UNDERSTANDING UNDERGRADUATE INTERDISCIPLINARY SCIENCE EDUCATION—THE COGNITION, CURRICULUM, AND CONCEPTUAL ASSESSMENT

by

HSIANGHAN SHANNON SUNG

(Under the Direction of Ji Shen)

ABSTRACT

The dissertation includes three studies that all contribute to the understanding of interdisciplinary science education. The first chapter offers an overview of the context of these studies. Chapters 2-4 present the three studies approaching interdisciplinary science education from a cognitive, instructional, and assessment perspectives, respectively. In Chapter 2, a clarification and revision process of a cognitive framework for interdisciplinary understanding (IU) is presented. The framework examines four critical aspects of IU: *integration*, *translation*, *transfer*, and *transformation*. In Chapter 3, a textbook analysis of a crosscutting concept, *osmotic pressure*, shows the inconsistency of definitions and interpretations across science disciplines. The findings reveal challenges and suggest possible remedies in coordinating science curricula to achieve interdisciplinary integration and translation. In Chapter 4, the cognitive framework proposed in Chapter 2 is applied to construct interdisciplinary science assessment items on the topic of energy. The last chapter summarizes the findings of the three studies and elaborates on the implications for the overall work of interdisciplinary science education.

INDEX WORDS: Interdisciplinary, science education, instructional collaboration, text analysis, discourse analysis, assessment, item response theory (IRT)

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DEDICATION

To Him who called me to achieve something I would not have accomplished with my own strength and knowledge; and to the dearest husband He granted me, Edward Sung.

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so sweet that I find myself calling wherever you are “home”. I am so thankful to have such a supportive family that helps to relieve the homesickness I have sometimes felt.

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TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The underlying benefit of interdisciplinary learning is that students can develop higher order thinking, metacognitive skills, and interdisciplinary understanding (IU) (Ivanitskaya, Clark Montgomery, & Primeau, 2002; Klein, 2010). IU is one's "capacity to integrate knowledge and modes of thinking in two or more disciplines" (Boix Mansilla & Duraising, 2007, p. 219). Boix Mansilla and Duraising (2007) argue that interdisciplinary learning elevates learners' cognitive advancement in a way that is impossible with a single discipline. While rooted in disciplines, IU provides learners with multiple disciplinary perspectives, encourages them to integrate knowledge, and facilitates their active construction and application of knowledge across different disciplines (Jones, Merrin, & Palmer, 1999; Ivanitskaya et al.2002). Fostering IU prevents learners from developing disciplinarily constrained vision and renders new perspective of knowledge that enables them to appreciate the holistic nature of knowledge (Repko, 2008; Schommer, 1994). Also, students' epistemological beliefs concerning the source, certainty, and organization of knowledge may be enhanced by interdisciplinary learning (Jones et al., 1999; Ivanitskaya et al., 2002). Interdisciplinary learning may also augment learners' agency in schools because such learning aims to help students see the connections between school knowledge and real world problems in their daily lives (e.g., Glenn, 2012).

The call for undergraduate science education in the U.S. provides a great opportunity for interdisciplinary research, such as exploring possible ways to integrate interdisciplinary science curricula and developing assessments targeting students' IU. In this dissertation. So, unless it is being pointed out explicitly, the term *interdisciplinary* in the dissertation is unfolded within the natural science context. The dissertation consists of three interrelated studies (chapters 2-4), each focusing on a different aspect of interdisciplinary learning. In this chapter, the context of the problem and the purpose of the studies are described; then an outline of each chapter is given.

Context of the Problem

There is a high demand for undergraduate interdisciplinary education (American Association for the Advancement of Science (AAAS), 2009; Achieve, 2010; Berlin Group for Radical Curriculum Reform, 2010). Interdisciplinary programs and initiatives are aiming to dissolve disciplinary barriers in the U.S. (e.g., Klein, 1994; Boix Mansilla, Duraisingh, Wolfe, & Haynes, 2009). Even within the context of natural sciences, AAAS has envisioned effective science learning as bridging the disciplinary core ideas and collaboration across science disciplinary borders (AAAS, 2009).

However, specification of disciplinarity has proven to be a potential barrier for college students' interdisciplinary learning (OECD, 2006). Three historical factors solidified the specification of disciplines in higher education: (1) the increasing demand for specialists from universities (Gibbons, 1998; Manathunga, Lant, & Mellick, 2006; Repko, 2008), (2) the reinforcement of discipline-based training in the faculty member recruitment processes (Bradbeer, 1999), and (3) the professionalization of knowledge along with the establishment of professional societies and journals (Klein, 2010). Overtime, institutions of higher education established discipline-oriented education with recognizable disciplinary infrastructures, which competes for limited resources within each institution.

Success notwithstanding, discipline-based education faces many challenges. One challenge is the specialized languages used in different disciplines: each discipline has developed its own terminologies to describe the natural world. In some cases, different terminologies from different disciples are used for the same phenomena; and on other occasions the same terms are used to refer to different phenomena. Educated through discipline-based programs, students may only “speak” and think in disciplinary-specific ways (Boix Mansilla & Duraising, 2007). As a consequence, they frequently neglect the importance of acquiring interdisciplinary-appropriate language to communicate across disciplines (Newell, 1983; Crease, 2010). Another challenge is that, disciplinary learning often becomes pure intellectual training that lacks applicability to solving real life problems (Newell, 1983; Klein, 1999). Discipline-based problems are typically simplified into special cases to help students master the concepts under discussion. The contexts are mostly designed intentionally to filter out irrelevant factors associated with problems This kind of practice fosters “tunnel vision,” restraining students from gaining insight to analyze the more complex problems through multiple perspectives.

Collaborative research and instruction across disciplines has become more common in academia (Zhou, Kim, & Kerekes, 2011), which imposes some inevitable challenge to promote interdisciplinary education. For instance, instructors and students are regularly unaware of the particular practices and beliefs of different disciplines to facilitate and expedite the more effective intercultural and/or interdisciplinary knowledge exchange (Manathunga et al., 2006). Therefore, collaboration across disciplines requires purposeful coordination to avoid miscommunication and even to apply findings formerly circulated only within disciplinary experts to resolve similar research questions in other disciplines (Collins, Evans, & Gorman, 2007).

Although interdisciplinary education may complement discipline-based education in many ways, to put interdisciplinary education into large scale practice still faces many challenges. One concern is that the practice of interdisciplinary education is often perceived as a composite without forming a coherent whole (Repko, 2008; Stokols, Hall, Moser, Feng, Misra, & Taylor, 2010). Truly, many centers and programs present discrete concepts from isolated fields, usually combining social, language, law, art, and science perspectives, without true integration (Lattuca, 2002; Manthaguna et al., 2006). This may be due to a lack of careful planning, resulting in a kind of interdisciplinary education that is treated as an arbitrary, hybrid disciplinary approach, or in Crease's words "a disciplinary mule—sterile, not creative" (Crease, 2010, p. 94). Students having this kind of composite courses may receive knowledge from various disciplinary perspectives without cognitive advancement. Subsequently, little transformative experience is created because of an absence of specific support and a lack of well-designed tasks (Spelt, Biemans, Tobi, Luning, & Mulder, 2009).

Effective interdisciplinary education offers learners the opportunity to integrate disciplinary insights, theories, and methods, and provides a chance for interaction across disciplinary cultures. A thorough synthesis of recent research from 1992-2009 (Spelt et al., 2009), however, revealed that there is still no empirical evidence indicating that interdisciplinary learning advances students' cognitive processes (Boix Mansilla & Duraising, 2007; Nikitina, 2005; Spelt et al., 2009). Claims about the merits of interdisciplinary education abound, yet many of them are supported by no more than "anecdotes, impressions and *a priori* reasoning" (Newell, 1992, p. 217). A lack of empirical data proving the effectiveness of interdisciplinary science education leads to several problems. For instance, instructors and students may not have a sense of how well their practices align with prior research or of which approach facilitates interdisciplinary learning more effectively than others. An absence of clearly established standards and measures is not compatible in an era of accountability.

Klein (2008) admitted that interdisciplinary assessment is the Achilles' heel of interdisciplinary education, and that it has not been addressed adequately. Since public awareness of interdisciplinarity is gradually increasing, there is a dire need to develop adequate assessment tool to understand more about students' IU. Nevertheless, just as Brown and Wilson (2011) pointed out, a "model of cognition" is usually the missing cornerstone for the construction of a measurement tool, cognition framework for IU should be examined or created first. Project Zero in Harvard University created a theoretical framework for assessing interdisciplinary tasks (Boix Mansilla & Duraising, 2007). Their assessment framework entails three core dimensions—*disciplinary grounding*, *advancement through integration*, and *critical awareness*—which shed light on the qualities of IU. Such a framework does not address the cognitive processes involved in solving interdisciplinary tasks. Therefore, the theoretical framework proposed by Boix Mansilla and Duraising can serve merely as a basis for assessing IU; a more concrete model of interdisciplinary cognitive processes is needed.

In brief, current interdisciplinary education lacks a coherent, cognitive framework to direct its curriculum and assessment development, and suffers from the scarce empirical evidence of the effectiveness of interdisciplinary approaches. This dissertation embodies three particular components of interdisciplinary education—a cognitive framework, curriculum, and assessment —with three empirical studies.

Purpose of the Studies

Understanding students' cognitive framework is emphasized in many education reform documents (NRC, 2000; Pellegrino, 2010). These critical elements are shown in the representation (Figure 1.1) that positions cognitive framework at the center of the Curriculum-Instruction-Assessment (C-I-A) triangle. In this framework, *curriculum* refers to the knowledge, skills, and learning activities enlisted in science disciplines, which teachers teach and students are supposed to learn; *instruction* is the methods of structuring teaching and learning activities to facilitate student learning of the content specified by the curriculum; *assessment* indicates the means used to measure student understanding with regard to important competencies; and *cognition framework,* which influences each vertex of the C-I-A triangle, means that the curriculum, instruction, and assessment need to build on sound learning theories. If we aim to revamp interdisciplinary science education, then a cognitive theory for interdisciplinary reasoning is indispensable.

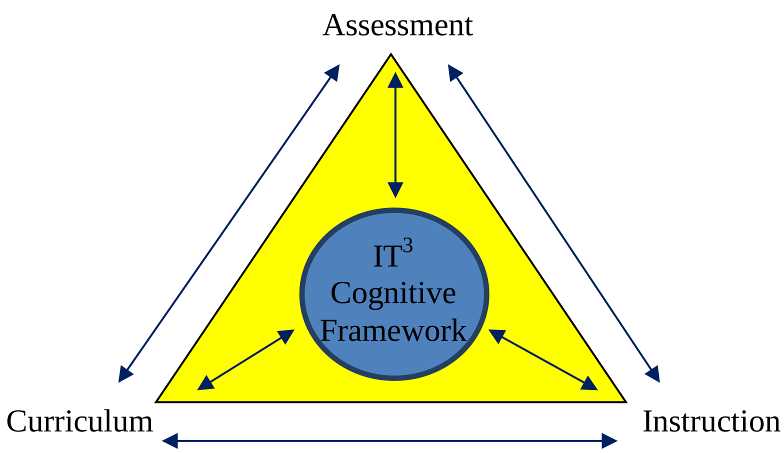

Figure 1.1. Representation of the interconnections among curriculum, instruction, and assessment and the pivotal role of theories of learning.

The purpose of this dissertation is to explore ways to improve interdisciplinary science education at the college level, from both theoretical and empirical approaches. The specific objectives, realized in the three studies in the dissertation, include (a) developing a cognitive framework for understanding the underlying processes of IU in science, (b) analyzing textbooks to determine how a common core idea is introduced in disciplinary curricular materials, and (c) applying the cognitive framework to construct interdisciplinary assessment items and determine learners' levels of IU in undergraduate education.

Background Information

The three studies that comprise this dissertation were inspired by a National Science Foundation-funded project—Designing Transformative Assessment for Interdisciplinary Learning in Science (DeTAILS). The DeTAILS project gathered a team of faculty members from different science emphasis. The ultimate goal of this research team was to create a measurement instrument that is reliable and valid to assess undergraduate students' interdisciplinary understanding in science (IUS). In the biweekly meetings, faculty members revealed their disciplinary perceptions toward a crosscutting concept and involved in the design of interdisciplinary assessment items. The research experiences led to the three studies to investigate current interdisciplinary science education.

This dissertation will be presented as a collection of three manuscripts: (1) "Toward a Cognitive Framework of IU"; (2) "Understanding Osmotic Pressure from an Interdisciplinary Perspective"; and (3) "Assessing Undergraduate Students' Energy Understanding from an Interdisciplinary Perspective." The first two articles were co-authored, while the third study was sole-authored. For the sole-authored article, I also received feedback and comments from my dissertation committee members, other faculty members, and colleagues.

In order to delineate interdisciplinary science education and address learners' IU, a cognitive framework (See Figure 1.1), which was constructed and revised iteratively, will be used as the foundation for IU instrument generation. The framework emerged as the meeting proceeded and was solidified based on the DeTAILS meeting discourse. A set of textbooks, which were recommended and provided by some of the DeTAILS faculty members, reflects the disciplinary curricular materials corresponding to Curriculum vertex. An instrument addressing undergraduate students' IUS was constructed. It serves as the assessment vertex in the C-I-A triangle. The instruction vertex was not included in the dissertation, but will be investigated in the near future. The discourse analysis, individual interview, and curricular material analysis as well as IU instrument implementation all contribute to a better understanding of interdisciplinary education.

Outline of Each Manuscript

The three manuscripts will contribute to a more in-depth understanding of interdisciplinary education on curriculum, instructional collaboration, and assessment of student understanding across disciplines. The first paper investigated and validated the theoretical framework for IUS through construing disciplinary experts' perceptions of common terminologies within an interdisciplinary meeting and individual interviews. The second paper recorded the evidence of different disciplinary perspectives toward a commonly used terminology in the curricular materials used in science instruction. The third article incorporated the cognitive framework into the construction of an interdisciplinary instrument for addressing learners' IUS and differentiating learners' IU with item response theory (IRT). All three articles are essential for answering the overarching questions: "What does IU comprise?" and "How can interdisciplinary understanding be fostered?" Since the implementation of genuine interdisciplinary education is relatively rare, very few resources exist for evaluating the effectiveness of interdisciplinary curriculum or instruction, not to mention the assessment of interdisciplinary learning outcomes. Therefore, Chapters 2, 3, and 4 connect tightly with one another based on the fact that each article contributes additional information to the ultimate goal of the promotion of interdisciplinary education. Figure 1.2 depicts the layout of the three studies in this dissertation.

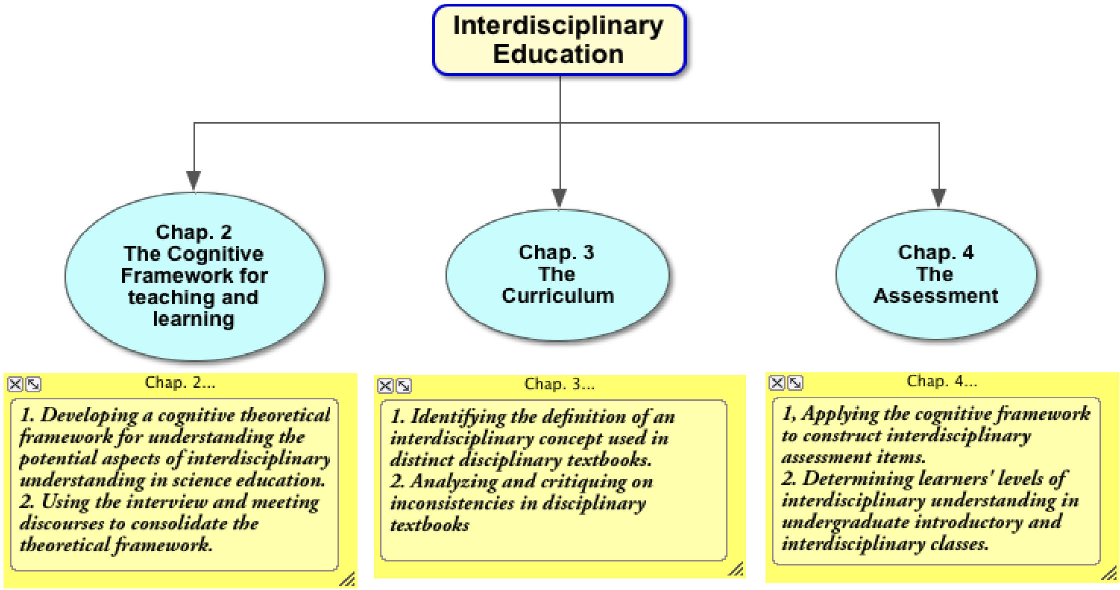

Figure 1.2. Layout of the dissertation.

Chapter 2 introduces a cognitive framework of IU and applies it to interpret the discourse of two DeTAILS meetings. Specifically, we examined four cognitive dimensions of IU: *integration*, *translation*, *transfer*, and *transformation* (i.e., the IT^3 framework). We applied the framework in analyzing the conversations among university faculty members from different science disciplines who are collaborators of the DeTAILS project. An iterative revision of the IT^3 framework through discourse analysis of the meetings was demonstrated in this study, including a detailed definition of each aspect. The IT^3 framework had evolved gradually after several rounds of coding. The results were reported and the implications of using the framework in conceptualizing interdisciplinary learning were discussed.

Chapter 3 presents an analysis of a particular crosscutting concept—*osmotic pressure*—from the perspectives of multiple science disciplines. The team identified 20 textbooks in physical sciences and life sciences based on the assumption that disciplinary textbooks reflect their curricula. The inconsistent definition of and the quantitative measurement of osmotic pressure across the disciplines were demonstrated in this chapter. The inconsistencies may confuse students who are encountering this concept when taking required science courses. The diverse perspectives taken by different disciplinary experts and passed on to the students might have caused this problem. The result suggested that a lack of explicit translation of terminology undermines the interdisciplinary integration and transfer (Nikitina, 2005).

Chapter 4 is devoted to investigating the IT^3 framework's application to the construction of an interdisciplinary assessment instrument. The instrument was designed to tackle students' IU of an overarching topic—energy—one of the most fundamental science concepts. Despite the commonality of the energy concept in each science discipline, distinct disciplinary culture introduces varying lens to look at this crucial concept. As a result, students enrolled in separate science courses may have difficulty grasping the complexity of and applying the energy concepts coherently to different contexts (i.e., a context-specific scenario) (Liu, Ebenezer, & Fraser, 2002). Such a phenomenon may be explained by the fact that students in current secondary and higher education are often, if not always, exposed only to a specific disciplinary aspect of energy. Besides, students' understandings of energy derived from diverse resources usually cannot be simply identified from a single disciplinary approach. The consequence of context-specific perspective restricts meaningful connections of their prior knowledge with the holistic view (Kirshenbaum & Webber, 2011; Newell, 2000; Repko, 2008). To address this disconnection problem, the energy assessment instrument was intentionally designed to connect energy topics that are usually found under different disciplinary contexts. Therefore, the study "*Assessing Undergraduate Students' Energy Understanding from an Interdisciplinary Perspective*" is essential.

Last, Chapter 5 connects the three studies in Chapters 2 to 4 to answer the key question "How can we promote interdisciplinary science education with the application of the C-I-A triad?" This chapter presents a synthesis of the contributions of each study to better understand assessing interdisciplinary science education. Moreover, a thorough discussion of the implications concerning how to apply the IT^3 framework to curriculum design, instructional collaboration, and assessment item construction is included in the summary of each manuscript. The significance and limitations of the studies are also discussed at the end of each chapter.

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CHAPTER 2

TOWARD A COGNITIVE FRAMEWORK OF INTERDISCIPLINARY UNDERSTANDING (IU)[1]

[1] Sung, S., Shen, J., and D. Zhang. To be submitted to *Science Education*.

Abstract

Students need to think and work across disciplinary boundaries in the 21st century. However, it is unclear what interdisciplinary thinking means and how to assess students' interdisciplinary understanding (IU). In this paper, drawing from multiple perspectives in the learning sciences, a theoretical framework that helps define interdisciplinary learning in science was formulated. Specifically, four cognitive dimensions of IU: *integration*, *translation*, *transfer*, and *transformation* (IT^3 framework) were examined. The framework is applied to the analysis of conversations among university faculty members from different science disciplines participating in an interdisciplinary project. Results are reported and the implications of using the framework in conceptualizing interdisciplinary learning are discussed.

Introduction

Collaborative research involving multiple disciplines is pervasive in many fields including Science, Technology, Mathematics, and Engineering (STEM) (Rhoten & Parker, 2004). This trend mandates college education to prepare students to think across disciplines in the 21st century (Engle, 2006; National Research Council, 2000). However, it is unclear what "interdisciplinary understanding (IU)" means, and little research has been conducted on establishing a cognitive model of IU (Boix Mansilla & Duraising, 2007). Furthermore, there are many barriers preventing students from becoming successful interdisciplinary thinkers and doers. For instance, typical assessment in a college science course focuses primarily on specific disciplinary topics. As a result, college students not only develop fragmented understanding in science (Linn, 2006; diSessa, 1993), but they are also reluctant to think beyond disciplinary constraints.

This paper aims to elaborate on a theoretical framework that can potentially answer the question "What constitutes IU?" A cognitive framework (Shen, Sung, & Rogers, 2012) was developed in the context of working on a larger project that aims to improve college students' interdisciplinary understanding in science (IUS). It can be used to guide the development of curricular materials, instructional approaches, and assessment items that target students' IU.

In the following, we first review relevant literature that informed our perspective. We then present our theoretical framework and elaborate on each key component of the framework. The empirical section explains how the framework is applied in analyzing the discourse of a dynamic group whose goal is to develop interdisciplinary science assessment items for college students. We report the results of our analysis and discuss the educational implications.

Relevant Literature and the IT^3 Framework

The learning sciences literature has provided many useful perspectives for examining the issue of IU. Here, particular perspectives that influenced the framework are highlighted.

There are different interpretations of IU. *Integration* seems a natural place to start with as interdisciplinary learning involves multiple sources of knowledge. For instance, Boix Mansilla and Duraising (2007) defined IU as "the capacity to integrate knowledge and modes of thinking in two or more disciplines or established areas of expertise to produce a cognitive advancement…in ways that would have been impossible or unlikely through single disciplinary means" (p. 219). Recognizing that students develop fragmented understandings of science topics, Linn and colleagues developed the framework of knowledge integration (KI) that emphasizes students' abilities in establishing connections among scientific ideas (Linn & Eylon, 2011; Linn, 2006). The framework promotes coherent understanding by encouraging students to add new ideas, distinguish new and existing ideas, develop scientific criteria to reconcile ideas, and build coherent connections between a science phenomenon with their prior knowledge or experiences across different dimensions of knowledge (Liu, Lee, & Linn, 2011).

With the dominance of specialized professions nowadays, effectively *communicating* the knowledge and outcome to audiences, who often come from different disciplines or non-scientific backgrounds, becomes critical. Boix Mansilla and Duraising (2007) highlighted the importance for learners to communicate their disciplinary knowledge to "people who do not speak the same language" (p. `224). Learners who are able to acquire sufficient language to converse on a similar topic or distinguish terminologies from another discipline are considered more competent in thinking across disciplines than those who need translation (Nikitina, 2005).

Therefore, acquiring different terminologies used across disciplines is highly desired for students to achieve IU.

Besides, students constantly face the challenge of knowledge *transfer* from one context to another, which is useful to delineate the application of discipline-oriented knowledge from one discipline to another (Bransford & Schwartz, 1999; Chin & Brown, 2000; Haskell, 2001). Research has shown that many factors contribute to or hamper students' knowledge transfer. Such factors are learners' prior knowledge, experiences, context of learning, and differentiating opportunities to develop deep understanding, to name a few (Klahr & Carver, 1988; Lave, 1987). Consequently, when encounter a novel situation or real-life problem requiring more complex cognition, students with strong conceptual framework to reactivate disciplinary "frames" of information will retrieve and apply information more quickly (Bransford, Brown, & Cocking, 2000; Hammer, Elby, Scherr, & Redish, 2005; MacLachlan & Reid, 1994, p.98). Successful transfer fosters deeper learning by enabling students to "venture their ideas more spontaneously" (Chin & Brown, 2000, p. 121). Capable transferors are also expected to give more elaborate explanations that refer to other disciplinary theories or tools and realize discrepancies in disciplinary knowledge and are more likely to approach the ordinary with extraordinary perspectives.

The IT^3 Framework

Building upon related literature, we argue that deep IU has four interconnected dimensions: *integration*, *translation*, *transfer*, and *transformation* (i.e., the IT^3 framework) (Shen, Sung, & Rogers, 2012). Each dimension is elaborated using examples from osmosis, an interdisciplinary science topic.

Integration

Considering the importance of linking distinctive ideas from different resources, the first dimension of the framework emphasizes knowledge integration across disciplinary boundaries. For instance, we may ask students to explain why eating a large amount of hyperosmotic food, such as cake or chocolate, without drinking water would cause an accumulation of water in the lumen of the digestive tract. To fully explain this phenomenon, students need to integrate knowledge in chemistry (e.g., solvation), biology (e.g., selectively permeable membrane of a cell), and physiology (e.g., structure and function of organs). Students with a higher level of interdisciplinary integration should identify the connections between disciplinary ideas in this context.

Translation

The comprehension of different terminologies used across disciplines is highly desirable for developing IU, and the *translation* component constitutes the second dimension of the IT^3 framework. Since many disciplines develop their own terminologies to explain similar phenomena, students who develop IU need to be able to translate scientific terms in order to communicate effectively with people from different disciplinary backgrounds.

For example, in plant biology, turgor pressure is the pressure of the cell contents enclosing the membrane (protoplast) against the cell wall due to osmosis, whereas in animal or medical physiology, intra-cranium pressure is the pressure exerted on the skull due to high fluid retention. These two discipline-bounded terms are similar as they present two concrete examples of osmotic pressure. A student who has developed IU of osmosis should be able to translate between these terms. Translation between terms does not have to occur *en masse*; in theory, one can just translate one term at a time.

Transfer

Interdisciplinary transfer occurs when students apply explanatory models and concepts learned from one discipline to another disciplinary context. One criterion is the ability to recognize the core structure of the system under study—matching the parallel elements or parts and their connections within the two systems. This falls into the category of “deep transfer” (e.g., Chin & Brown, 2000). Learners who use rote memorization will be less likely to succeed in an interdisciplinary task without applying knowledge they acquired in one field to a new context. In other words, a competent learner with IU can relate what he or she has learned in one discipline to another discipline in order to recognize and identify the common model or shared ideas.

Consider the following example; a student has learned the knowledge needed to explain the typical U-tube scenario demonstrating osmosis in a chemistry class. Two solutions with different solute concentrations in two sides of a U-shaped tube are separated by a selectively permeable membrane at the bottom, which only allows certain ions or molecules, usually water, to pass through. The system reaches equilibrium when a certain amount of water from the side with lower solute concentration moves to the side with higher solute concentration. When the student is asked to explain the function and process of osmosis in a plant cell, he or she may be able to transfer his/her knowledge learned from the U-tube situation. For instance, to recognize the similar system component, that is, the two solutions with different solute concentrations, the two solutions are separated by a selectively permeable membrane, and the net movement of water reaches equilibrium when osmotic pressure is balanced by another external pressure.

Transfer is different from translation in that it focuses on the understanding of the basic system or explanatory model that is being transferred as opposed to linking the conventional terminologies at the linguistic level used in different disciplines.

<u>Transformation</u>

The fourth dimension of IU is transformation. Students need to be able to apply explanatory models, concepts, tools and methods learned from one discipline to physically or conceptually change a system typically considered in a different discipline into while another novel system. An example in this category is reverse osmosis, a process that is frequently used in food engineering to purify water. Reverse osmosis is achieved by applying additional pressure to the higher solute-concentrated side. Because of the selectively permeable membrane, this process results in retaining large molecules and ions on the pressurized side of the membrane, forcing smaller molecules or ions to pass to the other side. Since students have already acquired knowledge of the regular osmosis process in sciences (existing system), they need to apply their knowledge and think/operate backwards to apply the idea to food engineering settings (new system) and make changes (purifying water). A mental thought experiment can also be categorized into this cognitive process dimension because it requires one's mental conduction of new setups in order to test hypotheses or predictions. The production of a new physical or conceptual system (based on old ones) is a key feature of transformation, which is different from transfer.

It is important to note that these four dimensions, as characterized above, are intertwined and non-exclusive to each other. For instance, as the translation process establishes links between parallel terms from two different disciplines, it is also integrating these terms. When the models and concepts of the first discipline are transferred to a new discipline, they may also need to be translated. An interdisciplinary transformation process typically requires both a transfer and a translation process, as the learner has to acknowledge the target system and compare it to a referent system in order to change it.

In the following, we describe how we apply the IT^3 framework to analyze and interpret a discourse among people coming from different disciplines. Through the analysis, we further refine our framework by laying out the subthemes within each dimension.

Applying the Framework

<u>Background and Data</u>

In this study, the IT^3 framework is applied to analyze the discourse of two interdisciplinary faculty group meetings. The group of faculty members came from different science disciplines and worked together to create interdisciplinary assessment items to be used in introductory science courses in physics, plant physiology, animal physiology, and chemistry. The faculty met roughly once every two weeks. The meetings were audiotaped and transcribed. Two (38 minutes and 92 minutes) out of 13 meetings were used to demonstrate our analysis. These two meetings were chosen because, in the first meeting, the faculty members encountered different and sometimes conflicting disciplinary perspectives while they were discussing a concept map on osmosis that they co-constructed. The conflicting views made these content experts eager to argue and learn other disciplinary perspectives. Therefore, we expected to see many dynamic interdisciplinary learning instances in this meeting.

However, the analysis revealed that there was no statement representing a transformation component in the first meeting. Consequently, another meeting was identified to model *transformation* process. This meeting focused on the inappropriate usage of the osmotic pressure formula, which is derived from the ideal gas law. A table enlisting osmosis-related terminologies was provided and discussed in this meeting.

Coding

The unit of our analysis is a coherent statement, defined as one or more sentences that deliver a stand-alone meaning. There are two layers of codes we apply to each statement (see Table 2.1 for features of these statements). The first layer of codes emerging from the coding process concerns the topic of the statement. That is, we first decided if a statement falls into one of the following three categories:

- *A concept-specific* statement involves specific scientific concepts and terminologies such as water movement and osmotic pressure.
- *A meta-level* statement talks about scientific understanding at a general, abstract, or representational level without involving specific scientific concepts or terms.
- *An instructional* statement touches upon issues related to teaching, learning, and assessment.

If a statement does not belong to any of the three categories or is irrelevant to interdisciplinary discussion, we categorized it as *non-interdisciplinary other*. If a statement falls into one of the three categories above, we then apply the second layer of codes, that is, the four cognitive processes of IU. If a statement falls into one of the three topical categories but cannot be coded as one of the four dimensions in the IT^3 framework, it is coded as interdisciplinary other.

This process resulted in five subcategories under each category. Plus the non-interdisciplinary-other category, there were 16 different codes that may be applied to a statement. Each statement was only coded into one of the three topical categories. If a statement includes two topics, then we further divided it into two separate statement units. If a statement involved multiple IT^3 codes within the same topic, we assigned equal weights to each code. For instance, if a statement within the concept-specific category involves both translation and transfer, we then assigned ½ for each.

Table 2.1[2]

Descriptions of the Intersection of Each Aspect and IT^3 Framework

	Content-specific: statements are about osmosis related or other specific concepts, resembling IU.	**Meta-level: statements on IU are at a general level or representational level (how to represent IU).**	**Teaching and Learning: statements on interdisciplinary instruction and learning.**
Integration	Statements embody integrating concepts, theories, tools, and methods learned from different disciplines to understand osmosis.	Statements suggest integrating concepts, theories, tools, and methods learned from different disciplines to understand natural phenomena and solve complex problems. Integrative understanding acknowledges that concepts carry different importance from different disciplinary perspectives.	Statements elaborate on the integrative aspect of IU. This may include the instructors' approach to a topic from different disciplinary angles at the beginning (differential integration) and moving into the interlinked center (commonality integration).
Translation	Statements embody translating osmosis-related terms in order to effectively communicate to members from a different disciplinary background and perspective.	Statements suggest translating scientific terms in order to effectively communicate to an audience from a different disciplinary background and perspective. Translation acknowledges different perspectives different disciplines bring, but emphasizes the same message different disciplinary perspectives intend to deliver.	Statements elaborate on the instructional aspect for incorporating or enacting learners' senses of translating scientific terms and units, which are often expressed differently to refer to the same thing.
Transfer	Statements embody applying explanatory models learned from one discipline to another, recognizing the similar system or core structure related to osmosis.	Statements suggest applying explanatory models learned from one discipline to another, recognizing the similar system or core structure under study. This may include how one reflects on a general transfer approach without mentioning specific concepts explicitly.	Statements elaborate on the enactment of students' application of the explanatory models learned from a particular discipline to another.

[2] This table only describes generic features of the three aspects and the IT^3 framework. Refer to the appendix for more comprehensive examples concerning the application of the framework.

Transformation	Statements embody explanatory models learned from one discipline to change an osmosis-related system in another discipline to a new system. This may include the modification of a mentally created thought experiment as an intention to demonstrate how to understand the explanatory models, tools, theories, and methods learned from one discipline to explain a cross-disciplinary question or problem.	Statements suggest an implicit modification of one's explanatory models learned from one discipline to change a system in another discipline to a new system. This may include a demonstration or description of one's adjustment of their epistemology concerning the explanatory models, tools, theories, and methods learned from one discipline to understand a cross-disciplinary question or problem.	Statements elaborate on the implementation or instruction of how students can use their disciplinary models, tools, theories, and methods to change a system found in another discipline and make a new one.

We coded each statement in the context of the utterance. On many occasions we needed to infer the references of a pronoun as well as components omitted by the speakers. Depending on a continuation of context carried in the previous statement, one unit can be coded as concept-specific even without an explicit indication of the scientific concept or term. For example, in the stand-alone statement "I think they are the same," the pronoun they referred to osmotic potential and water potential in a prior statement of another speaker.

We employed an iterative coding process that took several cycles. Dr. Shen initiated the coding framework and trained two coders, one from a biology background (me) and the other from physics background. The two coders independently coded all the statements. In each cycle, the coders coded a number of statements (30-50) and then compared their codes. The whole team then examined the inconsistent codes and discussed questions that arose in the coding until we reached agreement as a group. This process repeated for several cycles during which the interrater reliability (joint-probability of agreement) reaches adequate level (i.e., .85). All inconsistent codes were resolved through discussion.

<u>Meeting Analysis</u>

The first meeting we analyzed consists of 298 individual statements in total, while the second meeting consists of 495 statements. The interrater reliability (IRR) was calculated by tallying the consistency of two raters' codes. If the codes are consistent both in the aspect and the IT^3 dimension, the code was weighted one in contribution to the IRR estimate; if the codes lie in the same aspect (i.e., content, meta-level, or teaching/learning) but was coded under different IT^3 processes, or vice versa, the code does not contribute to the IRR estimate. However, if one rater considered a statement to involve two processes in the IT^3 processes and only one coincides with the other rater's code, the code comparison contributes ½ to the IRR estimate. None of the codes associate with more than two IT^3 processes. The first meeting reached .87 and the IRR for the second meeting was .85.

Results

First Meeting Analysis

At the end of the precedent meeting, every participant was asked to draw a concept map based on a list of osmosis-related terms. We compiled each concept map into a group concept map. The objective of this meeting was to discuss the group map. Table 2.2 lists the frequencies for each code for the first meeting analysis. In this conversation, in terms of topics, the faculty members were more engaged in concept-specific discussion (overall, 63% in this category, compared to 12% meta-level and 3% instructional). In terms of the interdisciplinary dimensions, they were mainly engaged in translation for each other (overall, 60% translation, 11% integration, and 8% transfer).

Table 2.2
Frequencies of Coding Results for the First Meeting.

	Integration	Translation	Transfer	Transformation	ID Other	Total
Concept	4	165.5	19.5	0	11	200
Meta-level	23	10.5	2.5	0	24	60
Instructional	5.5	1	1.5	0	4	12
Non-ID Other			26			
Total	32.5	177	23.5	0	39	272

It is noted that in the first meeting, when the faculty members talked about IU at a meta-level, they emphasized integration over the other dimensions (within the meta-level category: **integration, 38%**; translation 18%; transfer, 4%). In their concept-specific discussion, however, translation is the most common theme (within the concept-specific category: **translation, 83%**; transfer, 10%, integration, 2%).

The first part of the discussion (approximately 20% of the total time; not shown in the table) focused on the meta-level aspect, while the rest of the discussion was much more concept-specific. The meta-level comments mainly involved the structure of the concept maps that the faculty members created. For instance, the following conversations focused on how people from different disciplines would construct or perceive a concept map on osmosis (pseudonyms are used).

> Kevin: ….. It's like a physicist is focusing on one area of the concept map, almost to the exclusion of the other which is from one region and works his or her way out from there. Biologist might be starting from a different region, and eventually mixing those connections. But what's important in that concept map for the biologist is a lot of other stuff.
>
> Jo: So does it make sense what I heard from you is we could somehow incorporate … this region (on the concept map) is more physics related and this region is sort of biological context or physiological context.
>
> David: I think one of the big benefits of that project is that you give people the translation, because ultimately you're talking about the same thing. But in physics (people are) looking from angles as biologists do, but not because we impose physicists to teach biological way but you need to give something that you can approach this from a background of physics.
>
> Andy: sounds like a Venn diagram to me…. you know biology and physics, and you got overlap in the middle, and you got that core, and the perspectives that give you insight to that, am I right?
>
> David: I personally would never draw a diagram like that, but that's again, that's personal. I'm a more hierarchical person, and I would start with what I'm really interested from the top, and then I would be more detailed of the big picture when I go down to the bottom.…

Later in the meeting, when the faculty brought up different terminologies on the concept map, they started a heated discussion on the specific concepts. That is why concept-specific discussion dominated the rest of the meeting.

> Andy: Solute potential, I've never heard (of it)
> Jo: ok, so I just cross that out?
> Wendell: What does that mean?
> Jo: I don't know. It's on the map.
> David: Oh, well, wait wait wait, that should be over here for plant cell.
> Jo: Plant cell?

David: Yeah, in plant cells when you talk about water potential, … you have two components, one is solute potential,

Wendell: Sorry, you said in plant cell what?

David: ….In plants the water potential is made up of two parts, … what triggers osmosis has two parts, it's the solute potential which is usually equivalent with the solute concentration except it's backwards, if you look at the numbers. And the other part it's the pressure potential, which in essence represents by the cell wall where the pressure starts to building up, results in turgor pressure…

Similar discourse exchanges recurred in the rest of the discussion when animal physiologists used the term *osmotic pressure* to refer to the external pressure needed to stop water movement due to solute concentration gradient across a selectively-permeable membrane, while plant physiologists use the term *solute* (/*osmotic*) *potential* to refer to the factor of adding solute in a solution that drives water movement in osmosis. That difference contributes to the plant biologist's comment on seeing no "osmotic pressure" in a typical U-tube scenario (or an animal cell) because it is an open system; whereas plant cells have volume restrictions due to the rigid cell wall, which leads to pressure build-up. The group did not reach agreement on how to define osmotic pressure and reconcile the different terms at the end of this meeting.

Discussion (I)

There were several interesting themes that emerged from examining the first meeting discourse. In this section, we discuss what we learned from the analysis in light of the IT^3 framework.

Integration

Knowledge integration has been widely studied in science education (e.g., Linn, 2006). Here, we focus on *interdisciplinary* knowledge integration. From the meeting discussion, we see that two kinds of interdisciplinary knowledge integration were brought up. The first type, *differential integration*, is organizing concepts from different disciplines into a connected whole.

When the faculty members discussed the concept map, they noticed that there were concepts bounded by different disciplines on the map (see the first segment of quotes on the previous page). Being aware that certain concepts are rooted in specific disciplines is a strong indicator of deep disciplinary knowledge, which is a prerequisite to true interdisciplinary integration (Boix Mansilla & Duraising, 2007).

The second type of interdisciplinary knowledge integration, *commonality integration*, emphasized the shared common set of knowledge. On several occasions, people in the meeting talked about a shared "core" when thinking of an interdisciplinary topic such as osmosis. For instance, at the very beginning, Andy pointed out that "If we got a central connection about osmosis and then we relate those to biology and physics … is there a central core how we relate it to?" In these references, the "central core" is an integrated core set of concepts or big ideas that have been fused together from different disciplinary descriptions. This common set of concepts can be used to describe the underlying processes applicable to different disciplines. The common core that emerged from the discussion at the meeting may be represented as the shared region in a Venn diagram or the upper-level concepts in a hierarchical map.

The second type of interdisciplinary knowledge integration leads to transfer (or vice versa): as long as one develops the integrated common core, one can transfer it to different disciplinary contexts.

<u>Translation</u>

We noticed that the first one-fifth of conversation was spent on the meta-level aspect and the rest mostly touched upon concept-specific issues, which were cued by the terms used in different disciplines to describe osmosis. This indicates not only a shift of topics but also the group's engagement in reaching consensus regarding concepts and terminologies used to describe the same phenomenon. This process highlights the importance of the translation dimension of IU.

The most common translation strategy a person used in this meeting was to elaborate on a term from his or her own disciplinary perspective to make it intelligible and plausible. This showed a disciplinary-oriented system of thinking that may prevent successful interdisciplinary communication. For instance, when David was explaining the term *water potential*, he drew on his disciplinary knowledge and elaborated on the two typical components of water potential (see the second segment of quotes on the result section). Another translation strategy witnessed in this data set is the common reference to the U-tube case (see Figure 2.1), which is typically introduced in all the disciplines when teaching / learning osmosis. In these translation processes, one would also expect transfer of knowledge to internalize the newly translated terms.

Although our coders' interrater reliability improved significantly and reached a satisfactory level, it was difficult to determine whether a statement belonged to transfer or translation. Most of the coding disagreement was caused by the confusion between translation and transfer. This indicates that the two processes are probably more intertwined than the other processes and that there needs more clarification of the *transfer* and *translation* processes. The following are some insights gained through the data analysis process to differentiate transfer and translation.

First, a transfer process may include intradisciplinary and interdisciplinary ones. For instance, if one provides examples from his or her base discipline to apply to the context under discussion in the interdisciplinary meeting, it is categorized as intradisciplinary transfer, which is considered as deep translation. On the other hand, if one provides examples conventionally introduced in a discipline other than his or her major discipline to explain a phenomenon, it is coded as interdisciplinary transfer. The following piece of discourses took place after Jo drew an U-tube (see Figure 2.1) on the board and asked the team to point to where exactly the "osmotic pressure" is defined and what its magnitude is. The question elicited the unexpected realization of the apparent differences between several scientific terms associated with osmosis—"potential", "potential energy", and "osmotic pressure." The bold-formatted statements are **intradisciplinary transfer** and the italic-formatted statements are *interdisciplinary transfer*.

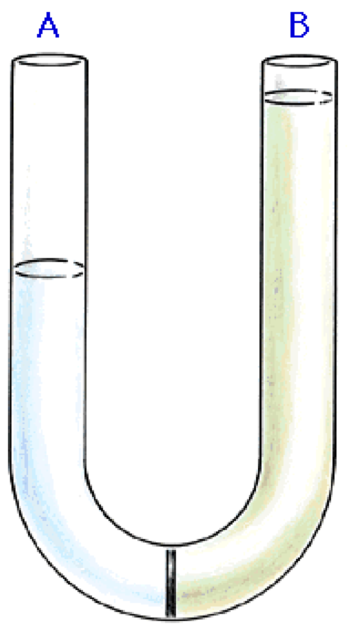


Figure 2.1. U-tube scenario.

Andy: but how do you realize that the water is going to cross? Cause if you're talking about potential.

Jo: So we have to realize that reaching the current status…

Andy: So that, the water potential, is being negated by the increase of osmotic pressure? Now you're saying…

Jo: [drawing an U-tube on the board (see Figure 2.1)] …is this part osmotic pressure [pointing to the raised column of solution (B) in the U-tube]?

David: *if it would be a closed system. The pressure caused by the closed system would be the pressure you could measure. In plant, that's turgor pressure that you measure.*

Andy: in my mind, do you only have a potential until something you have to put in equilibrium?

Kevin: No you only have a difference in potential until…the potential is still there.

Andy: If you negate it just happened.

Kevin: Doesn't matter

...

Kevin: I think you're getting hung up on the word of potential.

David: Yes.

Kevin: …which is a problem, **un thermodynamics, well I always have a problem with the word "potential" in thermodynamics, but potential in thermodynamics context doesn't mean the future ability to do something.**

David: how about the present ability… (laugh)

Wendell: so it means what?

Kevin: Potential and potential energy is different.

Kevin: *Chemical potential in the thermodynamics context is the amount of energy by adding or subtracting particles in the system.*

Kevin: So if I say that I have a particular system of one joule of water, in other word if I add a certain amount of water I would get one joule of energy one joule more of energy into that system.

Kevin: And now, the difference of energy in that system is something else could be used to do work. So there's potential energy there.

Kevin: **But the potential is still, if I have another bit of water, now I got two joules of energy, but my chemical potential is still one joule, because it's essentially on a per molecule basis or per unit of water basis.**

In the segment of meeting discourses given above, the italic statement uttered by David, a plant biologist, and by Kevin, a physicist, were the only two representing interdisciplinary transfer. David blended in the concept of closed system (usually learned in physical sciences) and applied it to explain his rationale about why there is no pressure in the U-tube scenario. On the contrary, thermodynamic topics could be introduced in physics and chemistry, so not every statement concerning thermodynamics uttered by Kevin was coded as transfer. Only one statement about the *chemical potential* stated by Kevin was considered as explicit interdisciplinary transfer. The bolded statements were merely applying the disciplinary knowledge to the target system under discussion, which were representative of intradisciplinary transfer. The IT^3 framework aims to address IU. Therefore, transfer in our framework only refers to *interdisciplinary transfer*. It also explains why the *transfer* is usually the least occurrence in the two meeting discourse analyses.

Second, at the surface level, a translation process may only involve the terminology level. But a *deep translation* may also occur. For instance, when a person is translating some disciplinary-specific term for an audience from a different discipline, he or she is basically explaining the concept to make it meaningful for those who are not familiar with its disciplinary connections. This may involve several levels. S/he may simply introduce the terms (e.g., David introduced the terms such as *water potential*, *solute potential*, and *pressure potential*). We called this *terminological translation*. Furthermore, s/he may extend the translation by adding relations of the terms (e.g., David explained that water potential is the sum of solute potential and pressure potential). We called this *relational translation*. Finally, s/he may provide concrete examples to which one can apply the terms. These examples are typically within the disciplinary boundary and/or drawn from common experience. We called this *concrete translation*. This is still interdisciplinary because the audience of the translation is from a different discipline. The latter two levels are considered deeper translation, compared to the first level (see Figure 2.2).

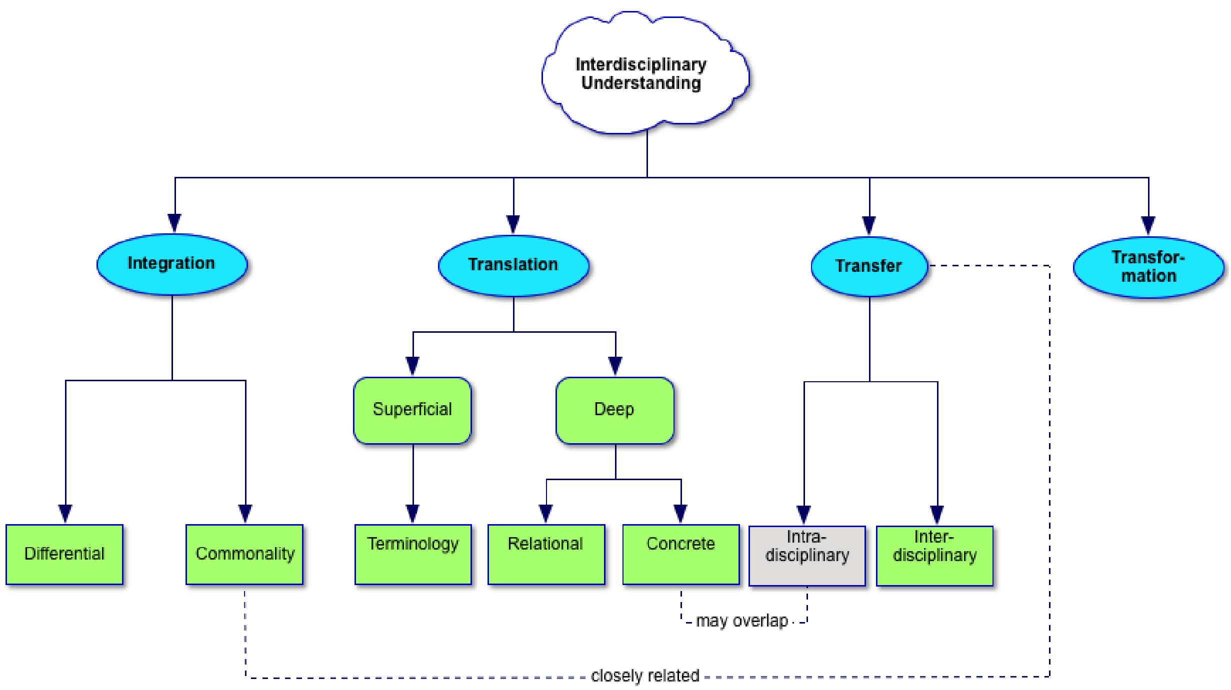


Figure 2.2. The refined IT^3 framework.

Confusion may arise when concrete translation overlaps with intradisciplinary transfer, especially when one is transferring concepts learned in one context (typically abstract) to explain concrete, everyday examples in order to translate for others. Specifically, in the context of interdisciplinary conversation, if one elaborates on any term or principle by explaining how it is applied to specific examples within one's own discipline, this statement was coded as translation—*deep translation*, instead of transfer. For example, when David attempted to clarify pressure flow to faculty from other disciplines by saying, "that added sugar attracts water, and it comes out of the xylem, that's right next to the phloem and so you get all these water rushing in which builds up pressure," one might be tempted to code this statement as transfer; however, the speaker only provided this phenomenon from his discipline, so this statement was characterized as deep translation. Figure 2.2 represents the refined IT^3 framework based on the discussion above.

Second Meeting Analysis

The meeting started with the unresolved problem about solvation and $\varphi = CRT$ (or MRT). The conversation centered on the differential hydration ability of different molecules. If different levels a molecule interact with water is being considered, the formula used to calculate pressure seems to oversimplify osmosis phenomena. Many thought-provoking statements were found in this meeting. Dynamic thought experiment and other *transformation* processes were observed in the discourse analysis.

Table 2.3 summarizes the second meeting, which took place more than one and half months after the first meeting. Similarly, the speakers uttered more statements concerning concept-specific aspect (75%, compared to 6.5% meta-level and 13% instructional). As for the interdisciplinary components, more than half statement units centered translation (53%), followed by interdisciplinary other (19%), integration (12%), transformation (9%), and transfer (5%).

Table 2.3
Frequencies of Coding Results for the Second Meeting.

	Integration	Translation	Transfer	Transformation	ID Other	Total
Concept	42	234	18	34	42	370
Meta-level	4	6	2	3	17	32
Instructional	11.5	12.5	2.5	4.5	31	62
Non-ID Other			31			
Total	57.5	252.5	22.5	41.5	90	464

Discussion (II)

In the first meeting, there was no statement that qualified as transformation. This may due to the unfamiliarity of the subject matter and time limit (38 minutes), the participants had yet fully captured the inconsistent views of each individual or developed a better understanding to reach the transformation stage. However, in the second meeting, the faculty members demonstrated more instances qualified as *transformation* domain (9%), mainly through thought experiments in order to clarify or confront the conventional perceptions of osmosis and solvation. The increased observation of transformation processes among these disciplinary experts facilitates the embracement of more integrative, encompassing, and dynamic discussions connoting IU.

Mental Thought Experiment

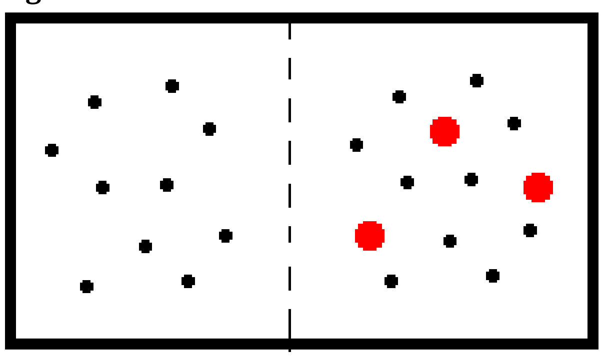
Statements embody explanatory models learned from one discipline to change an osmosis-related system in another discipline and applying to a new system. A *transformation* statement unit may include the modification of a mentally created thought experiment as an intention to demonstrate how to understand the explanatory models, tools, theories, and methods learned from one discipline to explain a cross-disciplinary question or problem. For example, the following discourses focus on comparing osmosis to gaseous selective diffusion (see Figure 2.3):

> Kevin: the thing is, we want to say that the sucrose has been hydrated, but I mean, are we saying that because we wanted to have water molecules around it or just we want to be in a solution rather than sitting on the bottom of the beaker.

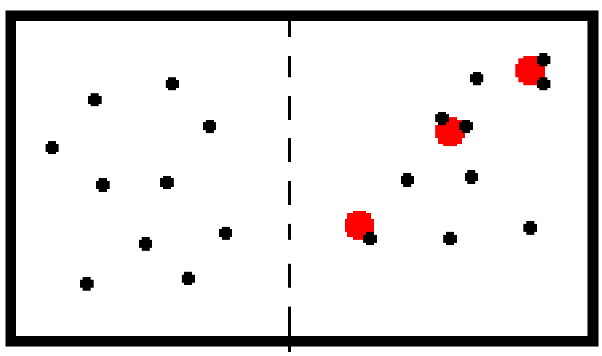
David: no, that' s the whole justification why osmosis occurs, right? **If that wouldn't happen if you wouldn't have attraction of water molecule reducing the free water** [note: no attraction between red and black dots in Figure 2.3 (a))]**, it would lose the concentration gradient in free water if you lose that reasoning, right?** [note: number of "free" black dots in the left and right compartments in Figure 2.3 (a) are the same)]

Kevin: see, I'm not convinced that's what's happening because I go back to the ideal gas model which is a very very bad model for what happens in liquid, I admit that but, but you can get the equivalent of osmosis with a purely ideal gas model

Kevin: So osmosis is water, so let's just talk about selective diffusion, **if I have gas A in two compartments, and a membrane that's permeable to gas A** [note: see black dots in Figure 2.3 (b))]**, then in addition I put some gas B over in one compartment but not the other** [note: see red dots in the right compartment in Figure 2.3 (b))]**, you would get the same behavior as osmosis.**



(a)



(b)

Figure 2.3. Depictions of the transformation processes in the discourse analysis.

Because both David and Kevin used the "If" clause, meaning they were hypothesizing a context by means of conducting thought experiments. In David's thought experiment, solute always hydrates and non-hydration solute particles are imaginary. This means, the speaker, in his head, transforms the real situation into an imaginary, different situation. Similarly, Kevin created an imaginary system for the subject under consideration to explain the content matter to other disciplinary experts. Afterwards, David extended this context by proposing the addition of "hydrated sucrose" to the solution (i.e., the black-dots-attached red dots) that has reached equilibrium.

> David: But now you're putting in the sucrose, the question is whether you're putting hydrated sucrose, or whether you put sucrose that hasn't attached water, yet, that's gonna be different on how much water you have on the left side.

The result of hydrated sucrose and the sucrose without water attached to it will impose different impact on the system. Such statement shows the change of an osmosis-related system with the addition of chemistry understanding (i.e., hydration of molecule), which is essential to resolve the question under discussion. Another problem encountered by this group of faculty members was whether a molecule's ability to attach water would affect osmosis. All the statements above indicated dynamic *transformation* processes from thought experiments.

Modification Based on Reflection

Besides the thought experiment, *transformation* processes were also found in one's resolution to a complicated problem based on meta-level speculation of an interdisciplinary concept.

> Jo: **this is the suggestion, I made this big table that's all you've seen, but there are still places I don't really understand, or I think it might be a conflict with the definitions and we sort of quickly discuss this table.**
> David: if you made something red, it means.
> Jo: That's the parts I still have some confusions…

Jo demonstrated and described the adjustment of his epistemology concerning the disciplinary-oriented theories, methods, and conventional usage of units. Based on the reflection, he synthesized relevant concepts and units identified in distinct science textbooks and websites. He compiled a table to discuss with other science disciplinary experts. The physical creation of a new means to communicate with an interdisciplinary group satisfies the criterion for *transformation* process.

<u>Emergence of Transformative Assessment</u>

After gaining more understanding of *transformation* processes in the thought experiment and the acts taken based on the conceptual refinement, innovative ideas and implications for teaching and learning also emerged. The discourse exchange was based on a horizontal tube scenario, which became one of the interdisciplinary questions later (see Figure 2.4).

> David: So we have to have a rule I think at some point, what do we want them to get and what potential or missions do we make in this.
>
> Jo: **right and regarding to the animation and assessment, we're going to make as you said we can start with very simple maybe one solute, no external pressure maybe horizontal tube, something like that very simplest one to see whether students get that.**
>
> Jo: And the next step is adding more and more things to the simulation, right? Maybe at some points we say these are optional if you want to study more advanced topics.

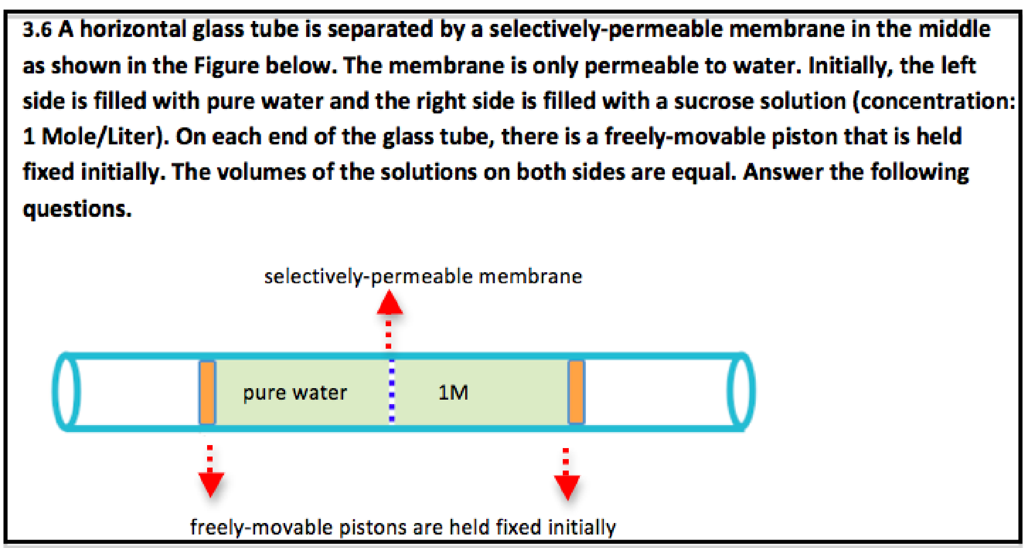


Figure 2.4. Depictions of the assessment stem emerged from the discourse exchanges.

Jo elaborated on the design of animation and assessment to determine whether students can use their disciplinary models, tools, theories, and methods to change a system found in another discipline and create while another new system.

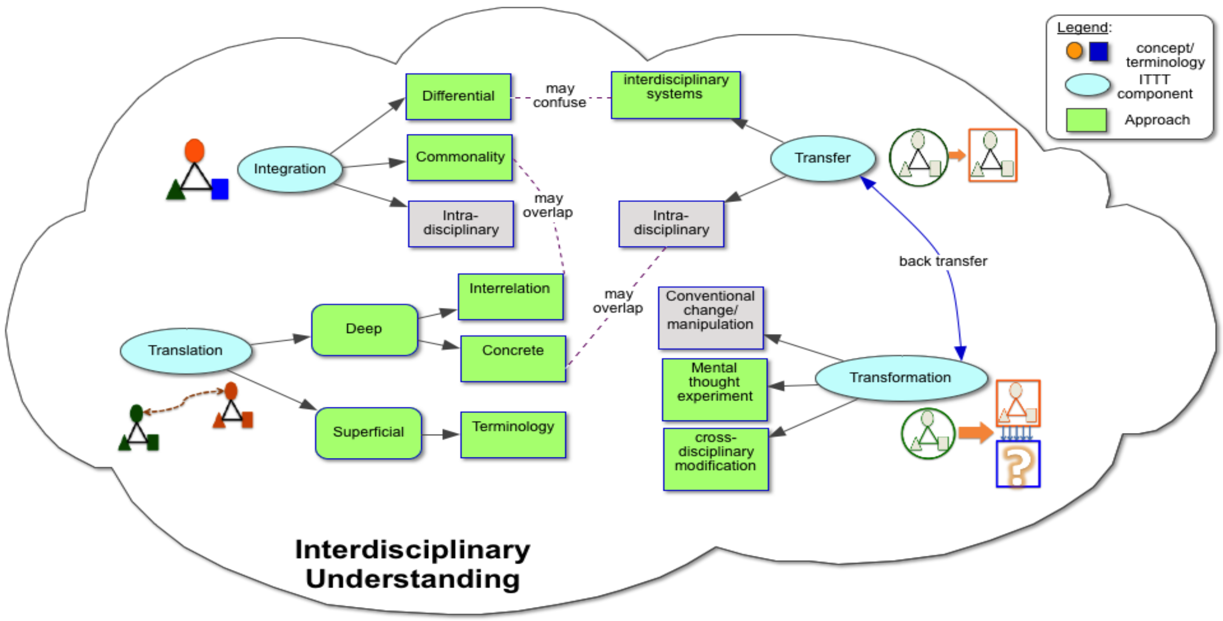


Figure 2.5. IT^3 framework revision.

Transformation aspect was better understood when one modifies an existing system and creates a new system mentally or physically to explain a phenomenon or test a hypothesis. It is more likely for a group to demonstrate this cognitive process when they encounter an incompatible reasoning to a phenomenon. That requires these scientists to reconstruct and refresh the assumptions from designated fundamental theories. Note that the *transformation* process we focus on excluded the conventional change/manipulation of concepts and existing experiments, which were already familiar to the whole group without any further modification. For example, once a novel mental thought experiment was completed, the following statement referring back to the same thought experiment was not coded as transformation anymore because the *transformation* has been done and there is no groundbreaking change in describing the created scenario. It leads to the possible link between *transformation* and *transfer* process, in which one utilizes a newly-created situation and applies it back to elaborate a phenomenon. The *back transfer* was found when the speaker tried to transfer back his revised view of osmosis to understand the ideal gas law.

Conclusions and Implications

In this paper, we elaborated a framework on IU that has four interrelated dimensions: *integration*, *translation*, *transfer*, and *transformation*. Our framework provides a theoretical foundation to understand the construct of IU. We then developed corresponding codes using this framework to analyze two segments of interdisciplinary faculty meeting with the focus on improving college-level integrated science education. We found that in the first meeting, the faculty members spent most of the time discussing concept-specific issues and engaged in the process of interdisciplinary translation. The second meeting revealed that the faculty members dwell on translating the concepts to one another 20% less frequently (83% to 63%) within concept-specific aspect.

The faculty members who sought to resolve the inconsistent usages of terminologies across disciplines demonstrated and confirmed the importance of nurturing the ability to translate in order to communicate with people who speak another “language” (Boix Mansilla & Duraising, 2007; Nikitina, 2005). The most difficult terms causing extensive clarification, objection, and discussion among the faculty members in this study were potential, osmotic potential, and osmotic pressure; this has significant educational implications when re-thinking teaching the topic of osmosis. Investigating how these terms are interpreted from different disciplinary-oriented is recommended. One important lesson learned from this study on the promotion of interdisciplinary learning is that if the faculty members encountered difficulty communicating with experts from other fields, we cannot expect our students to exercise these cognitive processes without scaffolds.

The current validation for the IT^3 framework seems a tedious and labor-intensive process; however, with the increasing demand to provide interdisciplinary education to the students with the expectation of fostering their higher order thinking, efforts to define and evaluate IU are necessary and valuable.

Promoting interdisciplinary education does not mean discarding disciplinary courses. In fact, the IT^3 framework involves advancement of disciplinary knowledge (i.e., intra-disciplinary) in order to communicate across disciplines. Students should be able to root their science knowledge in rigorous disciplinary training, and consciously elicit and apply their disciplinary perspectives to bring isolated concepts or inconsistent terminologies together in order to effectively communicate with others.

Limitations

In this study, only two particular meetings of faculty discussion were analyzed as a way to clarify and explain our framework. We expect the framework to further evolve if more empirical data are inspected by applying the IT^3 framework.

When we speak of interdisciplinarity, our views and data analysis are drawn from the perspectives within sciences. Applying this framework to include non-science domains is conceivable.

Acknowledgments

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Appendix A

Examples of the Two Layers of Coding

The content-specific and integration statement is in bold:

> Jo: I thought I understood, like when Andy wrote in the email, you know, you have to keep the free water, but you know when you go back to the formula, it's not gonna work anymore.
>
> Mike: Which formula?
>
> Jo: **The Van Hoff's, typically you need to calculate the solute potential or solute, osmotic pressure, whatever actually they have the same value if you use the same formula, right, cRT, mRT**
>
> Jo: **The Psi of solute equals negative miRT, and the m is the molar concentration of the solute.**

The formula itself might not be coded in the ITTT, but the conversation is about integrating these different ideas (osmotic pressure and solute potential) using this formula.

The meta-level and integration statements:

> Jo: So, now, we have two sorts of approaches, one is the core and connects to a different context, and somehow, we can put some that are related to biology and physiology or related to physics.
>
> Kevin: You can put hierarchy into that.
>
> Jo: And, we could make it a more hierarchical map.
>
> Kevin: We can do both.
>
> Jo: Yeah, we can do both.

Integrative understanding acknowledges that the different approaches carry different importance from distinct disciplinary perspectives (biology, physiology, and physics) into a hierarchical concept map. The realization requires meta-level reflection on different approaches usually taken by diversifying disciplinary experts.

The teaching-learning and integration statement is in bold:

> Jo: **Well, yeah, part of what David might be saying is that a biology student or biology instructor, you know, is also a physicist or whatever approaching this from a different perspective.**

> Jo: It's like a physicist is focusing on one area of the concept map, almost to the exclusion of the other, which is from one region and works his or her way out from there.

Jo talked about the student learning and the instructor's perception of a crosscutting concept. It implies that one approaches a topic from different disciplinary angles at the beginning (differential integration) and moves into the interlinked center (commonality integration). This is also a good demonstration of dividing one larger segment of a statement into two statement units because of the different topics identified in it.

The content-specific and translation statements:

> David: What is that? What does it mean?
>
> Kevin: Chemical potential? The change in the internal energy of a system when you add another one of those particles into the system. Ok, that's the most general definition.
>
> Jo: And, it can be converted to some other form.
>
> Andy: Isn't it in comparison to the starting point?
>
> Kevin: Well, it's in com…yes, in the sense that you're taking n measure of the chemical potential. You're taking a difference of energy between having n particles and n+1 particles.

These statements embody translating osmosis-related terms in order to effectively communicate to members from a different disciplinary background and perspective. David is an animal physiologist and he asked Kevin, who is a physicist, about the meaning of chemical potential and the timing, when it is measured.

The meta-level and translation statement is in bold:

> Kevin: I would say the water potential is still there even if you reach equilibrium.
>
> Kevin: …**and maybe that's not what a biologist would say. In which case, there's a, are differences of language.**
>
> David: That's exactly the problem, why nobody gets water potential and solute potential in plants, because its' absolutely defined and expressed like it's in physics, just completely counterintuitive with what you would in biology itself.

Kevin acknowledged distinct perspectives different disciplinary experts (e.g., biologist) bring, but in fact, they emphasized the same message just by using different disciplinary languages. The statement suggests a realization or reflection of the speaker that there are inconsistent scientific terms in different disciplinary backgrounds and perspectives.

The teaching-learning and translation statement is in bold:

> David: That's exactly the problem why nobody gets water potential and solute potential in plants, because its' absolutely defined and expressed like it's in physics, just completely counterintuitive with what you would in biology itself.
>
> David: **So, I think at least for that part we could actually translate that into biological term so it's more intuitive for people who are teaching that.**
>
> David: Because most of the people are just not teaching it at all because it's just a way mind twister.

David elaborated on the instructional aspect for incorporating or enacting learners' sense to translate scientific terms (water potential and solute potential as denoted in the first statement), which are often expressed differently to refer to the same thing. The segment of utterance was given by the same person but was divided into three different statements according to the different topical categories (concept and teaching-learning for the first two units). The second and third units both incorporated teaching and learning aspect; however, the third statement unit delivered a stand-alone meaning not in continuation from the prior statement.

The content-specific and transfer statement is in bold:

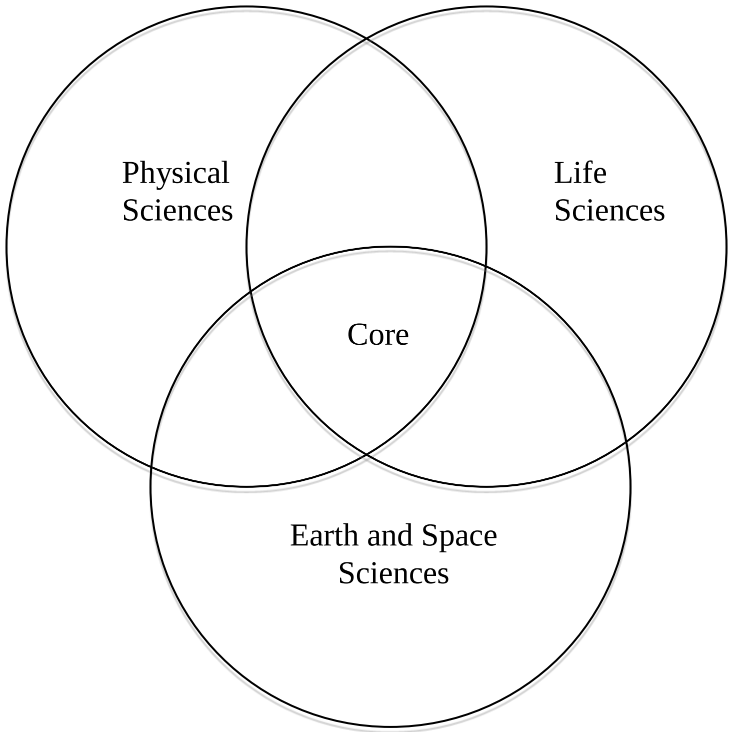
> Kevin: Right. So from a physics example, you can say, right this potential has a number and by something that we can measure all by itself,
>
> Kevin: but in order to have dynamics, something that change some sort of process happening, it must have a difference, it's the difference that drives those.
>
> David: and **I think it's actually maybe the problem I have, with the solute and pressure potential, because when people come to me and tell me well, that cell on its own in isolation has that pressure potential of that number and that solute potential..and I said what do you mean? What do you compare it to? That's what's on my mind**

Now David points out a problem: isolating a cell from its environment. If (solute or pressure) potential refers to some sort of solution difference across membrane, you cannot speak of solute potential of a cell detached from its environment. This is *transfer* because you apply the understanding/construct of potential from physical sciences to a plant biology context by point out how it is interpreted. One cannot simply assign a number to an isolated cell if the term "potential", as interpreted in physics, refers to difference between two solutions.

The meta-level and transfer statement is in bold:

> Andy: If we got a central connections about osmosis and then we relate those to biology and physics and then we work on how we, is there a central core how we relate it to?
>
> Andy: **If you understand the central core of osmosis, and you apply it in physics situation or biology situation, isn't there a central core that enables you to see the links between them?**
>
> Kevin: well, yeah, part of what David might be saying is that a biology student or biology instructor you know is also a physicist or whatever approaching this from a different perspective.

Andy recognized the similar system or core structure under study. He approached the "core" without mentioning about specific concepts explicitly. The "core" in the first statement unit could be an integrated core because it was not assigned to a disciplinary context (as defined in our transfer category). A "core" in a Venn diagram (see figure below) as one of the later statement mentions is an integrated unit. The *transfer* occurs when a "core" in one context is applied to another.



The teaching-learning and transfer statement is in bold:

> Kevin: We can focus on this area of the overall structure, but, Gosh, in biology they're going to focus on this area of the structure.
>
> Kevin: Look how we got connections of these things, we're gonna talk some of these stuff, and they're gonna talk some other stuff.
>
> Wendell: from my observation of my students and my own children, one of them is like this map, the other one is like hierarchy.
>
> Wendell: And I found good students, that they learned things with a core, integrated knowledge, and **then they extrapolate to physics, and biology.**

The second part of the last statement unit given by Wendell elaborated the enactment of students' application of the explanatory models (the core, integrated knowledge) learned from a particular discipline to another. Even though the first part of this statement was coded as *integration*, this example signified the application from disciplinary or integrated core to other science disciplines. Another more clear-cut example took place in explaining how to teach students to recognize the applicability of particular models:

David: I think that's the key to make a breakthrough to make those different solute and bringing together the solid footing and became kind of a model of our mind that we then start to explain everything, rather than having scenarios and we can only partly explain them.

Kevin: **right, or starting with a particular model say alright, this explains A, B, and C but it doesn't know, but it really really fails to explain D, E, and F but it's not a good model to teach them everything you want to teach them or maybe it's good enough.**

David: but maybe in the same time, we need to have the one that we have to attend everything if you really want to decide whether it's a good model for that model and how they all come together.

Kevin's statement provided a good example of the *transfer* process facilitated by the instructor. Students are expected to differentiate what contexts a model can or cannot be used to explain a situation.

The content-specific and transformation statements are in bold:

Kevin: the thing is, we want to say that the sucrose has been hydrated, but I mean, are we saying that because we wanted to have water molecules around it or just we want to be in a solution rather than sitting on the bottom of the beaker.

David: no, that' s the whole justification why osmosis occurs, right? **If that wouldn't happen if you wouldn't have attraction of water molecule reducing the free water, it would lose the concentration gradient in free water if you lose that reasoning, right?**

Kevin: see, I'm not convinced that's what's happening because I go back to the ideal gas model which is a very very bad model for what happens in liquid, I admit that but, but you can get the equivalent of osmosis with a purely ideal gas model

Kevin: So osmosis is water, so let's just talk about selective diffusion, **if I have gas A in two compartments, and a membrane that's permeable to gas A, then in addition I put some gas B over on one compartment but not the other, you would get the same behavior as osmosis.**

A *transformation* statement unit may include the modification of a mentally created thought experiment as an intention to demonstrate how to understand the explanatory models, tools, theories, and methods learned from one discipline to explain a cross-disciplinary question or problem. Because both David and Kevin used the "If" clause, meaning they were conducting thought experiments. In David's thought experiment, solute always hydrates and non-hydration solute particles are imaginary. This means, the speaker, in his head, transforms the real situation into an imaginary, different situation. Similarly, Kevin created an imaginary system for the subject under consideration to explain the content matter to other disciplinary experts.

The meta-level and transformation statement is in bold:

> Jo: **this is the suggestion, I made this big table that's all you've seen, but there are still places I don't really understand, or I think it might be a conflict with the definitions and we sort of quickly discuss this table.**
> David: if you made something red, it means.
> Jo: That's the parts, I still have some confusions.

Jo demonstrated and described his adjustment of his epistemology concerning the theories and methods by compiling a table to discuss with other science disciplinary experts.

The teaching-learning and transformation statement is in bold:

> David: So we have to have a rule I think at some point, what do we want them to get and what potential or missions do we make in this.
> Jo: **right and regarding to the animation and assessment, we're going to make as you said we can start with very simple maybe one solute, no external pressure maybe horizontal tube, something like that very simplest one to see whether students get that.**
> Jo: And the next step is adding more and more things to the simulation, right? Maybe at some points we say these are optional if you want to study more advanced topics.

Jo elaborated on the creation of animation and assessment to determine whether students can use their disciplinary models, tools, theories, and methods to change a system found in another discipline and create while another new system.

The content and other statement is in bold:

> Jo: yeah, I'm also very confused myself.
> David: **so maybe we can all think about, you know, Kevin comes up with an overview of what potential means**

The purpose is to translate, but nothing has been done, yet. It is just a proposal for translating the term “potential”. Therefore, it is coded under content-other.

CHAPTER 3

UNDERSTANDING OSMOTIC PRESSURE FROM AN INTERDISCIPLINARY PERSPECTIVE[3]

[3] Sung, S., Shen, J., Stanger-Hall, F. K., Wiegert, C., Li, W., Brown, S., and T. Robertson. To be submitted to *CBE-Life Sciences Education*.

Abstract

We examined the definitions of *osmotic pressure* (P_{osm}) in different well-circulated college science textbooks. Motivated by the discussion of a team of disciplinary experts from several disciplines, we examined 20 textbooks in biology, chemistry, physics, animal/plant physiology, biochemistry, and physical biochemistry. The analysis shows that the definitions or descriptions of P_{osm} in these textbooks include 5 categories in two related aspects: the conceptual definition (CD) of the term and the quantitative measure (QM) of the variable. Three main categories related to CD are: (1) P_{osm} is the force that pulls/drives water across a selectively permeable membrane into a solution with a higher solute concentration; (2) P_{osm} is the external pressure required to stop, prevent, or reverse osmosis; and (3) P_{osm} is the internal pressure of a solution or substance that develops through osmosis under volume constraint. Two categories of QM are: (1) P_{osm} is proportional to the solute (or water) concentration (gradient) across a selectively permeable membrane; (2) P_{osm} is measured through the additional pressure applied to stop osmosis. We also examined the defining contexts of the term in these textbooks, which resulted in 7 categories. The connections and possible inconsistencies among these different definitions or descriptions across disciplines are discussed.

Introduction

Interdisciplinary or integrated education has been advocated for decades for its perceived benefits. It elevates learners' cognitive advancement in a way that is impossible with a single discipline (Boix Mansilla & Duraising, 2007). It promotes deep, interdisciplinary understanding, that is, one's "capacity to integrate knowledge and modes of thinking in two or more disciplines" (Boix Mansilla & Duraising, 2007, p. 219). Interdisciplinary learning provides learners with multiple perspectives, which encourage them to integrate and apply knowledge across disciplines and make connections to the real world (Jones, Merrin, & Palmer, 1999; Ivanitskaya, Clark, Montgomery, & Primeau, 2002). It is also argued that interdisciplinary learning is more likely to enable students to develop metacognitive skills (Ivanitskaya et al., 2010; Newell, 2000; Repko, 2008; Steiner & Laws, 2006).

A paradox exists between discipline-based and interdisciplinary learning: although the knowledge from individual disciplines are the building blocks for interdisciplinary integration, the discipline-based training may create tunnel vision for students who do not appreciate the entirety of science (Klein, 1999, 2010; Lattuca, Voigt, & Fath, 2004; Repko, 2008). Discipline-based learning is usually framed to solve conceptually localized problems, which may discourage students' knowledge transfer from science classrooms to the real world (Boix Mansilla & Duraising, 2007; Gibbson, 1998; Newell, 2000; Rhoten & Parker, 2004). Furthermore, students learn disciplinary jargons, which may prevent effective knowledge integration and collaboration across disciplines (Finkenthal, 2001; Repko, 2008).

To address the challenges of discipline-based education and to help students develop interdisciplinary understanding within the natural sciences, we formed a team of scientists and educators from various disciplines to discuss issues related to interdisciplinary teaching and learning. Specifically, we developed and implemented an assessment instrument targeting osmosis. Experiencing difficulty reconciling the disciplinary use of certain terminologies related to osmosis (Sung, Shen, & Zhang, 2012), we turned to the typical textbooks used by our team members and examined the terminologies. Specifically, in this study we report our findings related to one term, osmotic pressure (P_{osm}), that caused the most confusion for us. The analysis showed that the definitions or descriptions of P_{osm} in these textbooks are often inconsistent. We believe that this finding sheds light on student learning about osmosis in particular, but also has important implications for helping students improve interdisciplinary integration and transfer among science classes in general.

***Understanding* Osmosis**

We chose the topic of osmosis because it involves multiple disciplines and has caused much confusion for students. Osmosis is typically defined as the net movement of water through a selectively permeable membrane from a region of lower solute concentration to a region of higher solute concentration. It is central to various life processes, such as plant water intake, cell expansion, water balance and transport in living creatures and in the environment. It is also related to many physical and chemical concepts, such as pressure, solutions, and the particulate nature of matter (Friedler, Amir, & Tamir, 1987). It was ranked the most important science concept in medical education (AAMC, 2011).

Although osmosis is an important science concept, it is also a poorly understood one (Fisher, Williams, & Lineback, 2011; Odom, 1995; Odom & Barrow, 1995, 2007). Research has shown that students have misconceptions concerning the mechanisms and processes of osmosis at all levels (Kramer & Myers, 2012a; Odom, 1995; Odom & Barrow, 1995, 2007). For example, students often think that the solvent stops moving once the solution reaches equilibrium or that the solute “absorbs” water from areas with low solute concentration. Students also may believe incorrectly that osmosis is influenced by life forces or requires an input of energy (Odom, 1995). In addition, osmosis is often introduced as a special case of diffusion across a selectively permeable membrane; however, the rate at which water flows is inconsistent with the diffusion theory (Kramer, 2013). The perception of osmosis as being driven by water dilution is also erroneous (Kramer & Myer, 2012b).

Playing a critical role in understanding osmosis, the concept of osmotic pressure (P_{osm}), has been controversial since its introduction by Pfeffer in the late 19th century. Later, van’t Hoff’s comparison of P_{osm} to the partial pressure in the ideal gas law has raised further debate (Berg, 2006). In a more recent article, Kramer and Myers (2012a) identified five common misconceptions people hold regarding osmosis, one of which is related to osmotic pressure: P_{osm} is interpreted as the partial pressure of the solute, which goes back to van’t Hoff’s theory. The authors pointed out that this is incorrect because this interpretation only applies when there is no solvent-solute interaction. Herroun (as cited in Berg, 2006) commented that the term P_{osm} is misleading and argued that there is no evident P_{osm} in the system, instead water passes the membrane with attractive force, which is opposite of Kramer (2013)’s repulsion theory. On the other hand, physiologist Harold Hammel suggested that two different pressures regulate solute and solvent, and P_{osm} is the enhanced solvent tension, which is equal to a negative external pressure (Hammel, 1979). This solvent tension theory was refuted later (as cited in Kramer, 2013). Similar terminology confusion was found in Sung, Shen, and Stanger-Hall’s (2012) study in which students in an introductory biology class incorrectly used P_{osm}, pressure potential, and water potential interchangeably.

Student misconceptions are resilient to even targeted instruction (Bransford, Brown, & Cocking, 2000; Wandersee, Mintzes, & Novak, 1994). One reason is that learners cannot visualize and therefore do not understand molecular level processes, critical in understanding osmosis (Odom, 2007; Odom & Kelly, 2001). Another less explored factor, as we have personally experienced and will show in this study, is that the terms related to osmosis used in different disciplines are not necessarily coherent or compatible (Friedler et al., 1987; Kramer & Myers, 2012a,b).

Methods

With the goal of sorting out the definitions and descriptions of the term *osmotic pressure*, we collected a convenient sample of 20 popular college-level science textbooks from our content experts (university faculty members in science disciplines). The list of the textbooks is shown in Table 3.1. There are 9 introductory textbooks, covering biology (5), chemistry (3), and physics (1), and 11 advanced textbooks, covering animal physiology (3), plant physiology (3), biochemistry (2), physical chemistry (2), and physical biochemistry (1). Note that we did evaluate 6 introductory physics textbooks, but only one of these included a consideration of osmosis and osmotic pressure.

After collecting the textbooks, we searched for the term *osmotic pressure* in the textbook index and obtained a copy of all relevant text in those chapters. The direct quotes were entered into an Excel spreadsheet for easy comparison and retrieval. Relevant diagrams and figures were also scanned and compiled.

When examining the texts, we first generated a list of shortened descriptions for each distinctive description. These descriptions were then assigned to tentative categories and subcategories to accommodate varying kinds of definitions and framing contexts. The categories were presented to the team for discussion, and the meaning of every category was clarified iteratively until consensus was reached.

We then applied the categories to code the texts: We checked off that category if the textbook contained a description that matched the category. The inconsistent occurrence of categories in an individual textbook was tallied. If a main category was divided into subcategories, and the text could be categorized into more than one subcategories, we still counted it as one incidence when comparing inconsistent P_{osm} definitions among categories. Additionally, given the idiosyncratic cultures of how science concepts are introduced in specific disciplines, we also recorded the contexts in which P_{osm} was described in the texts.

To compare and contrast the categories directly and visually, we also converted all the definitions using a generic U-tube scenario that occurs in many textbooks.

Table 3.1
The 20 Textbooks Examined in This Study Include Seven Science Disciplines

Level	Disciplines	Authors	Title (version)	Publisher
Intro-ductory	Biology	Brooker et al.	Biology (2nd)	McGraw Hills co.
		Raven et al.	Biology (9th)	McGraw Hills co.
		Reece et al.	Biology (9th)	Pearson
		Russel et al.	Biology: The Dynamic Science (11th).	Thomson Higher Educat
		Sadava et al.	Life: The science of biology (9th)	W. H. Freeman & Co
	Chemistry	Brown et al.	Chemistry: The Central Science (11th)	Pearson
		Whitten et al.	Chemistry	Brooks Cole.
		Zumball & Zumball	Chemistry (8th)	Brooks Cole
	Physics	Urone	College Physics (2nd)	Brooks Cole
Advanced	Physiology			
	Animal	Rhodes & Pflanzer	Human Physiology (3rd)	Saunders College Pub.
		Eckert et al.	Animal physiology: mechanisms and adaptations (3rd)	W. H. Freeman & Co
		Fox	Fundamentals of human physiology	McGraw-Hill's
	Plant	Raven et al.	Biology of plants (7th)	W. H. Freeman & Co
		Nobel	Physicochemical and environmental plant physiology (3rd)	Dana Dreibelbis
		Hopkins & Huner	Introduction to plant physiology (3rd)	Willey
	Physical Chemistry	Atkins & de Paula	Physical Chemistry	W. H. Freeman & Co
		Engel & Reid	Thermodynamics, statistical thermodynamics, and kinetics.	Pearson
	Biochemistry	Lehninger	Lehninger Principles of Biochemistry (4th)	W. H. Freeman & Co
		Moran et al.	Principles of biochemistry (5th)	Pearson
	Physical Biochemistry	Atkins & de Paula	Physical Chemistry for the Life Sciences	W. H. Freeman & Co

Results

The analysis shows that the definitions or descriptions of P_{osm} in the 20 textbooks included two related aspects: the conceptual definition (CD) of the term and the quantitative measure (QM) of the variable. We report these two aspects separately because they were not necessarily described coherently in the textbooks. We identified three categories for conceptual definition (CD I-III) and two categories for quantitative measurement (QM I-II, see Table 3.3). We describe the categories first, and then summarize the contexts used by the textbooks.

Conceptual Definition of P_{osm}

Conceptual Definition I (CDI)

The first category of CD emphasizes the causal connection between P_{osm} and water movement, i.e., P_{osm} leads to osmosis. More specifically, in this category, *osmotic pressure is defined as a "force" that drives/pulls water from a solution with lower solute concentration (or higher water concentration) into a solution with higher solute concentration (or lower water concentration) across a selectively permeable membrane.* For instance, an animal physiology textbook stated, "Starling suggested that water balance in capillary beds is a result of two opposing forces…blood pressure squeezes water and small solutes out of the capillaries, osmotic pressure pulls water back into the capillaries" (Sadava et al. 2011, p.1059).

We illustrate the meaning of P_{osm} of this category in two contexts shown in Figure 3.1: scenario (a) depicts a context analogous to a blood vessel with many factors being taken out for simplification; scenario (b) depicts a U-tube context, a common scenario across many textbooks.

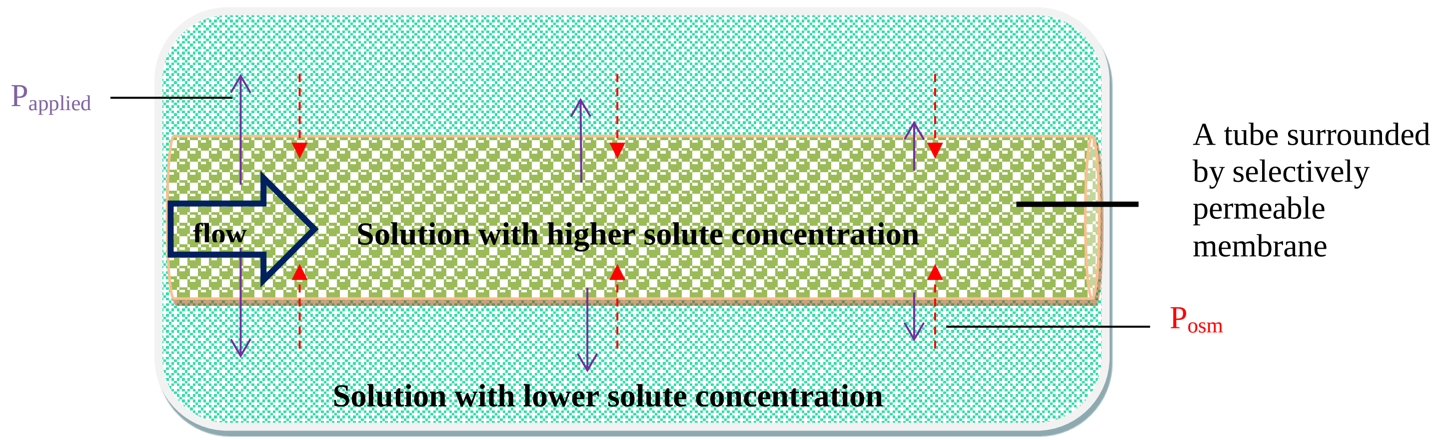
In Fig 3.1 (a), a solution of a higher solute concentration flows along a tube (analogous to a blood capillary) with a selectively permeable membrane immersed in a solution of a lower solute concentration. At a macroscopic level, there are two pressures regulating the movement of water in or out of the membrane at any given point: the pressure driving the flow of the solution inside the tube (analogous to blood pressure, note that this pressure may vary over time and decreases along the flow of the solution) and the P_{osm} caused by the solute or solvent concentration difference, as defined in CDI. The former pushes water out of the tube across the membrane whereas the latter drives/draws water in. When the two pressures are balanced with each other, there is no net water movement across the membrane. This definition of P_{osm} applies to cells as well. Some textbooks highlighted the consequence of water movement caused by P_{osm}. For instance, Nelson and Cox (2005) state, “Osmotic pressure tends to drive water into cells. If not somehow counterbalanced, this inward movement of water would distend the plasma membrane and eventually cause bursting of the cell (osmotic lysis)” (p. 57).

This scenario can be converted to a U-tube scenario shown in Figure 3.1 (b), which will be used throughout the paper as a reference context. In this context, there are two solutions in the two arms of a U-tube, separated by a selectively permeable membrane at the bottom. In this case, the solution on the left side has a higher solute concentration (analogous to the compartment enclosed in the tube in (a)) relative to the right side, resulting in the corresponding P_{osm} that drives water to move from the right to the left across the membrane. There is also an applied pressure exerted on the left column (analogous to the blood pressure). Note that the membrane in the U-tube in scenario (b) is only corresponding to a particular location of the membrane of the tube in (a), where the magnitude of blood pressure changes along the vessel.

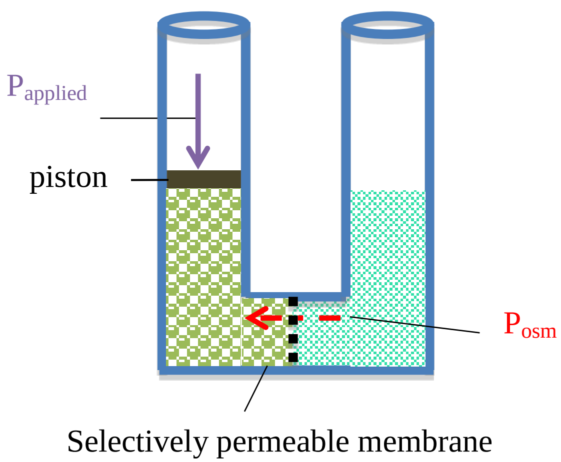
In this mechanical explanation, the solute concentration difference leads to P_{osm}, which in turn counterbalances a pressure caused by some external force (e.g., blood pressure) to regulate the water movement across a selectively permeable membrane. This mechanism is essential in understanding the homeostasis of blood volume in animal physiology. This model is analogous to the Newtonian force analysis and is fairly easy to comprehend. However, it creates some confusion as the formation of P_{osm} is not explained. The ideal gas model is simply incorrect. Furthermore, some textbooks (e.g., Sadava et al., 2012; Reece et al., 2011; Hopkins & Huner, 2003) in their descriptions equated pressure and force, which are two different physical variables (pressure is force per area). An example from Hopkins and Huner's plant physiology textbook (2003) stated "…the tube could be fitted with a piston that would allow us to measure the amount of force required to *just prevent* any increase in the volume of solution. This **force**, measured in units of pressure…is known as **osmotic pressure**."

Figure 3.1. Interpretation of P_{osm} in *CDI*: (a) Horizontal tube model: A tube (analogous to a blood capillary) surrounded by a selectively permeable membrane is immersed in a solution with a lower solute concentration. There is an applied pressure (analogous to blood pressure) drives the flow of the solution inside the tube. This applied pressure at the boundary of the membrane (purple arrows) pushes water out of the tube. P_{osm} (red-dashed arrows), caused by the solute concentration difference, drives/pulls water into the tube. (b) U-tube model: a U-tube is filled with two solutions in each of its two arms, separated by a selectively permeable membrane at the bottom. The one on the left has a higher solute concentration than the one on the right. There is an applied pressure exerted on the left column of solution drives the water from left to right across the membrane. P_{osm}, caused by the solute concentration difference, drives/pulls water from right to left across the membrane. Note that the membrane in the U-tube is only corresponding to a particular location of the membrane in (a).

(a)



(b)



Conceptual Definition II (CDII).

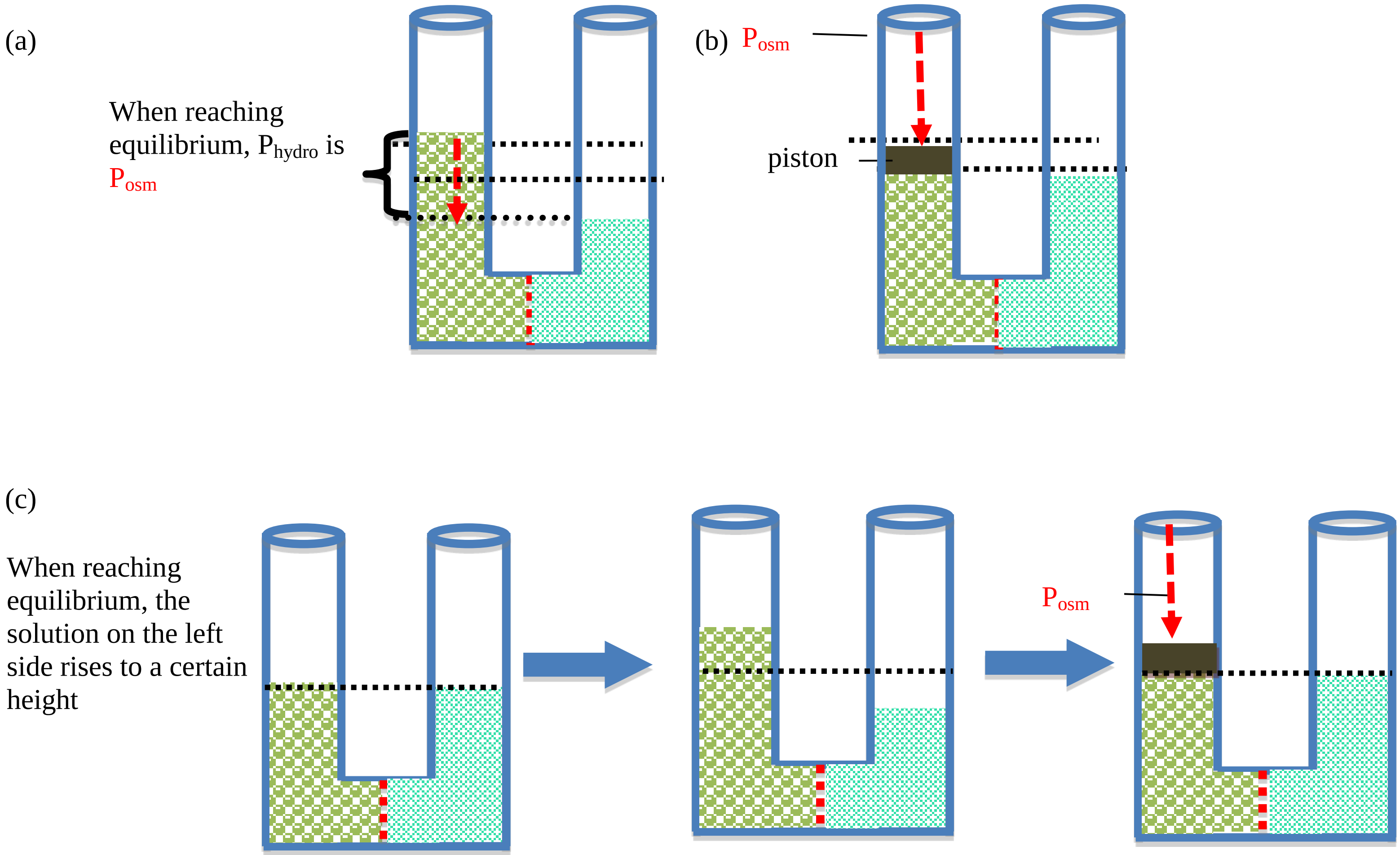
The second conceptual definition category defines P_{osm} as *the pressure needed to stop osmosis*. This definition of P_{osm}, with respect to its causal relationship with osmosis, is the opposite of CDI. The second category can be further divided into three subcategories based on the time point when the pressure is applied.

In the first subcategory (CDII-A), *P_{osm} is the hydrostatic pressure that results from osmosis.* This definition emphasizes the state when a dynamic equilibrium has been reached. Figure 3.2 (a) illustrates this definition for a typical U-tube scenario. An initial net water movement from the side with lower solute concentration (the right side) toward the side with higher solute concentration (the left side) causes the rise of the solution on the left side until an equilibrium is reached (the net flow of water is zero). The water movement by osmosis causes the build-up of an extra column of solution on the left side. At equilibrium, this raised column on the left side exerts a hydrostatic pressure toward the rest of the solution that pushes additional water back towards the right side, counterbalancing the water movement due to osmosis. This hydrostatic pressure was defined as P_{osm} in several textbooks: For example,

- "…there is a greater hydrostatic pressure on the solution than on the pure solvent. This excess pressure is called the osmotic pressure" (Zumdahl & Zumdahl, 2010, p.520)
- "to counteract this tendency [the net diffusion of water] and establish equilibrium, a hydrostatic pressure is necessary on the solution side. This pressure is often called the osmotic pressure" (Nobel, 2005, p.64).

This definition can be applied to the context of a cell as well. For instance, Brooker et al. (2010) described, "The tendency of water to move into a cell creates an osmotic pressure, which is defined as the hydrostatic pressure required to stop the net flow of water across a membrane due to osmosis" (p.108). Urone (2000), in his physics textbook, called this "back pressure," which is also (relative or absolute) P_{osm}: "The back pressure ρgh that stops osmosis is called the relative osmotic pressure if neither solution is pure water, and it is called the osmotic pressure if one solution is pure water" (p. 289).

Figure 3.2. Interpretation of P_{osm} in CDII: At the initial state, two solutions of different solute concentration are separated by a selectively permeable membrane and the left side has a higher solute concentration than the right side. (a) P_{osm} is defined as the hydrostatic pressure exerted by the risen column of solution after reaching equilibrium; (b) P_{osm} is defined as the external pressure needed to prevent osmosis from the beginning; (c) P_{osm} is defined as the pressure needed to reverse osmosis to reach the initial state.



In the second subcategory (CDII-B), *P_{osm} is the pressure required to prevent osmosis in the very beginning.* Unlike subcategory A, several textbooks characterized P_{osm} as the external pressure required to prevent any initial net water movement (Figure 3.2, b). Here are some examples:

- "the pressure required to prevent osmosis by pure solvent is the osmotic pressure" (Brown et al. 2009, p. 553).
- "[the osmotic pressure is] the pressure required to prevent the flow of solvent" (Moran et al. 2012, p. 35).

In the third subcategory (CDII-C), *P_{osm} is the pressure that would have to be applied to the solution to reverse the system to the initial state from the equilibrium state* (Figure 3.2, c). For example, Raven and his colleagues (2003) stated that "[osmotic pressure] is the pressure that must be applied to the piston to force the column of solution back to the level of the water in the beaker" (p. 75). In this definition, P_{osm} is the theoretical pressure required to negate the pressure built-up due to osmosis.

The three subcategories are closely related to one another. CDII-A looks at osmosis when the system reaches the final state of equilibrium; CDII-B imposes an external pressure to maintain the initial state; CDII-C proposes to reverse the equilibrium state back to the initial state. All three subcategories focus on the factor (or process) that counteracts the net water movement due to osmosis, which is exactly the opposite of CDI that views osmosis as induced by P_{osm}.

<u>Conceptual Definition III (CDIII)</u>

The third category treats *P_{osm} as the internal pressure of the solution exerted on its environment, which is limited in its ability to expand, due to the increasing volume of the* *solution generated by osmosis*. This approach is commonly used when a plant (or bacterial) cell is considered. The cell wall of a plant cell is fairly rigid, preventing the expansion of the cytosol inside the cell when its volume increases due to osmosis. Figure 3.3 (a) sketches the scenario of a sac (analogous to a cell) with a selectively permeable membrane constrained in non-elastic case (analogous to a cell wall), immersed in a solution. In this category, P_{osm} is pointing outward with reference to the sac.

Several textbooks explained the internal pressure of plant cells and some explicitly identified the pressure as the P_{osm}. For instance, Sadava et al. (2011) described the establishment of the internal pressure as the following, “However, the cell can’t expand because it is contained by the cell wall; thus, as water enters, the cell’s internal pressure increases and resists the further entry of water” (p. 742). Moran et al. (2012) elaborated further on the characteristic of this internal pressure:

> …water molecules tend to move across the cell membrane in order to enter the cell and dilute the solution inside the cell. The influx of water causes the cell’s volume to increase but this expansion is limited by the cell membrane… Most cells use several strategies to keep the osmotic pressure from becoming too great and bursting the cell…some species (e.g., plants and bacteria) have rigid cell walls that prevent the membrane expansion. These cells can develop high internal pressures (p. 35).

This interpretation of P_{osm} has another popular name, “turgor pressure,” as noted in Brooker et al. (2010): “in plants, P_{osm} is also called turgor pressure, or simply cell turgor. The turgor pressure pushes the plasma membrane against the rigid cell wall. An appropriate level of turgor is needed for plant cells to maintain their proper structure” (p. 108); and in Russell et al. (2011) “The osmotic pressure, called turgor pressure, pushes the cells tightly against their walls and supports the softer tissues against the force of gravity" (p.130).

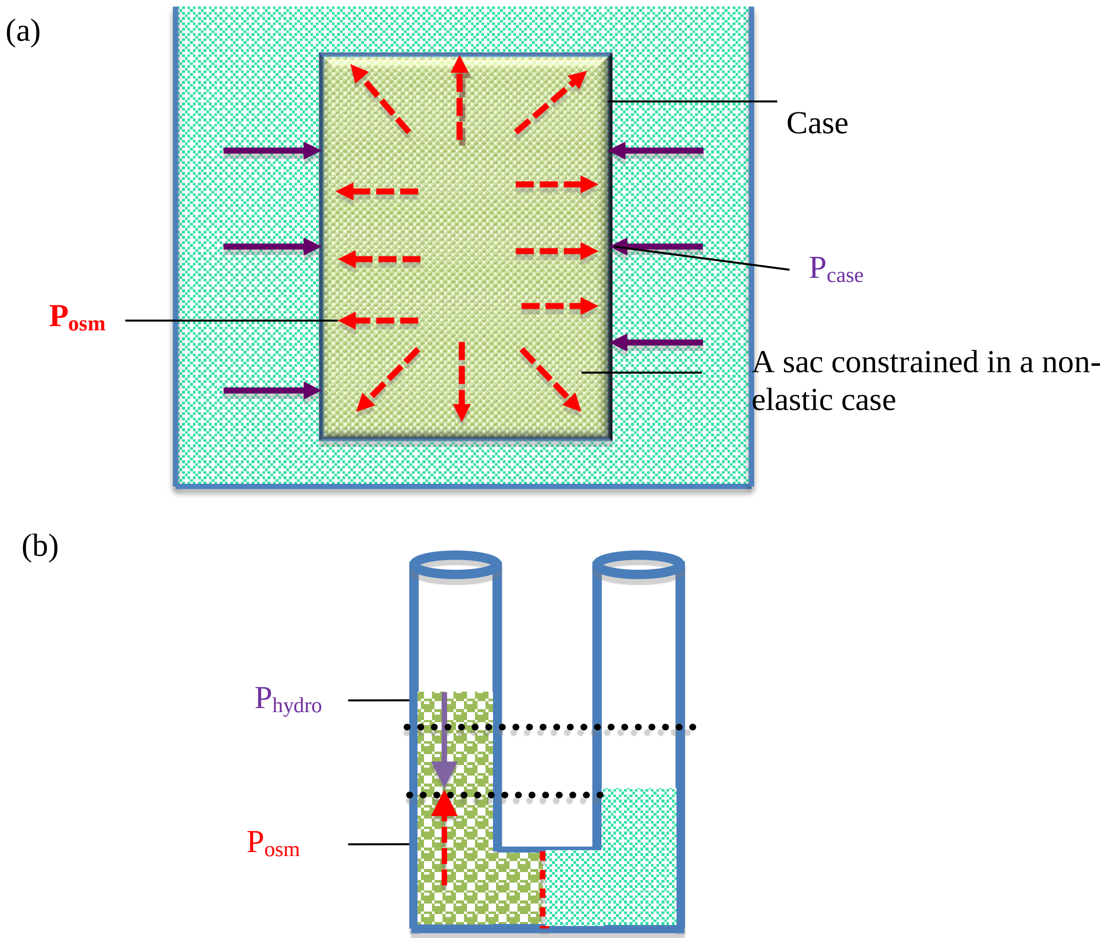
Some textbooks introduced a wall pressure as a counterbalance to turgor pressure. For example, Hopkins and Huner (2003) remarked, "In cells, the pressure component arises from the force exerted outwardly against the cell walls by the expanding protoplast. This is known as turgor pressure. An equal but opposite inward pressure, called wall pressure, is exerted by the cell wall" (p. 212).

Figure 3.3 (b) shows the U-tube scenario. For instance, Atkins and de Paula (2006) defined P_{osm} under the U-tube scenario in which hydrostatic pressure acts against P_{osm} (see Figure 3.3 (b)). They state:

> …the pressure opposing the passage of solvent into the solution arises from the hydrostatic pressure of the column of solution that the osmosis itself produces. This column is formed when the pure solvent flows through the membrane into the solution and pushed the column of solution higher up the tube. Equilibrium is reached when the downward pressure exerted by the column of solution is equal to the upward osmotic pressure (p.136).

Note that this definition contrasts CDII-A, which considers P_{hydro} as P_{osm}. In CDIII, P_{hydro} and P_{osm} counteract each other.

Figure 3.3. Interpretation of P_{osm} of the CDIII: (a) Sac model: A selectively-permeable membrane sac contains a solution with higher solute concentration. The sac is constrained in a non-selectively permeable case immersed in water or a solution of lower solute concentration. The case is rigid with little capacity for expansion and is approximately the same size as that of a sac. P_{osm} is defined as the internal pressure of the sac pushing against the wall of the case. (b) U-tube model: The top dotted line represents the initial height of solution, and the bottom dotted line indicates the level of the solution on the right when reaching equilibrium, P_{osm} is the internal pressure acting against the hydrostatic pressure (P_{hydro}), which is analogous to wall pressure in a plant cell.



Quantitative Measure (QM) of P_{osm}

In addition to categorizing conceptual definitions of osmosis we also sorted out the ways in which P_{osm} was measured or quantified in the textbooks. We identified two main categories denoting different ways of measuring P_{osm} or interpreting the value of P_{osm}.

Quantitative Measure I (QMI)

The first category of QM links the measurement of P_{osm} to solute concentration: *the magnitude of P_{osm} is calculated as a function of solute (or water) concentration of the solution under consideration.* This description goes back to the van't Hoff law, which states that P_{osm} of a dilute solution (i.e., an "ideal" solution) is the product of the universal gas constant (*R*), the absolute temperature (*T*), and the molar concentration of the solute (*M*): $P_{osm} = MRT$ (e.g., Atkin & de Paula, 2002). The molarity *M* can be expressed by *n*/*V*, where *n* is the number of moles of solute in the solution, *V* is the volume of the solution (Whitten et al., 2010). Therefore, as long as *M* and *T* are given, P_{osm} can be calculated. Whitten et al. (2010) described the basic factors affecting P_{osm} as the following:

> Osmotic pressure increases with increasing temperature because *T* affects the number of solvent-membrane collisions per unit time. It also increases with increasing molarity because *M* affects the difference in the numbers of solvent molecules hitting the membrane from the two sides, and because a higher *M* leads to a stronger drive to equalize the concentration difference by dilution and to increase disorder in the solution (p.545).

Their description depicted the thermodynamic nature of P_{osm}.

P_{osm} is a colligative property of a solution (Brown et al., 2009; Whitten et al., 2010; Zumdahl & Zumdahl, 2010), meaning that its magnitude only depends on the concentration of solute particles, regardless of the nature of the particles (Brown et al., 2009). If the solutes are strong electrolytes, the measure of electrolyte dissociation should be considered. Van't Hoff factor, *i*, was often used to describe the ratio of the moles of particles in solution and the moles of solute dissolved (Zumdahl & Zumdahl, 2010). In animal physiology, van't Hoff factor (*i*) and molarity (*M*) were combined and replaced by osmolality/osmoles (Eckert, 1978; Fox, 2009; Nelson & Cox, 2005; Rhoades & Pflanzer, 1996).

Some textbooks described the magnitude of P_{osm} as a property of a single solution. For instance, Rhoades and Pflanzer (1996) stated, "osmotic pressure is a property of a solution that is proportional to the solute concentration. A dilute solution will have a lower osmotic pressure than a concentrated solution" (p. 120). Fox (2009) also stated, "the greater the solute concentration of a solution, the greater its osmotic pressure. Pure water has an osmotic pressure of zero, and a 360-g/L glucose solution has twice the P_{osm} of a 180-g/L glucose solution" (p. 135).

Many other textbooks, however, explicitly pointed out the relative sense of this quantitative aspect. That is, P_{osm} is associated with the solute concentration of a solution relative to another, separated by a selectively permeable membrane. Therefore, what matters is the solute concentration difference between the two solutions. Furthermore, only the osmotically active solutes matter. For instance, Hopkins and Huner (2003, p.209) pointed out, "It is useful to note that an isolated solution cannot have an osmotic pressure. It has only the potential to manifest a pressure when placed in an osmometer." (An osmometer is a device for measuring pressure exerted due to osmosis). Nobel (2005) also argued against the existence of P_{osm} in an isolated solution by saying that "in the sense of requiring an applied hydrostatic pressure to maintain equilibrium, the answer [to the question concerning whether isolated solution has an osmotic pressure] is no" (p.65). The different perceptions of QM indicate the differences in describing the magnitude of P_{osm}.

QMI is common in animal physiology contexts. Reese et al. (2010) described how dissolved proteins in blood vessels are responsible for P_{osm}, "…these dissolved proteins are responsible for much of the blood's osmotic pressure (the pressure produced by the difference in solute concentration across a membrane)" (p. 909).

Quantitative Measure II (QMII)

The second category of QM directly measures pressure corresponding to the definitions of CDII or CDIII. These values can be obtained empirically. Specifically, *the magnitude of* P_{osm} *in this category is expressed by the numerical value of the pressure required to prevent, stop, or reverse osmosis* (corresponding to CDII) or *the value of the internal pressure of the solution due to the increasing volume of the solution generated by osmosis* (corresponding to CDIII).

In CDII-A, since P_{osm} is defined as the hydrostatic pressure that results from osmosis reaching equilibrium, it can be calculated as ρgh, where ρ is the density of the risen solution, g is the acceleration of gravity, and h is the risen height (Urone, 2000; Brooker et al., 2010). For CDII-B and CDII-C, P_{osm} is equal to the external pressure needed to either prevent osmosis at the beginning (e.g., Hopins & Huner, 2003) or reverse osmosis to its initial state after reaching equilibrium (e.g., Raven et al., 2003).

It should also be noted, however, that the three subcategories (CDII-A, -B, -C) do not give the same numerical values of P_{osm}. This was pointed out by Atkins and de Paula (2002), who remarked that "the entry of solvent into the solution results in its dilution, and so it is more difficult to treat than…[when] there is no flow and the concentrations remain unchanged" (p. 178). More specifically, if the three scenarios have the exact same initial setup (see Figure 3.2), the P_{osm} of CDII-B and –C are the same but that from CDII-A yields a P_{osm} with a smaller value (note that in CDII-C, the pressure is a variable, not a constant; however, what is considered here is the final pressure needed to reverse osmosis all the way back to its initial state/height of water column). This is because in CDII-A, the solution on the left side is diluted due to the water flow in from the right side, causing the concentration difference between the two sides to decrease. If only dilute solutions are considered, and the dilution effect is negligible, then the values are approximately the same. But this is not explicitly pointed out in most textbooks.

For CDIII, Hopkins and Huner (2003) described a method for directly measuring the internal pressure or turgor pressure in cells. They stated,

> [P. B.] Green devised a micromanometer (a manometer is a pressure measuring device) by closing off one end of a microcapillary tube and drawing out the other end to a fine point. When inserted into the vacuole of a giant cell of *Nitella*, a filamentous alga, the pressure of the cell serves to compress the gas volume in the tube. By measuring the volume change (using a microscope, of course) and applying the ideal gas laws (the product of pressure and volume is constant), the turgor pressure of the cell can be calculated (p. 543).

They then introduced a more sophisticated version developed by Zimmermann and Steudle (for more details, see p.543 in Hopkins & Huner, 2003).

Contexts for P_{osm}

In addition to the descriptions of P_{osm}, we also examined the contexts in which P_{osm} is presented in the textbooks. These contexts use either a physical setting or a biological setting. Table 3.2 lists the categories found in the textbooks.

Table 3.2

Categories for the Defining Contexts of Osmotic Pressure.

Setting	Codes	Meaning
Physical	P^1	U-tube or equivalent setup (e.g., a container with a membrane in the middle that separates two solutions)
	P^2	a tube with a membrane at the bottom in a solution, with an open-end sticking out of the solution
	P^3	a sac with a membrane in a solution in a container
	P^4	ideal gas
Biological	B^1	cells of all kinds
	B^2	cells with a cell wall such as plant cells or bacterial cells
	B^3	capillary or other circulatory system components of human or other species

Distribution of Definitions and Defining Contexts

Table 3.3 lists the distribution of the conceptual definitions (CDI-III) and quantitative measures (QMI-II) in these 20 textbooks. In the following, we first report the distribution of the individual categories among the 20 textbooks. Then, we describe the overall patterns with respect to the comparison between the introductory and the advanced textbooks and that between the physical sciences and the life sciences textbooks.

A total of 9 textbooks included CDI, which describes the P_{osm} in relation to the direction of water movement and concentration difference. All these textbooks were biology-related. As water homeostasis is critical for an organism's survival, it seems understandable that discussions of P_{osm} focused on the "driving force" for water movement. However, the defining contexts are split: out of these 9 textbooks, 5 of them explained P_{osm} using biological contexts and 6 of them used physical systems (note that 2 textbooks included both).

All except 2 biology textbooks included at least one subcategory of CDII: 10 textbooks included subcategory A, 11 included subcategory B, and only 2 included subcategory C. Apparently, CDII is most common when a physical setting is considered, as only 2 of these 18 textbooks used a biological context when describing P_{osm} in CDII. CDII provides essential information applicable to the measurement of the molecular weight of proteins or large molecules in chemistry utilizing column differences between pure water and a solution due to osmosis (Atkins & de Paula, 2006; Whitten et al., 2010).

In terms of CDIII, only 7 textbooks included this category, explicitly identifying P_{osm} as the internal pressure acting against an exerted, external pressure. Among these, 5 described the volume constraint due to the cell wall while 1 indicated that the internal pressure exists in all membrane-containing cells. All except one of these 7 textbooks used biological contexts when describing CDIII. Another 5 textbooks, other than the 7 mentioned above, used the term turgor pressure in biological contexts without explicitly equalizing it to P_{osm}. Therefore, we did not code them as CDIII in Table 3.3. No physics, chemistry, or animal physiology textbooks described P_{osm} from the internal pressure perspective. On the contrary, the internal pressure in plants[4] is an extremely important factor in the maintenance of normal cell shape and in water transportation. This concept received less emphasis in animal or physical sciences contexts, in which the structural volume constraint is less significant than in organisms with cell walls.

Of the 17 textbooks that contained quantitative measures of P_{osm}, all of them reported QMI, indicating that the most common way to derive the magnitude was to relate it to the measure of solute or solvent concentration differences. There were 6 textbooks that compared P_{osm} to the ideal gas law and used van't Hoff equation to explain the calculation of P_{osm}. As for QMII, which measures pressure directly, it was found in the physics, the plant physiology, the biochemistry, and the physical biochemistry textbooks. It is noteworthy that Nobel (2005)

[4] Since the internal pressure is usually described in terms of turgor pressure, not P_{osm}, in plant physiology textbooks, this trend is less obvious in Table 3.3.

provided detailed calculation for P_{osm} in the cell (Π^i) and the P_{osm} out of the cell (Π^o), which is counterintuitive to the notion that P_{osm} only renders one numeric measure (p.79).

Overall, 2 textbooks covered all five categories, 1 textbook covered four categories, 8 textbooks covered three categories, and 9 textbooks covered two categories (Note that when we count distinctive categories, we do not consider the subcategories of CDII). When comparing the introductory (n=9) and the advanced textbooks (n=11), it is noteworthy that the introductory textbooks had significantly fewer categories (p = .04): the mean number of categories for the introductory textbooks is 2.33 (SD = 0.50), whereas that for the advanced textbooks is 3.18 (SD = 1.08).

The categories in CD describe P_{osm} from different timings, causal relations, and directions, so if a textbook used more than one CD, it is considered as having different perspectives in its definition of P_{osm}. The majority of the textbooks (17 of 20) included at least one pair of different perspectives.

Moreover, the conceptual definitions and the quantitative measurements of P_{osm} do not necessarily match in a single textbook (e.g., when authors define P_{osm} using CDII, yet introduce QMI as quantitative measure of P_{osm}). Over half of the textbooks (12) included mismatching quantitative measures and/or missing correspondences with their conceptual definitions. None of these textbooks addressed these conflicts.

Overall, the defining contexts are related to the nature of the textbooks: the physical sciences textbooks (physics, chemistry, and physical chemistry) used physical contexts to discuss P_{osm} (17 out of 19 instances), whereas the life sciences textbooks showed mixed patterns--the introductory biology textbooks used more biological than physical contexts (6 vs. 2 instances) but the advanced texts (physiology, biochemistry, and physical biochemistry) preferentially used physical over biological ones (28 vs. 7 instances).

Table 3.3

The two aspects, conceptual definition (CD) and quantitative measurement (QM), of osmotic pressure are listed in relation to 20 discipline-oriented textbooks. If a category appears in a textbook, we inserted the code that denotes the specific context (see Table 3.2) in the corresponding cell.

Categories	Meaning	Introductory								
		Physics	Chemistry			Biology				
		Urone	Brown et al.	Whitten et al.	Zumdahl et al.	Brooker et al.	Raven et al.	Reece et al.	Russel et al.	Sadava et al.
CDI	The force driving/pulling water from lower solute concentration into higher solute concentration.						P^1	B^3	P^2	B^3
CDII	A pressure required to prevent, stop, or reverse osmosis.						B^1			
CDII-A	Hydrostatic pressure to interfere with osmosis.	P^1		P^2	P^2	B^2			P^2	
CDII-B	The pressure required to prevent osmosis in the beginning.		P^1	P^1	P^1					
CDII-C	The pressure required to reverse the pressure build up.									
CDIII	The pressure of the solution exerting on its environment, which is limited in the ability of expansion.					B^2			B^2	
QMI	The magnitude is produced/measured/expressed by solute/water concentrations.	P^1	P^4	P^4	B^2		P^1	B^3		B^3
QMII	The numerical value of the external/internal pressure needed to stop osmosis.	P^1								

Table 3.3 (continued)

Categories	Advanced										
	Physiology						Physical Chemistry		Biochemistry		Physical Biochemistry
	Animal	Animal	Animal	Plant	Plant	Plant					
	Eckert et al.	Fox	Rhoades & Pflanzer	Hopkins & Huner	Nobel	Raven et al.	Atkins & de Paula	Engel & Reid	Moran et al.	Nelson & Cox	Atkins & de Paula
CDI	B^3, P^1	P^3	P^2		B^2, P^1					B^1	
CDII											
CDII-A	P^1		P^2	P^2			P^2				P^2
CDII-B		P^3		P^2	P^1	P^2	P^1 , P^2	P^2	B^1		P^1, P^2
CDII-C						P^2				P^2	
CDIII					B^2			B^2	B^1	B^2	P^2
QMI	P^4	P^3	P^2	P^4	P^1		P^1	P^4		P^2	P^1, P^4
QMII					B^2	P^1	P^1			P^2	P^1

Discussions and Conclusions

In this study, we examined one specific concept (P_{osm}) in a set of 20 college science textbooks from multiple science disciplines. We found that there was a multitude of definitions and descriptions of osmotic pressure in college textbooks, which was the result of different perspectives on osmosis. These differences were rooted in the following considerations:

- time point of the osmotic process, as evidenced in the three subcategories of CDII;
- causal relationship, in the sense that P_{osm} drives osmosis (CDI) or restricts it (CDII & CDIII);
- spatial perspective, i.e., pressure being related to different parts of the system under consideration, leading to opposing views that considered the pressure as internal (CDIII) or external (CDII), and
- defining context, as our results revealed that although CDI was utilized in both physical and biological contexts, CDII was more often defined in a physical and CDIII in a biological context, and physical contexts were favored for both QMI and QMII.

These points are closely related to disciplinary perspectives, as different disciplines may focus on different systems and contexts. For instance, no physics, chemistry, or physical chemistry textbook described P_{osm} using CDI, which was the more prevalent perspective taken by animal physiologists. Similarly, as CDIII describes P_{osm} as the pressure exerted due to constrained space such as a cell wall, it was a more common approach among plant physiologists. While biologists tended to think in the context of two solutions, chemists and physicist tended to look at one solution relative to pure water (Urone, 2000; Brown et al., 2009).

To exacerbate the problem, the term P_{osm} is also easily confused with osmotic potential (or solute potential, Ψ_s). Some textbooks point out that P_{osm} and Ψ_s are numerically equivalent, only differing in sign: $\Psi_s = - P_{osm}$, where P_{osm} typically has a positive value (Hopkins & Huner, 2003; Nobel, 2005). Twelve textbooks included the term P_{osm} only, 6 texbooks included both terms without connecting them, and only 2 textbooks included both terms and explained the relationship between the two. A thorough examination of the term Ψ_s, however, is beyond the scope of this paper.

We believe our findings are not constrained to the particular term P_{osm}, but are likely toapply to many other terms as well. The diverse and inconsistent definitions of a single term can prevent students from making sense of related topics across (or even within) disciplinary boundaries in science, at least at the introductory level wherein students have not yet developed a deep understanding of the subject matter.

To conclude the paper, we propose the following strategies from the instructional side that may help students' interdisciplinary learning. In our instruction, we need to identify and attend to these crosscutting concepts that students learn across multiple disciplines (NRC, 2012). We should strive to present related terms utilizing multiple perspectives in a coherent manner and can situate the concept in concrete scenarios that link these different perspectives. The situated-learning can also be enhanced through differentiating and connecting the defining contexts of these terms, as these contexts are sensitive to disciplinary tradition and culture (Nikitina, 2005). We need to make sure our students receive consistent information across different materials and apply the information under appropriate contexts.

We envision an effort across disciplines within the scientific community that develops resources to help students develop interdisciplinary thinking. For instance, conflicts that presently arise from differences in discipline-based approaches to crosscutting concepts can be avoided or explained through an integrative review of a repertoire of these concepts (e.g., energy, potential, pressure). Identification of these concepts and provision of an interdisciplinary approach that does not bias towards specific disciplines will require balanced input from all the disciplines involved.

We envision the establishment of a shared resource that helps students integrate, translate, and transfer the crosscutting concepts (e.g., a website that contains a list of these crosscutting concepts and illustrates how they are similar and different in different disciplinary contexts). This kind of resource will require a collaborative and systematic effort that goes beyond single disciplines, and the endorsement of professional science organizations and federal funding agencies.

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CHAPTER 4

ASSESSING UNDERGRADUATE STUDENTS' ENERGY UNDERSTANDING FROM AN INTERDISCIPLINARY PERSPECTIVE[5]

[5] Sung, S. and J. Shen. To be submitted to *Science Education*.

Abstract

Although interdisciplinary education has been advocated for decades, standard science assessments are typically designed to assess disciplinary understanding (DU). In this study, we constructed assessments addressing students' interdisciplinary understanding in science (IUS) on the concept of energy, which is foundational to many science disciplines. The instrument was implemented in three science classes at the college level, two introductory and one advanced (*N* = 490). The Rasch model in the item response theory (IRT) was applied to test model-data-fit and to obtain students' IUS levels. One-way ANOVA demonstrated that there were significant differences in ability levels among the physical biochemistry, physics, and biology classes. The results show that the Rasch model fits the observed dataset but the test reliability (person separation index) is low. It indicates that the current IUS-E instrument is not sensitive enough to distinguish between high and low performers. The applications and implications are discussed.

Introduction

Energy-related concepts, such as energy transfer, transformation, degradation, and conservation, are critically important for understanding not only physical and biological processes or changes in the world (Liu & McKeough, 2005; Pinto, Couso, & Gutierrez, 2005; Stylianidou, 1997), but also economics and other social issues. Therefore, an energy literate individual should have a solid foundation of energy concepts in various disciplines and a thorough understanding of how energy is used in everyday life (DeWaters & Powers, 2011). Nevertheless, a report revealed that only 12% of Americans passed a basic quiz on energy-literacy topics (Coyle, 2005).

Many people have misconceptions regarding energy consumption, energy conservation, and its impact on global climate (Attari, DeKay, Davidson, & de Bruin, 2010; Watts, 1983). Numerous studies targeting learners' understanding of energy revealed gaps in their grasping the concepts of conservation of energy (the 1st law of thermodynamics) and energy degradation (the 2nd law of thermodynamics) (Liu & Collard, 2005; Liu & McKeough, 2005; Neumann, Viering, Boone, & Fischer, 2013). Most students do not have opportunities to link these closely-related concepts learned in classroom settings (e.g., laws in physical sciences) to their daily lives (e.g., energy conservation, muscle contraction, decomposition, and equilibrium) (Barak, Gorodetsky, Chipman, & Gurion, 1997; Bransford & Schwartz, 1999; Cunningham, 2011; Chin & Brown, 2000; Haskell, 2001). The energy concept is often used loosely and interchangeably with other terms in daily life. For instance, the vitalistic notion of energy possessed by living entities might be perceived differently from the energy concepts in the non-living world (Barak et al., 1997).

Studies on Energy Understanding

Many researchers were motivated to study people's energy understanding from different perspectives. Early literature approached energy topics from discussions of physics (more concrete perspectives) and metaphysics (more abstract perspectives) (Bunge, 2000; Chi, Slotta, & deLeeuw. 1994; Driver & Warrington, 1985). Energy understanding was also studied from characterizing the structure of learners' conceptions using tools such as concept maps (Ebenezer & Fraser, 2001; Liu & McKeough, 2005; Liu, Ebenezer, & Fraser, 2002). With advancement of statistical methods, the studies of energy understanding shifted from qualitative-oriented to quantitative-inferenced based on developmental growth/learning progressions, which apply rigorous theory-driven assessment perspectives (Lee & O. L. Liu, 2009; Liu & Collard, 2005; Liu & McKeough, 2005). DeWaters and Powers approached the topics of energy from students' perceptions of renewable energy and energy conservation. They found students to be rather unprepared to reason the energy issues encountered in everyday life (DeWaters & Powers, 2006, 2009).

There have been several studies and theories about assessing energy concepts in discipline-neutral contexts (Bunge, 2000; Duit, 1985; Ebenezer & Fraser, 2001; Liu, Ebenezer, & Fraser, 2002; DeWaters & Powers, 2006, 2009). Here I highlight two approaches for assessing energy understanding. The learning progression approach combines science concepts and psychology to formulate theory-driven assessment of students' development of energy concepts (Jin & Anderson, 2012; Lee & O.L. Liu, 2009; Liu & Collard, 2005; Neumann et al., 2013). The learning progression research on energy usually concentrates on the students' cumulative and cognitive advancement across continuous grades. The progression studies shed light on the notion that learners' conceptual development can be differentiated into higher and lower levels, depending on whether they reached certain conceptual understanding levels. These qualitative and quantitative analyses provide a statistical foundation for my study.

The energy literacy approach focuses on examining students' science literacy specific to energy; for instance, effective participation in energy issues, decisions making and actions that are influential in their local environment or even with regard to global scale issues (Attari et al., 2010; DeWaters & Powers, 2006, 2007, 2011). DeWaters and Powers's (2011) energy literacy survey took the form of multiple-choice questions and is convenient for implementation. The main focus of this instrument came from a renewable energy and energy conservation perspective. The approach, similar to interdisciplinary understanding, provides insight of embedding energy topics in real life problems. It does not, however, bear crucial representations or implications of the way each discipline deals with energy topics. It ignored the applications of the laws of thermodynamics to link the real life problems.

Despite the diverse approaches taken previously to understanding energy topics, very few studies have focused on bridging energy topics across disciplines. In this study, I will mainly focus on constructing a measure to assess students' energy understanding from an interdisciplinary viewpoint.

Interdisciplinary Understanding of Energy

Interdisciplinary understanding (IU) in this research is perceived as "the capacity to integrate knowledge and modes of thinking in two or more disciplines…in ways that would have been impossible or unlikely through single disciplinary means" (Boix Mansilla & Duraising, 2007, p. 219). IU offers learners multiple perspectives that help them construct complex knowledge and appreciates the holistic nature of knowledge (Schommer, 1994). Equipped with IU, students can develop higher order thinking and metacognitive skills (Ivanitskaya et al. 2002;

Klein, 2010). IU can also help students better solve real world problems (Boix Mansilla & Duraising, 2007; Drake & Burns, 2004; Newell, 2000; Steiner, & Laws, 2006).

To narrow down the scope of this study, my study focuses on the natural sciences, such as physical sciences, life sciences, engineering and technology, and earth and space science. More specifically, since energy is a crosscutting concept (Achieve, 2013), it makes a good candidate for demonstrating interdisciplinary understanding in science (IUS). The instrument I developed is thus dubbed IUS-E (interdisciplinary understanding of science, using energy as an example).

In sum, energy is a challenging concept for college students, and interdisciplinary learning is in great demand (AAAS, 2009; Klein, 2010; Newell, 2007). However, previous studies have not examined students' understanding of energy through an interdisciplinary perspective. In this study, I tackle these two challenges through developing a valid and reliable instrument to measure college students' IUS-E.

Research Questions

The following questions guided the study:

1. How can items be designed to assess undergraduate students' understanding of energy from an interdisciplinary perspective?
    a. What components should be considered to design the IUS-E items?
    b. How can the IUS-E items be validated?
2. How can psychometric analyses of an instrument measuring interdisciplinary understanding of energy be interpreted?
    a. How well can the items differentiate student performance in an interdisciplinary class from students who are taking introductory science?

b. How can the assessment results be applied to revise the instrument?

Theoretical Framework

Core Ideas Related to Energy

What is Energy? Energy is an abstract concept because it is neither a substance nor a procedure (Chi et al., 1994). It was first defined when scientists discovered that this numerical quantity (measured in joule) remain unchanged regardless of the changes in nature (Feynman, 1963, p. 4-1). There are various types of energy in our daily lives that can be categorized into two forms—kinetic and potential energy. Kinetic energy is also commonly known as the energy of motion and potential energy is the stored energy of an object. The latter depends on the configuration of an object or its relation to a reference point (Morris, Hartl et al., 2013).

The first law of thermodynamics, or the conservation of energy, states that energy is neither created nor destroyed. Instead, it can be transferred or transformed. Energy transfer refers to the progress of reaction without a change in the forms of energy (i.e., chemical energy to chemical energy); energy transformation refers to the progress of reaction involving some alternation of energy forms (i.e., gravitational energy to electrical energy).

If the total amount of energy remains the same, why is there warning for energy crisis? The answer lies in the fact that not every form of energy is available for human utility (Cunningham, 2011; Feynman, 1963; Lambert, 2013; Morris et al., 2013). The view that some energy converts to an unusable form automatically, and that energy degradation is not exclusively attributable to human consumption is not commonly registered in a laymen's mind. The laws denoting how much energy is available are called the laws of thermodynamics (Feynman, 1963, p. 4-8), which are used to describe relations of macroscopic variables, such as heat and its relation to energy and work (Engel & Reid, 2006). Specifically, the notion of unavailable energy is closely related to the concept of entropy.

Similar to energy, entropy was first used to describe a constant quantity that is related to temperature in “reversible” heat cycles. In irreversible thermodynamic processes, however, there is always an increase in entropy expressed by “the heat delivered at unit temperature” (Feynman, 1953, p.44-12). The effect of the increasing entropy in a reaction is that the efficiency is never perfect because there is always portion of energy being dissipated, oftentimes in the form of thermal energy (Eckert, Randall, & Augustine, 1988). The increase of entropy is summarized in the second law of thermodynamics: “*Entropy in an isolated system*[6] *is always increasing*.”

The IT^3 Framework

Brown and Wilson (2011) identified the cognition model to be the missing corner on the construct map of assessment instrument. Therefore, before the introduction of actual item development, a framework directing the IUS-E instrument design is critical.

In order to acquire a deeper understanding of the construct in the IUS-E, we should recognize possible cognitive processes that are involved. I adopted the IT^3 framework (Shen, Sung, & Rogers, 2012) to conceptualize IUS that highlights four critical aspects: integration, translation, transfer, and transformation (i.e., the IT^3 framework, see energy examples in Table 4.1). The IT^3 framework (Shen et al., 2012), provides an interdisciplinary learning framework that includes the components of knowledge integration, transfer of learning, translation of interdisciplinary terms, and transformative learning. Table 4.1 lists these four components and corresponding examples on the topic of energy.

[6] Isolated systems: Systems that can exchange neither matter nor energy with the surroundings.

Integration

Recognizing that students develop fragmented understanding or “islands of knowledge” in science topics (Taylor, 2006, p. 89), Linn and colleagues developed knowledge integration (KI) framework, which emphasizes students’ abilities to establish connections among scientific ideas (Linn, 2006; Linn & Eylon, 2011). The KI framework promotes coherent understanding by encouraging students to add new ideas, distinguish new and existing ideas, develop scientific criteria to reconcile ideas, and build coherent connections between a science phenomenon and their prior knowledge or experiences across different dimensions of knowledge (Liu, Lee, & Linn, 2011). Based on the insight of KI, I further explored the role of scientific knowledge integration in IU.

Translation

It is crucial to communicate the knowledge and outcomes of interdisciplinary work with audiences from different disciplines. Boix Mansilla and Duraising highlighted how important it is for learners to communicate their disciplinary knowledge to “people who do not speak the same language” (2007, p. 224). Nikitina (2005) also used the analogy of second language acquisition with students’ development of IU. Learners who are able to identify similar ideas or distinguish terminologies used inconsistently among disciplines are considered more competent in thinking across disciplines than those who needs translation. In brief, a more successful interdisciplinary conversation and collaboration depends partly on how well one applies novel terminologies they acquired in one discipline to another. Competent translation skills help carry on a scientific discourse with people speaking another disciplinary language (i.e., coming from another field).

Transfer

Students constantly feel incapable of transferring scientific knowledge learned in one context to another (Bransford & Schwartz, 1999; Chin & Brown, 2000; Haskell, 2001), not to mention applying it to a real world situation. Practically, Wegner (2006) suggested that transfer is not a means to acquire increasingly abstract mental representations but the incremental refinement of knowledge resources to account for contextual variations. That is, learners' prior knowledge, experience, and opportunities to develop deep understanding, language, and contexts of learning may contribute to or hamper student knowledge transfer (Klahr & Carver, 1988; Lave, 1987). The transfer of learning is an essential determinant for IU that focuses on students' abilities to recognize and retrieve the essential understanding of one system and relate it to the crosscutting concept of another context, which is similar to the assimilation process (Wolfe, Reyna, & Brainerd, 2005).

Because the nature of IU requires the accreditation of contextual variations and the transfer of knowledge among science disciplines, it constitutes the third cognitive process in assessing IUS.

Transformation

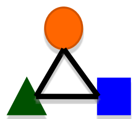
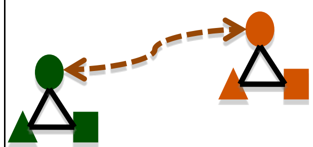
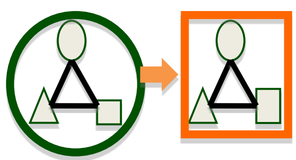
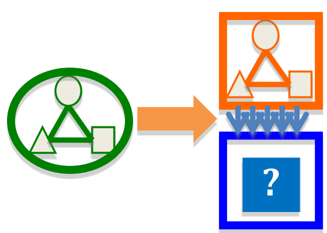
Transformation is essential in determining whether students are able to modify the knowledge they acquire (Mezirow, 2000; Shen & Confrey, 2007). In addition to the process of fitting and recognizing what they have learned in one discipline to apply in another discipline, "they must transform their current inadequate epistemic positions and create new structures" (Golding, 2009, p. 20). The emphasis of the attempt to modify existing systems to learn in order to utilize the adapted perception to make sense of a novel system constitutes the fourth element of the IT^3 framework.

The IT^3 framework focuses on the ability of students to demonstrate their IUS through the process of *integrating* ideas learned from distinct disciplines, *translating* corresponding terminologies among various subjects (that either represent similar concepts with different terms or recognize the same idea with varying terms), *transferring* knowledge acquired in one discipline to another, or *transforming* the understanding acquired in one discipline into a modified concept in another discipline.

Since the nature of *translation* and *transformation* processes require more elaboration on students' parts, and the objective of this study is to model a convenient approach by analyzing the multiple-choice questions, the quantitative analysis focuses only on the *integration* and *transfer* processes.

Table 4.1

Four Dimensions of Assessing Energy Understanding from an Interdisciplinary Perspective.

Dimensions of IU: (Operational Definition)	**Diagrammatic Representation***	**Key Features for Assessment**	**Examples on Energy**
Integration: Students need to integrate concepts, theories, tools, and methods learned from different disciplines to understand natural phenomena and solve complex problems.		-incorporate everyday experiences and/or complex phenomena that involve concepts from different disciplines and require students to integrate these concepts	Fully explaining the digestion of a marshmallow in digestive system requires knowledge in chemistry (e.g., activation energy), biology (e.g., enzyme), and physiology (e.g., structure and function of organs).
Translation: Students need to be able to translate scientific terms or scenarios in order to effectively communicate to an audience from a different disciplinary background.		-compare similar scientific terms from different disciplines -match terms from different disciplines -elaborate on a term from a different disciplinary perspective	In physical sciences, combustion is the burning of an object with fire; in life sciences, a similar scenario is ”burning calories” in your body, a process accomplished not with fire but with the chemical energy in your body.
Transfer: Students apply explanatory models learned from one discipline to another, recognizing the similar system under study.		-present a context typically associated with a different discipline -using contexts that share a core structure -provide additional background knowledge tied to the new discipline	ATP breakdown requires activation energy to break the terminal phosphoanhydride bond, and then, high chemical potential energy is released, which is analogous to two negatively charged-balls glued together. When the wax used to glue them together is melted by heat, there is repulsive electric potential energy released.
Transformation: Students use explanatory models learned from one discipline to change a system in another discipline into a new system.		- change a system using mechanisms from a different disciplinary perspective - analyze and predict the effect when a change typically considered in one discipline is introduced to a system in another discipline	The light wavelengths for photosynthesis lie within the range of visible light. If we replace visible light with ultraviolet light, the electrons are activated in a chaotic manner. Instead of harvesting useful energy from electron transport chain, there would be free radicals that will damage the plant cells. It has been changed to cancer treatment.

* Legends of the diagrammatic representation: A small colored shape represents a concept, theory, or tool from a particular discipline; a big colored shape with small shapes enclosed represents a context typically considered in a particular discipline; a dashed-line with a double-sided arrow represents a translation process; a solid line with an arrow represents a transfer process; a solid line connected perpendicularly with a solid arrow represents a transformation process.

Methodology

Item Construction

The IUS-E item construction process followed the paradigm established by, e.g., Haladyna, Downing, and Rodriguez (2002), Liu (2009), Wilson (2005), and Dreyfus, Redish, and Watkins (2011). I first identified the construct of interest (i.e. students' IUS-E). Specifically, two major cognitive processes – integration and transfer – were identified to be the target of the IUS-E. Preliminary information about the target sample of respondents was accomplished by interviewing course instructors, obtaining the course syllabus, and sitting in the science classes including biology, physics, and physical biochemistry. This step not only helped to obtain the entry-level energy understanding of participants in different classes but also inspired the design of more interdisciplinary items. The IUS-E items were categorized into different energy topics, including energy transfer and transformation, thermodynamics/entropy topics, and Gibbs free energy/kinetic and potential energy (see Tables 4.2 and 4.3) which all center on the application of the first two laws of thermodynamics. Both the preliminary and main IUS-E items were designed according to Wilson's (2005) suggestions. There were four types of question formats for the preliminary study, including multiple-choice, two-tiered multiple-choice, true or false, and open-ended question types (Sung, Shen, & Kim, 2013). After the initial collection and data analysis, the main study only included multiple-choice and two-tiered multiple-choice/open-ended question. Responses students gave for the open-ended questions and their endorsement to the second-tier multiple-choice questions were used to revise the items. Typical responses to the IUS-E instrument were obtained to serve as item revision references. The item revision is an iterative process in constructing measures (Wilson, 2005).

Table 4.2
Table of IUS-E Instrument Specification-Version A

	Integration	Transfer
Energy tranfer and transformation	9	1
Thermodynamics/entropy	3	3
Gibbs free energy/kinetic and potential energy	5	6
Subtotal (%)	56.7	33.3

Table 4.3
Table of IUS-E Instrument Specification-Version B

	Integration	Transfer
Energy tranfer and transformation	9	2
Thermodynamics/entropy	3	3
Gibbs free energy/kinetic and potential energy	4	6
Subtotal (%)	53.3	36.7

Interviews with think-out-loud technique were also conducted in order for respondents to provide their rationale to particular questions of interest. Experts reviewed the items and rate the relevance of these IUS-E items with objectives. Followed by the item design was the identification of outcome space based on research-based categories (i.e., recognizing respondents cognitive processes based on the IT^3 framework). This step is essential in establishing validity for the IUS-E items. A thorough inspection of the possible involvement of cognitive processes could show whether students demonstrated desired outcomes across different groups. If respondents demonstrate unpredictable patterns of cognitive processes in responding to the IUS-E items in different groups, the instrument might not be valid.

The last step to construct an IUS-E instrument was to apply the appropriate measure model. In this study, item response theory (IRT) was applied to analyze the data. The measurement model I applied was the Rasch model in which only item difficulty (*b*) and student ability (θ) are considered. In Rasch model, the probability of the respondent *n* to get a dichotomous question *i* right is denoted by the expression:

$$\Pr(X_{n,i} = 1 \mid \theta, b) = \frac{e^{(\theta_n - b_i)}}{1 + e^{(\theta_n - b_i)}}$$

The term (θ_n - b_i) is the log odds, or simply called logit. Persons at the same logit scale have approximate 50% chance of getting the corresponding item(s) correct. Persons positioned at higher logit scale have greater than 50% chance of responding to the item right, and vice versa (Glynn, 2012). Unlike the two-parametric logistic (2PL) model, the discrimination of items (*a*) is assumed to be equal. The guessing effect (*c*) considered in three-parametric logistic (3PL) model was also neglected in the Rasch model. The Rasch modeling result was used to situate students on a continuous latent logit scale representing learners' levels of IUS.

Question design

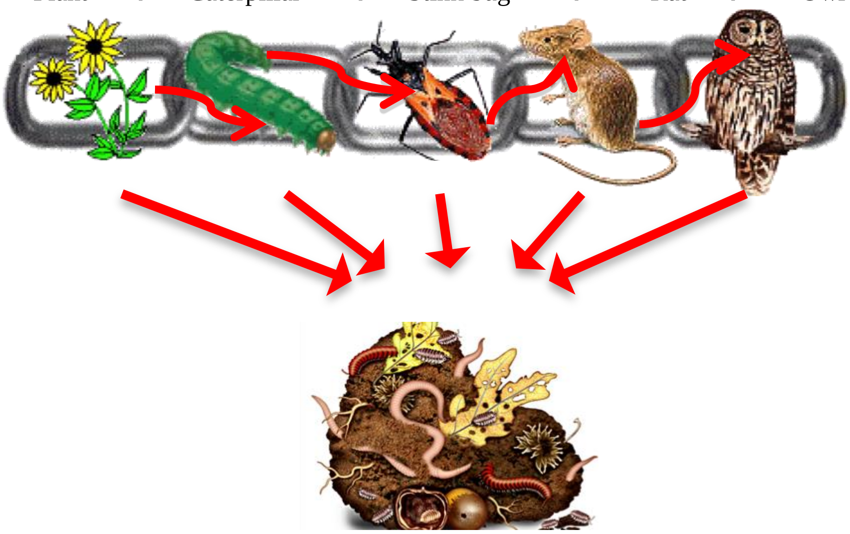
To explore whether the components in the IT^3 framework can be woven into the question design, I used energy topics to demonstrate the IUS-E instrument design. Only *integration* question is shown here.

The term *entropy* is often introduced in physical sciences but seldom connected with everyday phenomena in life sciences, such as the muscle contraction and decomposition processes involving the dissipation of thermal energy. As a result, the students may have treated the entropy concept as a physical sciences topic, which is isolated from living systems. Supposedly, the second law, entailing the entropy topics, is also applicable to explain the energy degradation phenomena both in the non-living and living entities.

To connect the physical scientist's concept of entropy and real life phenomena, we can examine a question concerning food decomposition that can serve as a good example linking the second laws of thermodynamics with the tendency of decay. A multiple-choice question may integrate the law with the phenomenon in life sciences.

B 2.8: Decomposition or decay of an organism after death involves breaking down the organism into simpler molecules (see the figure below).

Plant → Caterpillar → Stink bug → Rat → Owl



Decomposer

2.8.1. Choose the best description for the relationship between entropy* and decomposition processes.

A. Entropy is not created or destroyed in the universe.
B. Entropy of the system increases locally but remains the same globally.
C. Entropy increases in converting complex molecules to simpler molecules.
D. Entropy increases due to the fixation of carbon into organic molecules.

Note: * Entropy is a mathematical term to describe the heat delivered per unit temperature and the possibility for subjects to redistribute. It is also known as the disorderliness of a system.

This question is a demonstration of *integration* process, integrating biological decomposition process with laws of thermodynamics. The Key for this question is C. An extension of option C could be designed to be that “the increase of entropy accompanies an increase of thermal energy.” So the relationship between entropy and energy could have been more straightforward. In option A, entropy increases gradually not staying the same. Also, this does not describe decomposition process. In B, according to the second law of thermodynamics, entropy does not remain the same. It increases gradually. D. Entropy decreases during carbon fixation. The decomposition process involves the break down of organic molecules into inorganic molecules and return to the element cycle.

Rationales for the design of *translation, transfer*, and *transformation* questions and a full version of the IUS-E instrument are in Appendix B.

Five questions in each version of the IUS-E survey were two-tiered. For the types of second-tiered questions in each version of the energy survey, one out of the five questions was multiple-choice, and four others were open-response.

Item Revision

Based on the preliminary IUS-E items that were implemented in the pilot study, some items with similar difficulty levels were of middle difficulty on the Wright map (Sung, Shen, & Kim, 2013). I reduced or revised the IUS-E items that are of the similar difficulty levels because too many items possessing similar difficulty levels cannot offer new information to the examiners and are a waste of time for test takers. Some difficult questions were modified into two-tiered questions to solicit more information about the prior knowledge of respondents. Besides the life sciences, physical sciences, and earth and space sciences. Even though each item may elicit more than one component in the IT^3 framework, since the cognitive processes are not completely exclusive to each other, only the major cognitive process in the IT^3 framework was recorded for simplicity. I modified the assessment items from accessible test banks (e.g., MCAT and Campbell, 2009), prior research results (Conzelman, Dellai, Diebolt, & Steele, 2012; Talanquer, 2011), published literature (Vilafane, Bailey, Loertscher, Minderhount, & Lewis, 2011), science courses (including physical biochemistry, renewable energy, and ecology classes), Lambert's discussion of entropy (Lambert, 2013), and the discussions with a variety of faculty members. Questions were situated under interdisciplinary contexts. The instrument has been designed to address the concepts involved in different forms and processes of energy, including energy transfer, transformation, degradation, and the laws of thermodynamics, which stringently link physical and biological sciences with engineering.

Validity and Reliability

Content validity. In addition, seven faculty members from physical science, biological science, science education, and educational psychology, as well as four doctoral students whose backgrounds are in chemistry, physical biochemistry, biology, and physics critiqued the energy instrument. Four content experts from different disciplines, including physics education, physical sciences, and biological sciences, were recruited to determine whether the IUS-E assessment items are related to the energy concepts as outlined. Inappropriate content, such as assessment questions that were farfetched to students' current conceptual understanding was either modified or eliminated. Also, since the whole instrument was divided into two versions, the content of both versions were supposed to cover similar energy topics and are regarded as parallel to each other (see Tables 4.2 and 4.3).

Construct validity. The underlying construct in this survey is the IUS that is to be elicited by this IUS-E item. The factor analysis examination or other eligible unidimensionality checks (e.g., dimensionality check by item residual variance (Embreston & Reise, 2002)) are crucial to satisfy the powerful assumption of unidimensionality in the item response theory (IRT). Item separation obtained from Winsteps also provides information for construct validity. Also, criterion-related validity is not applicable to this study, because the measure is not going to be used to correlate with an observable behavior, status, or criterion.

Internal consistency. The reliabilities of the IUS-E items and survey takers were determined by the Rasch model estimation. Person and item reliability can be calculated based on person and item separation index obtained from the Winsteps program. The person reliability index corresponds to the test reliability in classical test theory, indicating the replicability of person ordering if the same group of participants were given another parallel test (Glynn, 2012; Linacre, 2013). The item reliability index indicates the reproducibility of item ordering if the same test were given to similar group of respondents (Glynn, 2012; Linacre, 2013). Both reliability indexes can "be interpreted on its 0-1 scale in the same way as Cronbach's alpha" (Glynn, 2012, p. 1332). Item reliability is unique to IRT. Reliability higher than .8 is considered acceptable.

Participants and Procedures

Participants

The content I aimed to cover requires the students to have at least one or two semester(s) of chemistry classes to provide meaningful answers. So, the survey was only administered to the introductory biology, physics, and advanced level physical biochemistry classes, as chemistry classes were the prerequisite for all three classes. The introductory biology is in the first semester of a two-semester introductory course for science majors; the introductory physics is a continuation of introductory physics for science and engineering students; the advanced physical biochemistry is an elective course to senior or honor students in biochemistry and molecular biology students.

Two versions of the IUS-E items was administered to a convenient sample from the introductory biology class with approximately 600 students in two sessions, the introductory physics class with approximately 100 students, and the senior interdisciplinary science class with approximately 80 students.

Item Administration and Data Collection

The survey was embedded in the online Web-based Inquiry Science Environment (WISE) interface (Slotta & Linn, 2009) and was assigned as an extra credit assignment for the students. Since the implementation of items were treated as extra credits, in order to test the whole pools of IUS-E items and in the meantime, avoid fatigue and elicit quality responses, the items were divided into two comparable versions. Similar to the pilot study, these two versions of the IUS-E survey covering similar energy topics (Versions A and B) that were randomly assigned to students in all three groups. Participants taking each version could be treated as an equivalent group. In group A, there were 16 participants in physical biochemistry, 175 enrolled in a biology class, and 30 in a physics class; in group B, there were 22 participants from physical biochemistry, 199 from biology, and 38 in a physics class. The participants were allowed ten to fourteen days to complete the whole survey, including a brief background inventory asking their gender, preferable language usage, whether they would like to be interviewed briefly, courses taken, and their feedback to the IUS-E survey. The approximate time to complete the survey was 30-45 minutes.

I also conducted eight semi-structured interviews with participants from different classes, including four from a biology class, two from a physics class, and two from a physical biochemistry class. Each interview lasted approximately 25-45 minutes. The interviews were to allow respondents on elaborating their rationales for their survey questions.

Data Analysis

The data with low response rates (< 30%) were deleted in both versions. I treated the deletion as random missing data, which was different from treating the missing data as the non-random missing data from low-ability respondents (DeMars, 2002). All the open-ended responses were retained for detecting learners' prior knowledge, including their understanding and misconceptions for the particular energy topics. Multiple-choice items are usually considered to be more reliable (Liu, Lee, & Linn, 2011), so the open-ended responses were not used as quantitative data in the initial analysis, which excluded almost all of *translation* and *transformation* questions in the IUS-E. Therefore, only *integration* and *transfer* questions were considered in the quantitative analysis. Also, the only two-tiered question in each version was given one composite score, 0 or 1. That is, only the responses getting both tiers correct were assigned 1, otherwise, was 0. The item responses of each individual were used as a vector to be analyzed with the Rasch model in the Winsteps 3.0 software. Rasch family models have been used repeatedly by many scholars in science education and educational research (e.g., Liu, 2010; Wilson, 2005). Therefore, I applied Rasch modeling first, checking model-data-fit, and then estimate whether the discrimination and guessing parameters from 2PL and 3PL models lie in the acceptable range.

The one-way ANOVA for person measures estimated for the three science classes and the Exploratory Factor Analysis were analyzed in SPSS statistics software version 20. One-way ANOVA was conducted to determine whether students' average abilities in distinct science classes are significantly different from each other. *Post-hoc* Tukey's test was performed to determine which pair of classes differs significantly from each other. Reliability was estimated both with the classical test theory (CTT) and the IRT. If reliability falls under acceptable range (<.8) *post-hoc* reliability check should be conducted to determine possible means to increase the reliability index. Reliabilities for *integration* and *transfer* questions were also analyzed with SPSS and Winsteps.

Table 4.4
Correspondence of the Anchor Items on Both Versions

Version A	Version B
2.5.2	2.5.2
2.9.2	2.7.2
2.13.1	2.11
2.14.3	2.12.2
2.15.1	2.15.1
2.15.2	2.15.2
2.17.1	2.14.1

Linking procedures aligning both versions on the same scale were applied. Because it enabled the researchers to investigate a bigger pool of questions based on the assumption that these two groups are equivalent. This approach is especially beneficial to test prototype instrument, which is being constructed at the initial stage. The linking method was accomplished by embedding seven anchor items into the items on both versions (see Table 4.4). In other words, even though there were two versions of survey, the anchoring items allowed the investigators to link and compare these two energy surveys using the same scale. Item measures in both separate linking and concurrent linking were presented.

The assumptions in analyzing the data with Rasch model were that the data were unidimensional and locally invariant. IRT applies powerful assumptions to the observed scores (Allen & Yen, 2002). Unidimensionality was checked with the examination of item residuals, which demonstrated the correlation coefficients between item measures and their measures on an additional dimension (Liu, 2010). The unidimensionality referred to the measurement of one's construct (Hambleton, Swaminathan, & Rogers, 1991), whereas local independence suggested that items are uncorrelated with one another when learner ability is held constant statistically (Reise, Widaman, & Pugh, 1993). In other words, learner ability is the only factor influencing a respondent's answers to the question (Hambleton et al., 1991). Differential item function (DIF) was used to determine local invariance of the two versions.

A plot (i.e., Wright map), which provides information about a person's ability and item difficulty simultaneously was constructed. This map is often used to identify the gaps between items with different difficulty levels. Such information on the person-item gap congruently implies a need to omit certain items at similar difficulty levels and replace them with items at various difficulty levels. By referring to the Wright map results, items of high quality can be selected for the IUS-E instrument. In this way, only the items that place students on a scale with differential abilities will be considered as one criterion for high quality items to be retained.

Infit and outfit were inspected in this study. Item infit/outfit indicate whether students from a high ability group and a low ability group perform "normally" as predicted. A large infit value for one item implies that a person's ability close to a particular item difficulty level is not consistent with the model's prediction. A large outfit value for an easy item indicates that a high ability level student fails to respond to the question correctly, and vice versa. The item parameters, infit/outfit parameters, and the Wright map were derived for both versions.

The interview data were only used to revise the IUS-E questions, I will concentrate mainly on the quantitative data analysis in this study.

Results

Model-Data-Fit

The model-data-fit was examined through outfit statistic check, estimation of item discrimination, and asymptote representing guessing effect The person abilities and item difficulties in the two versions was estimated together using the linking method (Linacres, 2013). Persons and items are placed along the logit scale.

```
                PERSONS - MAP - ITEMS
                    <more>|<rare>
  2                       +
                       .  |
                          |  A2.16.4
                          |
                          |
                      .#  |T
                          |
                          |
                       .  |
                       .  |
                       .  |  C3
                         T|
  1                    .  +  B2.13.2  C7
                       .  |  A2.10.1  A2.16.2  A2.8.1
                          |S A2.10.2  A2.5.1
                      ##  |  B2.10.3
                      .#  |  A2.11.2
                     ###  |  B2.8.2
                     .##  |  B2.4.5
                         S|
                  .#####  |  A2.12.1
                    .###  |  A2.9.1   B2.13.3  C2
                  .#####  |  A2.11.1  C4
                  .#####  |  C6
  0              .######  +M
                          |
                  .#####  |
                  .##### M|  A2.4.3   A2.7.1   B2.4.3   B2.8.1
                 .######  |
                  .#####  |  B2.13.1  C1
                          |  A2.14.2  A2.16.3
           .############  |  B2.4.4
                          |  B2.12.1  B2.13.4
                          |  A2.14.1  B2.4.6   B2.9.1
                .#######  |S
                         S|  B2.7.1
 -1                  .##  +
                    .###  |
                          |
                      .#  |  B2.5.1
                          |
                      .#  |  B2.10.1  C5
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 -2                    .  +
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 EACH '#' IS 5.
```

Figure 4.1. The Wright map of person-item measure of concurrent linking. each “#” symbol means a subgroup of five people and a “.” represents less than 5. “M” is the mean, “S” is one standard deviation from the mean, and “T” is two standard deviation from the mean.

The Wright map shows that person abilities and item difficulties matched. The Wright map (see Figure 4.1) shows that although overall students’ abilities spread about evenly over a range from -1.48 to 1.82 logits, there are a few gaps in items. For instance, Question A2.16.4 is too difficult and it was not used in differentiating learners’ abilities (no persons at that logit level). Also, there are large item gaps between logit 1 and 2. Subjects whose abilities fall within those gaps were not clearly differentiated by the IUS-E instrument, which will result in large measurement errors. The addition of items at the corresponding difficulty levels is necessary. On the contrary, there are several items clustered around logit 0 and 1 that measure similar IUS levels. In order to differentiate learners better, deletion or modification of these items with duplicative difficulty levels into more varying degree of difficulty levels is recommended.

```
     SUMMARY OF 480 MEASURED PERSONS
-------------------------------------------------------------------------------
|          RAW                          MODEL         INFIT        OUTFIT     |
|         SCORE     COUNT    MEASURE    ERROR      MNSQ   ZSTD   MNSQ   ZSTD |
|-----------------------------------------------------------------------------|
| MEAN      10.5      23.1       -.22     .47      1.00     .0   1.01     .0 |
| S.D.       3.6       1.0        .67     .04       .15     .9    .22     .9 |
| MAX.      21.0      24.0       1.95     .76      1.44    2.7   1.96    2.8 |
| MIN.       2.0      22.0      -2.24     .44       .65   -2.7    .48   -2.6 |
|-----------------------------------------------------------------------------|
| REAL RMSE    .48  ADJ.SD     .46  SEPARATION   .96  PERSON RELIABILITY  .48 |
|MODEL RMSE    .47  ADJ.SD     .48  SEPARATION  1.02  PERSON RELIABILITY  .51 |
| S.E. OF PERSON MEAN = .03                                                   |
-------------------------------------------------------------------------------
        VALID RESPONSES:  59.2%
PERSON RAW SCORE-TO-MEASURE CORRELATION = .89 (approximate due to missing data)
CRONBACH ALPHA (KR-20) PERSON RAW SCORE RELIABILITY = .36 (approximate due to missing data)

     SUMMARY OF 39 MEASURED ITEMS
-------------------------------------------------------------------------------
|          RAW                          MODEL         INFIT        OUTFIT     |
|         SCORE     COUNT    MEASURE    ERROR      MNSQ   ZSTD   MNSQ   ZSTD |
|-----------------------------------------------------------------------------|
| MEAN     129.4     284.1        .00     .14       .99    -.1   1.00     .0 |
| S.D.      64.9      93.2        .80     .02       .06    1.3    .10    1.4 |
| MAX.     359.0     480.0       1.82     .21      1.14    3.4   1.25    3.1 |
| MIN.      27.0     221.0      -1.48     .10       .87   -2.5    .80   -2.6 |
|-----------------------------------------------------------------------------|
| REAL RMSE    .14  ADJ.SD     .79  SEPARATION  5.60  ITEM   RELIABILITY  .97 |
|MODEL RMSE    .14  ADJ.SD     .79  SEPARATION  5.66  ITEM   RELIABILITY  .97 |
| S.E. OF ITEM MEAN = .13                                                     |
-------------------------------------------------------------------------------
UMEAN=.000 USCALE=1.000
ITEM RAW SCORE-TO-MEASURE CORRELATION = -.75 (approximate due to missing data)
11078 DATA POINTS. LOG-LIKELIHOOD CHI-SQUARE: 12967.91 with 10560 d.f. p=.0000
```

Figure 4.2. Summary of Rasch modeling statistics. Separation index is the ratio of adjusted standard deviation over root mean square error.

All the infit and outfit were within acceptable range [0.7- 1.3] (Wright & Linacre, 1994). The outfit plot of the concurrent anchor item calibration demonstrated satisfactory distribution of outfit values lying between 0.8 to 1.25. The results indicate a good model-data-fit.

The test information functions of the two versions were maximum at latent trait measure $\theta = 0$ (Figures 4.3 (a) an (b)). Version B had higher test information (5.24) than Version A (4.88). Higher test information can be attributed to the more items in Version B.

Overall person separation and reliability is also helpful in determining model-data-fit. Figure 4.1 shows a summary of Rasch modeling for the IUS-E survey based on a sample of 480 subjects. The test differentiated subjects with a separation index of .96 based on the empirical data, or 1.02 based on the model expectations if there was a perfect model-data-fit. The Cronbach alpha for those separation indices are .48 and .51, which also represent test reliability. A low separation index (e.g., < 2.0) and alpha (e.g., < .80) are indications that the instrument is not sensitive enough to differentiate high and low performers.

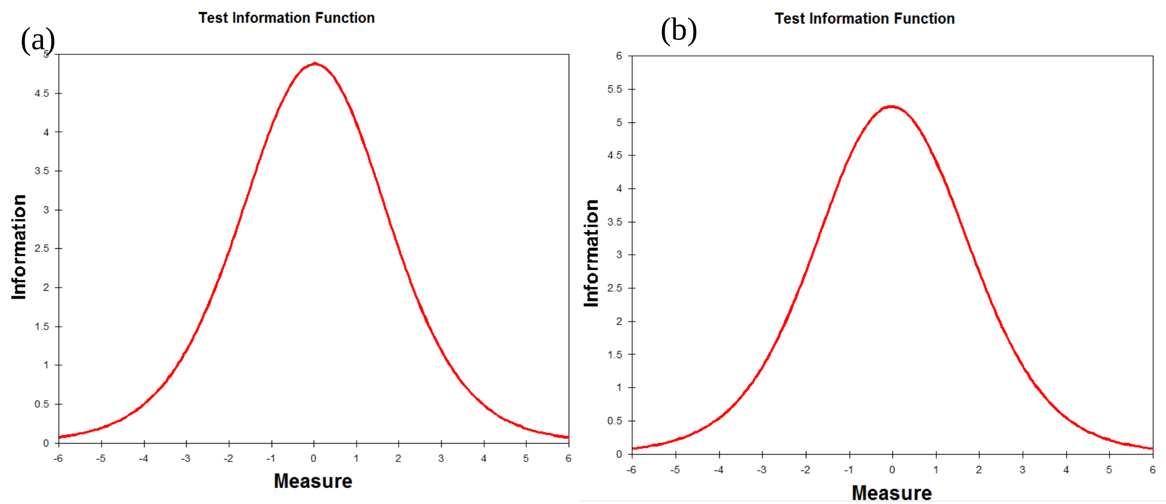

Figure 4.3. Test information function for (a) Version A and (b) B.

On the other hand, the item separation index is 5.6 based on the empirical data, or 5.66 based on the model expectations. The Cronbach's alpha for those separation indices were both .97. High item separation verifies the item hierarchy, implying that the number of person sample is large enough to confirm the item difficulty hierarchy, or construct validity of the IUS-E instrument. This may be caused by very narrow range of subject ability variance. More items may be needed to increase the person separation, and thus the test reliability (Linacre, 2012; Liu, 2010). The reliability for *transfer* items in Versions A and B are .15 and .05; the reliability for *integration* items in Versions A and B are .22 and .51, respectively. The Cronbach's alpha estimates from SPSS and Winsteps were the same.

In order to investigate the cause of low reliability, further reliability check with suggested deletion of items from SPSS has increased the reliability in both versions. In Version A, after deleting four items, the Cronbach's alpha increases from .38 to .49; in Version B, after deleting one item, the Cronbach's alpha increases from .55 to .57. Even though the reliability increased a little after ridding of some items, it was still not significant enough to reach acceptable cutting point at .8.

IUS-E Ability among the Classes

A one-way analysis of variance (ANOVA) was conducted to evaluate the relationship of the respondents' ability measures in the three science classes (Tables 4.5 and 4.6). The independent variable, the science class factor, included three different classes: Biology (BIOL), Physics (PHYS), and Physical Biochemistry (BCME) classes. The dependent variable was the person ability measures based on their item response vectors, which represent respondents' IUS. The ANOVA was significant for version A (F_A (2, 218) = 3.724, p = .026), which means that there is a difference in ability between the classes students enrolled in. The η^2 of .033, which meant that the strength of the relationship between the science classes and the person ability measure of the IUS-E items was small to mediocre. In other words, the science class factor accounts for 3.3% of the variance of the IUS.

Table 4.5
Means and Standard Deviations for Person Measure Estimate in Science Classes in Group A

Science Class	*M*	*SD*	*N*
BCME	-0.231	0.71	16
BIOL	-0.620	0.60	175
PHYS	-0.428	0.71	30

Table 4.6
Means and Standard Deviations for Person Measure Estimate in Science Classes in Group B

Science Class	*M*	*SD*	*N*
BCME	0.627	0.73	22
BIOL	-0.055	0.66	199
PHYS	0.314	0.68	38

The test of homogeneity of variance was insignificant, $p = .625$, indicating that the error variance of the IUS variable was equal across groups. The Tukey HSD *post-hoc* test revealed that in Version A, there was a significant difference ($p = .046$) between the person ability measures between the BCME class and the BIOL class. The ability measure for BCME student was better than the BIOL class with logit .39 difference. But, there was no significant difference between the PHYS class and the BCME class ($p = .564$) or between the PHYS class and the BIOL class ($p = .263$). The boxplot for the three classes is presented in Figure 4.4.

The ANOVA was also significant for version B, F_B (2, 256) = 13.509, $p = .000$. The η^2 of .095 means that the strength of relationship between the science classes and the percentage correct on the IUS-E items were mediocre. The factor of the different science classes accounted for 9.5% of the variance of the IUS. The *post-hoc* test, such as Tukey HSD test, revealed that, in Version B, there was a significant difference ($p = .000$) among the person ability measures between the BCME class and the BIOL class. There was also a significant difference between the PHYS and BIOL classes. The students in BCME and PHYS classes possessed higher ability estimates than the BIOL class, but there was no significant difference between the PHYS class and the BCME class ($p = .191$).

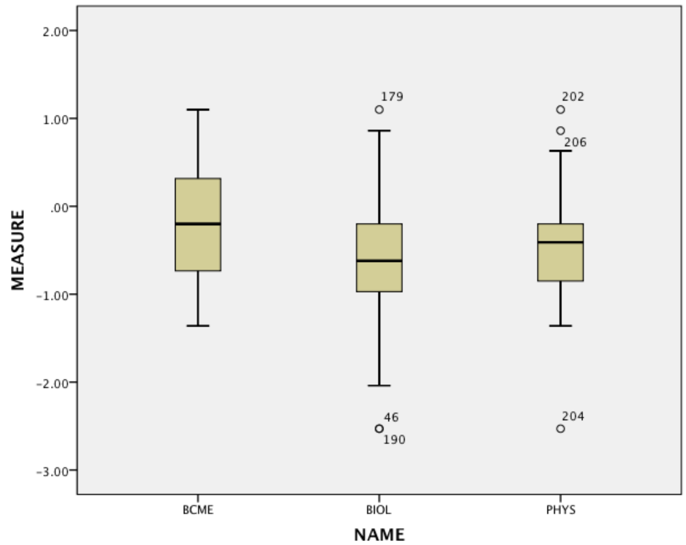

Figure 4.4. The boxplot for person measures for IUS-E Version A in the BCME, BIOL, and PHYS Classes.

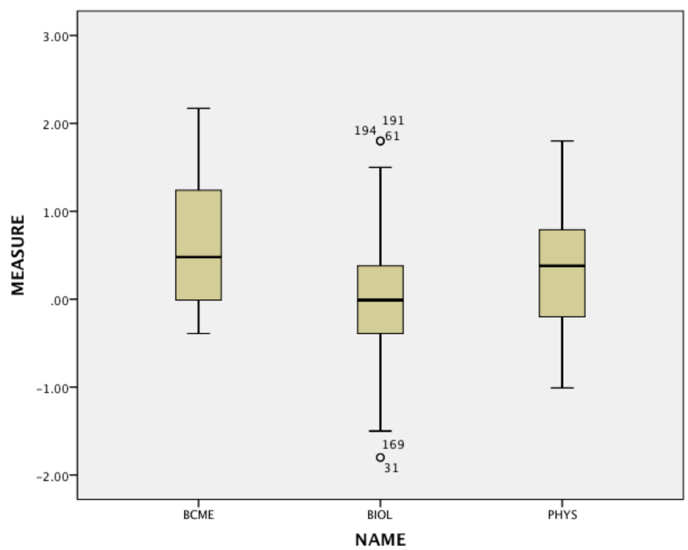

Figure 4.5. The boxplot for person measures for IUS-E Version B in the BCME, BIOL, and PHYS Classes.

The finding is similar to Lee and Liu's (2010) study for secondary school students taking life sciences, earth sciences, and physical sciences. The tentative explanation they gave was the greater number of courses taken by the participants and the content covered in physical sciences class enabled higher level of thinking in energy (Lee & Liu, 2009). The boxplot for the three classes is presented in Figure 4.5.

Dimensionality of Items

The dimensionality of items was also examined after linking the items in Versions A and B. The variance component Scree plot derived from Winsteps is shown in Figure 4.6. The common variance among the item responses explained by Rasch dimension was 19.3%. Unexplained variance was then evaluated to determine whether there is other significant dimension. Rasch principal component analysis (PCA) enabled the detection of unexpected patterns for groups of items. The potential multidimensionality was examined with contrasts within the data. The variance due to the largest of these contrasts was only 3.6%. Its eigenvalue was 1.8, which is lower than the smallest strength to be considered a dimension (i.e., eigenvalue > 2) (Glynn, 2012; Linacre, 2013). The eigenvalues of other contrasts were also less than 2, implying that no additional dimension was significant enough to violate the unidimensionality assumption. In addition to investigating dimensionality by Rasch PCA, I also determined the correlation of item and item residuals as recommended by Embreston and Reise (2002).

```
     Table of STANDARDIZED RESIDUAL variance (in Eigenvalue units)
                                               -- Empirical --    Modeled
Total raw variance in observations     =        48.3 100.0%         100.0%
 Raw variance explained by measures    =         9.3  19.3%          17.4%
   Raw variance explained by persons   =         2.3   4.7%           4.2%
   Raw Variance explained by items     =         7.1  14.6%          13.2%
 Raw unexplained variance (total)      =        39.0  80.7% 100.0%   82.6%
   Unexplned variance in 1st contrast  =         1.8   3.6%   4.5%
   Unexplned variance in 2nd contrast  =         1.7   3.4%   4.2%

       STANDARDIZED RESIDUAL VARIANCE SCREE PLOT

        VARIANCE COMPONENT SCREE PLOT
      +--+--+--+--+--+--+--+--+
  100%+  T                    +
      |           U           |
V  63%+                       +
A     |                       |
R  40%+                       +
I     |                       |
A  25%+                       +
N     |                       |
C  16%+     M                 +
E     |           I           |
   10%+                       +
L     |                       |
O   6%+                       +
G     |                       |
|   4%+        P              +
S     |                 1  2  |
C   3%+                       +
A     |                       |
L   2%+                       +
E     |                       |
D   1%+                       +
      |                       |
  0.5%+                       +
      +--+--+--+--+--+--+--+--+
        TV MV PV IV UV U1 U2
         VARIANCE COMPONENTS
```

Figure 4.6. Table of standardized residual variance (in Eigenvalue units) and Scree plot.

Figure 4.7 is the dimensionality map that shows how items are correlated with a potential additional construct within the item residuals. Any items with a high correlation (i.e., the absolute loading or correlation coefficient is greater than 0.4) may indicate that those items measure more than one construct. Figure 4.5 shows that most items fall within the range of small factor loadings (-0.4, +0.4). However, one item A, B 2.4.5 is outside the range, which means that it measures more than one construct. The question is a two-tier item, due to the violation of unidimensionality, it needed to be revised. Overall, item residual analysis shows that the items lie between acceptable dimensionality range. The result fulfills the unidimensionality assumption for applying the Rasch model. On the contrary, the result could also be interpreted as non-dimensionality as there is no prominent single factor to explain the variance of the IUS-E instrument. Each factor only contributes to a small portion of explaining the overall variance. This is the major challenge of this “prototype” assessment instrument (S. M. Glynn, personal communication, March 19, 2013).

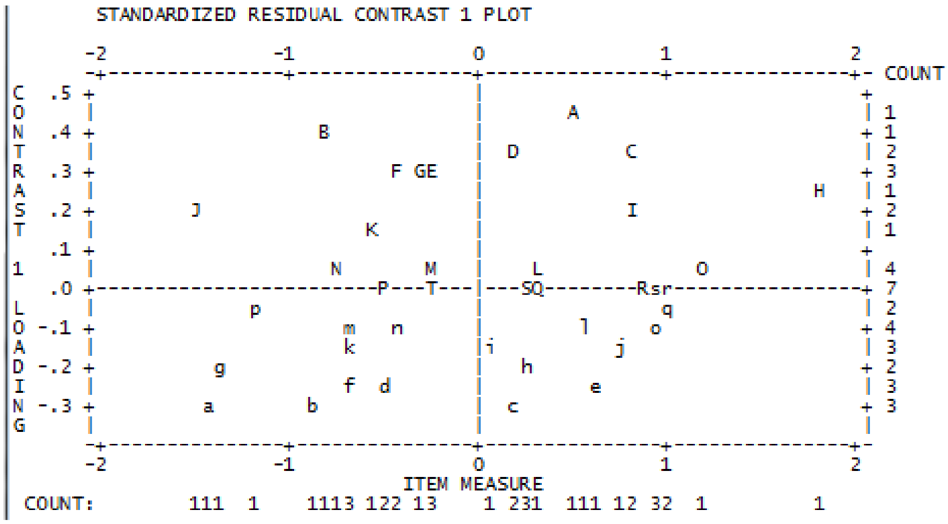

Figure 4.7. Dimensionality of item residuals. Loadings are correlation coefficients between item measures and their measures on an additional dimension. Items with correlation coefficients beyond the ± 0.4 range are potentially measuring an additional dimension.

Differential Item Function

Also, local invariance assumption was applied to the analysis of differential item function (DIF) based on seven anchor items in versions A and B. When items are biased, their difficulty measures will be statistically significantly different between subsamples. There is no significant difference between item difficulty measures for Group A and Group B. For instance, in Question C1, the difference between the difficulty measures is .27 logit in favor of Group B, which indicates that the item was a little bit more difficult for Group A than for Group B. Both the *t* test (p = .198) and the Mantel Haenszel (p = .252) test, which is a chi-square statistic, show that the difference was not statistically significant for Question C1. Similarly, Questions C2-C7 were not statistically significantly different in Group A and Group B.

In Tables 4.7 and 4.8, raw total scores range from 0 to 22 in Version A and 0 to 24 in Version B, because there were 22 and 24 multiple-choice items respectively. Each raw total score is correspondent with one Rasch scale score, that is, the measure, together with its standard error of measurement. By consulting this table, users of IUS-E can find out their subjects' Rasch scale scores based on their raw total scores and use the Rasch scale scores for subsequent

Table 4.7

Conversion of Ordinal Scale Raw Scores to Interval Scale Logit Measures in Version A

Score	Measure	SE	Score	Measure	SE
0	-4.67	1.05	12	.21	0.45
1	-3.50	1.04	13	.42	0.46
2	-2.53	0.76	14	.63	0.47
3	-2.04	0.64	15	.86	0.48
4	-1.67	0.56	16	1.10	0.50
5	-1.36	0.53	17	1.37	0.53
6	-1.10	0.50	18	1.67	0.57
7	-.85	0.48	19	2.04	0.64
8	-.62	0.47	20	2.52	0.76
9	-.41	0.46	21	3.28	1.04
10	-.20	0.45	22	4.54	1.05
11	.01	0.45			

Table 4.8

Conversion of Ordinal Scale Raw Scores to Interval Scale Logit Measures in Version B

Score	Measure	SE	Score	Measure	SE
0	-4.64	1.84	13	.19	0.44
1	-3.39	1.03	14	.38	0.44
2	-2.63	0.75	15	.58	0.45
3	-2.16	0.63	16	.79	0.46
4	-1.80	0.57	17	1.01	0.48
5	-1.50	0.52	18	1.24	0.50
6	-1.25	0.50	19	1.51	0.53
7	-1.01	0.47	20	1.81	0.57
8	-.79	0.46	21	2.17	0.64
9	-.59	0.45	22	2.65	0.76
10	-.39	0.44	23	3.41	1.03
11	-.20	0.44	24	4.66	1.84
12	-.01	0.44			

statistical analysis. The separate and concurrent linking method revealed similar ordering of item measures results. So, I only conducted further analysis from the concurrent linking result. The plot (i.e., the Wright map, see Figure 4.1) for concurrent linking analysis indicates the seven anchor items spread pretty evenly from the easy to difficult levels. Both the person and item measures did not exceed logit +2 or logit -2.

Discussion

Validity

The first research question concerning the components and validation processes of interdisciplinary items was accomplished with the IT^3 cognitive framework and the various approaches to establish proper validity. The face, content, and construct validity were established by the faculty members, graduate students, as well as with the respondents. Face validity of the IUS-E content is based on the interdisciplinary nature it appears. Content validity is grounded in the correctness and the appropriateness of integrating energy topics across distinct disciplines. Nevertheless, I could not identify any interdisciplinary content experts to inspect whether these items are interdisciplinary enough and whether the energy topics covered are representative sampling to demonstrate students' IUS-E. Construct validity was examined through students' interviews and the dimensionality check to confirm whether such items solicited the designated IUS construct. High construct validity was inferred from item separation index, which is a measure unique to IRT model, revealed high construct validity of the IUS-E instrument. The components addressing IUS and the triangulation of validity check for the IUS-E instrument was accomplished in this study.

Model-Data-Fit

The second research question targets the psychometrics properties of the IUS-E. There is good model-data-fit between the observed dataset and the Rasch model. It indicates that the Rasch model is suitable to explain the IUS-E item responses. The Rasch model assumes equal discrimination among items with default discrimination equals 1. Also, no guessing effect is considered in the Rasch model, meaning that the lower asymptote is close to 0 and the higher asymptote reaches 1. Discriminate estimate from 2PL and guessing effect estimate from 3PL inspected with Winsteps indicated no unexpected bias discrimination or guessing. This check confirmed that the Rasch model described the observed data well.

Ability Differentiation

The classical test theory (CTT) can differentiate group ability means more effectively than the modern test theory. The result from One-Way ANOVA indicated that the students taking senior interdisciplinary course and physics possess significantly higher ability than those from the introductory biology classes in both versions. Students from BCME class, which is a senior level interdisciplinary course, were expected to perform better on the interdisciplinary instrument than those who are taking introductory science class; however, since the sample size varied dramatically between BCME class (a total of 38 participants) and BIOL class (a total of 374 participants), it is quite challenging to simply differentiate higher level students from lower level ones by their locations on the person map. Therefore, the determination of whether students enrolled in higher-level interdisciplinary course perform better than the lower level ones is better achieved with the classical test theory (one-way ANOVA). Person map from IRT is not an effective means to examine clustered subjects. The findings showed that the IUS-E survey was capable of discriminating students possessing differential IU. The problem still remains, where exactly the differences are derived from? Since the instrument was unable to differentiate ability levels of BCME and PHYS students, the common argument one might formulate is whether the IUS-E instrument is testing students' physical sciences understanding rather than IUS. The question requires additional research.

Dimensionality

The study revealed that the dimensionality of this energy survey might be questionable from Factor Analysis (FA). The evidence supporting the assumption of unidimensionality was relatively weak from the FA. On the contrary, there were no significant dimensions being detected from the FA. The result from FA explains about 20% of the variance of the items, which is small but common at the initial stage of instrument construction. It may imply that the presumption for IUS as a stand-alone construct is not fully validated with FA. It is at the borderline of non-dimensionality. Further analysis on the inter-item correlations also revealed that there were statistically insignificant correlations between most of the items in Versions A and B. It indicated that the items seem to measure irrelevant construct. However, some of the questions with significant correlation were the subsets of questions targeting on similar energy topics. The preliminary dimensionality check and inter-item correlation result implies that there are gaps among different subgroups of topics.

Nevertheless, Embretson and Reise (2000) gave positive comments on using the analyses of residual covariance terms after fitting the data with a particular nonlinear factor model (i.e., IRT model in this study). They stated that the comparison of the ratio of the first to second eigenvalues is under debate (Embretson & Reise, 2000, p.228). The authors introduced the affordances of analysis of residual covariance as a potential alternative. Therefore, even though no prominent dimension was detected from FA, the analyses of residual covariance confirmed that all items were within acceptable range of unidimensionality assumption.

Reliability

One major challenge of the IUS-E was that the test reliability inferred from person separation index was low, indicating that the IUS-E instrument is not sensitive enough to distinguish respondents with varying degree of IUS if the instrument were to be implemented again to another sample of participants. Low person separation might be attributed to the very narrow range of IUS ability in the population. One recommendation to increase test reliability is to include more items with varying difficulty levels. The low reliability might also imply that the IUS-E constitutes several different subcategories, such as the energy topics introduced in isolated disciplines and the involvement of distinct cognitive processes not included in the analysis. The former view was reflected in the survey responses attached at the end of the IUS-E instrument. Approximate 30% respondents perceived that the energy topics have been introduced in fragmented contexts in different disciplines so they are isolated; the latter hypothesis requires the inclusion of students' responses to the originally excluded cognitive processes (i.e., *translation* and *transformation* questions) and conducts the person separation analysis again.

Moreover, since the IUS-E instrument is an innovative and experimental survey, there might be factors we overlooked or not considered but are detrimental for test reliability. An instrument is unreliable "...whenever an examinee responds to a set of test items, his or her score represents only a limited sample of behavior..." (Crocker & Algina, 1986, p.105). For instance, we proposed four types of cognitive processes including *integration*, *translation*, *transfer*, and *transformation*; however, since the question types for *translation* and *transformation* were non-multiple-choice items, I did not include questions in the Rasch model analysis. In this way, only a subset of cognitive processes (*integration* and *transfer*) were sampled and analyzed. There could be a lack of representative items to elicit possible cognitive processes. An addition of items addressing either the *translation* or *transformation* process might be able to test this hypothesis. These factors could be tested in the future research.

In the interviews, all eight students had a hard time recognizing the close link between the conversions of potential energy to other forms of energy right away. For example, when they were prompted to think-aloud the underlying mechanisms of the electricity converted from solar energy, none of them can rationalize it without any hint. Such case is analogous to the conversion of chemical concentration differences in the cellular level mechanisms. Also, interviewees tended to use the equilibrium concept directly without a realization of the underlying laws of thermodynamics. If respondents treated these items as testing merely separate energy topics, they could not integrate the underlying, essential laws connecting the energy topics. Students' perceptions about these items will affect the approaches or the cognitive processes they used to answer the IUS-E instrument because the instrument was designed to be construct-oriented. Many items may only serve as a limited sampling of the entire pool of interdisciplinary items. Simply put, the sampling variance in the IUS-E construct might be greater than expected if students did not use the targeted construct to respond to the instrument.

Entropy and Energy Degradation

I found the open-ended questions on the IUS-E to be incapable of soliciting one major conceptual understanding of interest--the natural tendency of distribution of any matter. Understanding the tendency of distribution will help students to internalize that entropy concept is fundamental for driving the equilibrium of a system. Conventional terminology connoting this phenomenon is "energy degradation", which indicates that the reaction is irreversible in an open system when reaches equilibrium. However, some scholars argued against using the term "degradation," because it might raise potential confusion that energy is degraded or lost, is contradictory to the law of the conservation of energy. Possible modification of eliminating the usage of "energy degradation" is replace it with "energy dissipation," which "specifically relates to the view of students understanding that in each transformation or transfer process some of the energy is transformed into thermal energy and knowing the underlying mechanism (e.g., friction)" (Neumann, Viering, Boone, & Fischer, 2013, p.184). Neumann et al. also proposed a new term "energy devaluation," which "relate to students understanding of the characteristics of the process of energy degradation itself (including understanding the idea of entropy)" (2013, p.184). Energy devaluation is closely related to the objective of the IUS-E design in this study.

Some useful questions to stimulate conceptual conflict or dilemma are: Why does a system reach equilibrium spontaneously? Why does a reaction cease net change when it reaches equilibrium? What does energy concept have to do with the concentration gradient? These are all challenging concepts to convey in undergraduate science classes. The survey enables instructors to elicit useful information regarding what types of energy topics imposed more intellectual challenge on the students' IUS. From an investigator's perspective, examining the energy topics through interdisciplinary lens provided new insight to view energy topics from more integrative and transferrable contexts.

Stratification of Each Cognitive Process

A drawback of the application of Rasch model was that the results did not demonstrate special statistical properties for different cognitive processes. In other word, an instrument comprising these four processes denoted in the IT^3 framework cannot be differentiated with the Rasch analysis. The impact of each cognitive process on test performance is also largely unknown without *post-hoc* test. More indepth interview on each item may help better inform, revise, and consolidate the interpretation of each cognitive process identified in the IT^3 framework. Also, in order to decompose the cognitive processes on items with quantitative analysis, multiplecomponent latent-trait model (MLTM) could be applied to items for which subtasks are available to identify the components (Linden & Hambleton, 1997). MLTM is applicable for complex tasks involve processes for solutions, usually from cognitive psychology perspectives. Potential subtasks that made up the IUS-E instrument represent the *integration*, *translation*, *transfer*, and *transformation* processes. Such analysis like MLTM can be conducted to explore particular stimulus features to enact each cognitive process.

Item revision

Both quantitative and qualitative data provided substantial information for item revisions. The interview data also helped me to identify some weakness of the IUS-E and the factors that might increase students' cognitive loading. These semi-structured interviews helped me to realize the effectiveness of the items to elicit respondents' specific IUS understandings. The quantitative data linked items on both versions and enabled a comparison of the item difficulty levels on the same scale through anchor items. The person ability and item difficulty measures were also placed on the same logit scale to be compared and interpreted. The major observation for the IUS-E instrument is the relative small span of item measure (i.e., -2 to +2), which often can be found with a range of -4 to +4 on the logit scale.. Even though the range of item difficulty levels seem to be rather limited than other instrument, they were sufficient to measure the respondents' IUS without many outliers. The Wright map depicts a good spread of anchor items without any detection of bias between A and B groups according to the DIF analysis. So the items with duplicate item difficulty may be deleted to make the implementation process more time-efficient.

Through item measure estimate, questions with repetitive difficulty levels or similar question contexts were examined and some of them were eliminated from the final version of IUS-E. According to the item measures estimated with the Rasch model, the most difficult item was A2.16.4. This question was designed to use the analogy of gravitational potential energy of the earth and compared to the role of water, which possesses chemical potential energy. Twice as many students endorsed to the option of “potential energy” (25.3%) instead of the desired option of “water” (12.2%). There was a disagreement between the experts regarding the correct comparison of the role of earth and water. This initial speculation might also reflect the difficulty estimate of this item. On the contrary, 40.7% of students correctly responded to a similar analogy question asking about the relationship between gravity and potential energy in B2.13.3. Therefore, the option “potential energy” in item A2.16.4 might introduce confusions and should be deleted. However, participants’ open-ended responses explaining the rationale to the role of earth were informative concerning their understanding across disciplines. For example, when student perceived the earth to be analogous to activation energy by writing “The earth is the activation energy that pulls the ball to the ground“ (respondent A26), I interpreted the respondent had misconception about activation energy. Because activation energy is defined as the energy required to overcome a threshold to trigger a reaction. The earth does not satisfy this activation energy definition. Students chose kinetic energy to be analogous to the earth by giving the rationale that “The earth causes the ball to fall which means that the ball will be in motion due to gravity“ (respondent A46) and “the earth has kinetic energy because it’s always in motion” (respondent A190) missed the target at which this question aims. The falling of a ball converts potential energy into kinetic energy; however, the kinetic energy concept does not explain the fundamental role the earth plays. In addition, the open-ended response can also confirmed one’s successful reasoning of the earth and the water analogy—“I chose [as] water because it is going to help break apart the bond” (respondent A50).

The item possessing the second highest difficulty measure is the anchor item C3 (i.e., A2.13.1 and B2.11). An approximate equal probability of endorsement to each option was observed (28.6%, 20.5%, 24.3%, and 26.6% for A, B, C, and D, respectively). This question is retained because it might have elicited the confusions students had concerning equilibrium and energy under a closed system.

Interestingly, B2.13.2 was of similar difficulty level with the anchor item C7 (i.e., A2.17.1 and B2.14.1). Item B2.13.2 asked about the analogy of the ball with phosphate groups (Pi), while the anchor item inquired about the transfer of two negatively-charged balls to the ATP hydrolysis. These two questions seem to be more or less duplicative in this instrument. So I will retain the charged-ball item and delete B2.13.2. One purpose of designing the two versions of instrument was to investigate the effects of the order of presenting the ball-to-the-wall and ATP hydrolysis questions. My assumption was that the items would be easier for the respondents if the students were exposed to a more familiar context and then presented with a similar setting under a distinct context. For instance, in Version A, students were exposed to the more familiar context of ATP hydrolysis setting prior to the ball-to-the-wall question. There were two items out of three questions, which were designed concerning ball-to-the-wall context in Version A (i.e., A2.16.2 and A2.16.4), were determined to be more difficult in the concurrent linking approach when compared to the similar items in Version B. Our hypothesis was that if students can transfer their understanding of ATP hydrolysis correctly, the following ball-to-the-wall question would appear to be less difficult. However, since the ball-to-the-wall items in each version were different, such comparison was invalid. A2.16.2 (wall) and A2.16.4 (the earth) seemed to be less intuitive for students to connect the ball-to-the-wall context with the ATP hydrolysis than B2.13.1 (flame) and B2.13.3 (gravity). The former two represent more concrete image in the system than the gravity concept. For the connection of flame and activation energy, maybe there was a hint from the combustion of marshmallow in B2.12.2. It might explain the differences in the percent-correctness for B2.13.1 (flame, 56.4%), B2.13.2 (ball, 25.5%), and

B2.13.3 (gravity, 40.5%). Therefore, the order-effect may require the implementation of exact same items to test the underlying hypothesis.

A2.10.1, A2.16.2, and A2.8.1 were placed on similar item difficulty level and not aligned with the respondents. A2.10.1 connected the decomposition, entropy, spontaneity of reactions, and the energy requirement in breaking of bonds; A2.16.2 inquired about the analogy of the wall with ADP; and A2.8.1 is the integration of Redox (i.e., reduction and oxidation) reaction in the photosynthesis. These questions solicited IU of energy from different content aspects. Even though they are of similar difficulty level, I will still retain A2.10.1 and A2.8.1 and only get rid of A2.16.2 because B2.13.2 can represent the same question set. Similar decision was made for A2.10.2 and A2.5.1.

Anchor item C2 denoting NPP (i.e., A2.9.2 and B2.7.2) can be deleted because it possesses similar difficulty level with A2.9.1, which is a more general representation of the first law of thermodynamics. Also, as noted before the gravity concept in B2.13.3 may be a better question to elicit the transfer process of respondents than the more vague link of the earth and water (A2.16.4). A2.11.1 (the Gibbs free energy and entropy item) and the anchor item C4 (i.e., A2.14.3 and B2.12.2, the question about the comparison of combustion and digestion of marshmallow) were situated in similar difficulty level. Both of these questions are retained because they elicited distinct IU of energy. The former item transfers the Gibbs free energy concept in physical sciences sense to explain the decomposition and the increase of entropy in life sciences context; while the latter represented the transfer process of physical combustion in the environment to the cellular "combustion" in life sciences.

A2.4.3, B2.4.3, A2.7.1, and B2.8.1 were placed on at similar difficulty level. The former two denoted the effect of fluorescent light bulb. Since A2.4.3 had to undergo major change of wording, I retained B2.4.3 for the final IUS-E version. Because only 49.3% respondents got A2.7.1 right, so the item is suitable to differentiate students. A2.7.1 is retained for the final version. For B2.8.1, though about 50% of students get the correct answer by endorsing the correct option that there is an increase of entropy in decomposition process, 24% endorsed to option B, where entropy remains the same globally. It is retained to go with B2.8.2, which was not overlapping with any other item difficulty. B2.13.1 concerning flame would be deleted and the anchor item C1 (i.e., A2.5.2 and B2.5.2) is retained. A2.14.2 is the first-tier of a multiple choice, since there is no differential weight for this item with only three options; I deleted A2.14.2 and kept A2.16.3 with the analogy of wax and bond. A similar item for B2.12.1 was also embedded in Version A (A2.14.1), I kept B2.13.4 and rid of B2.12.1. Items A2.14.1 (which was already chosen for final version), B2.4.6, and B2.9.1 were also of similar difficulty. So, since B2.4.6 and B2.9.1 focus on different IU, I would keep these three questions. B2.10.1 asked about the application of renewable energy, over 75% of students answered the question correctly. Therefore, B2.10.1 is deleted as well.

Some features of questions without overlapping difficulty measures are also discussed here. The result for B2.8.2 showed that only 33% of students chose the correct response B, 37% endorsed option D, which denotes the entropy to maintain the balanced state. Similar to B2.8.1, both questions confirmed the popular perception that entropy should somehow be balanced, which is contradictory to the law. It implies that even though students perceive the phenomenon to be comparable by avoiding option A (only 14% endorsement), they failed to integrate the law under a given living system.

After a deletion of similar item measures, there were 27 multiple-choice questions kept from the step-wise analysis from the item difficulty measures. However, the low test reliability implies that more items are required, therefore, items with higher reliabilities that were not included in the final versions are added back to the question pool. Likewise, items with very low reliability that were included based on difficulty measures were examined again. This procedure may increase the reliability for selecting higher quality items to be included in the final IUS-E survey. In sum, the final IUS-E instrument implemented in spring 2013 has 34 multiple-choice questions (see Appendix).

Contribution

Promoting interdisciplinary education does not mean discarding disciplinary courses. Our cognitive framework—the IT^3—considers the advancement of disciplinary knowledge in order to communicate across disciplines. Students should be able to root their science knowledge in rigorous disciplinary training and consciously elicit and apply their disciplinary perspectives to bring isolated concepts or inconsistent terminologies together in order to effectively communicate with others. The exploratory process of this study will provide an informative procedure for educators who are interested in tackling the possibility of measuring students' IU quantitatively. The steps for creating a reliable and valid assessment instrument were discussed so that instructors can construct assessment items that are applicable for meeting their needs. The standard operational procedures for constructing an interdisciplinary instrument will also be useful as formative and summative assessments to inform the educators or instructors who are involved in interdisciplinary collaboration. The potential of IUS item generation is promising in an era of accountability.

Limitations

Even though the Rasch model fit well for the data, the validity of the IUS-E might be questioned because of a lack of genuine "interdisciplinary science" experts to advice on the item revisions in order for the instrument to reach higher construct validity. Besides, energy topics are usually bound within particular disciplines despite of their close relationship across disciplinary boundaries. With an instrument targeting on a snapshot of students' IUS might elicit relative crude results affording limited implication. Since there was no intervention, such as training or formal instruction on how to practice different cognitive processes that are involved in explicit expression of IUS. Promoting interdisciplinary science education and students' familiarity of practicing interdisciplinary thinking is the next step. Collaborative work on improving an interdisciplinary instrument should be further investigated to accomplish desirable psychometric properties.

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Appendix B

IUS-E Example Questions for IT^3 Framework

The IUS-E survey also explores an analogy concerning why additional conversion of energy into a closed system is required in most real-life situations. The combustion of a marshmallow has a negative ΔG, but the combustion does not happen spontaneously until an additional input of energy is invested. An essential analogy to understand this seeming violation of spontaneity pertaining to free energy is formulated in a macroscopic setup with a ball stuck to the wall with wax. Even though the tendency of the ball to drop to the ground has negative ΔG, the ball cannot convert the potential energy to kinetic energy without breaking free of the wax attachment, which resembles the bonds between molecules. There must be a little activation energy invested in order to release a greater amount of energy stored in the form of gravitational potential energy. Similarly, the ATP hydrolysis reaction requires an input of energy to break the bond between two phosphate groups and enact a series of reactions, which surpass the input of energy to activate the hydrolysis reaction (see Questions A 2.16 and B 2.13 in Appendix I).

Besides, the IUS-E instrument also includes many questions about energy transfer and transformation by means of the electromagnetic radiation. For example, the energy conversion in a fluorescent light bulb was used to solicit "translation" aspect in the IT^3 framework. Also, an open-ended question for the comparison of chloroplast and solar panel was created to determine whether students can recognize similar systems in different disciplinary contexts.

2.6. A PV panel is designed to capture a particular portion of the light spectrum (e.g., UV light) to excite electrons inside the device. The excited electrons move to n-type silicon while the "holes" (positively charged particles) are left in the p-type silicon. The flow of electrons generates electrical current (see Figure a). Similarly, most plants utilize light energy to convert CO_2 into glucose. Refer to Figure b for the structure of a chloroplast and Figure c for the mechanism.

2.6.1. An electron transport chain couples with the transfer of protons (H^+) across the membrane.

Why is this process similar to the energy harvesting of the PV panel in converting light to electricity? Use one or two sentences to **explain how** the energy harnessed in the chloroplast is similar to the PV panel.

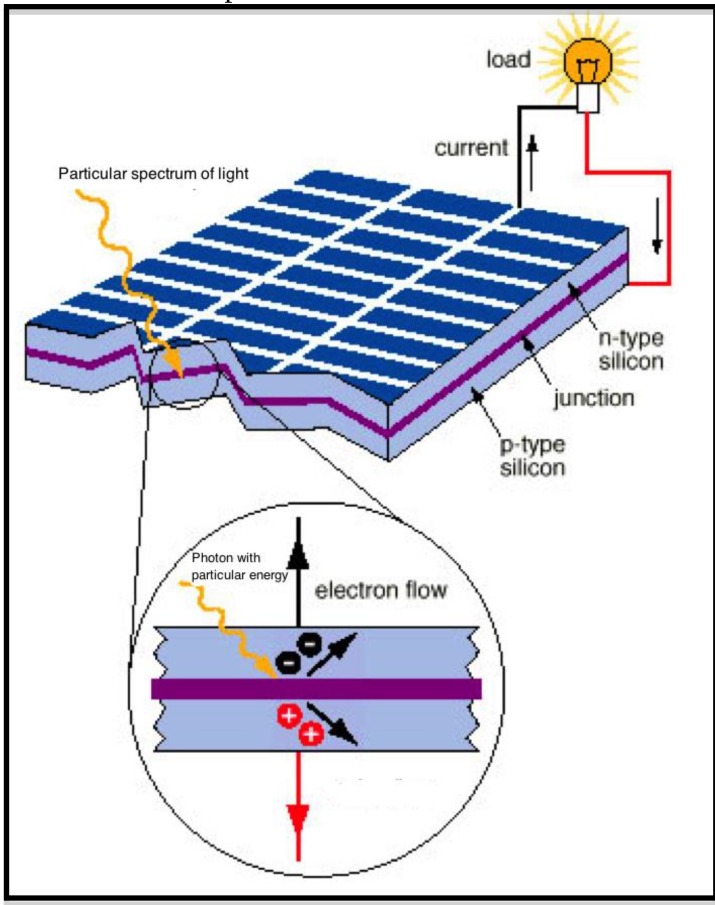


Figure a

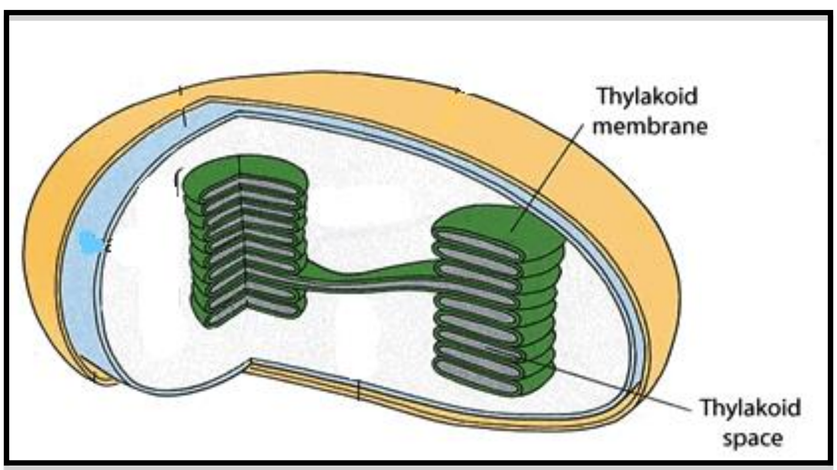


Figure b

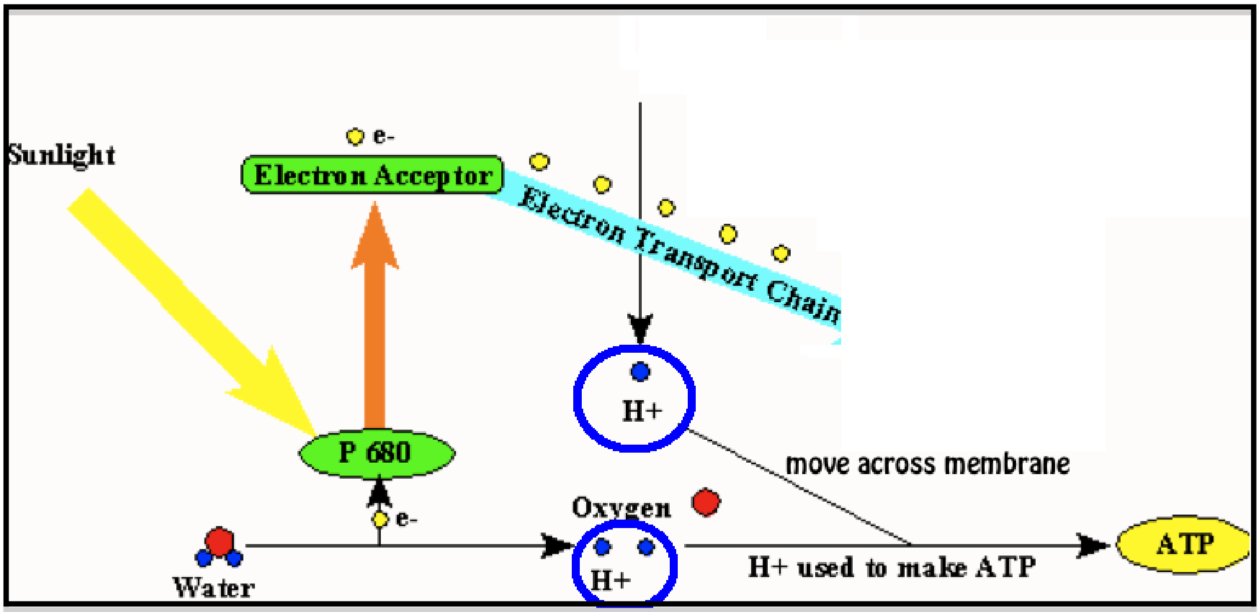


Figure c

The question was designed to elicit *transfer* process students used to distinguish the light energy used in a chloroplast is also being utilized in a solar panel. Similarity of these two systems are that these structures utilize energy from sunlight, create electric potential energy across two regions, and convert the electric potential energy into another form of energy. The contrast are: the PV panel makes better use of UV light and the chloroplast mainly utilizes visible light; one is inorganic and the other is organic reaction; the energy harnessed in PV panel is used for electricity; and the energy harvested in chloroplast is used to convert to fix carbons for further work, etc.

Due to the requirement of a proactive manipulation of one's disciplinary conceptual understanding, the *transformation* process cannot be solicited with a passive endorsement on a multiple-choice question. The second-tier open-ended questions, thus, became major source to distinguish learners' practice of *transformation*. Questions that ask respondents to modify or change some theory or method to accomplish the goal can be treated as *transformation* question. An example posed after the combustion of marshmallow demonstrated how a *transformation* question was posed.

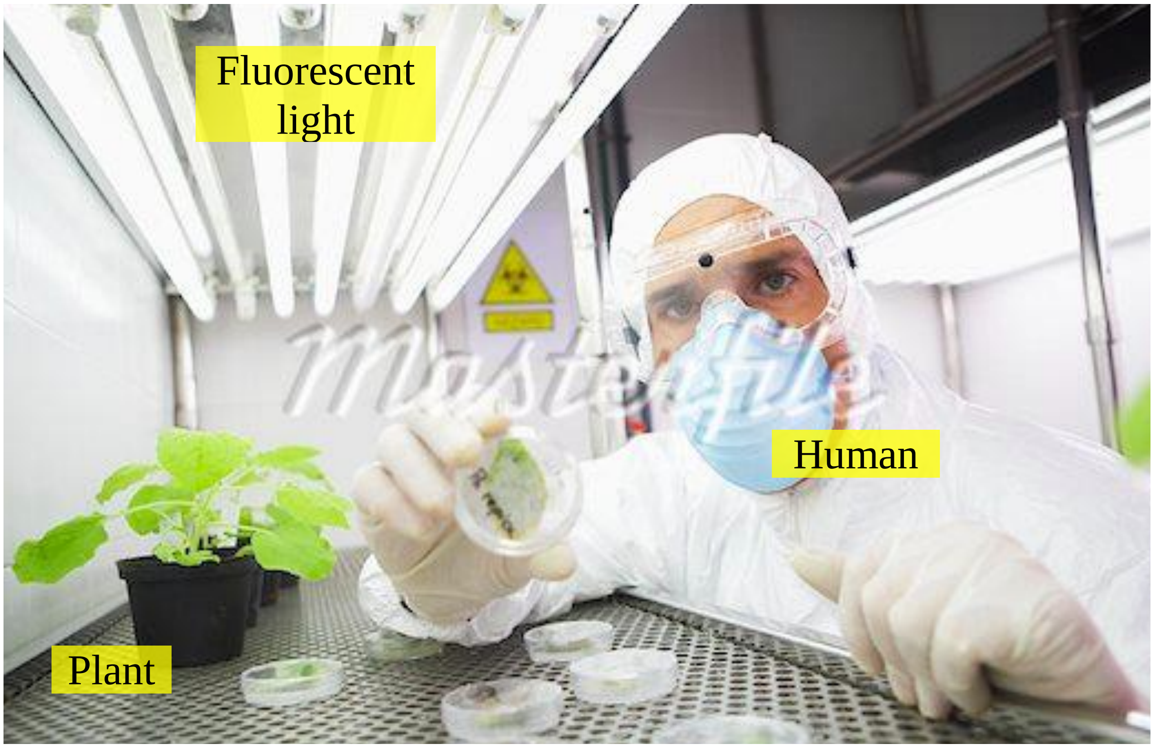
B 2.12.3. Besides heating it up, explain how do you increase the energy of a marshmallow?

This question was embedded in a question set in comparison of marshmallow digestion and combustion. It was designed to solicit respondents' manipulation and modification of their prior knowledge to answer this question. Any descriptions of applying extra work to the definite system a marshmallow is placed in would be an acceptable demonstration of *transformation*.

In sum, the IUS-E questions were not only designed to solicit the IT^3 cognitive processes but also demonstrated the possible connections of essential crosscutting concept in energy transfer and transformation, the laws of thermodynamics, and Gibbs free energy. They also incorporate a variety of energy-entropy key ideas, where entropy is a function of free energy available in a closed system. The equilibrium of a system indicates that no free energy is available to carry out further work, which can serve as flexible application of the second law of thermodynamics. All of these factors contribute significantly to the composition of the IUS-E.

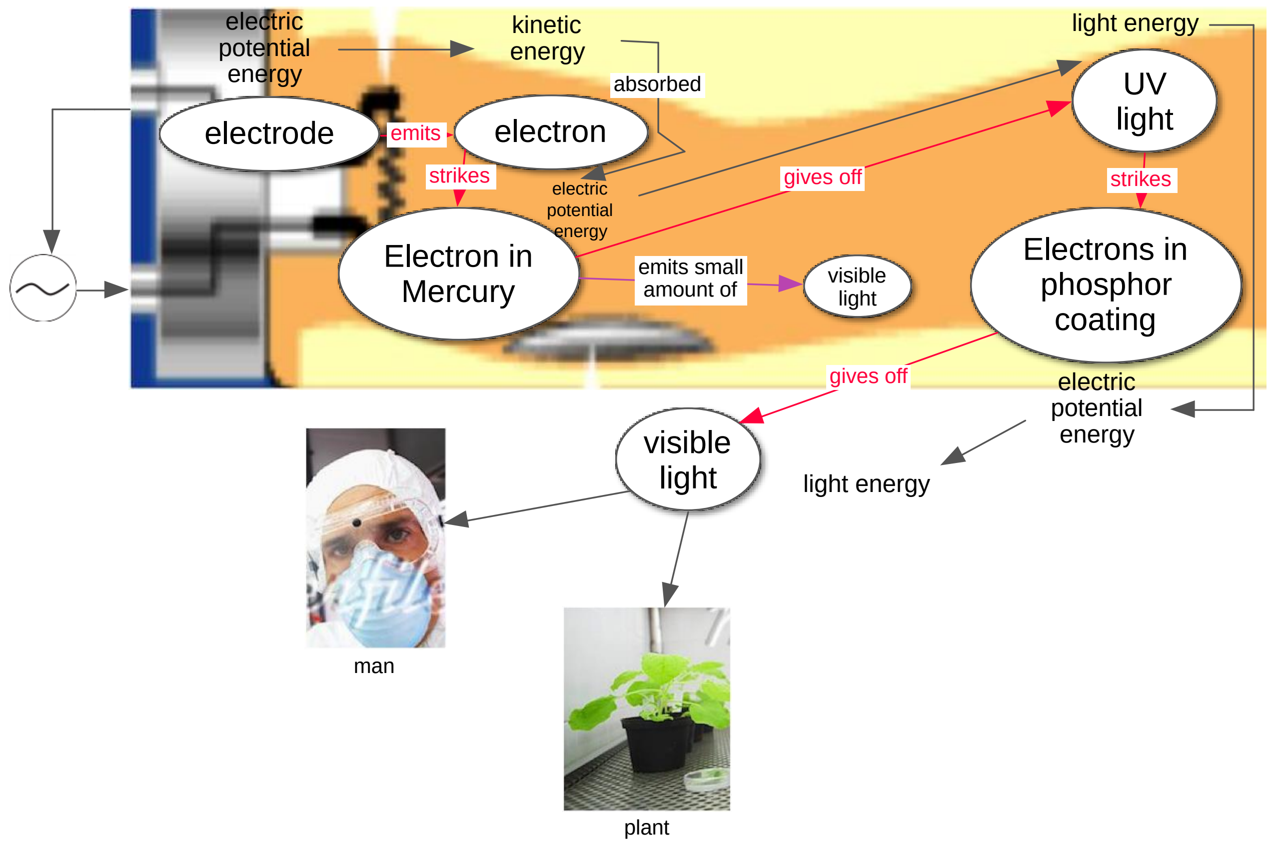
Interdisciplinary Understanding in Science—Using Energy as an example (IUS-E Form A)

First set of questions:
The energy transformation in a fluorescent light bulb is compared to the energy transformation in photosynthesis, where UV light plays different roles in these two cases. In the former scenario, UV rays strike the electrons in the phosphorous coating and emit visible light, and in the latter case, UV rays constitute a threat to the energy harvest of plants. There is integration, translation, transfer, and transformation involved in this set of questions.



The major process of fluorescent lighting occurs in several steps shown in this figure:

1. The electrode emits electron
2. The electrons strike and excite the electrons in mercury
3. The electrons in mercury fall back to the lower energy state and give off UV light and a little visible light
4. UV light travels from mercury to the phosphor coating
5. UV light strikes and excites electrons in phosphor coating
6. The electrons in phosphor coating fall back to lower energy state and give off visible light
7. The visible light from phosphor coating travels to the man and plant



Note: The black arrows indicate the flow of energy in different forms.

2.3.1 The mechanism by which a fluorescent light bulb functions is shown in the figure. Which step(s) represent energy **transfer** process(es)? (Choose ALL that apply)

A. The electrode emits electron
B. The electrons strike and excite the electrons in mercury
C. UV light travels from mercury to the phosphor coating
D. The electrons in phosphor coating fall back to lower energy state and give off visible light
E. The visible light from phosphor coating travels to the man
F. The visible light from phosphor coating travels to the plants
G. None of the above

2.4.1. Explain in your own words what energy transfer is.

Key:
C, E, F

- The question entails the steps from electrical potential energy to shed visible light in fluorescent bulb. The intentional separation of each energy conversion process is to elicit the understanding of energy-related terminologies that are used to describe the designated phenomenon.
- This disciplinary neutral question can serve as differential/commonality integration. The differential integration is determined by the selection of C, E, F step. Students identify the distinct terminology used to describe the trace of light as energy transfer process. In the meanwhile, they recognize all the rest steps to be described with a term other than energy transfer.
- The second tier is a translation question to triangulate their choice in the first tier.

2.3.2. The mechanism by which a fluorescent light bulb functions is shown in the figure. Which step(s) represent energy **transformation** process(es)?

A. The electrode emits electron
B. The electrons strike and excite the electrons in mercury
C. UV light travels from mercury to the phosphor coating
D. The electrons in phosphor coating fall back to lower energy state and give off visible light
E. The visible light from phosphor coating travels to the man
F. The visible light from phosphor coating travels to the plants
G. None of the above

2.4.2. Explain in your own words what energy transformation is.

Key:
A, B, D

- The question entails the steps from electrical potential energy to shed visible light in fluorescent bulb. The intentional separation of each energy conversion process is to elicit the understanding of energy-related terminologies that are used to describe the designated phenomenon.
- This disciplinary neutral question can serve as differential/commonality integration. The differential integration is determined by the exclusion of C, E, F steps. Students identify the distinct terminology used to describe the trace of light not to belong to energy transformation process. In the meanwhile, they recognize all the rest steps to be described as energy transformation.
- The second tier is a translation question to triangulate their choice in the first tier.

2.4.3. Compared to the conditions under regular light bulbs, how would a ***person*** be affected if we replace all the regular light bulbs with those without phosphor coating? (Except for the lighting set up, the growing condition is the same.)

A. He will not see any light emitting from this bulb.
B. The high energy UV light would damage the skin.
C. He will see very bright purple light emitting from this bulb.
D. There is no effect on the person.

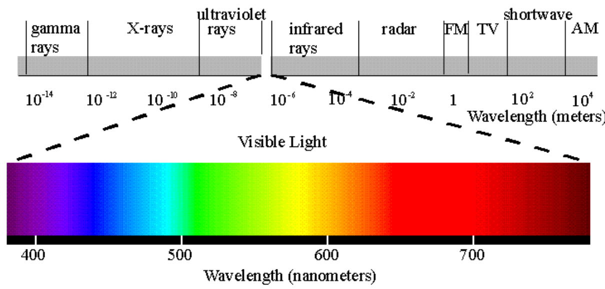
Key:
B

- The question focuses on the effect of UV light on man.
- It is an integration question, question itself is Tm.

2. Please use the figure below to answer the following questions.

The following figure demonstrates the light spectrum of visible light. Most plants that utilize sunlight to make essential nutrients have light harvesting pigments called chlorophyll. Knowing that the light harvesting pigments capture light wavelengths of 680nm (Photosystem II [PSII]) and 700 nm (Photosystem I [PSI]) most effectively.

Note: Electromagnetic energy is inversely proportional to the wavelength.



2.5.1. Based on this figure, which of the following statement is **NOT** correct about the effect of solar radiation?

A. Infrared does not have enough energy to excite electrons in the PSI and PSII.
B. Ultraviolet (UV) rays exceed the energy required for electron excitement.
C. Light harvesting pigments in the PSI and PSII capture particular visible light.
D. UV rays facilitate photosynthesis in the PSI and PSII and increases biomass.

Key:
D

- The question focuses on the relationship between wavelength and energy, as well as the effect of UV light on plants.
- It is an integration question.

2.5.2. When a photon excites electrons and is absorbed by an electron, what happens to the **energy of the photon** (with magnitude **E**)?

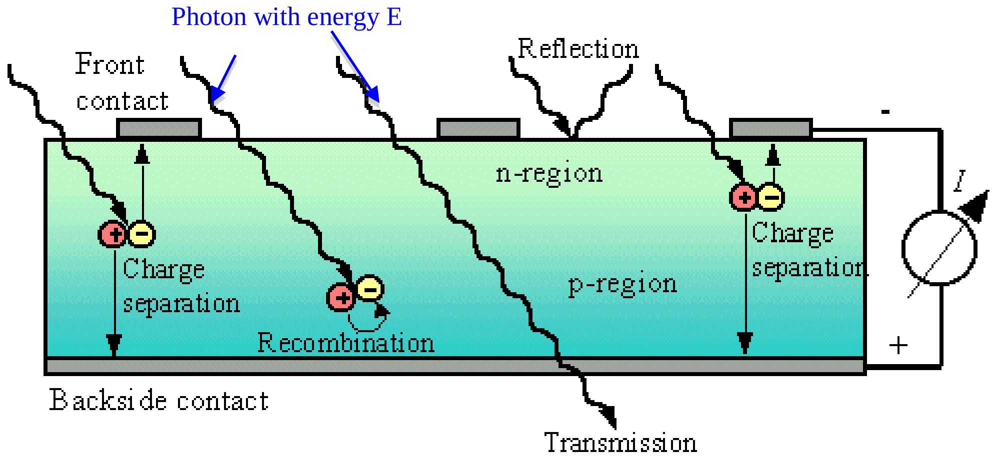
A. Part of E is transferred to one electron and the rest is transferred to other electrons.
B. All of E is used to convert an electron from a lower to a higher energy state.
C. Half of E is transferred to the electron and the other half is dissipated as thermal energy.
D. Only a very small portion of E is needed to excite an electron from the ground state to an excited state.

Key:
B

- Students usually have misconceptions that whenever there is energy conversion, there is a loss of energy; however, photon energy is 100% converted into the electrons. The energy waste occurs when electrons fall back to lower energy levels.
- This is a commonality integration. The same principle can be found in every disciplinary scenario.

2.6.1. Using a photovoltaic (PV) panel is a method of generating electrical power by converting solar radiation into direct current electricity. Different kinds of PV panels require ***different wavelengths*** of photon energy to excite the electrons from the positive (p-)region to the negative (n-)region to create an electrical current. The **energy conversion efficiency** of photosynthesis in a typical plant life cycle is energy available for growth (X) over total sunlight energy (Y) (i.e., X/Y). The solar **energy conversion efficiency** of a PV cell is energy available to be converted to electricity (Z) over total sunlight energy (Y) (i.e., Z/Y).

Comparing to the **average** energy conversion efficiency value for photosynthesis (X/Y), the **average** energy conversion efficiency for the PV panel (Z/Y) is ____________ that in photosynthesis.



A. higher than
B. lower than
C. equal than
D. not comparable to

Key:
A

- The energy converted from photosynthesis has to be used to maintain life. The conversion rate for plants is 1~8%, while algae can be as efficient as 12%. But on average, there is only 5% of energy that is available for growth. The average PV panel can convert light energy to electricity at about 10% efficiency.
- This is a transfer question, since the translation of what energy efficiency is done for the respondents.

2.6.2. Use one or two sentences to explain your choice to the previous question concerning energy conversion efficiency.
Key:

- See above.
- Transfer question.

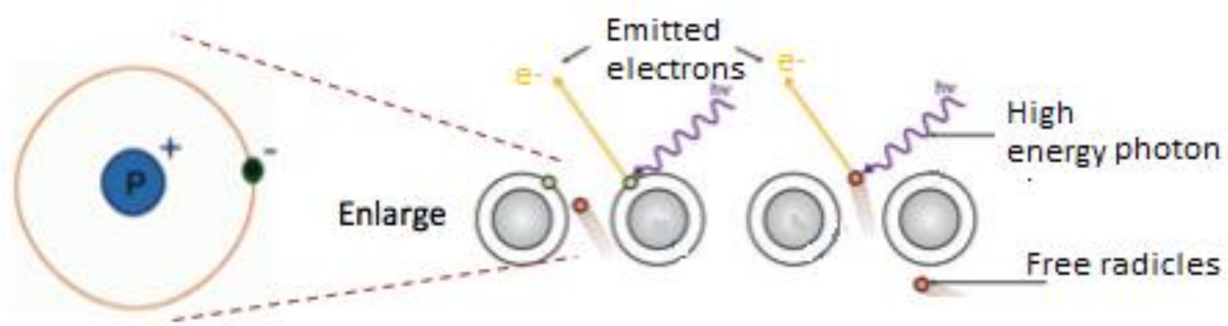
2.6.3. Some crops can use sunlight in a more efficient manner. One example of achieving better energy conversion efficiency is by means of different compartments for reactions. Also, plants can increase conversion of light energy through different accessory pigments to expand the spectrum for energy capture. How can you apply the principles reflected in these natural phenomena to increase the efficiency of energy conversion in PV panels?

Boico, F., & Lehman, B. (2012) Multiple-input Maximum Power Point Tracking algorithm for solar panels with reduced sensing circuitry for portable applications. *Solar Energy*, 86(1), 463–475
Key:

- In the PV panel, there is no compartmentalization. So we can design the device with a separation in the middle of p-region and n-region to increase the concentration gradient of electrons. By doing so, the electrical potential energy is greater, thus harnessing greater electricity. Also, there can be different layers of photon contact areas that are designed to capture different spectra of light. It will increase the reactivity of the PV panels to different light spectra.

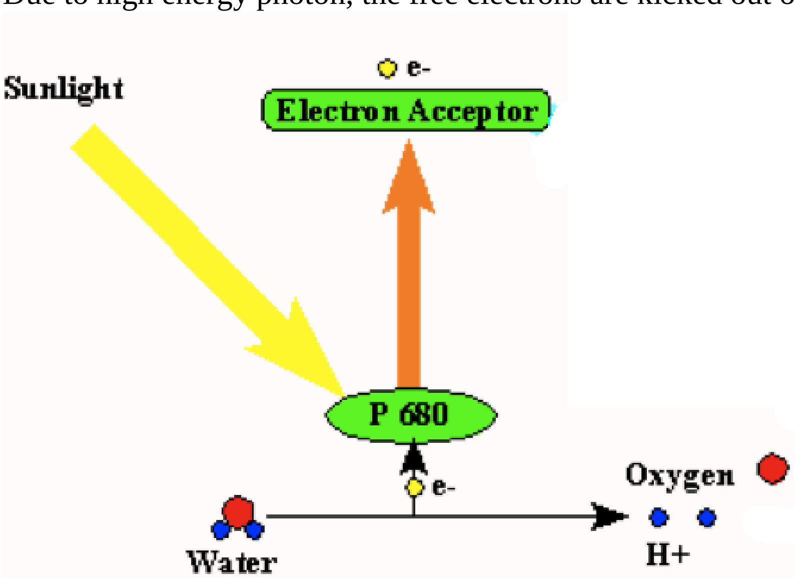
- This question is a transformation one, which is made to modify a scenario found in one discipline to modify the engineering design.

2.7.1. In the figure below, the atoms are exposed to high energy photon. What happens if the photon (light particle) possesses a much higher energy than is required to excite an electron to a higher bound energy level?



A. The electron is captured by the nucleus.
B. Free electron/ion is produced in the process.
C. The electron is destroyed by photon.
D. Photon is reflected from the electron.
E. Photon is split into two (or more) lower energy photons.

Key B:
Due to high energy photon, the free electrons are kicked out of the orbital.



http://www.uic.edu/classes/bios/bios100/lecturesf04am/lect10.htm

2.8.1. The figure shows that molecule P680 becomes excited (i.e., P680*) after electrons in P680 absorb light energy. P680* gives off electrons, leaving P680 in a non-excited, oxidized state (i.e., $P680^+$). Electrons in water replenish the electrons of $P680^+$, restoring it back to regular P680. What statement best describes the energy levels of water, P680, P680*, and $P680^+$?

(Note: 1. P680 is one of the reaction centers in plants that absorbs light energy. 2. When a molecule loses electrons, it is oxidized, and when a molecule gains electrons, it is reduced.)

A. Water gives off electrons more easily to P680 than $P680^+$.
B. P680* is a more easily reduced than P680.
C. P680 becomes P680* resulting in positive free energy change, so it is a spontaneous reaction.
D. P680* is more easily oxidized than $P680^+$.

Key:
D

- After the electrons are knocked out from P680*, electron holes in $P680^+$ is replenished by the electrons from water molecules.
- A. Water gives off electrons to $P680^+$ more easily. B. P680* is stronger oxidizing agent that gives off electrons to other molecules. C. Not spontaneous because it has positive free energy.
- This question is an integration one.

2.9. The figure below shows a hypothetical food chain in which each organism is prey for another (indicated by arrows). Assume that the organisms only feed on the designated species. Refer to the food chain below and answer the following questions:

Note:
The number below each organism represents the energy provided for the next organism

2.9.1. For living organisms in the food chain above, which of the following specifically follows from the **first law of thermodynamics** (which is also known as the principle of conservation of energy)?
A. The organism ultimately must obtain all of the necessary energy for life from its environment.
B. The entropy of an organism decreases gradually throughout time as the organism grows in complexity.
C. The thermal energy of an organism has to remain constant for chemical reactions to take place.
D. Organisms grow by converting energy directly into organic matter.

Key:
A

- B and C are not denoting the first law. D—organisms do not grow by converting energy to matter.
- This is an integration question.

2.9.2. Primary producer biomass is the foundation of this particular food chain. The primary producer transforms inorganic compounds that are used in maintenance and growth. Energy that is invested in new tissue or offspring within a given time frame is called net primary productivity (NPP). What best describes NPP?

A. NPP of a plant is primarily derived from the nutrients in the soil.
B. NPP indicates the total biomass produced that can feed the primary consumer.
C. NPP represents the total amount of energy absorbed by the plant.
D. NPP is not influenced by the energy conversion efficiency of the plant.

Key:
B

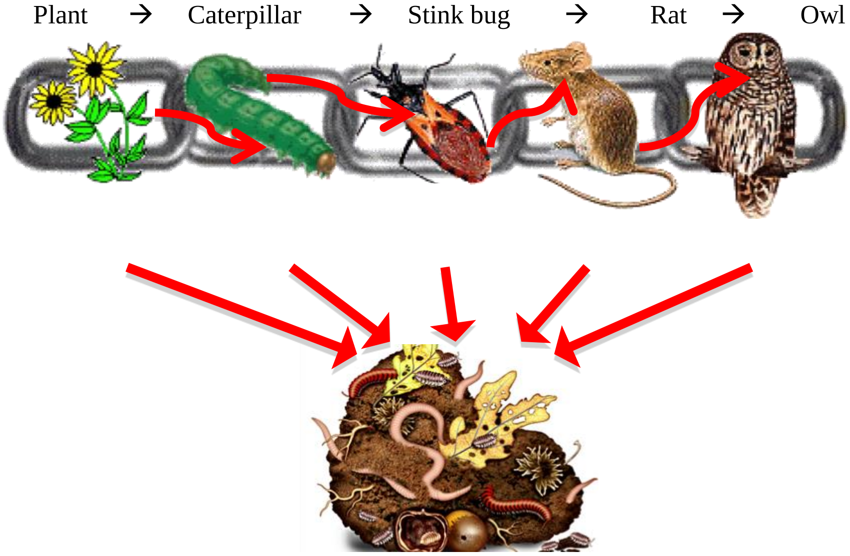
- A. is a notorious misconception perceived by students regarding where the nutrients are from. Most of them think that they come from the soil. C. The total amount of energy absorbed are not used for growth or reproduction. D. NPP is higher when conversion efficiency is better.
- The question is a commonality integration of light and chemical energy into biological system.

2.10.1. Decomposition or decay of an organism after death involves breaking down the organism into simpler molecules (see the figure below). Which statement is **LEAST** accurate in describing the change of organic material?

A. The decomposition process is more spontaneous than assimilation of molecules.
B. Breaking the bonds between/within molecules releases energy to be utilized by decomposers.
C. Some energy is released in the decomposition process.

D. The decomposition process enables the basic elements to return to their natural cycles.

Plant → Caterpillar → Stink bug → Rat → Owl



Decomposer

Key:
B

- A. as regards to free energy change, decomposition results in an increase of entropy, in turn, lowers free energy. In a sense, decomposition is more spontaneous than assimilation. B. Breaking bonds requires energy. C. Decomposers can harness some energy from the process of decomposition. D. Decomposition process breaks down big molecules and releases carbon, hydrogen, oxygen, and other elements back for their cycles.

- This question is an integration one. Integrating biological decomposition process with energy associated with chemical bond breaking concept.

2.10.2. Whenever energy is transformed in an irreversible reaction, there is always an increase in the entropy of the universe. How does this phenomenon apply to the food chain?

A. The lower the entropy, the more likely a reaction will occur spontaneously.
B. The higher the entropy, the more work a system can do to the environment.
C. Free energy (G) of the universe increases gradually.
D. Free energy (G) of the food chain decreases gradually.

Key:
D

- The question is essential to elicit students' understanding of the gradual decrease of free energy that is available to perform work. That is why continuous food consumption is required to sustain life.
- A. The higher the entropy, the more likely a reaction will occur spontaneously. B. the higher the entropy, the less work a system can do. C. free energy of the universe decreases gradually.
- This is an integration question, combining laws of thermodynamics with the energy levels for reactions.

2.11. Organisms survive under very limited range of environmental conditions, for example, a relatively constant pressure and temperature. For that reason, individuals can only use a portion of the potentially available energy in those limited environmental conditions. This usable energy is called *free energy* (*G*):

$\Delta G = \Delta H - T\Delta S$, ΔG is free energy change, ΔH is enthalpy (a measurement of the total energy in the system) change, ΔS is entropy change, and T is temperature.

2.11.1. In a system that remains at constant temperature and enthalpy, when food sources are spontaneously converted to molecules of lower molecular weight, there is an increase in free energy.

A. True
B. False
C. Not enough information

Key:
B

- Respondents may be confused with the energy harvested in food digestion or nutrient utilization with free energy.
- Referring back to the formula $\Delta G = \Delta H - T\Delta S$, when ΔS increases, given constant H and T, the ΔG decreases.

- This is actually transfer because the "energy" in biological contexts might be treated differently in physical science. This stresses on the different scale each discipline focuses on. Free energy denotes different meaning from energetic sources, which is usually inferred in biological science.

2.11.2.According to the 2nd law of thermodynamics, there is an inevitable trend of an increase in the entropy of a growing organism.

A. True
B. False
C. Not enough information

Key:
B

- When an organism is growing, the entropy within the body decreases.
- Transferring thermodynamics found in physical science to biological activity.

2.11.3. In a living organism, over a period of time, the organism is energetically in equilibrium (i.e., $\Delta G = 0$). This means that the organism does no work on its environment.

A. True
B. False
C. Not enough information

Explain your choice in one or two sentences.

Key:
A

- The question focuses on a more extensive time rather than a snapshot of free energy change. In this case, free energy change equals zero, or $\Delta G = 0$ denotes the fact that the free energy is at steady state in the organism.
- This is a transfer question. Usually, ΔG is only discussed under molecular chemical reactions. When the concept is applied to explain the entire steady state of an organism, some assumptions may be challenged or even not transferrable. However, the question is justifiable because when overall ΔG of the organism is 0, it reaches steady state. Positive and negative G cancels out. Therefore, the organism does no work on its environment.

2.12.1. Due to an inevitable increase of entropy in the universe, the usable energy is decreasing gradually. Which of the following statements best describes "renewable energy"?

A. Renewable energy can be recycled and reused after being consumed.
B. The energy source can be replenished by nature quickly.
C. It is any energy source that does not use fossil fuels.
D. Renewable energy produces very little air pollution.

Key:
B

- The concept of renewable energy is relatively new. Therefore, a question like this can determine students' perceptions about the definition of renewable energy.
- A. energy is not recyclable. C. energy source, such as electricity, does not belong to renewable energy. It is only the derivative of renewable energy. D. Some fuels made from renewable energy sources can produce more air pollution.

- Integration question. Tying the increase of entropy as an inevitable factor to decrease usable energy (thermodynamics) with the engineering topics. Physical laws are thus combined with practical engineering concepts.

2.12.2. What renewable energy source could you create for a household? Provide an example and elaborate on how to utilize this renewable energy source (Be creative!).
Key:

- Keep in mind the definition of renewable energy is not recycling materials or turning of light after use. It is considered to be capable of being replenished in a relatively short time. Collecting syngas from compost or converting the mechanical work into electricity would be possible approaches. For instance, running on treadmill provides a lot of kinetic energy that is capable of generating the LED screen, light bulb, and the operation of small machine. Also, installing PV panels to capture sunlight energy is another way of a renewable energy source.
- This is a transformation question that is intended to elicit students' understanding of renewable energy as well as designing a way to create the source of energy for a household.

2.13.1. A system at chemical equilibrium __________.

A. consumes chemical energy at a steady rate
B. has zero kinetic energy
C. consumes or releases energy depending on whether it's endergonic or exergonic
D. can do no work

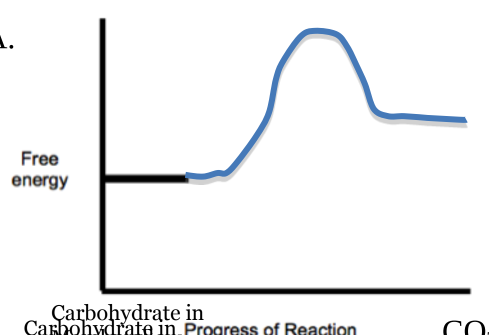
Key:
D

- The question is meant to assess students' understanding regarding chemical equilibrium, work, and energy level.
- This is a discipline-neutral integration problem, connecting the notation of a system at equilibrium has little usage of carrying out work.

Q. Suppose that on a camping trip, you decided to roast marshmallows (a carbohydrate consisting of simple sugar) over the campfire and eat it.

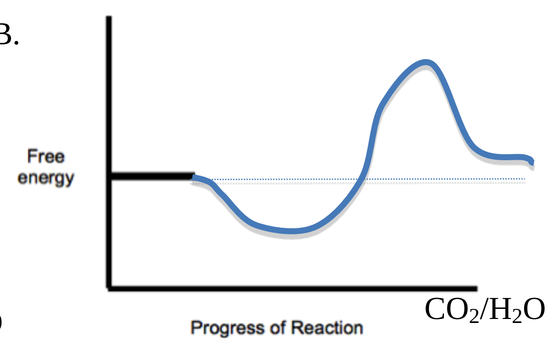
2.14.1. Which of the following diagrams best represents the change in the free energy of the system as the marshmallow is digested (the carbohydrate is transformed into CO_2 and H_2O)?

A.



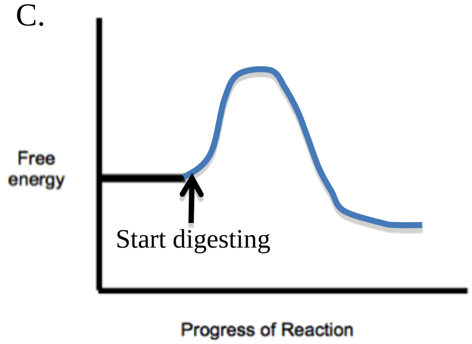
Carbohydrate in Marshmallow
Carbohydrate in Marshmallow
CO_2/H_2O

B.

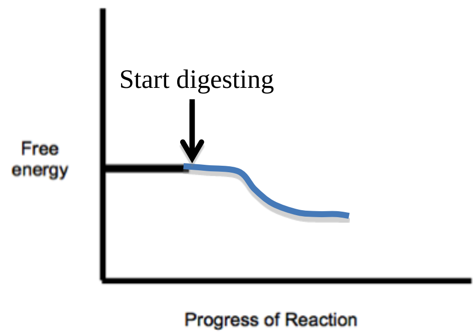


CO_2/H_2O

C.



D.



Key:
C

- The question explores how well students can interpret the graph with free-energy and progress of reaction in relation to the combustion of marshmallow. The question, when stands alone, does not represent interdisciplinary question. However, when compared to the digestion of marshmallow in an organism.
- These questions represent a transfer process.

2.14.2. Compared to combustion, the breakdown of carbohydrate in digestive system requires less activation energy.

A. True
B. False
C. Not enough information

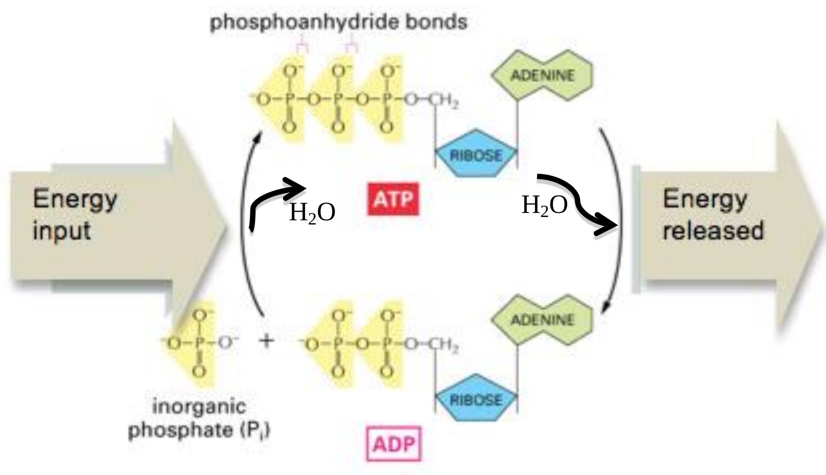
2.14.3. Select the best statement for your choice above.

A. The physical system and biological system are not comparable.
B. More activation energy is required in the living organism because is highly controlled.
C. More activation energy is required in the combustion because there is no facilitating factor.
D. More activation energy is required in the combustion because a lot of heat is released.

Key:
A and C

- Because of the facilitation of enzyme in living organisms, the activation energy is relatively less than the breakdown of marshmallow in the air.
- This is a transfer question, relating the physical combustion with biochemical cellular respiration.

Q. ATP is a high-energy carrier used in your body that enables you to perform all kinds of activities. The figure provided below shows that when ATP is broken down into ADP, there is a release of energy. This reaction is spontaneous in terms of the overall free energy change (i.e., ΔG = -30.5kJ/mol). If not needed, ATP can persist in a cell for a relatively long period of time.



2.15.1. $ATP^{4-} + H_2O \rightarrow ADP^{3-} + Pi^* + H^+$ is an exergonic reaction ($\Delta G = -30.5 kJ/mol$). Does the breakdown of ATP involve an initial input of energy?

A. Yes
B. No
C. Not enough information

Note:
* $Pi = HPO_4^{2-}$

Key:
A

- Breaking the phosphoanhydride bond requires an input of energy, which is provided by the reaction of whole system.
- Integrating energy topics in biological context by means of bio-currency—ATP.

2.15.2. How would you expect potential energy to change in the formation and breaking of phosphoanhydride bond?

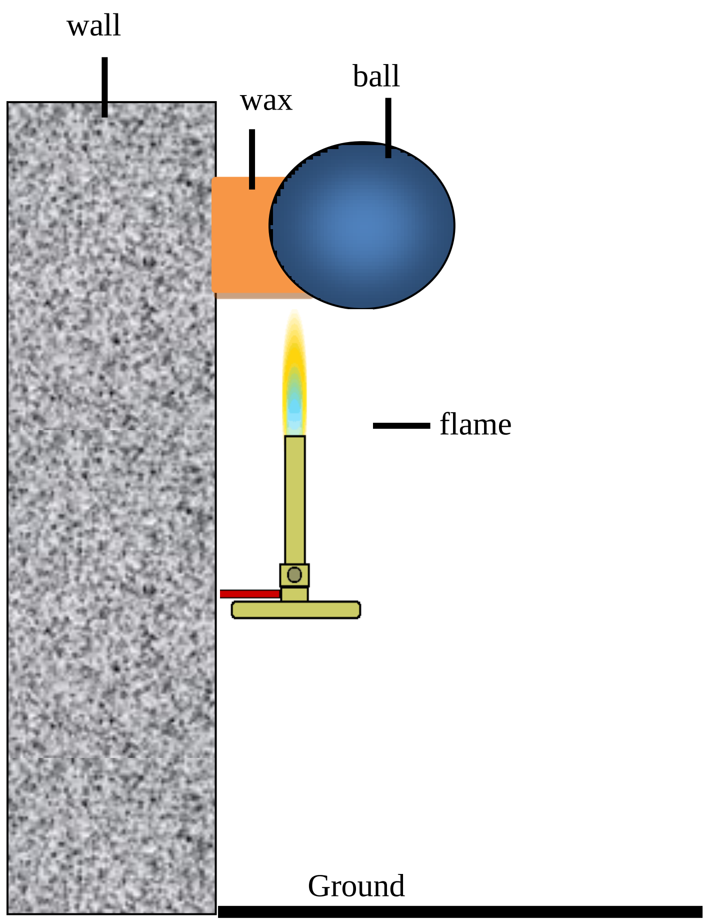
A. Pi is a negatively charged molecule, so phosphoanhydride bond formation stores energy not releases energy.
B. The activation energy is required to break down the phosphoanhydride bond and new bond formation in solvation releases energy.
C. The formation of phosphoanhydride bond and solvation of ADP and Pi requires an initial input of energy.
D. ATP hydrolysis is a spontaneous reaction, which releases energy, no initial input of energy is required.

Key:
B

- The question addresses the energy of formation and breakage of bonds. It is always true that the formation of bonds releases energy, while the breaking of bonds releases energy. A. Formation of bond releases energy. C. formation of bond does not require an input of energy. D. The initial input of energy does not associate with spontaneity directly.
- The question is a transfer one, where chemical bonding principle is applied to explain ATP hydrolysis in biological systems.

2.16.1. A ball is glued (attached) to a wall with wax (see the figure below). Assume that the experiment was conducted at a location **WITHOUT** gravity. If heat is applied to melt the wax, what would you expect to observe? Explain your answer to the question above in terms of kinetic and potential energy.
Key:

- The setting is inspired by the source of potential energy based on gravity. In a location without gravity, the wax does not have to apply additional force to "hold" the ball. Therefore, there is little change after the wax is melted. The expansion of wax when it's heated may exert slight force on the ball.



2.16. Suppose that we set up the experiment on the earth. In what ways do the components in this wall-wax-ball example correspond to ATP breakdown?

2.16.2. wall,

A. ATP
B. ADP
C. Phosphate group (P_i)
D. Water (H_2O)
E. bond
F. Activation energy
G. Potential energy
H. Kinetic energy

Key:
B

2.16.3. wax,

A. ATP
B. ADP
C. Phosphate group (Pi)
D. Water (H_2O)
E. bond
F. Activation energy
G. Potential energy
H. Kinetic energy

Key:
E

2.16.4. the earth.

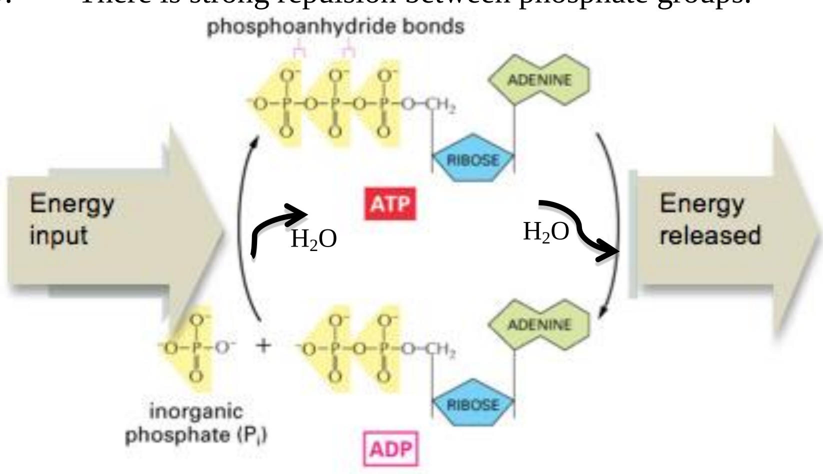
A. ATP
B. ADP
C. Phosphate group (P_i)
D. Water (H_2O)
E. bond
F. Activation energy
G. Potential energy
H. Kinetic energy

Key:
D

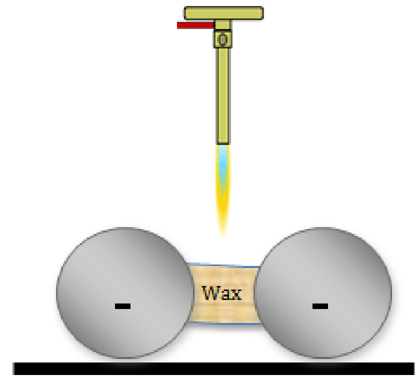
2.16.5. Justify your choices above in one or two sentences.

2.17.1. Two negatively-charged balls are glued together with wax and placed on a surface without friction. Compare the two reactions as shown below. How the charged-balls example is analogous to ATP hydrolysis?

A. There is strong attraction between Adenosine and the phosphate groups.
B. There is strong repulsion between Adenosine and the phosphate groups.
C. There is strong attraction between phosphate groups.
D. There is strong repulsion between phosphate groups.



v.s.



Key:
B

- The question highlights the repulsion effect, which contributes to the release of energy in ATP hydrolysis.
- The question is a transfer one because of the similar elements found in different systems. The charged-ball scenario is more physical science-related.

Interdisciplinary Understanding in Science—Using Energy as an example (IUS-E Form B)

(Exclude figures in this parallel test. Refer to Form A for detailed figures)
First set of questions:
The energy transformation in a fluorescent light bulb is compared to the energy transformation in photosynthesis, where UV light plays different roles in these two cases. In the former scenario, UV rays strike the electrons in the phosphorous coating and emit visible light, and in the latter case, UV rays constitute a threat to the energy harvest of plants. There is integration, translation, transfer, and transformation involved in this set of questions.

The major process of fluorescent lighting occurs in several steps shown in this figure:

A. The electrode emits electron
B. The electrons strike and excite the electrons in mercury
C. The electrons in mercury fall back to the lower energy state and give off UV light and a little visible light
D. UV light travels from mercury to the phosphor coating
E. UV light strikes and excites electrons in phosphor coating
F. The electrons in phosphor coating fall back to lower energy state and give off visible light
G. The visible light from phosphor coating travels to the man and plant

Note: The black arrows indicate the flow of energy in different forms.

2.3.1 The mechanism by which a fluorescent light bulb functions is shown in the figure. Which step(s) represent energy **transfer** process(es)? (Choose all that apply)

A. The electrode emits electron
B. The electrons strike and excite the electrons in mercury
C. UV light travels from mercury to the phosphor coating
D. The electrons in phosphor coating fall back to lower energy state and give off visible light
E. The visible light from phosphor coating travels to the man
F. The visible light from phosphor coating travels to the plants
G. None of the above

2.4.1 Explain in your own words what energy transfer is.

Key:
C, E, F

- □ The question entails the steps from electrical potential energy to shed visible light in fluorescent bulb. The intentional separation of each energy conversion process is to elicit the understanding of energy-related terminologies that are used to describe the designated phenomenon.
- □ This disciplinary neutral question can serve as differential/commonality integration. The differential integration is determined by the selection of C, E, F step. Students identify the distinct terminology used to describe the trace of light as energy

transfer process. In the meanwhile, they recognize all the rest steps to be described with a term other than energy transfer.

- The second tier is a translation question to triangulate their choice in the first tier.

2.3. 2. The mechanism by which a fluorescent light bulb functions is shown in the figure. Which step(s) represent energy **transformation** process(es)?

A. The electrode emits electron
B. The electrons strike and excite the electrons in mercury
C. UV light travels from mercury to the phosphor coating
D. The electrons in phosphor coating fall back to lower energy state and give off visible light
E. The visible light from phosphor coating travels to the man
F. The visible light from phosphor coating travels to the plants
G. None of the above

2.4.2 . Explain in your own words what energy transformation is.

Key:
A, B, D

- The question entails the steps from electrical potential energy to shed visible light in fluorescent bulb. The intentional separation of each energy conversion process is to elicit the understanding of energy-related terminologies that are used to describe the designated phenomenon.
- This disciplinary neutral question can serve as differential/commonality integration. The differential integration is determined by the exclusion of C, E, F steps. Students identify the distinct terminology used to describe the trace of light not to belong to energy transformation process. In the meanwhile, they recognize all the rest steps to be described as energy transformation.
- The second tier is a translation question to triangulate their choice in the first tier.

2.4.3. Some think that if people are exposed too much to fluorescent light, they will be tanned by the UV radiation. Why is this phenomenon not possible for an intact fluorescent light bulb?

A. A majority of the UV radiation is directly converted to thermal energy that heats up the bulb.
B. The UV radiation emitted in the tube does not have enough energy to damage DNA in skin cells.
C. Most UV radiation is captured as potential energy by the phosphor coating and does not penetrate the bulb.
D. The UV radiation in the light bulb does not have enough energy to trigger the accumulation of melanin (black pigment in skin cell).

Key:
C

- The UV light produced in the middle of visible light emission can serve as a factor for respondents to ponder over the safety issues for human beings.
- This is an integration question, combining energy levels in physics with

biology.

2.4.4. If the fluorescent light bulbs in this figure were manufactured without phosphor coating, but was installed properly. There would be ____________.

A. mainly UV light
B. mainly visible light
C. UV light only
D. visible light only

Explain in one or two sentences about your reasoning for the option.

Key:

A

- Under regular electricity supply, all the processes happening before UV light strikes phosphor coating is intact. So there would be UV light emitted combined with small amount of visible light.
- This is a disciplinary neutral question, which is an essential intermediate step to situate students on the same page before they respond to the effect of the removal of phosphor coating to organisms. (I recommend not to analyze this item by means of IRT, because it violates the local independence assumption. On the other hand, the follow up question does not test the same light emission concept, so I can still consider analyzing this question if there is a lack of quality items.)
- The question itself is a transformation question. Since the transformation has been completed, student responses can only be treated as transfer. Student responses demonstrate their ability to recognize the new system without an essential factor—phosphor coating.

2.4.5. Plants are grown in a growth chamber where all light is provided by light bulb. Compared to the growing conditions under regular light bulbs, what is the consequence to a ***plant*** if we replace all the usual light bulbs with those without phosphor coating? (Except for the lighting set up, the growing conditions are the same.)

A. There is no change to the growth rate.
B. The plant will grow faster.
C. The plant will grow slower.

2.4.6. Select the statement that **best explains** your choice.

A. More free electrons with higher kinetic energy will be produced because of UV light.
B. More plant biomass will be produced because UV light has high energy.
C. The plant can capture same amount of irradiation from the light bulb to sustain living.
D. The plant does not use the energy of UV light to convert inorganic into organic materials.

Key:

C and A or C and D

- The question focuses on the effect of UV light on plants.
- It is an integration question.

Introduction:

The following figure shows the structure of the magnesium atom:

Two electrons are found at the first orbital energy level, eight electrons at the second orbital energy level, and two electrons at the third energy level. When electrons are orbiting at their appropriate orbital energy levels, they are considered to be at steady state.

2.5.1. Chlorophyll is the pigment that absorbs light energy in plants. The following figure illustrates a hypothetical atom in a molecule of chlorophyll. The figure shows that there are different levels of energy associated with electrons in different orbitals. When an incoming photon with energy E transmits its energy to an electron in figure (a), what will happen to the energy according to this figure? Energy of the photon ________________________.

A. excites and is absorbed by an electron.
B. excites another photon into a higher energy state.
C. is converted entirely into thermal energy.
D. photon is converted to electric current.

Key:
A

- B. not exciting another photon
- C. not converting the energy to thermal energy entirely, only partially.
- D. light energy is converted to kinetic and potential energy
- This is superficial commonality integration

2.5.2. When a photon excites electrons and is absorbed by an electron, what happens to the **energy of the photon** (with magnitude **E**)?
A. Part of E is transferred to one electron and the rest is transferred to other electrons.
B. All of E is used to convert an electron from a lower to a higher energy state.
C. Half of E is transferred to the electron and the other half is dissipated as thermal energy.
D. Only a very small portion of E is needed to excite an electron from the ground state to an excited state.

Key:
B

- Students usually have misconceptions that whenever there is energy conversion, there is a loss of energy; however, photon energy is 100% converted into the electrons. The energy waste occurs when electrons fall back to lower energy levels.
- This is a commonality integration. The same principle can be found in every disciplinary scenario.

2.6. A PV panel is designed to capture a particular portion of the light spectrum (e.g., UV light) to excite electrons inside the device. The excited electrons move to n-type silicon while the "holes" (positively charged particles) are left in the p-type silicon. The flow of electrons generates electrical current (see Figure a). Similarly, most plants utilize light energy to convert CO_2 into glucose. Refer to Figure b for the structure of a chloroplast and Figure c for the mechanism.

2.6.1. An electron transport chain couples with the transfer of protons (H^+) across the membrane. Why is this process similar to the energy harvesting of the PV panel in converting light to electricity? Use one or two sentences to **explain how** the energy harnessed in the chloroplast is

similar to the PV panel.
Figure a

Figure b

Figure c

Key:

- Similarity: Both of these structures utilize energy from sunlight, create electric potential energy across two regions, and convert the electric potential energy into another form of energy.
- Contrast: The PV panel uses UV light, the chloroplast utilizes visible light; one is inorganic, the other is organic reaction; the energy harnessed in PV panel is used for electricity, and the energy harvested in chloroplast is used to convert to fix carbons for further work.
- This is a transfer question.

6. The figure below shows a hypothetical food chain in which each organism is prey for another (indicated by arrows). Assume that the organisms only feed on the designated species. Refer to the food chain below and answer the following questions:

Note:
The number below each organism represents the energy provided for the next organism

2.7.1. The energy flow (indicated by green arrows) is an example of ________, and energy lost as heat (indicated by blue arrows) is an example of ___________. Choose the best answer.

A. Energy transfer; transformation
B. Energy transformation; transfer
C. Energy transfer; convection
D. Energy conservation; transformation

Key:
A

- This question is applicable to different disciplinary context. It is designed to elicit students' tendency concerning term use.
- The possible endorsement of terminology used to describe energy conversion can be treated as differential integration.

2.7.2. Primary producer biomass is the foundation of this particular food chain. The primary producer transforms inorganic compounds that are used in maintenance and growth. Energy that is invested in new tissue or offspring within a given time frame is called net primary productivity (NPP). What best describes NPP?

A. NPP of a plant is primarily derived from the nutrients in the soil.
B. NPP indicates the total biomass produced that can feed the primary consumer.
C. NPP represents the total amount of energy absorbed by the plant.
D. NPP is not influenced by the energy conversion efficiency of the plant.

Key:

B

- A. is a notorious misconception perceived by students regarding where the nutrients are from. Most of them think that they come from the soil. C. The total amount of energy absorbed are not used for growth or reproduction. D. NPP is higher when conversion efficiency is better.
- The question is a commonality integration of light and chemical energy into biological system.

Q. Decomposition or decay of an organism after death involves breaking down the organism into simpler molecules (see the figure below).

2.8.1. Choose the best description for the relationship between entropy* and decomposition processes.

A. Entropy is not created or destroyed in the universe.
B. Entropy of the system increases locally but remains the same globally.
C. Entropy increases in converting complex molecules to simpler molecules.
D. Entropy increases due to the fixation of carbon into organic molecules.

Note:* Entropy is a mathematical term to describe the possibility for subjects to redistribute. It is also known as the disorderliness of a system.

Key:
C

- A. entropy increases gradually. This does not describe decomposition process. B. According to the second law of thermodynamics, entropy does not remain the same. It increases gradually. D. Entropy decreases during carbon fixation.
- Integration question. Integration biological decomposition process with laws of thermodynamics.

2.8.2. Living organisms increase in complexity as they grow, resulting in a decrease in the entropy of an organism. How does this relate to the **second law of thermodynamics***?

Note:
* **Second law of thermodynamics:**An expression of the tendency that over time, differences in temperature, pressure, and chemical potential equilibrate in an isolated physical system. From the state of thermodynamic equilibrium, the law deduces an inevitable increase of entropy and explains the phenomenon of irreversibility in nature (from wiki).

A. Because of the increase in order in living organisms, they do not obey the second law of thermodynamics.
B. As a consequence of growing, the increase in entropy in the organism's environment is greater than the decrease in entropy as the organism grows.
C. The entropy of an organism equilibrates gradually throughout time as the organism grows in complexity.
D. As a consequence of growing, the decrease in entropy as the organisms grow is exactly balanced by an increase of the universe's entropy.

Key:
B

- As the second law implies an increase of entropy of the universe, it appears controversial when an organism grows in a more orderly manner.
- A. all of the systems obey the laws. B. (Key) Even though the entropy may decrease within an organism, when considering the whole environment, the entropy increases. C. This choice considers the growing stage (refer to the growing in complexity sentence) of an organism. Even though one may argue that these two situations are not comparable because the mass also increases (kln(n) only applies under constant n, p, t). The choice is wrong because the entropy does not reach equilibrium. D. The entropy is not exactly balance in the growing process.
- This is an integration question, combining laws of thermodynamics with the energy levels for reactions.

Q 2.9. Organisms survive under very limited range of environmental conditions, for example, a relatively constant pressure and temperature. For that reason, individuals can only use a portion of the potentially available energy in those limited environmental conditions. This usable energy is called *free energy* (*G*):

$\Delta G = \Delta H - T\Delta S$, ΔG is free energy change, ΔH is enthalpy (a measurement of the total energy in the system) change, ΔS is entropy change, and T is temperature.

2.9.1. In a system that remains at constant temperature and enthalpy, metabolism becomes spontaneous when it results in an increase of entropy in the universe.

A. True
B. False
C. Not enough information

Key:
A

- Spontaneity indicated by free energy change in biological systems is the main focus of this question. When ΔS increases, while H and T remains constant, ΔG decreases. However, we do not have enough information given to determine whether ΔG will decrease below negative.
- The question involves the transfer of thermodynamics to biological metabolism.

2.9.2. The free energy in a living organism can increase, decrease, or remain the same over a period of time.

A. True
B. False
C. Not enough information

Key:
A

- Free energy undergoes dynamic process to sustain life. Cellular reactions often take place with the coupling reactions. Reactions that produce higher energy are used to overcome the activation energy of other reactions.
- Transfer of free energy concept in thermodynamic that associates with cellular

interactions to macroscopic life sustaining phenomenon.

2.9.3. In a living organism, over a period of time, the organism is energetically in equilibrium (i.e., $\Delta G = 0$). This means that the organism does no work on its environment.

A. True
B. False
C. Not enough information

Key:
A

- The question focuses on a more extensive time rather than a snapshot of free energy change. In this case, free energy change equals zero, or $\Delta G = 0$ denotes the fact that the free energy is at steady state in the organism.
- This is a transfer question. Usually, ΔG is only discussed under molecular chemical reactions. When the concept is applied to explain the entire steady state of an organism, some assumptions may be challenged or even not transferrable. However, the question is justifiable because when overall ΔG of the organism is 0, it reaches steady state. Positive and negative G cancels out. Therefore, the organism does no work on its environment.

2.10.1. Some people promote using electric cars or electric bikes that can be recharged by plugging into the outlet. The following figure shows the pie chart of fuel for electricity generation in the United States. Does electric transportation mainly use renewable energy?

A. Yes
B. No
C. Not enough information

http://www.epa.gov/cleanenergy/energy-and-you/index.html

2.10.2. Explain in one or two sentences for your choice.

Key:
B

- The figure shows the percentage of energy sources for electricity generation. In the United States, the electricity is mainly made from coals. Therefore, the transportation does not mainly use renewable energy. Some people might confuse “green energy” with “renewable energy”.
- This is a discipline-neutral question focusing on differential integration of green energy and renewable energy. Both are important concept in energy literacy. They constitute important means for interdisciplinary understanding.

2.10.3. Light-absorbing pigments in plants utilize the energy from the sun to obtain nutrient. Which type of energy and the unit of energy from the sun contributes most to an increase in plant biomass?

A. Thermal energy from heat; Calorie (Cal)
B. Energy from electromagnetic radiation; kilojoule (kJ)
C. Chemical potential energy from glucose; joule (J)

D. Electrical potential difference; Volt (V)

Key:
B

- The question is designed to tackle the understanding of students concerning the form of energy to be used for plant photosynthesis.
- The question is a differential integration one, because students have to differentiate different disciplinary-specific forms of energy and pick the best answer.

2.11. A system at chemical equilibrium __________.

A. consumes chemical energy at a steady rate
B. has zero kinetic energy
C. consumes or releases energy depending on whether it's endergonic or exergonic
D. can do no work

Key:
D

- The question is meant to assess students' understanding regarding chemical equilibrium, work, and energy level.
- This is a discipline-neutral integration problem, connecting the notation of a system at equilibrium has little usage of carrying out work.

2.12.1. Which of the following diagrams best represents the change in the free energy of the system as the marshmallow burns (the carbohydrate is transformed into CO_2 and H_2O)?

Key:
C

- The question explores how well students can interpret the graph with free-energy and progress of reaction in relation to the combustion of marshmallow. The question, when stands alone, does not represent interdisciplinary question. However, when compared to the digestion of marshmallow in an organism.
- These questions represent a transfer process.

2.12.2. Select the best statement for your choice above.

A. The physical system and biological system are not comparable.
B. More activation energy is required in the living organism because is highly controlled.
C. More activation energy is required in the combustion because there is no facilitating factor.
D. More activation energy is required in the combustion because more heat is released.

Key:
C

- Because of the facilitation of enzyme in living organisms, the activation energy is relatively less than the breakdown of marshmallow in the air.

- This is a transfer question, relating the physical combustion with biochemical cellular respiration.

2.12.3. Besides heating it up, explain how do you increase the energy of a marshmallow?
Key:

- Heating the marshmallow is related to the increase of kinetic energy. One can raise the marshmallow to a higher position to increase its potential energy.
- This is a transformation question that associates with thought experiment.

2.13. A ball is glued (attached) to a wall with wax (see the figure below). Assume that the experiment was conducted at a location **WITHOUT** gravity.
11. Suppose that we set up the experiment on the earth. In what ways do the components in this wall-wax-ball example correspond to ATP breakdown?

(2.13.1) flame,

A. ATP
B. ADP
C. Phosphate group (P_i)
D. Water (H_2O)
E. bond
F. Activation energy
G. Potential energy
H. Kinetic energy
I. Adenine
J. Ribose

Key:
F

(2.13.2) ball,

A. ATP
B. ADP
C. Phosphate group (Pi)
D. Water (H_2O)
E. bond
F. Activation energy
G. Potential energy
H. Kinetic energy
I. Adenine
J. Ribose

Key:
C

(2.13.3) gravity.

A. ATP
B. ADP
C. Phosphate group (P_i)

D. Water (H_2O)
E. bond
F. Activation energy
G. Potential energy
H. Kinetic energy
I. Adenine
J. Ribose

Key:
G

2.13.4. If heat is applied to melt the wax, what would you expect to observe?

A. The ball falls to the ground
B. The ball is attracted to the wall
C. There is little change
D. Not enough information

Key:
C

- The setting is inspired by the source of potential energy based on gravity. In a location without gravity, the wax does not have to apply additional force to “hold” the ball. Therefore, there is little change after the wax is melted. The expansion of wax when it’s heated may exert slight force on the ball.
- The question is an integration one, even though the generation of this question involves transformation.

2.13.5. Explain your answer to the question above in terms of kinetic and potential energy.

- The setting is inspired by the source of potential energy based on gravity. In a location without gravity, the wax does not have to apply additional force to “hold” the ball. Therefore, there is little change after the wax is melted. The expansion of wax when it’s heated may exert slight force on the ball.

2.14.1. Two negatively-charged balls are glued together with wax and placed on a surface without friction. Compare the two reactions as shown below. How the charged-balls example is analogous to ATP hydrolysis?

A. There is strong attraction between Adenosine and the phosphate groups.
B. There is strong repulsion between Adenosine and the phosphate groups.
C. There is strong attraction between phosphate groups.
D. There is strong repulsion between phosphate groups.

v.s.

Key:
B

- The question highlights the repulsion effect, which contributes to the release of energy in ATP hydrolysis.

- The question is a transfer one because of the similar elements found in different systems. The charged-ball scenario is more physical science-related.

Q: ATP is a high-energy carrier used in your body that enables you to perform all kinds of activities. The figure provided below shows that when ATP is broken down into ADP, there is a release of energy. This reaction is spontaneous in terms of the overall free energy change (i.e., ΔG = -30.5kJ/mol). If not needed, ATP can persist in a cell for a relatively long period of time.

2.15.1. $ATP^{4-} + H_2O \rightarrow ADP^{3-} + Pi^* + H^+$ is an exergonic reaction (ΔG = -30.5kJ/mol). Does the breakdown of ATP involve an initial input of energy?

A. Yes
B. No
C. It depends
D. Not enough information

Note:
*Pi = HPO_4^{2-}

Key:
A

- Breaking the phosphoanhydride bond requires an input of energy, which is provided by the reaction of whole system.
- Integrating energy topics in biological context by means of bio-currency—ATP.

2.15.2. How would you expect potential energy to change in the formation and breaking of phosphoanhydride bond?

A. Pi is a negatively charged molecule, so phosphoanhydride bond formation stores energy not releases energy.
B. The activation energy is required to break down the phosphoanhydride bond and new bond formation in solvation releases energy.
C. The formation of phosphoanhydride bond and solvation of ADP and Pi requires an initial input of energy.
D. ATP hydrolysis is a spontaneous reaction, which releases energy, no initial input of energy is required.

Key:
B

- The question addresses the energy of formation and breakage of bonds. It is always true that the formation of bonds releases energy, while the breaking of bonds releases energy. A. Formation of bond releases energy. C. formation of bond does not require an input of energy. D. The initial input of energy does not associate with spontaneity directly.
- The question is a transfer one, where chemical bonding principle is applied to explain

ATP hydrolysis in biological systems.

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

Discussions

The dissertation explored factors influencing undergraduate students' interdisciplinary understanding in science (IUS). The studies were guided and organized around the Curriculum-Instruction-Assessment (C-I-A) triad using the Integration-Translation-Transfer-Transformation (IT^3) cognitive framework as the central component (see Figure 5.1).

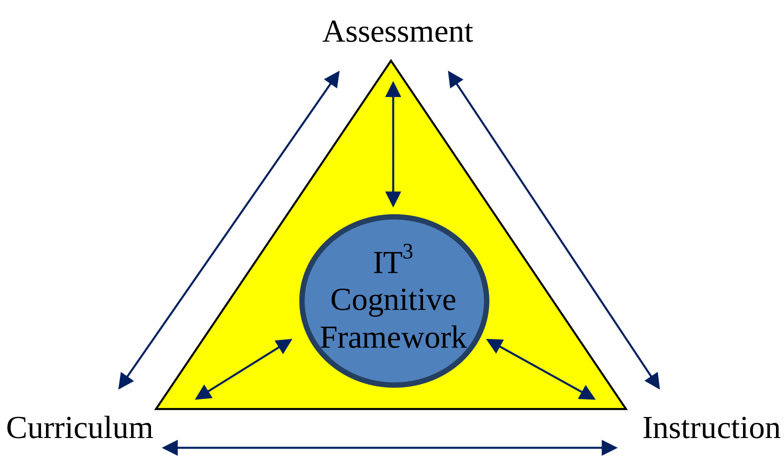


Figure 5.1. Representation of the interconnections among curriculum, instruction, and assessment and the pivotal role of theories of learning.

Chapter 2 was used to respond to Brown and Wilson's (2011) comment that there is a prolonged problem of a missing piece in describing an assessment system—a lack of an explicit model of cognition to regulate instrument generation and validation. The validation conducted in Chapter 2 focused on the model of cognitive processes associated with IUS. The results indicate that the proposed IT^3 cognitive processes for IU were not entirely exclusive to one another. In

Chapters 3 and 4, two of the three vertices, "Curriculum" and "Assessment," on the C-I-A triangle were investigated with the guidance of the IT^3 framework. In Chapter 3, a particular aspect in the IT^3 framework—*translation*—was scrutinized by analyzing a crosscutting concept found across the disciplinary science curricula. The study examined the ways in which college-level textbooks currently handle the concept—*osmotic pressure*—and debate the probable effects of their approaches to help students transfer and understand osmosis topics. Findings suggest that inconsistent explanations are surprisingly prevalent, usually in the form of the incongruent *translation* of concepts in/across science disciplinary textbooks. The "special cases" (Bryce & MacMillan, 2009, p. 754) are found constantly in introductory science textbooks (e.g., "special cases" that only work by controlling other factors). Each disciplinary-based textbook presents a concept in a way that allows an explanation of a particular situation only under its disciplinary-focused constraint (Geller, Dreyfus, Sawtelle, Svoboda, & Turpen, 2013). The problems about *translation* in/across the textbooks were evident, but the absence of examples facilitating *integration*, *transfer*, or *transformation* processes in most textbooks also worthies our attention.

The finding from textbook analysis also implies that, in order to sustain IU, the curriculum design should go beyond the factual and declarative level of knowledge. The instructors should situate a crosscutting concept under a more constraint-free context that is closer to real-life situations (Geller et al., 2013). Many of the disciplinary-oriented textbooks reviewed only presented a narrow perspective of a concept that is applicable in certain disciplinary contexts. While more interdisciplinary-focused textbooks incorporate more diverse insights to approach the same term or concept. Usually, these interdisciplinary-oriented textbooks are used only for higher-level science classes not to the benefit of introductory science classes. If we were to foster the development of more IU, more research is recommended to determine the sequence of curriculum that helps render diverse cognitive processes in constructing and applying IU.

In Chapter 4, the application of the IT^3 framework to generate interdisciplinary assessment items was explored. Students' responses to each item for the "Interdisciplinary Understanding of Science, using the Energy topic" (IUS-E) instrument in Chapter 4 was analyzed and estimated as their immeasurable and unobservable trait—IUS. Item response theory (IRT) was applied to analyze the vectors of students' responses. Rasch model fits the data well; however, the dimensionality was not apparent and reliability of the IUS-E was low. The result reported by Factor Analysis (FA) indicated that no apparent evidence supporting the assumption of unidimensionality in the underlying construct—IUS—prevailed. Even though the item residuals check and the fit analysis both revealed no multidimensionality issue, the non-dimensionality problems identified from FA, which is a popular dimensionality check method, should be further addressed. Potential causes for violating the dimensionality assumption may result from learners' diversifying perceptions toward the IUS-E questions. Many of them reported that they feel the energy concept is not an interdisciplinary one because it has been introduced in distinct classes without an explicit connection. To resolve this problem, the breadth of topics should be reduced in future research. In brief, all three studies were closely connected for advancing interdisciplinary science learning and for the contribution to the understanding of IU.

Overall, the IT^3 framework showed success to some degree in understanding IUS. There was good inter-rater reliability in applying this framework to analyze the faculty members' conversation between three raters. The framework's validity was also determined by differentiating utility of each unit of statement to the associating IT^3 cognitive processes. The acceptable reliability and validity proves the potential usability of this framework. Two of the three studies conducted in this dissertation could serve as pioneers for establishing a better understanding of interdisciplinary science education—by formulating an innovative cognitive framework (e.g., the IT^3 framework) and constructing a quantitative measure. Few frameworks, if any, are especially generated to address learners' IUS, so the IT^3 framework created in this dissertation is a good reference for educators when they are considering the cognitive processes involved in interdisciplinary learning. A model of cognition could also coordinate every element in the C-I-A triangle to strive toward the predestined goals and objectives of interdisciplinary science education. If the curriculum, instruction, and assessment are not aligned with a solid cognitive framework, they will introduce fragmented pieces of information that simply touch upon the designated standards or objectives but insignificant to facilitate interdisciplinary science learning. That is why the IT^3 framework is important in laying a foundation for other essential parts of interdisciplinary education.

However, the IT^3 framework, as a novel construct for IU, also faces several challenges. In the beginning, because of the novelty this IT^3 framework presented to us, we found the first few rounds of establishing inter-rater reliability to be very difficult, because many statements were construed as crossing two cognitive components. Also, some coders overlooked the intention of a speaker, while others considered the purpose of an utterance. For instance, a statement may be coded as both "translation" and "integration" if a speaker has to first translate a term and explain how the new term is applicable to another disciplinary context. In this case, the integration process in the IT^3 also involved a translation of the term. Usually, we tended to divide such statements into two segments and coded the former as "translation" and the later as "integration"; however, if the discourse unit is inseparable, then we either divided the score into half translation and half integration or applied the speaker's intention obtained from the context of utterance. The distribution of the score between two components resulted in blurry borders between each IT^3 cognitive process. These processes were not as straightforward or clear cut as we originally considered. But since these reasoning processes were not exclusive to each other, correlations between different components are inevitable.

Also, the characteristic of *translation* and *transformation* requires more elaboration on students' part; therefore, these two cognitive processes in the IT^{3}framework may not be suitable to be elicited with multiple-choice items. This imposes a constraint on including these two aspects in the Rasch model analysis in the current study. Despite some overlapping cognitive processes in analyzing the meeting discourse and less flexibility of constructing *translation* or *transformation* items, the theoretical framework for understanding learners' IUS remains valuable. The coding framework and procedure enabled us to decipher potential cognitive processes an individual utilizes in discussing an interdisciplinary topic. Such a blurry boundary between the IT^3 aspects could be overcome by formulating a more solid rule when coding the discourse analysis. In other words, the overlap of the cognitive processes does not jeopardize the inter-rater reliability but could be consolidated with iterative communication and a revision of the researchers' understanding to the framework.

One consideration for applying the IT^3 framework was that, were it not for the faculty members from distinct disciplinary departments, the discourse analysis conducted in that study would not represent a good demonstration of IU. This highlighted the importance of interdisciplinary collaboration across science disciplines, including collaborative research and instruction. The problem of current instruction in a so-called interdisciplinary course is often divided according to each professor's content expertise (Geller et al. 2013). As a result, there is little genuine integration or intentional transcendence of disciplinary borders on the part of the teachers that helps pupils to achieve interdisciplinary cognitive advancement (Modo & Kinchin, 2011). So, the curriculum embedding interdisciplinary objectives should be considered by prospective educators first in order to promote highly collaborative interdisciplinary teaching. Critical evaluation and feedback from colleagues of distinct disciplines enables instructors to be more conscious about what components are expected in a successful interdisciplinary course. Ultimately, genuine interdisciplinary instruction can realize the engagement of learners in exercising the different cognitive processes specified in the IT^3 framework.

Current Interdisciplinary Curricula

A study dedicated to promoting interdisciplinary learning in neuroscience is a good example of designing curricula informed by an interdisciplinary theoretical framework to promote holistic understanding (Modo & Kinchin, 2011). The researchers used a specific case study concerning the cause of Alzheimer's disease to describe superficial learning, deep learning, and interdisciplinary learning identified in their study (p. A72). They stressed that "…an interdisciplinary understanding is exemplified by understanding how particular elements from one discipline are also relevant to another and how they are part of the same problem" (p. A72). It clearly stresses that the interdisciplinary learning requires recognition of "disciplinary otherness" and awareness of scales when compared with superficial and deep learning. In fact, it is closely related to the *commonality* and *differential integration* process in the IT^3 framework regarding the core idea shared by separate disciplines as well as one's approach to a topic from different disciplinary angles at the beginning.

Paxson's (1996) framework for designing a task-based course is also an exemplar for designing interdisciplinary curricula from collaborative teaching perspective. The study suggests that instructors should collaborate to generate the task-based curriculum that goes beyond sole emphasis on each instructor's expertise. It implies that generating cooperative learning activities in fostering transferrable learning experiences matters more than deepening factual knowledge learning from detached contexts (Bransford, Brown, & Cocking, 2000). Therefore, a supportive, collaborative team of instructors is one of the determinants to successful interdisciplinary curricula.

The promotion of interdisciplinary education should not be taken as the propaganda against disciplinary curricula. There are still prevalent, deep-rooted "prerequisite" perceptions held by many undergraduate science instructors. The concern about making a revolutionary jump to eliminate disciplinary curriculum is reinforced in the recruitment process of collaborators to implement the IUS-E instrument. Two experienced faculty members teaching introductory chemistry classes expressed their concerns about the IUS-E instrument. Both of them claimed that the IUS-E items were not suitable to be implemented in an introductory chemistry class, because it contained concepts students have not been exposed to since high school. In this case, the professors still considered the acquisition of preliminary disciplinary knowledge before taking an interdisciplinary assessment instrument to be essential. Their advice was confirmed by the interviews with the undergraduate students. The respondents expressed that they have to recall knowledge from chemistry classes in order to respond to a good portion of the questions in the survey.

Such perceptions were contradictory to the researchers' point of view. Supposedly, the IUS-E items do not require participants' prior deep understanding of the content matter. The necessary information to respond to the question was given in the direction of the IUS-E instrument for the students to demonstrate their *integration, translation, transfer, or transformation* cognitive processes. The incongruent interpretation of the same instrument was rooted in the instructors' and the researchers' distinctive perceptions for the purpose of the IUS-E assessment. The popular view of acquiring IU is by taking required disciplinary-oriented courses and leveling up sequentially (Sung & Shen, 2013). This mentality will be challenged in the long run with the call for interdisciplinary learning (AAAS, 2009).

Besides, the inconsistent definition indicated that the current textbooks' treatments of an interdisciplinary concept might be insufficient/inappropriate to meet the new trend of interdisciplinary education. Many textbooks used by instructors failed to allow learners to link prior, relevant experiences with a key idea (Stern & Roseman, 2004, p. 555). Consider a student taking science courses that present the same concept differently, how confused this student may be. Hence, instructors must be aware of the problem before taking action to remedy such inconsistencies. Through classroom explanations and time allotted to construct meanings, coherent agreements could be reached among students enrolling in diverse science classes (Bryce & MacMillan, 2009). Providing supplementary references on the target concept from multidisciplinary-encompassing-perspective textbooks should also help address the problem of disconnection between disciplines. Otherwise, some persistent and robust disciplinary assumptions may prevent learners from making a successful transition from conventional disciplinary understanding to IU.

Conclusions

There is a call for increasing interdisciplinary education for K-16, yet there is still a gap between the current educational systems and the forthcoming learning objective. This dissertation afforded an opportunity for science educators to examine possible ways to achieve interdisciplinary science education. The present research was executed with the goal of promoting interdisciplinary science learning by formulating a cognitive model, which can inform the curriculum, instruction, and assessment vertices that are basic components to create an appropriate learning environment to foster and elucidate IU. The findings indicated that the current disciplinary science curricula have to undergo modification to eliminate incongruent definitions for delivering the same concept or describing the same terminology. On the other hand, the initial quantitative results encourage the application of the Rasch model to interpret participants' IUS through their responses to the IUS-E. Admittedly, the respondents' ability and the item difficulty were both clustered in the middle of the logit scale, meaning that the IUS-E is only suitable to estimate students' IUS at a mediocre level. More iterative revisions and implementations of IUS-E are expected in order to obtain an instrument containing items with varying degrees of difficulty. However, without proper training and scaffolding, it is unrealistic to design interdisciplinary items that could be considered as of lower difficulty levels. The investigation of creating materials for interdisciplinary science education is still at the preliminary stage, but the studies presented in this dissertation could serve as one of the incremental efforts to understand interdisciplinary science education better.

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