and that her understanding of chemistry allowed her to move beyond memorization of her biology content.

She became aware of these differences while trying to help her brother with his high school chemistry homework. When she tried to explain the associated concepts, he remarked that, rather than learning those concepts, his class had focused on example problems. This led Laura to reflect on her experiences and on the nature of learning.

Laura: ...looking back on it that was kind of what I thought learning was, just like seeing all these different types of problems and being able to use those examples to do other ones. But now with everything I've learned this year it's— that's like not the way you should learn I don't think.

K. Kohn: What do you think the way you should learn is?

Laura: More so like concepts so that you can apply them to every situation. Not just learning one equation or one type of problem and then being able to recognize other compounds that are that type of reaction or something. More so, I don't want to say general because it is still pretty specific but having a lot of ideas about the same things but to the point where they kind of overlap. Because I feel like in high school it was always kind of like, well this unit is like this and then you never really talked about it

> again. But in this class [CLUE] I feel like everything builds off of each other—…information we've learned never really went away. I feel like that's a better way of learning it because then you're not just memorizing stuff. *(Interview 1)*

During the interview, she described her high school chemistry course as being algorithmic, fast-paced, and fragmented; and she described her understanding of chemistry as having been shallow and procedural, saying “In high school I never really struggled but I definitely didn't actually understand things. I knew how to do the problems...” and that she could get away with memorizing things. However, she seems to have been describing the presence of conceptual threads or core ideas in general chemistry, which were at once both general and specific. She went on to discuss the way the material in general chemistry was structured to build from one concept to the next. This interconnectedness of the material helped her develop “a more genuine understanding, because we've— it's never really went away. Everything affects everything else.”

This also influenced how she approached problems in chemistry. In high school, she attempted to recognize and directly match the problem to some prior knowledge, giving up easily if she was unable to do so. In comparison, Laura believed that she was able to “think through” problems after having taken CLUE, saying that “you can almost see how you might be able to figure out something new that you're learning based on things you already know.”

> It depends on the situation but [in college chemistry] just given certain information, you can figure out a lot of different things, which is something I never really did before...normally, like in high school chem, I would look at something. If it didn't fit the specific equation or whatever that I'd learned before, I would just be like, “Oh, well, I don't know how to find that.” But now I feel like if I have enough time and I can really think through it, I could get from one place to another relatively easily. *(Interview 1)*

Many of the differences Laura noted between her high school and college chemistry courses were goals of the CLUE curriculum reform: the scaffolding of concepts to become increasingly sophisticated, the regular and explicit connections between ideas, the desire for students to be able to explain as opposed to memorize. Additionally, Laura found that her increased understanding of chemistry allowed her to understand biology in a deeper way. In AP Biology, she was “in the routine of trying to strictly memorize things" and she lacked an understanding of why things occur. In comparison, she found that she would regularly use knowledge from her general chemistry course to help her "figure things out." For example, she described her understanding of structure, interactions, bond strength, and energy as being useful for thinking about cellular processes.

> I think learning about different things in bio, like structures and certain reactions that happen within the cell, like different cellular processes, I have a really good understanding about them from chem, because I'll be able to tell, "Oh, well, that is that kind of bond and it has this much energy," or "in comparison—" I can't predict the number but, "In relation to this, it probably has more or less and so that means that it's this kind of reaction. It'll produce energy which might do this." I feel like, overall, it's usually different things I know from chemistry help me understand cellular processes, which is basically all the class is about in bio. *(Interview 1)*

We cannot make claims regarding the sophistication of Laura's content knowledge.[5] However, she clearly valued conceptual understanding over memorization.

These values persisted through all four interviews and appear to have influenced her perception of course expectations. In Year 2, Laura was enrolled in both microbiology and genetics, which represented polar opposites regarding the extent to which she was expected to use her content knowledge. While she enjoyed the subject matter of both courses, she disliked the need to memorize lists of microbe names and "what they do."

> It's a lot of memorization for sure. I think that was really the way to succeed in that class was just to memorize everything you learned. It was pretty hard, honestly, for me because I'm more like having to do biology problems or thinking about ... I don't know, like experiments and what they proved and what would happen if something else went different and stuff like that…we really didn't talk about any sort of mechanisms of how anything happens. It was a lot of just memorization. *(Interview 2)*

The things Laura found to be missing from her microbiology course, discussing mechanisms and working through problems, were an integral part of her genetics course. In genetics recitations, she was required to really apply her knowledge.

> You have to really think hard about [the problems]. And that's what I like, I think because it's not just memorizing information for a test...she always wants us to know how to solve a problem in

[5] The purpose of these interviews was to elicit student perceptions regarding connections between their chemistry and biology courses. And so, no course materials or content-based questions were provided

> a different way... [Our instructor] focuses a lot on being able to interpret every single part of what a question is asking you. And how everything in the problem can either be dependent of each other or be independent. *(Interview 2)*

Laura focused on how problems in her genetics course required her to apply her knowledge and consider the effect of changing different aspects of the problem. Her contrasting descriptions of these courses highlight her continued belief in the importance of conceptual understanding and knowledge application. As shown above, this perspective appears to have originated from her experience taking general chemistry, the impact it had on her honors introductory biology course, and how these courses compared to those she took in high school. In her second interview, she reflected on that relationship.

> I never got an A on a biology test because I knew how to balance a chemical equation, type of thing. But I feel like it definitely did help me understand things, which then I got the grade I got. It, again, influenced it, but I think it was definitely more so it helped me, for sure, with actually learning and understanding things, as opposed to just memorizing them and forgetting them later. It was more so I understood the mechanism of a biological process. *(Interview 2)*

Laura did not experience direct assessment of her chemistry skills or content knowledge in her biology course. However, she recognized an indirect influence on her retention and understanding of the biology content matter. Across the four interviews, Laura was consistent in her belief that chemistry should be a prerequisite for cell and molecular biology for that reason, though she noted in Interviews 2 and 4 that it was not necessary. In both cases, it is a contrast between memorizing and developing conceptual understanding that leads her to this conclusion.

> Laura: I feel like there's stuff in chemistry that will help you understand biology better. Not to say-- I honestly think that there's some bio classes, just the way they're taught, that you could totally just take it without taking chem and memorize it and get through it. But I feel like chemistry does help you actually understand things in terms of biological processes. *(Interview 2)*

> Laura: I feel like I could've gotten through my freshman year biology class without really knowing chemistry, like I would've just memorized it, but I probably would've forgotten most of it and not understood most of it. I would've just been memorizing it and repeating what they said to me. But I feel like in biochemistry, I wouldn't have been able to do that. I would've been, honestly, pretty lost if I hadn't taken any chemistry, and even just because if I hadn't actually understood what I had learned in biology, I wouldn't be able to understand what I was learning in biochemistry. The reason I understood what I learned in biology was because of chemistry. *(Interview 4)*

Notably, while she thought that she could have "gotten through" her introductory biology course without general chemistry, Laura believed that she would have been at a disadvantage once in biochemistry. In Interview 4, two years after having taken general chemistry and honors introductory biology, Laura still believed that those courses had an impact on her current understanding. While Laura's attentiveness to these relationships were likely influenced by her participation in regular interviews on the subject, her expectations demonstrated an awareness of the difference between rote and meaningful learning.

One notable example from biochemistry was related to Laura's difficulty understanding Michaelis-Menten kinetics. As Laura was having a hard time interpreting the graphical representations and the proportional reasoning demonstrated by her instructor, she attempted to memorize the relationships between the variables.

> I could understand what was happening in the sense of if the $K_M$ is decreasing, then something else might increase, kind of do that kind of thinking, but when it came to understanding the actual graphs, the actual work he wanted me to do, I did not know how to translate it from one mode to another. *(Interview 3)*

However, she reflected on a question from her final exam which led to her realization that the kinetics could be understood based on changes to the enzyme structure and properties. In this way, she could use her understanding of interactions to think about the affinity between the enzyme and substrate.

> I know one of the questions on the final was about if you changed an aspartate to glycine, what would happen? What would happen to the KM? That was trying to show that if you changed it from a charged residue to a non-charged residue, it would lower the KM because it wouldn't be able to form the ... it wouldn't be able to interact the same way with whatever the other molecule that they were giving you. I think that was a better idea of what he was actually trying to teach us... *(Interview 3)*

She recalled considering the cause and effect relationships between the presence of amino acids with different properties (e.g. charge or size) on protein folding. However, despite the possibility of using similar reasoning to understand enzyme kinetics, she had not made that connection at the time.

> …going back to the proteins and the amino acids, understanding how the charge of a molecule or the size of it might affect the way that it interacts in a process later on. For the enzyme

> kinetics unit, he kind of ... I don't know. I think he kind of taught it in a way that was really confusing for me because it was a lot of graphs. He would teach it in a way that if this goes up, then this goes down. I felt like I had to memorize that when in reality I should have been trying to understand it. *(Interview 3)*

These two units were taught by different instructors (as this was a team-taught course). As such, the explicit connection may have not been made or perhaps not to a sufficient extent for Laura to recognize. Additionally, students may have been expected to apply what they had learned earlier in the course. Regardless of the reason, this was a moment for Laura where she found herself memorizing out of necessity.

**Course connections regarding energy: Expectations vs. reality**

Energy is known to be a notoriously difficult concept for students (and instructors) to understand (Barak *et al.*, 1997; Carson & Watson, 2002; Chen *et al.*, 2014; Galley, 2004; Nordine, 2015). And, as seen in Chapter 4, discussing kinetic and potential energy transfer across the disciplines of chemistry and biology is particularly problematic (Kohn *et al.*, 2018). For example, there is a prevalent disconnect regarding the relationship between energy and the breaking/forming of bonds. Introductory chemistry instructors often discuss the relationship in the context of Hess's law, indicating that breaking bonds requires energy through graphical representations and positive bond enthalpy values. In comparison, introductory biology courses tend to focus on more complex systems of reactions and thus, apply Gibbs free energy calculations in an attempt to explain reaction coupling. Therefore, it is not surprising when students use ATP hydrolysis to support their statement that (at least sometimes) breaking bonds releases energy ("Cell energy and cell functions," n.d.; Cooper & Klymkowsky, 2013b; Storey, 1992). To help students develop a more coherent understanding of energy across the disciplines, chemistry and biology instructors must work together to make connections between their courses. And yet, some may argue that providing a mechanistic explanation of energy in chemical and biological systems is better suited to upper level courses. For this reason, Laura's discussions of energy as she progressed from introductory chemistry and biology courses to biochemistry, provide an interesting opportunity to consider connection making across disciplines.

During her first interview, Laura emphasized the centrality of energy concepts (Table 6.1). In general chemistry, she considered energy to be a big idea describing it as "what everything's most-connected to so far". She felt that by understanding energy she could predict or explain other aspects of a system, such as the strength of intermolecular forces or the stability of a product. In honors

**Table 6.1 Energy in Year 1 *(Interview 1)***

| |
|---|
| <u>General Chemistry</u><br><br>I think the thing I feel like that we've learned most about is just energy in general, and Gibbs free energy, enthalpy…because once you understand— I don't want to say "the energy aspect," but kind of that. If you understand that, say, a reaction's exothermic, I feel like you can work backwards and figure out a lot more about it: "Why might it be?" or, "What does that say about the strength of the bonds or the intermolecular forces?" and stuff like that. |
| <u>Honors Introductory Biology</u><br><br>We learned about cell respiration and photosynthesis pretty in-depth, so that, actually the chemistry came in handy a lot because you're looking at, a lot of times, how one thing goes to another and there are so many steps along the way that sometimes you're like, "What?"<br><br>I don't know, when you really think about it, it makes sense...Like when we learn certain things about structure, knowing what kind of bond that would be or how this is interacting with this helps you figure out where it might be going. It's like in steps of cell respiration and the glycolysis and the citric acid cycle, if you can see— you can tell from what you know in chemistry that, "Oh, that might not carry a negative charge well," or, "That's unstable." So then you can predict what it might change into and what might happen or if it'll produce energy or if it needs energy to happen.<br><br>So I think that helped a lot with that unit. I don't know. I feel like it wouldn't have made much more sense to me than it did last year [in high school]. Last year when we did this unit, I was so lost, in AP bio. But this year, I understood it a lot more. I understood why, I don't know, it was happening and why ATP was needed to do this or why it produced ATP and stuff like that. |
| <u>Themes Connecting Chemistry and Biology</u><br><br>I mean, because my bio class is centered on biological processes. Chemistry is all about— well, not all about, but a lot about chemical reactions. I think that in order to understand both, you have to understand energy and what's really going on energy-wise. How it's changing and what that means. And without energy, what would happen or stuff like that. So I feel like, in both classes, it affects it in the same way or sense of it's always needed. So it's a really prevalent thing that keeps coming back. |

introductory biology, she described her understanding of energy, in conjunction with forces and interactions, as having been particularly helpful for thinking about metabolic reactions and ATP. Laura even named energy as a theme that connects chemistry and biology. However, her perspective on energy during her Year 2 interview was drastically altered.

In comparison, Laura did not discuss energy or related concepts in her Year 2 interview until prompted. At first, she was asked to think generally about energy as a theme that connects chemistry and biology. However, Laura appeared to be so unpracticed in thinking about energy that she was directed to focus on her recent coursework.

K. Kohn: …another theme that people will consider to span both chemistry and biology is energy. Why do you think they consider energy to be a theme?

Laura: I don't know. I'm kind of blurry on what you even mean by energy. Just like that energy is energy is needed for bio and chemical processes to happen, type of thing?

K. Kohn: Kind of, yeah. I mean, broadly just however you discuss energy in your courses. Do you discuss energy in your courses?

Laura: Not really. Not that I can think of off the top of my head…I mean, it definitely sounds familiar from last year, but not as much this year *(Interview 2)*

When asked about organic chemistry, microbiology, and genetics individually, she only recalled discussing energy in organic chemistry. And, even then, it was not an experience she could talk about in any depth.

> [In organic chemistry] first semester when we were talking about stability of molecules we would talk about ... We did energy diagrams, but I really can't remember why we did them…. Like if this molecule has low energy, what does that mean for its stability or what does it mean for how it might react? But I don't really remember the connection that deeply because we only talked about it first semester for a little bit. *(Interview 2)*

This is particularly notable given her use of stability to think about metabolic reactions in honors introductory biology (Table 6.1). Despite the emphasis with which she had discussed energy and her ability to make connections between her courses in Interview 1, Laura was not even confident about what she was being asked to consider with respect to energy in Year 2. This seems to suggest that her conception of energy had become more diffuse, perhaps due to a lack of any coherent or even consistent discussion of energy in her courses.

During Interviews 3 and 4, Laura described energy as a concept that had been important in biochemistry but in a different way than it had been in general chemistry. As such, she discussed energy as a rather superficial connection between her courses, if at all.

> Laura: I think that it could be [a theme that spans chemistry and biology], but I'm not really seeing it right now. I feel like, depending on the way a course was taught, it could incorporate it more. I feel like I'm seeing it a lot more in chemistry as a really relevant theme, and then in biochem it's a background theme. I don't know how to explain it. It's a big idea, but in a very different way. *(Interview 3)*

> Laura: I think because in chemistry and biology, you're talking a lot about different reactions, like chemical reactions and then enzyme react…I know that we talk a lot about does this reaction take energy, does it release energy, and that kind of stuff. So I feel like in both disciplines, that's just something that you include, kind of. *(Interview 4)*

The input or output of energy associated with reactions, described above in Interview 4, was her only real connection between the courses. Laura had previously indicated that her courses were connected by discussions of thermodynamics. However, it became clear that this was a superficial connection at best, as she later noted that they did little more than define enthalpy and entropy at the beginning of biochemistry. For biochemistry, she considered the big idea as having been the cell's ability to prevent inefficient uses of energy through regulatory processes.

> The cell has a lot of different ways of regulating itself to make sure that energy isn't wasted…I feel like everything kind of goes under that…the way they taught the class was, they would kind of teach you the basics of what's going on at a really molecular level, and then it would kind of build up to why is that important or why is that helpful to the cell. Why does that contribute to its regulation, how it's preventing it from wasting energy that it just went through all these processes to make. *(Interview 3)*

Later in this same interview (3), she described her biochemistry course as having discussed "all new" energy content (other than Gibbs free energy), further supporting a perceived disconnect between her chemistry and biochemistry courses.

By focusing on different content, her courses could have led to a shifting perspective on energy; and so, she was asked whether she conceptualized energy differently based on her recent course experiences. During Interview 3, she was unsure saying that she thought about energy "in the moment" in general chemistry but had not really returned to that content since. When asked the same question during Interview 4, she simply stated, “I don't think so.” As this was her final interview, she was prompted to think back on her understanding of energy over the past three years.

K. Kohn: Do you think that your understanding of energy has grown at all after having taken biochemistry?

Laura: I mean, I would say that I recognize more terms. Like if someone's like "Oh, that's a stable molecule," I'm like "Oh, that's a good thing." But I don't really know, I don't really think it helped me develop any deep understanding of it.

K. Kohn: Do you feel that there's been any point in time in the past where you may have had a better understanding of energy or maybe just even been more comfortable thinking about energy than you are today?

Laura: I do. Now that we've been talking about it, I do feel like I remember in general chemistry learning a lot about it. Like when we would learn about reactions, we'd learn about changes in energy and draw diagrams and stuff like that. And I feel like in the moment I really understood it, but now I don't really remember it because we don't really talk about it as in depth, so I feel like I kind of forgot to remember it. *(Interview 4)*

Unfortunately, while she recalled having had a deeper conceptual understanding of energy during Year 1, she did not appear to have gained or even retained that understanding, perhaps due to the inconsistency with which the concepts were discussed over Years 2 and 3.

**Making connections between structure, properties, and function**

Structure-function relationships are a prevalent theme in the biology education and disciplinary research literature (American Association for the Advancement of Science, 2011; College Board, 2015; NRC, 2012a). Similarly, the relationship between structure and properties is considered essential to understanding chemistry (College Board, 2014; Cooper *et al.*, 2013; Talanquer, 2017). The concepts of structure, properties, and function are intrinsically connected. And yet, most research studies explore student understanding of the relationship between, at most, two of the three concepts (e.g., Cooper *et al.*, 2013; Hmelo-Silver & Pfeffer, 2004). Laura’s first interview, as a member of Cohort 1, reflected those disciplinary distinctions. Whereas the revised protocol introduced the concepts of structure, properties, and function simultaneously without any reference to predefined relationships, Laura was prompted to consider structure-function and structure-property relationships in turn, with the implication that these were not just related concepts but variations on the same idea. And yet, Laura described structure, properties, and function as distinct but related concepts, consistent with the findings presented in Chapter 5. Not only did these students make cross-disciplinary connections without instructional or curricular supports, but Laura also did so despite a potentially, more restrictive set of interview prompts. Further, she maintained a sense of these connections throughout her four interviews, recognizing the relationship between structure, properties, and function to be a valuable and crosscutting component of her courses. This is starkly contrasted with her perspective on energy across her chemistry and biology course work.

As previously noted, the SPF section of Laura's first interview began with a discussion of the relationship between structure and function. She described a familiarity with this relationship. However, this had not been garnered in her Year 1 courses (i.e., general chemistry and honors introductory biology), but rather during AP Biology. Her instructor had discussed structure-function relationships as a central theme of a curricular redesign. In comparison, she found her current courses to have given the concept less consideration, stating that "we haven't really talked about it a lot directly this year" (*Interview 1*). She still recognized structure-function relationships as having been important, though more implicit, in her college courses.

> I think it means that you have to understand what the molecule looks like at a molecular level to be able to understand what it's going to do or how it might behave. Then that determines how it might react, how it might be used…I think that's big in both classes *(Interview 1)*

However, upon introduction of the relationship between structure and properties as an alternative phrasing, Laura began relating all three concepts, describing properties as a way to connect structure and function.

K. Kohn: So if I also refer to it as the relationship between structure and properties, does that make you think of anything different, or do you consider those two ways of saying it to be similar?

> Laura: I think that structure and properties almost makes more sense, because, for example, back to the protein thing, if you— sometimes, you might know its properties…But you might not know what it does. But knowing properties helps you get closer…I feel like properties is more of a step along the way…going from structure to function. *(Interview 1)*

This conception of the SPF relationship was one that she returned to during subsequent interviews. In Year 2, when the terms structure, properties, and function were reintroduced as associated with a theme that spans chemistry and biology, she noted:

> The structure affects the properties of a molecule and then those properties affect the way it works. Because if something goes wrong with the structure when it's, when the molecule's being made or something, then it might not have the same properties as it should and then it might not function the same way as it's supposed to. *(Interview 2)*

That year, Laura again described the SPF relationship as having been important but not explicitly discussed. In organic chemistry, she referenced the connection between function group structure and the way it reacts. In genetics, she recognized the SPF relationship in their comparisons of DNA and RNA. Microbiology had been the exception. Earlier in the interview, she stated that her course had discussed the structures and functions of various microbes. However, with respect to making connections among those ideas she said, "I just feel like we didn't really learn a lot in terms of concepts…it was a lot of memorizing. So, I just really didn't think about it in these types of terms."

From Laura's perspective, her understanding of the relationship between structure properties and function was something that she had built over time. During Interview 3, this made her question whether other students who had different prior experiences would have considered the SPF relationship as having been necessary for understanding the first semester of biochemistry.

> It exists so much in biochemistry that, like that relationship, that it would be really hard to teach it and understand it without it. But at the same time, I kind of feel like that's because I'm aware that that relationship exists, and I'm like seeing it, and thinking about it, due to past classes and stuff. *(Interview 3)*

When describing the impact her prior chemistry courses had on her understanding of biochemistry (Table 6.2), Laura initiated a discussion of the relationship between structure, properties, and reactivity, noting that knowledge of properties, such as charge and stereochemistry, had influenced her understanding of the behaviors of molecules and macromolecular structures, such as protein denaturing and substrate enzyme binding. The SPF relationship came up again when she was asked to consider themes that chemistry and biology (Table 6.2). Notably, across the four interviews, Laura described *function* as how a thing behaves or functions *(verb)*. And from the first, she included examples that spanned chemistry and biology, discussing catalysis, reactivity, the role a molecule might serve in a reaction or process (e.g. as an acid or base, as an enzyme or substrate, etc.), and how something might behave under varied conditions.

**Table 6.2 Making Connections Across Courses**

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| **Connections between chemistry and biochemistry** |
| I already knew a lot coming in from [general] chemistry and organic chemistry about determining atomic and molecular structure and how those structures influence the properties and the ability to interact with other molecules. *(Interview 3)* |
| **Themes the span chemistry and biology** |
| I think that like one of them would probably be that the whatever you're dealing with, whatever molecule at the molecular level, like it's structure and properties kind of cause any like behaviors of it...I'm trying to think of like an example of that, but just basically that like the chemical properties and, yeah, of like biological molecules affect the way that they interact with other molecules and go through certain processes. Like how they're broken down or how they're formed and stuff like that. *(Interview 3)* |

Laura perceived function as having been more emphasized in biochemistry than structure or properties. Not only did she think structure and properties were discussed less often, but she suggested that understanding function had been the ultimate goal.

> In chemistry and biology, I think about it as like an equal relationship on the three sides. But then in biochem, I feel like it is more so like a buildup type of thing. Like structure is important for properties and properties are important for function… [In chemistry and biology,] we spent a lot of time learning about structure and a lot of time learning about properties and a lot of time learning about function. Whereas in biochem, we kind of talked about structure for like one lecture of a unit and then properties for like the second one and then function for like the rest of them. *(Interview 3)*

Additionally, she stated that she was unable to think about the SPF relationship during lecture, because "I was trying to write everything down, and I was thinking so fast that I wasn't making those connections unless the professor was kind of pointing them out." However, when she was working on her own, while studying or during an exam, she believed that she was frequently thinking about the relationship between structure, properties, and function.

> It helps me kind of pull from different ideas that we've talked about. I might not know how to solve something I've never seen before, but if I know and can understand certain aspects of it, then I can pull around and kind of think about it in a different way that could help me more so develop a thought about it *(Interview 3)*

So while Laura considered the SPF relationship to be necessary for understanding biochemistry and valued the relationship when solving unfamiliar problems, she had benefited from her experiences in Years 1 and 2. She identified these courses as having spent considerable time on the concepts of structure, properties, and function, which potentially allowed her to continue to make connections when working independently in biochemistry.

It is important to note that these interviews also reinforced the SPF relationship for Laura. At the end of Interview 4, she said as much.

> I remember we talk about this one [the SPF relationship]. I can never remember how we lay it out, but I feel like it helped me in biochemistry because we talked about it in our interviews… Like when I started seeing the information presented in that order, I feel like I kind of remembered it and that helped me learn. *(Interview 4)*

It is impossible to know the extent to which our conversations influenced her retention of the relationship between structure, properties, and function. However, throughout her interviews, Laura continually referenced the discussion of these concepts in her current and past courses, all the way back to high school. Additionally, the extent to which she could make connections and discuss the crosscutting concepts of energy and SPF relationship varied drastically despite both having been topics of all four interviews.

## Conclusions and implications

Across the three years that Laura was interviewed, she progressed from honors introductory biology and general chemistry to more advanced courses in both disciplines to biochemistry. These interviews included discussions of her individual courses, the connections between them, and two crosscutting concepts (i.e., energy and the relationship between structure, properties, and function). Laura appeared to have benefited greatly from her early courses. She gained a new perspective on learning as being more than memorization and algorithmic problem solving. She recognized energy as a central theme that connected the concepts within and between her introductory courses. And she described the relationship between structure, properties, and function despite these concepts being introduced as the predefined structure-property and structure-function relationships. However, these successes were not sustained to the same degree throughout her Year 2 and Year 3 courses.

Comparing her college courses to those she took in high school, Laura recognized that she was developing a conceptual understanding of the content. She was able to construct explanations and make predictions. Laura believe that she could use her knowledge of chemistry to understand why things occurred in biology; and she extended that belief in the influence of her prior courses into biochemistry. Throughout all four interviews, when asked her opinion on the matter, Laura asserted the benefits of listing the first semester of general chemistry as a prerequisite for biology.

Despite Laura's perceptivity of connections among her courses, her ability to discuss the crosscutting concepts of energy and the relationship between structure, properties, and function varied significantly. Across her four interviews, Laura continued to describe the SPF relationship as a valuable framework for thinking about her courses. She considered the relationship to have been intrinsic to various concepts (e.g., reactivity of functional groups in organic chemistry, enzyme-substrate binding in biochemistry) and ultimately described it as necessary for truly understanding biochemistry. Further, she used the SPF relationship to make connections to her prior knowledge when studying and taking exams. However, she questioned whether she recognized these benefits based on her prior course experiences.

This is a particularly insightful statement given the apparent decrease in Laura's ability to discuss energy concepts. While Laura described energy as a central concept in her introductory chemistry and biology courses, in her Year 2 courses (i.e., organic chemistry, genetics, and microbiology), she barely even recalled it as having been a topic of discussion. In biochemistry, Laura recognized energy as having been an important concept, especially with respect to understanding the important of regulation for maintain cellular energy efficiency. However, she described energy as a "background theme" and only made superficial connections to the energy concepts learned in her introductory courses. In her first interview, Laura described her knowledge of energy from general chemistry as having allowed her to predict or explain other aspects of a system in both of her introductory courses, but she did not see her more advanced courses as having deepened her understanding of energy. These findings suggest that Laura's advanced course work encouraged and supported the retention of her understanding of the SPF relationship but did not sufficiently build on her prior knowledge of energy. As she said in her final interview, "I feel like I kind of forgot to remember."

Laura's discussion of these two crosscutting concepts across her four interviews illustrate what can happen to a student's understanding over time. Although it was not always explicitly discussed by her instructors, Laura consistently recognized the utility of thinking about the relationship between structure, properties, and function in her courses. Alternatively, she rarely thought about energy during Year 2; and when it became a topic of conversation again in biochemistry, it was not strongly connected to her prior knowledge. Perhaps if she had more use of her understanding during Year 2, she would have recognized deeper connections between her course, but perhaps not.

For students to benefit from course prerequisites, instructors must work together to build bridges between courses regardless of the discipline(s) they are affiliated with or department they belong to. Instructors of advanced courses can no more dictate what is taught in introductory ones than vice versa; and ignorance of students' prior academic experiences or future course expectations is helping no one. One way to overcome these conceptual disconnects would be to collaboratively describe a set of learning expectations across a common sequence of courses taken by a large proportion of students. While interdisciplinary collaborations such as these may be perceived as a rather large undertaking, there is assistance to be found in the literature that can not only provide a starting point for such conversations (American Association for the Advancement of Science, 2011; Loertscher, Green, Lewis, Lin, & Minderhout, 2014; NRC, 2012a) but also insight on how this work can be encouraged and sustained across time (Reinholz & Apkarian, 2018).

# CHAPTER 7: CONCLUSIONS, IMPLICATIONS, AND FUTURE WORK

This dissertation has explored the intersection of chemistry and biology through the eyes of undergraduate students co-enrolled in disciplinary courses. Focusing on two crosscutting concepts, energy and the relationship between structure, properties, and function (NRC, 2012a), I interviewed fifteen students about how they perceived their introductory chemistry and biology courses as being connected (or not). One of these students, Laura (a member of Cohort 1, which consisted of 22 students; discussed in Chapters 3 and 6) participated in four interviews across three years as she progressed from general chemistry and honors introductory biology to move advanced coursework culminating in a two-semester biochemistry course sequence. Using crosscutting concepts as a conceptual framework for this analysis has provided the opportunity to investigate student experiences and their perceived understanding of underlying, thematic concepts in varied disciplinary contexts.

## Energy: A difficult concept without a clear, cross-disciplinary perspective

The many difficulties associated with understanding energy has been well described across disciplines (Becker & Cooper, 2014; Chabalengula *et al.*, 2012; Cooper & Klymkowsky, 2013b; Nordine, 2015). Even the most knowledgeable experts (e.g. Richard Feynman; 1977) recognize the complexity of the concept. As such, it is no surprise that introductory life sciences and preprofessional majors described in Chapter 4 had difficulty describing the mechanistic importance of energy in complex, biological systems. Interestingly, these students were considerably more confident in their understanding of energy in chemical systems. Most students were able to discuss foundational concepts such as potential energy (11 of 14), the canonical relationship between energy and bond breaking/formation (12 of 14), and collisions as the mechanism of kinetic energy transfer (10 of 14) in the context of chemistry. However, these same concepts were more not well connected to students' understanding of biology. Only two students mentioned potential energy as it relates to biological systems. Five students believed their chemistry and biology courses provided conflicting information regarding whether energy is required to break a bond or if it is released. And students expressed varied opinions regarding the relevance of collisions in biological systems. It is important to recognize that chemistry and biology courses are likely to have different disciplinary perspectives and learning goals for their students. However, in the context of this study, the introductory courses share a common goal that is, to facilitate students in developing a coherent and constructive understanding of energy across contexts. And yet, students were neither sufficiently prepared nor supported by their chemistry and biology experiences to meaningfully discuss the kinetic and potential energy transfer mechanisms their courses valued (i.e., through collisions and reaction coupling, respectively). For those students who do not go on to more advanced courses, this is especially problematic. Not only have we potentially left them with misconceptions regarding energy, a concept with tremendous societal significance, but we may have given them the impression that the disciplines of chemistry and biology are in conflict.

The situation is further compounded by Laura's diminishing ability to discuss energy as she became more removed from her introductory courses, suggesting that even those with a strong conceptual understanding can regress without sufficient opportunities to apply their understanding. Laura appears to be an insightful and attentive student who valued conceptual understanding over memorization. After taking general chemistry and honors introductory biology, she described energy as a central and crosscutting concept. She believed she could use her knowledge of energy to predict and explain, and to make connections both within and across her courses. However, after her second year, Laura was barely aware of how she could connect energy to her courses and stated, "I'm kind of blurry on what you even mean by energy." Within the context of biochemistry, Laura largely discussed energy while justifying the importance of cellular regulatory processes. Throughout these later interviews, Laura recognized that her ability to make connections and consider energy in chemistry and biology had changed. As she said in interview 4, "I feel like in the moment I really understood it, but now I don't really remember it because we don't really talk about it as in depth, so I feel like I kind of forgot to remember it.” Unfortunately, Laura represents what can happen when students do not continually engage in the consideration and application of their knowledge.

These interviews paint quite a depressing picture of students’ ability to discuss energy and make connections within and between their courses. However, it is important to realize that this is a notoriously challenging concept, even for those with more disciplinary expertise than undergraduate students (Gonzales, 2011). To address energy from a coherent, holistic scientific perspective, instructors must be able to recognize their own disciplinary assumptions and expectations as well as those of others. For example, biologists work with complex systems and it may not always be realistic to attend to the energy changes associated with the breaking and forming of bonds within a series of metabolic reactions. However, if biology instructors are aware that students perceive a conflict between their courses regarding those energy changes, they may better appreciate the nuances and implications of how they present and apply energy in their own course. Similarly, many chemistry instructors spend considerable time discussing systems that have little use for the many life sciences and pre-professional students they teach (e.g. ideal gases, standard conditions). Neither chemistry nor biology instructors should feel alone in remediating these problems. In fact, such work is much more likely to be successful when done in collaboration. Not only can instructors use each other as a resource for broadening their own understanding of energy in more varied systems, but they can also work together to establish common objectives and assessments.

## Structure, properties, and function: A relationship with potential

In the disciplines of chemistry and biology, the relationship between structure, properties, and function is often referenced but rarely with an explicit connection made among all three concepts. In biology, discussions tend towards structure-function relationships (American Association for the Advancement of Science, 2011; College Board, 2015). In chemistry, the emphasis is on the relationship between structure and properties (College Board, 2014; Cooper *et al.*, 2017). And yet, these three concepts are clearly interconnected (NRC, 2012a). However, if courses do not present these concepts in a unified and crosscutting way, I wanted to explore how students would perceive the connections between them.

As discussed in Chapter 5, students co-enrolled in introductory chemistry and biology courses acknowledge variations in how their courses presented structure, properties, and function. Most considered structure-property relationships to be an implicit and integrated part of their chemistry courses while they felt that their biology course explicitly emphasized structure-function. Additionally, only three students appeared to have a productive conception of function in the context of chemistry. Notably, most of these students converged on a relationship between these concepts, stating that structure determines properties, which determine function, without any curricular supports to facilitate this synthesis. Laura too described this relationship, and even under less conducive circumstances. During her first interview, using the original protocol, structure-property and structure-function were introduced as established relationships and potentially two ways to refer to the same idea. And yet, Laura immediately identified properties and function as distinct but related concepts. She continued to recognize this relationship in her advanced courses though she considered that her ability to do so may have been a result of her prior experiences.

Students were considerably more successful making connections between their chemistry and biology courses regarding the SPF relationship as opposed to energy. However, there were those who could have benefited from a more consistent and coherent discussion of these relationships across their courses (e.g., Serina, Joseph, and Evelyn). Such discussions could also expand students' ability to use the SPF relationship as a framework for thinking through and making predictions about complex and unfamiliar phenomena (as suggested by Shelly, Joseph, and Ruth, among others).

**Two crosscutting concepts, dissimilar results**

The stark difference between students' ability to synthesize and connect their understanding of the SPF relationship across their chemistry and biology courses and their difficulty in doing so when discussing energy begs the question, what is it about these crosscutting concepts and their presentation in science courses that facilitate or hinder students? One contributing factor may be associated with the abstract nature of energy as a concept, and the scientific language used to describe it (Nordine, 2015). No matter the disciplinary perspective, energy can only be understood through its impact on a system. It cannot be experienced or measured directly. As such, energy has been traditionally conceptualized in disciplinary specific ways that are not always simple to reconcile. In comparison, structure, properties, and function are components of a categorizing and connection-building framework that relies on familiar, colloquial terminology. The students in this study interpreted structure and properties similarly, regardless of the disciplinary context; and the definitions and examples provided were not reliant on scientific expertise. For example, structure was described by Priyah as "how something is set-up and what it's made of" and Lida referred to properties as "adjectives to describe the structure." While the term function was not as consistently understood by students across disciplinary contexts, this may have been less than problematic due to a second possible contributing factor.

Whereas discussions of energy were largely distinctive, a shared understanding of both structure and properties was implied across both courses. In introductory biology, many energy concepts were discussed during the first few lectures as a review of relevant chemistry concepts. However, for most of the semester, energy was more generally discussed or referenced briefly. In general chemistry, ATP and reaction coupling (arguably the most recognizable, biologically-focused energy topics) were only discussed in the last few weeks of the two-semester course sequence. So, while students noted that energy was relevant in both courses, they did not have much practice applying fundamental concepts in both contexts. In comparison, chemical structures and properties were discussed in both introductory courses. Students learned how to draw Lewis structures, determine polarity, and consider forces and interactions between molecules in their general chemistry course. This information was explicitly referred to and directly applied in introductory biology when discussing content such as protein folding and the cellular membrane. Further, this understanding was used to consider structure-function problems. And so, students attributed the differences between how their courses presented the SPF relationship as a matter of emphasis. To this point, it is important to consider that both instructors expressed a longer history of attention to how they teach the SPF relationship in their courses, whereas consideration of instruction on energy was more recent.

## Impacts of the curriculum

It is impossible to discuss the findings presented in this dissertation without considering the impact of the learning environments these students experienced. Neither of the courses in which students were enrolled were what might be called “traditional” either in their approach to content or their pedagogy. Both courses were part of a multidisciplinary transformation effort where the instructors for general chemistry (GC1/GC2) and the introductory biology course (B1) valued the crosscutting concepts (as a component of three-dimensional learning; NRC, 2012a). As a part of the larger research project, these instructors regularly engaged in conversations that required some degree of understanding and reconciliation among disciplinary perspectives as they considered what counts as evidence of three-dimensional learning in assessment (Cooper *et al.*, 2015). Further, their engagement in this project is indicative of a shared vision for education aligned with the *Framework*. Additionally, the general chemistry curriculum was designed from the ground-up, and has been iteratively refined since, to facilitate students in the building of a well-connected framework around four big ideas (including energy and structure-property relationships) and supported by research (Becker & Cooper, 2014; Cooper *et al.*, 2013; Cooper & Klymkowsky, 2013a; Cooper, Klymkowsky, *et al.*, 2014; Underwood *et al.*, 2016; Williams, Underwood, Klymkowsky, & Cooper, 2015). Though at an earlier stage in its transformation, the introductory biology course also aimed to take a big ideas approach, emphasizing *(Matter and) Energy* and *Structure Determines Function* as two of the seven core biology concepts. By describing a course in terms of big ideas (or disciplinary core ideas) instruction can be focused on facilitating students in developing increasingly sophisticated understanding of a limited number of essential concepts that can be broadly applied across disciplinary topics (American Association for the Advancement of Science, 2011; Cooper *et al.*, 2017; NRC, 2012a). These factors suggest that, while I have described both successes and failures, the conclusions drawn regarding students' ability to make cross-disciplinary connections the findings here almost certainly represent a "best case scenario" compared to what might be found under more traditional circumstances.

## Future work

My research has focused on students' perspectives of their academic experiences. Through interviews, I explored the connections they perceived among their courses across disciplines, and in Laura's case, across time. I believe these findings can be used to promote stronger connection-making through more explicit discussion of kinetic and potential energy transfer, and the relationship between structure, properties, and function, in both chemistry and biology courses. Furthermore, common and parallel assessments can be used to characterize students' ability to apply these crosscutting concepts in context.

### Structure, properties, and function

The SPF relationship has the potential to be applied as a framework for making cross-disciplinary connections, considering unfamiliar phenomena, making predictions, and constructing explanations (NRC, 2012a). The introductory chemistry and biology courses at MSU already emphasize portions of this relationship, discussing structure-property and structure-function relationships, respectively. And, while many of the students interviewed were able to synthesize these relationships, converging on the understanding that structure determines properties, which determine function, there were those who could have benefited from more instructional support. By discussing structure, properties, *and* function in both introductory courses, I believe that we can facilitate students in the development of a more sophisticated understanding of the SPF relationship and apply it across contexts.

While students described structure and properties similarly in the context of chemistry and biology, function was not as universally conceptualized. Similarly, while function has been defined as the purpose, role, or outcome of a system or system component, each of these definitions has implications for how function might be interpreted by students; and it is not clear what effect they have on students understanding of structure-function relationships. Furthermore, function is also used in the context of design to an objective towards which a scientist or engineering is working through the manipulation of a structure and therefore, its properties. However, in the discussion and observation of natural systems, it would be inappropriate to imply that function is the purposeful result of some agent. General chemistry is a large-enrollment, service course required for many major programs, including those in the life sciences and engineering. Therefore, understanding varied disciplinary perspectives on function and their similarities, differences, and potential implications would be valuable for designing instruction and assessment on the SPF relationship.

To explore this, I propose that faculty who teach undergraduate courses in biology, engineering, and chemistry be interviewed, as they can not only speak to their disciplinary expertise but also to their instructional choices. I would ask them to describe function as they would to a student in their course; and then have them compare that to how function is used in examples that are provided representing other contexts (e.g. from both a natural and a design perspective, and at different scales). One goal of these interviews would be to have each faculty member establish a generalizable definition of function as it pertains to their course while also considering its limitations in other contexts. This information could then be used to inform the explicit discussion of function in chemistry and the creation of assessments that promote a coherent understanding of the SPF relationship across disciplines.

**Designing assessments** There are numerous opportunities to extend the discussion of structure-property relationships in the CLUE general chemistry curriculum to include function. For example, in Chapter 3, graphite and diamond are compared to illustrate the dependence of macroscopic properties on atomic-molecular structure. Despite being made up entirely of carbon, the characteristics of these materials vary drastically. These discussions could be further contextualized by including functional applications of the materials (e.g. the use of diamond tipped drill bits or graphite in pencil lead when discussing variations in hardness). Furthermore, an activity could be created engaging students in the engineering practice of designing a solution (NRC, 2012a). Students could be provided with an objective function and asked to describe what properties the material should have. They could then be asked to consider what this might mean about the molecular-level structure of the material. The CLUE curriculum discusses the structure-property relationships of other materials and products such as metals and metal alloys, and the odor eliminator Febreze. These examples could be reframed to strengthen connection making to function from a design perspective and to discuss the role of chemists and engineers in that design.

Similarly, to illustrate the connections between chemistry and biology, the current progression of concepts bridging structure and properties in CLUE can be harnessed (Cooper, Underwood, Hilley, *et al.*, 2012). Students begin to learn about forces and interactions early in the course and are taught how to interpret two-dimensional Lewis structures to determine the three-dimensional shape and overall polarity of molecules. In combination, this knowledge can be used to consider the lipid bilayer, protein folding and binding, and other biological phenomena. I believe a series of complementary activities given in both general chemistry and introductory biology could help to reinforce such connections. The assessments would be paired to explore the structure-property-function relationship of a phenomena from both perspectives. For example, an activity given in general chemistry would be tailored to the learning goals of the course and students' prior knowledge, while still providing information and asking students to make inferences about biological function; a complementary activity administered in introductory biology would be scaffolded around the same phenomena but with different expectations for student responses. As with any assessment I suggest, these activities would need to be designed in collaboration between biology and chemistry faculty and should be subjected to a revision and analysis cycle. It is no easy task to scaffold an activity that is both accessible and challenging, using prompts that are sufficiently explicit without leading the student.

**Mechanisms of energy transfer**

I would suggest a similar approach to exploring student understanding of potential and kinetic energy transfer in the context of actual phenomena within their courses. However, given the difficulty students (and instructors) have understanding energy, let alone connecting energy concepts across the disciplines, designing accessible assessments would require extensive cross-disciplinary discussions. Ultimately, I envision two sets of common or parallel activities that could be given in general chemistry, introductory biology, and biochemistry. One line of inquiry would focus on students understanding of potential energy transfer via reaction coupling and ATP. A second investigation could explore kinetic energy transfer via collisions. Given the difficulty of this topic, it may be valuable to start by interviewing biochemistry faculty regarding how they would explain these two types of energy transfer and the expectations they have for their students. This would inform assessment design and provide an understanding of what a sophisticated response would look like.

**APPENDICES**

**APPENDIX A: Interview protocol for Cohort 1**

Prompts that were removed in the revised protocol are in red and those that were edited are in blue. These changes are described in detail in Chapter 3.

<u>Background</u>

1. Tell me about your college experiences thus far. How is it going?
    a. Major, future plans
    b. Science courses in HS

<u>Reflection on Individual Courses</u>

To start out, we are going to talk about your chemistry and biology courses individually.

*Chemistry – repeated for each chemistry course taken in the past year*

Thinking first about your general chemistry course(s). (General Chemistry 1 & 2 were discussed together if the student had taken both courses)

2. Tell me about your experience taking general chemistry in college.
    a. Are you enjoying it? Are you finding it worthwhile? How does it compare to your high school experience (or previous times taking chemistry if applicable)?
3. Take a few minutes and brainstorm a list of some of the things you learned in general chemistry this past year (including General Chemistry 1 & 2).
    a. Could you briefly tell me about the things on your list?
        i. Follow up on ideas which are vague or confusing (the goal here isn't to learn everything they know about a topic, but to understand what they have listed).
        ii. How do you see these ideas as related?
        iii. Would you group any of these together into bigger categories?
            1. What would you call these bigger categories?

b. Thinking about your general chemistry course as a whole, what do you think some of the big ideas or take-home messages were?
    i. Why would you consider these big ideas?
c. Are there some ideas that you keep coming back to throughout the course?
    i. What about _____? Was this concept discussed regularly or more infrequently?

*Biology – repeated for each biology course taken in the past year*

Now let's talk about your cell and molecular biology class (this is the students first biology course).

4. Tell me about your experience taking biology in college.
    a. Are you enjoying it? Are you finding it worthwhile? How does it compare to your high school experience?
5. Take a few minutes and brainstorm a list of some of things you learned in this biology course similar to the process you did before.
    a. Could you briefly tell me about the things on your list?
        i. Follow up on ideas which are vague or confusing (the goal here isn't to learn everything they know about a topic, but to understand what they have listed).
        ii. How do you see these ideas as related?
        iii. Would you group any of these into bigger categories?
            1. What would you call these bigger categories?
    b. Thinking about the course as a whole this semester, what do you think some of the big ideas or take-home messages were?
        i. Why would you consider these big ideas?
    c. Are there some ideas that you keep coming back to throughout the course?
        i. What about _____? Was this concept discussed regularly or more infrequently?

Connections and/or Contradictions Between the Courses

Now let's talk about your experience taking both biology and chemistry.

6. What has that been like for you?
    a. Could you compare your experiences?
7. Can you describe the ways in which you see your chemistry and biology courses as being connected?
8. Are there any ideas or topics that you covered in biology or chemistry that you find difficult to connect to what you have learned in your other class?
9. Tell me about any ideas or topics that you covered in your chemistry class(s) that you found useful in thinking about biology?
    a. How did you find that helpful (or unhelpful if they state negative attitude)?
10. How about ideas or topics that you covered in your biology class that you found useful in thinking about your general chemistry course?
    a. How did you find that helpful (or unhelpful if they state negative attitude)?
11. How do you see the ideas or topics as overlapping between your biology and chemistry courses?
12. Are there places where you think there's a mismatch between what you are leaving in biology versus chemistry?
    a. Any concepts that were presented in conflicting ways?

Crosscutting Concepts

Sometimes scientists talk about themes that connect chemistry and biology.

13. What do you think some of those themes might be? (If necessary, rephrase using "same idea discussed in different ways" or "crosscutting concepts")

a. How was _____ talked about in [chemistry/biology]?

b. In what ways do your two classes treat ______ similarly?

c. How do they talk about ______ differently?

*Energy*

14. Many people consider energy to be a theme that spans chemistry and biology.

    a. Why do you think that is?

    b. Tell me about some of the ways you talk about energy in [chemistry/biology]?

    c. Describe for me how energy relates to some of the topics you have discussed in [chemistry/biology]?

    d. Can you describe some instances where you think there was overlap in how energy was discussed in your chemistry and biology courses?

    e. Can you describe some instances when energy was discussed differently in your chemistry and biology courses?

*Structure-Function and Structure-Property Relationships*[6]

15. The relationship between a structure and its function is also considered to be a theme.

    a. What do you think of when I say that?

        i. (if they respond positively) Tell me about how you think about the relationship between structure and function in [chemistry/biology]?

    b. What if I referred to this as the relationship between a structure and its properties? What does that make you think of?

        i. (if they respond positively) Tell me about how you think about the relationship between structure and properties in [chemistry/biology]?

[6] The structure, properties, and function section was completely reframed to introduce these concepts together as opposed to in specifying predefined relationships.

Students who responded positively to both function and properties were asked the following questions.

c. How do you think about the meaning of function versus properties?

d. When you think about your chemistry and biology courses, do you consider either of these phrases, “structure and function” or “structure and properties”, to be more fitting?

Before asking the following questions, the interviewer established which phrasing the student preferred and used this language moving forward. In some cases, this meant saying both “structure and function” and “structure and properties”.

e. Can you describe some instances where you think there was overlap in how the relationship between structure and _____ was discussed in your chemistry and biology courses?

f. Can you describe some instances in which the relationship between structure and _____ was discussed differently in your chemistry and biology courses?

<u>Chemistry as a Prerequisite for Biology</u>

16. Many colleges require that students take some chemistry as a prerequisite for biology.
    a. Why do you think this is the case?
    b. In your opinion, should general chemistry be a pre-requisite for biology?
        i. Why do you say that?
    c. Are there any chemistry ideas that you think are necessary to understand biology?
        i. Why do you think those ideas are necessary?

Scientific Practices

*Course Activities*

So now we are going to talk to you about some of things that you do in your courses.

17. Tell me about the types of things that you are asked to do in your [chemistry/biology] class.
    a. How do you approach those types of questions?
    b. Inquire about exams, homework, and in-class activities as necessary.

*Activities of Practicing Scientists*

In this last section, we are going to start off talking about chemists and biologists, just scientists in general.

18. Tell me about some of the things that you think [chemists/biologists] do on a daily basis.
    a. Follow up on any activities that resemble the scientific practices from the *Framework*
19. Let's talk about experimentation.
    a. Why do you think scientists run experiments?
    b. Tell me about some of the processes involved in running experiments?
        i. Do you see any of these processes as being common among different types of scientists?
        ii. In your lecture courses, have you ever been involved in similar processes?
            1. Follow up if either course was not discussed.

*Constructing Explanations*

20. Chemists and biologists often use evidence to explain observations.
    a. What does this mean to you?
    b. Can you give an example from your [chemistry/biology] course where you used evidence to explain an observation or phenomena?

c. Rephrased as necessary:

    i. using data to explain what we see

    ii. pieces of information to support an explanation

d. In your examples from chemistry and biology, were there similarities in how you would use explanation?

e. Were there differences in how you would use explanation in your chemistry and biology courses?

*Using Models*

21. Chemists and biologists will also use pictures to help predict and explain phenomena.

    a. What does this mean to you?

    b. Can you give any examples from your [chemistry/biology] course where you used a picture to help you predict or explain phenomena?

    c. Rephrased as necessary using representations, graphs, diagrams, or models

    d. In your examples from chemistry and biology, were there similarities in how you used _____ to predict or explain?

    e. Were there differences in how you used ______ to predict or explain in your chemistry and biology courses?

## APPENDIX B: Revised interview protocol for Cohort 2

<u>Background</u>

1. Tell me about your college experiences thus far. How is it going?
    a. Major, future plans
    b. Science courses in HS

<u>Reflection on Individual Courses</u>

To start out, we are going to talk about your chemistry and biology courses individually.

*General Chemistry 1 & 2*

Thinking first about your general chemistry course. (Verify that they were in CLUE last semester).

Let's talk about the course as a whole (i.e. both General Chemistry 1 & 2).

2. Tell me about your experience taking general chemistry in college so far.
    a. Are you enjoying it? Are you finding it worthwhile? How does it compare to your high school experience (or previous times taking chemistry if applicable)?
3. Take a few minutes and brainstorm a list of some of the things you learned in general chemistry this past year (including General Chemistry 1 & 2).
    a. Could you briefly tell me about the things on your list?
        i. Follow up on ideas which are vague or confusing (the goal here isn't to learn everything they know about a topic, but to understand what they have listed).
        ii. Check that the list covers both semesters of general chemistry (if students only list material for second semester then ask them to be sure to include both semesters).
    b. Thinking about your general chemistry course as a whole, what do you think some of the big ideas or take-home messages were?
        i. Why would you consider these big ideas?

*Cell and Molecular Biology Course*

Now let's talk about your cell and molecular biology class (this is the students first biology course).

4. Tell me about your experience taking college biology this semester.
    a. Are you enjoying it? Are you finding it worthwhile? How does it compare to your high school experience?
5. Take a few minutes and brainstorm a list of some of things you learned in this biology course similar to the process you did before.
    a. Could you briefly tell me about the things on your list?
        i. Follow up on ideas which are vague or confusing (the goal here isn't to learn everything they know about a topic, but to understand what they have listed).
    b. Thinking about the course as a whole this semester, what do you think some of the big ideas or take-home messages were?
        i. Why would you consider these big ideas?

<u>Connections and/or Contradictions Between the Courses</u>

Now let's talk about your experience taking both biology and general chemistry.

6. What has that been like for you taking both of these courses? (students are taking Cell and Molecular Biology the same semester as General Chemistry 2)
    a. Did you find taking them at the same time beneficial in any way?
7. Can you describe the ways in which you see your chemistry and biology courses as being connected?
8. Were there any ideas or topics that you covered in your general chemistry class that you found useful in thinking about your biology course?
    a. How did you find that helpful (or unhelpful if they state negative attitude)?

b. When you are sitting in your biology course, how often would you say you think back to your general chemistry course?

9. How about ideas or topics that you covered in your biology class that you found useful in thinking about your general chemistry course?
    a. How did you find that helpful (or unhelpful if they state negative attitude)?
    b. When you are sitting in your general chemistry course, how often would you say you think back to your biology course?
10. Many colleges require that students take some chemistry as a prerequisite for biology.
    a. Why do you think this is the case?
    b. In your opinion, should general chemistry be a pre-requisite for biology?
        i. Why do you say that?
    c. Are there any chemistry ideas that you think are necessary to understand biology?
        i. Why do you think those ideas are necessary?
11. Thinking again about your experience in both general chemistry and biology, have there been times where you felt confused about how a concept was discussed in one course compared to the other?
    a. How did you come to notice that?
    b. How did that affect your experience?
    c. Do you feel that it was detrimental in anyway?
    d. How have you dealt with that?
12. Are there places where you think that information from one course has conflicted or contradicted with something you learned in the other course?
    a. How did you come to notice that?
    b. How did that affect your experience?

c. Do you feel that it was detrimental in anyway?

d. How have you dealt with that?

<u>Crosscutting Concepts</u>

Sometimes we think about concepts or themes that span both chemistry and biology; ideas that connect them.

13. Do you have any ideas about what some of those themes might be?
    a. Can you explain why you would consider that a theme?
    b. Do you think that understanding that idea has helped your understanding chemistry/biology]?

*Energy*

14. Many people consider energy to be a theme that spans chemistry and biology.
    a. Why do you think this might be?
    b. In what ways have you talked about energy in your general chemistry course?
    c. In what ways have you talked about energy in your biology course?

Two concepts were discussed in more detail, energy transfer and the conservation of energy. Energy transfer was introduced first, unless discussion of conservation of energy was initiated by the student. The following questions were asked about both concepts.

15. Let's discuss the concept of [energy transfer/conservation of energy – insert where appropriate below].
    a. What does this concept make you think of?
    b. How does this concept relate to the topics you discussed in [chemistry/biology]?
    c. Do you think that this concept was emphasized in either of your courses?

i. (If only one course is mentioned) What about your other course?

ii. (if no for either course) Do you think that it should have been covered in your courses?

d. Do you think that this concept is important for understanding other ideas in [chemistry/biology]?

16. If students discussed energy transfer and conservation of energy together at any point:

    a. How would you describe these two ideas as being related?

Thinking more generally about energy as a theme that spans chemistry and biology

17. Do you think that your understanding of energy was more important for one course over the other or equally important for both?
18. Do you think that most of what you learned about energy came from one particular course or did they work together to improve your understanding?
19. Were you able to use what you learned about energy in one course to help understand your other course?

*Relationship between Structure, Properties, and Function*

Another theme that people might consider important for both chemistry and biology consists of three ideas: structure, properties, and function. (write the terms out on the *Livescribe* paper)

20. What do you think of when I say the term structure?
    a. properties?
    b. function?
21. Can you describe how you see these ideas as being related to each other?
22. How do you think about these concepts with respect to [chemistry/biology]?
    a. Have you used all three ideas in [chemistry/biology]?

b. For [chemistry/biology], would you order these ideas into a progression of any sort?

23. Why would do you think the relationship between these ideas would be considered a theme that spans both chemistry and biology?
    a. Do you think that these ideas and their relationship were emphasized in either of your courses?
        i. (if no) Do you think that it should have been?
        ii. What about the other course? (student directed which course was discussed first)
        iii. Do you feel they were emphasized to an equal extent?
    b. Do you think that your understanding of the relationship between these ideas came more from one course over the other or did they work together to improve your understanding?
    c. Do you think that understanding of the relationship between these ideas was more important for one course over the other or equally important for both?
    d. Can you think of any times when you used a progression of these ideas in your chemistry/biology course?
    e. Were you able to use what you learned about this progression in one course to help understand your other course?
        i. What about the other direction (chemistry to biology / biology to chemistry)?
    f. Has anyone ever talked to you about this these ideas and their relationship before?
    g. Have you ever thought about the connection between these ideas explicitly before?

## APPENDIX C: A third approach: The common discussion of potential and kinetic energy transfer

The transfer of kinetic energy via collisions is an essential component to the initiation of energy transfer, providing the activation energy for reactions, and for controlling the formation of molecular complexes (e.g. the dissociation of an enzyme-product complex or the DNA-protein interactions involved in gene expression). However, it is insufficient to explain how energy is transferred from one reaction to another, either in chemical or biological systems. Disciplinary experts acknowledge the fundamental importance of reaction coupling, but it is uncommon for introductory science courses to provide an explanation of the underlying mechanism. This may be due to the difficulty in constructing an explanation that is both appropriate and satisfactory for students, and that is feasible for instructors to tackle given the constraints of their courses. The disconnect between chemistry and biology on the subjects of molecular collisions and reaction coupling undermines students' abilities to use these concepts to construct complementary explanations of biological systems.

Consider first the explanatory value of collisions to biological systems. Most instances of energy transfer originate with a collision. It is only through the direct interaction of molecules (perpetually in motion) that changes between or within systems can occur. Therefore, it is difficult to think critically about what is happening at the molecular level without understanding the stochastic nature of collisions. The cellular environment is incredibly crowded resulting in the frequent collisions of molecules; some of these collisions will lead to reactions, while others will not. It is difficult to reconcile this basic fact with how Clarice and Aaron described the metabolic cycles. To believe that energy flows "down the chain of events" implies a superficial understanding of systems that could provide little support for considering how changes in the concentrations of the various reactants involved may alter such processes. It certainly makes it difficult to understand how reaction systems can run in reverse (e.g. in the case of gradient driven ATP synthesis and ATP hydrolysis driven gradient formation), particularly in an age where new techniques are revealing the stochastic behaviors of single cell systems that are relevant to a range of biological processes (Symmons & Raj, 2016). For example, phenotype variation between genetically identical organisms arises through stochastic variation and impacts resistance to drugs and survival (ibid). By incorporating collisions into the descriptions of chemical and biological systems in our courses, we can provide a more realistic picture of what is occurring at the molecular level.

While reaction coupling is more commonly referenced than collisions in introductory biology courses, it is difficult to provide a coherent explanation of the process that is accessible to both students and instructors. While there are approaches being developed that do emphasize reaction coupling, there are currently no assessment data to show how students respond to this approach (Klymkowsky, 2010; Klymkowsky *et al.*, 2016). Typically, little more than a definition is provided in biology courses. And in chemistry courses, reaction coupling is usually discussed (if at all) in the context of Hess's Law - typically shown as a simple algebraic addition of two (often seemingly unrelated) reactions rather than a mechanistic explanation. Though some may argue that this is sufficient for chemistry, our work shows that this has left some students feeling dissatisfied with their understanding. If we want students to understand how reactions can be coupled to drive thermodynamically unfavorable processes, we need to negotiate what an appropriate explanation in both disciplines would look like, what it contains and explicitly acknowledges.

Ideally, we might want students to explain that energy transfer mediated by ATP actually involves the transfer of a phosphate group from ATP to the reactant. This results in a 'common intermediate' which is more reactive than the unphosphorylated reactant. Therefore, less energy must be supplied by collisions for the next step, in which *the intermediate* undergoes the following reaction. These ideas quickly become complicated when put in the context of a complex series of reactions such as those in glycolysis. And so, if we want students to develop a foundational understanding of the molecular level mechanism upon which to build, it is necessary to begin with a simple example

(Appendix D). It is not our intention to suggest that biology majors should be required to develop expertise in the field of chemistry or even that all biology majors require the same understanding of chemistry. However, given the numerous education reform efforts that highlight the importance of energy in both chemistry and biology (American Association for the Advancement of Science, 2011; College Board, 2014, 2015; NRC, 2012a; Tansey *et al.*, 2013), we would argue that this is a topic that should be given particular attention.

Whatever the approach used to improve the ways that students can connect energy ideas across disciplines, the question is, how much of this can we expect students in introductory courses to understand and whose responsibility is it to address this material? Can we expect biology faculty who teach an already crowded curriculum (at least as delineated in common textbooks) to make room for a complex molecular explanation of reaction coupling? Conversely, do chemistry faculty make room in their courses for an explanation of reaction coupling that goes beyond a simple use of Hess's Law? To provide a foundation on which to build their understanding, we would propose using a collisions-based Le Chatelier explanation of reaction coupling from an equilibrium perspective (Appendix D). Our work shows that it is currently difficult for students to reconcile what they are presented with in introductory chemistry and biology courses in a way that leads them to a coherent (trans-disciplinary) understanding of why and how reactions are coupled. Simply implying that ATP 'is' energy leads to the erroneous idea that energy is released when the 'high energy' bonds of ATP are broken.

## APPENDIX D: An explanation of reaction coupling

The question of how energy is transferred through biological systems is fraught with problems. In biology courses, ATP is often referred to (at least implicitly) as some kind of energy currency – which is not incorrect – the more ATP units produced, the more energy is eventually available to drive unfavorable processes. However, as discussed in the main body of the paper, this idea can lead students to believe that ATP **is** energy, or that it contains energy in its bonds that is released when the bonds are broken. The question then, is how can we help students understand energy transfer in biological systems without the need for a Ph.D. in physics or chemistry?

If we want to help students understand the mechanism by which ATP can drive unfavorable reactions, we have to get across to students how these reactions are coupled by common intermediates. Often this fact is obscured by the presentation of energy transfer in both chemistry and biology. For example, in chemistry rather than emphasizing coupled reactions, most students are drilled in the use of Hess's law, where they are taught to add, multiply or subtract chemical equations as if they were algebraic equations to determine the overall energy change for a multistep reaction[7]. In biology, coupling is usually presented as the reaction of interest driven in some mysterious way by ATP hydrolysis, which is often represented as a separate reaction, rather than providing the common intermediate by which the reactions are linked.

In fact, ATP is NOT hydrolysed during any coupled reaction (hydrolysis literally means reaction with water). ATP reacts with one component of the reaction to form an intermediate, which then reacts with the other component to form the product. The important point is that there is a common intermediate (the phosphorylated reactant). While it is true that the overall effect is that ATP is hydrolysed ($ATP + H_2O \rightarrow ADP + Pi$), this is not the mechanism by which ATP coupled reactions occur.

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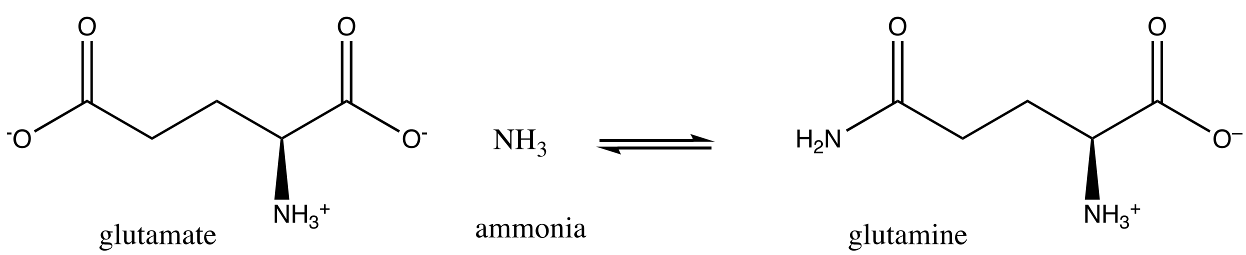
[7] A particularly pernicious example: https://en.wikipedia.org/wiki/Hess%27s_law

Since this idea is so difficult and so fraught with problematic understandings, we recommend that a relatively simple model system be used. A possible example (simplified here for clarity) is the reaction of glutamate acid to form glutamine (a model for any peptide bond formation) which is a thermodynamically unfavorable reaction $\Delta G > 0$. The equilibrium position for this reaction normally lies to the left. The question then is how and why does this reaction occur in biological systems?

**Figure A.1 Endergonic Reaction of Glutamate and Ammonia**

Glutamate + $NH_3$ ⇆ Glutamine $\Delta G > 0$

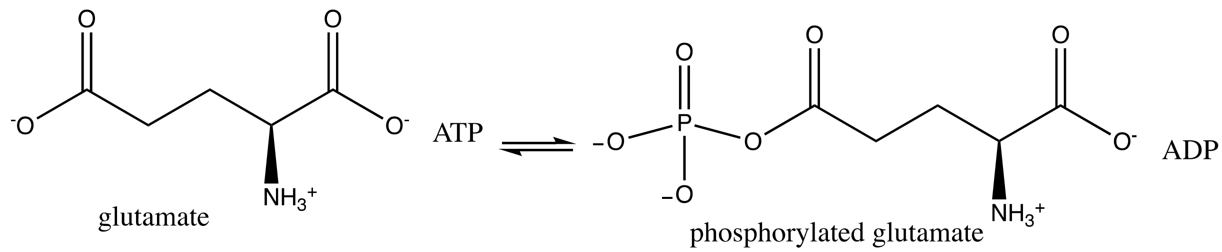



The answer to this can be understood in several ways: the first is the application of Le Chatelier's principle. Rather than directly reacting glutamate and ammonia, glutamate instead reacts with ATP. This reaction is exergonic (ATP is very reactive – it has high potential energy) and produces the phosphorylated glutamate – which is also very reactive. To describe this, we say that the glutamate is 'activated' through an ATP-based phosphorylation reaction to give phosphorylated glutamate. Now the reaction between glutamate phosphate and ammonia (producing glutamic acid) is thermodynamically favorable.

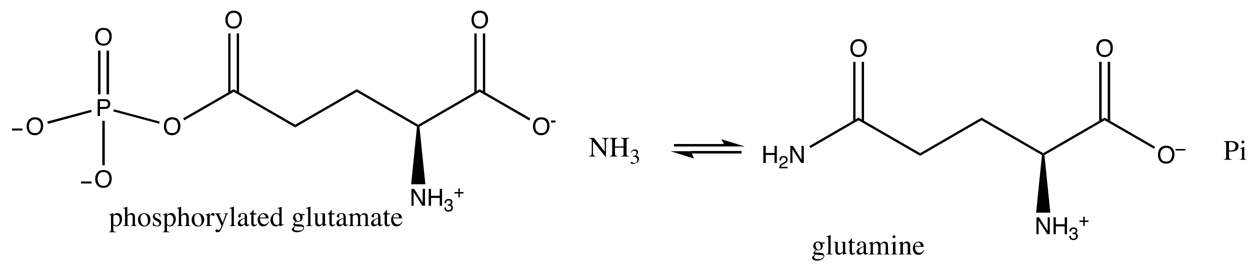
**Figure A.2 Activation of Glutamate with ATP**

Glutamate + ATP ⇆ Phosphorylated Glutamate + ADP $\Delta G < 0$

Phosphorylated Glutamate + $NH_3$ ⇆ Glutamic acid + P(phosphate) $\Delta G < 0$





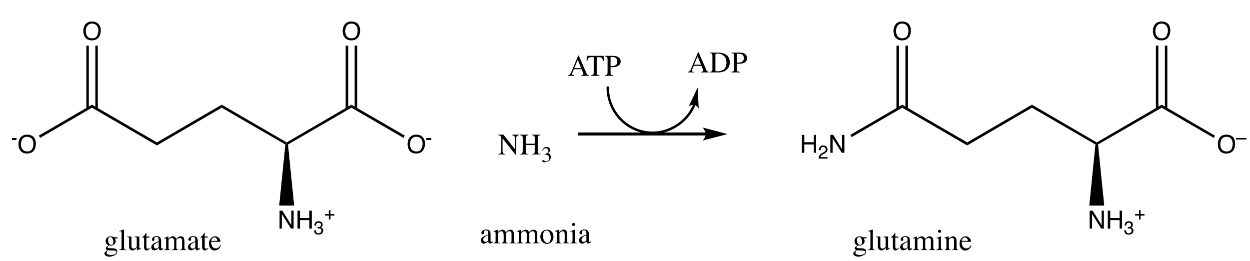




These two reactions are linked by a common intermediate, the phosphorylated glutamate, which as soon as it is formed is used up in the next reaction which disturbs the equilibrium from the first reaction and causes more phosphorylated glutamate to be formed. Recall, Le Chatelier's principle states that when a stress is applied to any reaction at equilibrium, the position of equilibrium shifts to counteract the stress.

During the reaction ATP does end up as ADP (+ phosphate), but it is an integral part of the reaction mechanism. As noted, in biology texts the reaction might be shown like this:

**Figure A.3 A Misleading Net Reaction**





While this is a perfectly reasonable shortcut, once students understand the coupling mechanism, it does give the impression that it is the separate hydrolysis (bond breaking) of the ATP that is driving the reaction.

Energy transfer mediated by ATP typically involves the transfer of a phosphate group from ATP to the reactant. This results in a 'common intermediate' which is more reactive than the unphosphorylated reactant, and which reacts to produce the final product. Note, at no time is ATP hydrolyzed by water. This example provides a simple model for presenting the role of ATP coupled reactions: by splitting the reaction into two parts (both of which are thermodynamically favorable), coupled by a common intermediate, such that the overall reaction becomes favorable.

A second way to consider this coupled reaction is without thinking about the mechanism. However, in this case, it is important to emphasize that it is the production of stronger (lower potential energy) bonds in ADP +Pi that releases energy, rather than breaking a bond in the ATP. After all, bond formation releases energy while bond breaking absorbs energy. The overall (net) energy change depends on the difference in bonding energy between the reactants and products. It is the production of more stable (lower potential energy) products that releases energy.

## APPENDIX E: Structure-property and structure-function relationships as described in curriculum reform documents

**Table A.1 Structure-property and structure-function relationships as described in curriculum reform documents**

<table>
<tr><th>Reference</th><th>Structure-Property</th><th>Structure-Function</th></tr>
<tr><td rowspan="2">AP Chemistry Curriculum Framework (College Board, 2015)</td><td>Big Idea 2 (p. 19)<br>Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules, and the forces between them.</td><td>Big Idea 2 - Essential Knowledge 2.B.3.e (p.27)<br>The structure and function of many biological systems depend on the strength and nature of the various Coulombic forces.</td></tr>
<tr><td colspan="2">Big Idea 5 - Essential Knowledge 5.D.3.b (p. 62)<br>The functionality and properties of molecules depend strongly on the shape of the molecule, which is largely dictated by noncovalent interactions.</td></tr>
<tr><td>AP Biology Curriculum Framework (College Board, 2015)</td><td>Big Idea 4 (p. 78) - Biological systems interact, and these systems and their interactions possess complex properties<br>Enduring Understanding 4.A: Interactions within biological systems lead to complex properties<br>Essential Knowledge 4.A.1: The subcomponents of biological molecules and their sequence determine the properties of that molecule.<br>Essential Knowledge 4.A.4: Organisms exhibit complex properties due to interactions between their constituent parts.</td><td>Big Idea 4<br><br>Enduring Understanding A<br>Essential Knowledge 4.A.2 (p. 82)<br>The structure and function of subcellular components, and their interactions, provide essential cellular processes.<br><br>Enduring Understanding B<br>Essential Knowledge 4.B.1 (p. 89)<br>Interaction between molecules affect their structure and function</td></tr>
</table>

**Table A.1 (cont'd)**

| | | |
|---|---|---|
| Tansey, Baird, Cox, Fox, Knight, Sears, & Bell (2013)<br><br>American Society for Biochemistry & Molecular Biology | | Essential Concept - Macromolecular Structure and Function (p. 294-5)<br><br>*Structure and Function are Related*<br>The function of a protein, nucleic acid, or other macromolecule is defined to a large extent by the specific molecular interactions it takes part in. Those interactions are in turn dictated by the structure of the macromolecule...<br><br>*Macromolecular Structures are Dynamic*<br>Macromolecular structures are not static. Conformational changes large and small are often critical to function…<br><br>*Some Macromolecules are Intrinsically Unstructured*<br>Segments of some proteins, and in a few cases entire proteins, are intrinsically unstructured…The lack of structure in solution may facilitate a function in which interactions must occur promiscuously with several other molecules, as documented for some proteins with a signaling function.<br><br>*Macromolecular Function is Subject to Regulation*<br>A wide variety of possible covalent modifications (e.g. partial proteolytic cleavage, intrachain and/or interchain disulfide formation, glycosylation, and phosphorylation) occur, and play a role in regulation, cellular targeting of the protein, or directly in the protein's function. |
| "Anchoring Concepts Content Map for General Chemistry" (Holme and Murphy, 2012) | Anchoring Concept - Structure & Function (p. 6)<br><br>Chemical compounds have geometric structures that influence their chemical and physical behaviors.<br><br>(A) Atoms combine to form new compounds that have new properties based on structural and electronic features.<br><br>(E) Three-dimensional structures may give rise to chirality, which can play an important role in observed chemical and physical properties<br><br>(F) Reactions of molecules can often be understood in terms of subsets of atoms, called functional groups.<br><br>(G) Periodic trends among elements can be used to organize the understanding of structure and function for related chemical compounds.<br><br>(H) Many solid state, extended systems exist, and geometric structures play an important role in understanding the properties of these systems. | |

**Table A.1 (cont'd)**

<table>
<tr><td rowspan="2">A Framework for K-12 Science Education (NRC, 2012)</td><td colspan="2">Crosscutting Concept - Structure & Function (p. 84)<br>The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.</td></tr>
<tr><td>Core Ideas PS1.A: Structure and Properties of Matter (p.104)</td><td>Core Ideas LS1.A: Structure and Function (p.143)</td></tr>
<tr><td>Vision & Change (AAAS, 2011)</td><td>Systems (p. 13)<br>A systems approach to biological phenomena focuses on emergent properties at all levels of organization, from molecules to ecosystems to social systems...Through these models, researchers seek to relate the dynamic interactions of components at one level of biological organization to the functional properties that emerge at higher organizational levels.</td><td>Core Concept - Structure & Function (p. 12)<br>Basic units of structure define the function of all living things. Structural complexity, together with the information it provides, is built upon combinations of subunits that drive increasingly diverse and dynamic physiological responses in living organisms. Fundamental structural units and molecular and cellular processes are conserved through evolution and yield the extraordinary diversity of biological systems seen today.</td></tr>
<tr><td>College Board Science Standards (2009)</td><td>Standard C.2 - Matter and Change (p. 123-4)<br>The properties of matter and the changes that matter undergoes result from its atomic–molecular level structure. For any chemical or physical change, matter is conserved.<br>C.2.2 Structure–Property Relationships - Students understand the relationship between molecular-level structure and chemical and physical properties.</td><td>Unifying Concept - Form & Function (p. 4)<br>[Quotes NSES 1996]</td></tr>
<tr><td>Engineering in K-12 Education: Understanding the Statue and Improving the Prospects (2009)</td><td>Engineering Concept in the category of systems - Emergent Properties (p.125)<br>Not all systems can be analyzed in terms of causal behaviors or a direct, linear sequence of events. Another framework for understanding systems is focusing on behaviors that emerge from dynamic interactions among system components. These emergent properties can be global, aggregate, or macrolevel behaviors that emerge from local, simple, or micro-level interactions between (or among) individual elements or components of a system.</td><td>Engineering Concept in the category of systems - Structure-Behavior-Function (SBF; p. 122)<br>SBF, a framework for representing a system, can be used to describe both natural and designed systems. SBF relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior).</td></tr>
</table>

**Table A.1 (cont'd)**

| | | |
|---|---|---|
| National Science Education Standards (1996) | Structure and Properties of Matter (p. 178) | Unifying Concept - Form & Function (p. 119)<br>Form and function are complementary aspects of objects, organisms, and systems in the natural and designed world. The form or shape of an object or system is frequently related to use, operation, or function. Function frequently relies on form. Understanding of form and function applies to different levels of organization. Students should be able to explain function by referring to form and explain form by referring to function. |

**APPENDIX F: Student responses when prompted to describe function in GC1/GC2**

Most (11 of 14) described function as more applicable in B1

Clarice: [Function is] I guess what each thing is supposed to be doing. I don't know. I can't really, relate it back to chem, not that I can think of right now. But like, bio I guess...the function of cellular respiration is to like get CO— or not make $CO_2$, but like, yeah, no, make $CO_2$. And like give off $CO_2$. Like that's the function of that cycle. Whereas I don't know I don't really think about it like that in chem.

Evelyn: Function, I automatically think of biology, like the different organelles and all their different functions that they have inside of a cell...I have a harder time applying function to chemistry… properties reminds me chemistry and then function reminds me of biology.

John: Uh, chemistry— with like the acid— with acid bases is pretty easy and how the— an acid's going to have the hydrogen that you can give up, on a very electronegative atom and how that's structured. I'll just draw HCl I guess...taking in the hydrogen to make up for, the lost electrons would be its property. And then the function would be, um, **just the acidicness**— I don't really know the function here...I guess you don't talk about the function as much because like you're not really talking about like what they're going to end up doing, I guess? As opposed to like bio where you talk about like what the function— like what it actually does.

Lida: In chemistry I would say we do a lot on the structure and properties. **For function, I guess that would be the actual reaction that produces something**. **But I don't know**, in chemistry I think it's harder for me to be like, 'Oh, this reacted with this to produce NaCl.'...I don't think of that as function, like what is this all doing? It's not doing anything...for bio I think it's a lot easier for me to incorporate that. Whereas function in chemistry, I don't know, I think it's easier for me to imagine structure and properties rather than function because I don't think there's a lot of chemicals that we're actually using to do something with.

Louanne: And I think I relate function more to like biology a little, definitely a little bit more than I do in chem. But then like structure and properties, I think I relate more to chem than bio...Function I would say a little bit more into biology, just because biology you're thinking more of how things like work to move on to the next step. Where in chemistry, I don't know— Like **I know we're like mixing chemicals and all that stuff. And I guess you could probably think of that as like a function**, but I would definitely put function more into biology than I would chem.

Natalie: Function is what something does specifically, so just what it does. What a certain molecule does or what a certain reaction does I guess, would be its function...I think that probably the thing we talked about least in chemistry is function. **Now that we're talking about reactions we're talking a little bit more about function, I would say**...I think biology has a lot more to do with function though than chemistry does. We talked a lot more about how these different things work in different living systems then you really do in chemistry. I think you're more focused on structure and properties there.

Priyah: [In GC1/GC2] I can see the structure and properties part but the function I kind of don't see, if that makes sense. I get how atoms interact and how that affects the property like if it's— like for metals, like if it's malleable or like hard or that. But then I don't know how that would relate to its function I guess...I think the structure, well like structure and function are more like biology and then the structure and properties are more chemistry I think...**for like metals conducting electricity and stuff. So that would be their function and— or would that be property?** I feel like these are kind of related— well they're all related but these kind of blur together. But they conduct electricity and that relates back to its structure with the electrons and how they can move freely and— **I guess the function would be how you could use the metals like wires** and stuff I guess.

Ruth: In chemistry, [function] makes me think of— (pause) not much. Maybe I think of like **compounds as drugs**, or something like that. Biology, I think of proteins functioning and I think of organelles and— But mainly proteins, I think a lot of proteins...it's weird for me with function for chemistry...I think the part where structure can change the properties was emphasized more [in GC1/GC2]. I didn't feel like there was much talk about function.

Serina: [In GC1/GC2] for structure I think of like drawing out the Lewis structure and drawing out reactions and what happens. Properties, knowing if like the properties of like a metal and a nonmetal and knowing those differences. I can't really think of function so much in chemistry, but definitely structure and properties...but I feel like I'm better able to relate these three words in biology than chemistry...I'm able to know in biology like how things do function versus in chemistry?

Shelly: For biology [function] would be like what they do and then for chemistry I would more of relate it to what— how they react with each other and what each part of the thing does I guess. Hard time putting it into words...for chemistry I would think structure and properties a little more...we haven't really talked about the functionality of it, just like what it does and like the, scientific reasons behind it. But we haven't really talked about like— aside from just the little bit of **pH and buffers in the human body, like that's where we're getting into a little more functionality,** but otherwise it's more of just like, the structure and how that relates to the properties with it.

Simon: When I think about function, yeah I guess I just think about how— It's job. Whatever it is, whether it's a molecule, **whether or not it will hydrolyze another molecule or whether or not it'll form a complex or whether or not this electronegative atom will interact with this non-electronegative atom**...I think if you define [function] as what happens, it's not going to really work for chemistry... [In GC1/GC2] For me, it should be properties to structure.

**Three students expressed no difficulty applying function to chemistry**

Aaron: So based on the structure and based on the properties, I see function as the combining of this and then you can determine what the function is or you can predict what the function is going to be. I think function is simply what comes of it. After you've determined the properties and analyzed the structure of something, function is what would naturally come of that, I guess. If that makes sense. If we're given a reaction and then I draw a Lewis diagram, then **I can see the function as a reduction— as a redox reaction versus acid-based reaction**. I look more at the properties in chemistry than I do anything else because I personally think that that's a bigger reason of why something is, which would be the function...**I think of the function as the answer**, I guess, as what I'm trying to get to.

Daniel: In biology we talk about how the structure determines the function by like, 'Oh, if an amino acid is polar then it can cross the lipid bilayer.' Maybe it's the other way around, but something like that maybe. And I guess in chemistry we talk about it as maybe polar and nonpolar structures, **how they interact** with other polar and nonpolar structures, stuff like that.

Joseph: [In GC1/GC2] A function, let's see. I have ideas. I just don't know how to word them, you know?...So properties like what kind of bonds are being formed between two atoms. So I don't know. Just anything, any different atom, what kind of bonds are being formed, and that will determine the kind of strength they'll need to overcome the bonds. That's actually a property, like the strength needed to overcome a bond, then the different structures. [00:57:01] So the different atoms combined to form different structures, then that structure will have a certain function.

## APPENDIX G: Overlap between structure and properties

Joseph describing...

> shape as structure: The shape of whatever we're talking about...When I think of structure, I automatically think of structure determines function.
>
> shape as properties: Let's see. Like what kind of characteristics everything has. Just size, I feel like is a big property. Size, shape, stuff like that.

Aaron describing…

> shape and size as structure: When I think of structure, the immediate thing I think of is a shape of some object, really basic. That's what I would think of. Then I would think of, how big size-wise. I guess that's the same thing as shape.
>
> types of bonds as properties: Like electronegativity, effective nuclear charge, if something is polar and nonpolar...If one molecule has bonded this way and another molecule has bonded this way, then those would have different properties maybe, or those are different. Those are the properties. This is covalently bonded; this is ionically bonded.

Clarice describing…

> shape as structure: Like a Lewis structure. Like— or like what shape like if it's going to— like tetrahedron or a trigonal planar. It makes me think of that...When I think of bio I think of like, 'Oh, DNA structure is double helix'

Shelly describing…

> shape as properties: Like what, the characteristics that come with different things. Like their reaction abilities, their physical properties too, like their shape and, in macroscopic like colors and everything and how that— all of that kind of stuff and solid or liquid or gas, that kind of thing.

Ruth describing…

> types of bonds and interactions as structure: I think of the types of bonds that are occurring, the different elements— or I guess molecules that are being bonded to each other. I think of the arrangement of the molecules and— Yeah. I think that's probably what I think of...I think of something very similar in about biology, but I also think of, I guess— (pause) There was like, for proteins specifically there were different levels of the structure. So there was the just, the sequence of nucleotides and then there was how those form like, alpha helices and beta pleated

sheets, and then how those interact. Then like, the final structure of the protein, how everything is folded in on itself.

John describing…

shape and polarity as structure: Like the shape or polarity of a substance or, uh— (three knocks) uh, I cannot think of what it is— element or atom or something… [In biology] I would say the structure's like the same— just how something's composed.

size and polarity as properties: Uh, if it's polar or nonpolar— size— big, small— hydrophobic, hydrophilic.

**APPENDIX H: Additional quotes describing connections between GC1/GC2 and B1**

Lida: ...you don't understand the function unless you understand the first two [structure and properties]...my [high school] biology class we just learned the functions of everything...I was like, 'Okay, great, that's what that does. But why? You didn't explain why it does that.'...most bio classes, especially in high school, I'm sure all the bio classes will just teach you the function of things, they won't teach you the structure or the properties. So you can just memorize functions, but then you don't actually understand how they work unless you learn in chemistry the structure and the properties in order to take it over to bio…

Natalie: ...I mean I feel like the structural knowledge and the properties came a little bit more from chemistry. And then applying that in biology, I see more of the functional aspects of things and how they relate to the function but I think that it seems pretty equal, equally coming from the two in the classes. Yeah, I would say it's a little bit more evenly distributed between the two, my overall understanding of them...I've definitely heard the phrase, 'structure determines function' a lot more in biology than I've heard in chemistry but I think that it would hard to relate structure to properties and things like that without having learned chemistry.

Ruth: I think [the courses] worked together because I took what I learned in chemistry from structure determining properties, and was really able to apply that when I was thinking of structure going from properties and then that really changing the function, in biology...I think it was helpful because realizing that if you change the structure, no matter how small that change may be, maybe you're just swapping this element for another element, it can completely change the whole entire property of that compound. I think that realizing that made it helpful to not just go like, 'Oh, it doesn't seem like much has changed when I write it,' but it may have changed a lot.

Simon: Say, if I'm in biology and [the instructor] asks me to think about how this protein is structured, like what amino acids make it up, the first thing I think about is how that would relate if I were to try and do this in chemistry. Because it's just easier for me to, you know, draw out the Lewis structure of the amino acid and see how it interacts...[In GC1/GC2] Like when you have water, it's easy for you to say that this water molecule will hydrogen bond with this water molecule and, you know that's the end of it...thinking about that in terms of biology, I can see why it would do that and I can see how that could be important to how water functions in the body. So it just— I guess it helps me understand the bigger picture of what these things really mean.

**APPENDIX I: Additional quotes describing the relative necessity of considering properties**

**Clarice:** ...now that like you've kind of gone through both [courses], I can see like how they intermix. You can kind of skip the properties in bio. You kind of go from structure to function. So you— it's not like focusing on each one every time...you're supposed to have that understanding so they can kind of skip a step. Whereas in chem, it kind of like builds it up. It kind of gave me the initial understanding...

**Natalie**: It would be helpful to know its properties obviously, and I think that you couldn't get really a holistic view of its function without knowing its properties but I think you could still kind of analyze how the structure affects the function without always knowing the properties.

**Shelly**: [In GC1/GC2] ...the structure determines what properties it has and then the properties, you can use those to determine what the function would kind of would be...Because I could see structure going to function right away without needing to think about the properties but, I guess it all depends on what you're talking about at the time…[In B1] the more you get into more talking about cells and replication and all that, you think of structure-function. And properties are more like when you're thinking about the biological molecules...for like ribosomes or whatever, they have a part where mRNA combine and then they have the tRNA binding sites and then they just— I wouldn't really know any exact properties for that. We just talk about the function of it. It allows tRNAs to come in and bind to the codons and it's just the function of it. I don't really know any exact properties of it.

## APPENDIX J: Students describing linear relationship S → P → F

**Clarice**: ...like when you think about structure, you think like it gives it its properties. So then its properties eventually give it its function. They kind of lead up to one another…I feel like one leads to the other and you kind of have the basis of structure to understand like where the properties come from and then, understand like the properties to get where like the function comes from.

**Daniel***: Like first you have the structure, which determines properties I guess. And I guess properties and the function kind of work hand in hand together, the structure determines both of that I think...Well, I guess the properties do affect the function of whatever we're talking about, the molecule or atom or whatever, but the structure's really what determines what properties and function it does have...the structure determines what properties it does have, and those properties allow it to carry out the function.
**chosen representation: S→ P & F*

**Evelyn**: I'd say if something has a specific structure, that gives it specific properties, which then gives it a specific job or function.

**John***: The structure kind of determines the properties and the properties determine the function...depending on how you look at it in both properties and structure can be kind of flipped, which one you look in which way— because something— some properties could lead to a different structure.
**chosen representation: (chemistry) S→ P; (biology) S/P → F*

**Lida**: You can't tell the function without the properties. You can't tell the properties without the structure. So if you don't know the structure of a molecule then you don't know the properties of a molecule, and in order to know the function, then you need to know what the properties are.

**Louanne**: I think function is more like what it does, and property is more like what causes it to do that, and then structure is more like what makes it able to cause it to do that...So, yeah whenever I think of function, I just think of it actually doing something. And properties is more just like why.

**Natalie**: I'd say structure is the basic thing...I don't know how I would order properties and function. Because structure definitely determines the function of something but I think it also kind of determines the properties it has. So I don't know if you could really say something's— I mean I guess you could say something's properties determine its function, so maybe that would just be in the order that it's given there, I guess if I had to order the three.

**Ruth**: I think [the courses] worked together because I took what I learned in chemistry from structure determining properties, and was really able to apply that when I was thinking of structure going from properties and then that really changing the function, in biology.

**Shelly***: So because the structure determines what properties it has and then the properties, you can use those to determine what the function would kind of would be...I could see structure going to function right away without needing to think about the properties but, I guess it all depends on what you're talking about at the time, kind of thing.
**chosen representation: S→ P & F*

**APPENDIX K: Students describing alternative relationships**

**Aaron:** So based on the structure and based on the properties, I see function as the combining of this and then you can determine what the function is or you can predict what the function is going to be. I think function is simply what comes of it. After you've determined the properties and analyzed the structure of something, function is what would naturally come of that...I feel as though the structure is a property of something...I think both classes do a pretty good job of not only saying that the structure determines function or that property determines something's function, but just examples and utilizing that. I think it gives an even better understanding of that phrases 'structure determines function' and 'properties determine function.'

**John***: Oh, like amino acid change and how an ar— amino acid chains and how like the R group, depending on if that's polar or nonpolar, is going to affect the shape of that protein. And then that protein leading to— the different shape in the protein either leading to like the proper function or if there's like something wrong, where a polar end is supposed to be non-polar. That's going to change how something functions and whether something's able to like bind to it or not.
**An example of his assertion that properties can determine structure. For the SPF relationship description, see Appendix J*

**Joseph**: When I think of structure, I automatically think of structure determines function...I feel like the different properties will determine what kind of structure is formed, and then depending on what structure it is will determine what kind of function it has...I feel like everything that we learn goes back to structure determines function, everything that we learn...A function is how it will work. For instance last semester we were given something called RAS which works at the checkpoint to not let things go through. So when the structure was altered, then the function was different, whereas it could have functioned properly and allowed damaged cells to go through and cause uncontrollable replication, so stuff like that...I use more so structure and function, but I know properties plays a role as well. We've definitely covered that for sure. (pause) I just can't determine— I don't know what kind of properties it has.

**Priyah**: [In GC1/GC2] I can see the structure and properties part but the function I kind of don't see, if that makes sense…[In B1] I think [properties] are important and I think we might have learned about it but I just never paid attention but, I think we might just skip it...…I think maybe they [properties and function] blur in biology and that's why I haven't noticed specifically, like all the property of this one molecule leads to the function. I think that they do blur together in both [courses]…

**Serina:** I know that the structure determines the function so they're— like these are all related. And the function of something has different properties...the structure has properties and the structure has a function so, I just, those three words are very closely related and we revisit that idea a lot...I would say like structure and properties, like those are kind of very closely related and then like the last would be function...Oh yes, so like I would put structure and then properties like, at like the— I don't know they're very closely related, like so I would say they're the same and that these two things determine the function of something

**Simon**: Well I know that structure determines function and I know that the properties will determine its structure, at least to some degree...If you have a sequence of amino acids and you know that this one has an oxygen attached to a hydrogen, you know it's capable of hydrogen bonding with something else that also has a hydrogen attached to a highly electronegative atom. So you know that it'll fold in that way so they're connected. So you can determine what sort of structure they're going to have…[In bio] Structure determines function which determines properties...the structure of tRNA, if you look at that, you can see that it has a structure with a binding site. And this binding site will allow something to attach to it like an amino acid. And because it can attach it's capable of moving that amino acid. But because we look at the structure of DNA and it doesn't have any binding sites, it doesn't have active sites, it doesn't have allosteric sites, we know that there's nothing it really does. It just sits there...And (pause) when we look at how structure determines its function, after we know what function it has, we can sort of tell what (pause) what it's going to do, like what properties it'll have, whether or not it can move—...Hydrophilic molecules can't pass through the lipid bilayer because they can't be dissolved because it's just so non-polar. So they have to be brought in by something like a protein...So if we know what the structure is, if we know what the function is we can sort of tell whether or not it needs to be diffused into the cell which will have a different result than it being able to just pass through.

**chosen representation S → F → P (bio); P → S (chem)*

## APPENDIX L: Additional quotes describing the relationship in use

**Aaron**: Then in chemistry, every single time before I attempt a problem— like I said, a lot of times you draw a Lewis diagram. You could just write out a molecule itself and determine the properties of that molecule and ask if it can hydrogen bond or is it polar or whatever. And then it will help determine— even then, if you know it's covalent, you can say 'that's strongly bonded together.' So you can even keep going and going and going and then you'll get a better, a more confident or viable answer. That would be the function. The answer is the function.

**Evelyn**: I think it's more of a universal thought process. Like I feel like this applies to everything, almost everything at least. Like understanding the basic structure, like that's the foundation of it. And then from there that determines its properties and function. I feel like that works for many things in both courses. It's not just one unit.

**Joseph**: Yeah when we're given a question [in B1], [structure determines function] is one of the concepts I actually kind of understand in biology. So I feel like no matter what kind of question we're given, I always try and see how I can relate it back to that, because that can give me a better understanding, or guide me in the right direction. So I try and relate it back to that.

**Lida**: ...if I'm presented with a function, like this is what this does. If I'm not given any background. Based off of what I've learned about structure and properties, depending on what the function is, sometimes you can work backwards and give a very educated guess, I guess. You can't just know, but you can give a fairly educated guess as to what the actual structure and properties would be, why that function's happening.

**Ruth**: So, if you can look at something's function, you can relate it back to its properties or structure, and you can also do the other way around. You look at something's structure, and you can maybe think of what its function might be.

**Shelly***: I don't think I do it explicitly, but I feel it's definitely the progression of thought. Because you do, you have to think— like when you're given a problem you have to think, 'Well okay, I have to draw this out.' And then 'Okay, I'm looking at this Lewis structure' and then 'Well now I have to determine how this does this.' So it's not like— I don't think I think like, 'Okay structure to like properties function,' like that's the progression of thought in general, just done in progressive ways of with you doing the material itself.
**Quote also included in article Table 5.6*

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