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Disciplinary Foundations for Solving Interdisciplinary Scientific Problems

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Problem-solving has been one of the major strands in science education research. But much of the problem-solving research has been conducted on discipline-based contexts; little research has been done on how students, especially individuals, solve interdisciplinary problems. To understand how individuals reason about interdisciplinary problems, we conducted an interview study with 16 graduate students coming from a variety of disciplinary backgrounds. During the interviews, we asked participants to solve two interdisciplinary science problems on the topic of osmosis. We investigated participants' problem reasoning processes and probed in their attitudes toward general interdisciplinary approach and specific interdisciplinary problems. Through a careful inductive content analysis of their responses, we studied how disciplinary, cognitive, and affective factors influenced their interdisciplinary problems-solving. We found that participants' prior discipline-based science learning experiences had both positive and negative influences on their interdisciplinary problem-solving. These influences were embodied in their conceptualization of the interdisciplinary problems, the strategies they used to integrate different disciplinary knowledge, and the attitudes they had toward interdisciplinary approach in general and specific interdisciplinary problems. This study sheds light on interdisciplinary science education by revealing the complex relationship between disciplinary learning and interdisciplinary problem-solving.

Keywords: *Interdisciplinary learning; Problem-solving; Science education*

Introduction

Problem-solving has been a major interest in science education research (Eylon & Linn, 1988; Heyworth, 1999). Much research has been conducted to study how students solve problems within specific science disciplines, including physics (e.g.

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Chi, Feltovich, & Glaser, 1981), chemistry (e.g. Taasoobshirazi & Glynn, 2009), and biology (e.g. Nehm, 2010). Many factors, such as problem conceptualization, problem-solving strategy, and attitudes, have been identified to influence students' problem-solving processes (e.g. Anderson, 2005; Dalgety, Coll, & Jones, 2003; Smith, 1992). This line of work contributes significantly to our understanding of how to help students solve disciplinary problems. However, when dealing with complex problems in the real world that require knowledge from multiple disciplines, students may suffer from isolated knowledge and discipline-specific reasoning (Dreyfus, Redish, & Watkins, 2011). Not surprisingly, more attention has been drawn to interdisciplinary science learning, including problem-solving in interdisciplinary contexts (e.g. AAAS, 2011; NAE & NRC, 2014; NRC, 2005). Proliferated practices and advocates notwithstanding, little research exists in how individuals solve interdisciplinary science problems (Borrego & Newswander, 2010; Klein, 1990).

In this study, we investigated how individuals solve interdisciplinary problems. Interdisciplinarity has various connotations (Klein, 2002). In this paper, it refers to the connections of different scientific disciplinary fields commonly taught in secondary and college levels, including physics, biology, and chemistry. Interdisciplinary approaches help students create deep and holistic understanding about complex phenomena by integrating methods, tools, perspectives, concepts, and theories from two or more individual disciplines (NRC, 2005; Wagner et al., 2011). In this sense, interdisciplinary approach is not conceived as being opposite to disciplinary approach. On the contrary, it is grounded in its disciplinary foundations (Boix Mansilla & Duraisingh, 2007). It is critical, therefore, to understand the relationship between interdisciplinary problem-solving and its disciplinary foundations.

Specifically, in this exploratory, interview study, we examined how disciplinary, cognitive, and affective factors influence people's interdisciplinary problems-solving processes. Our research questions were as follows: (1) How do participants conceptualize interdisciplinary problems based on their disciplinary learning experiences? (2) What strategies do participants use to integrate different scientific disciplinary knowledge to solve interdisciplinary problems? (3) What are participants' attitudes toward general interdisciplinary approach and specific interdisciplinary problems? Answers to these research questions may contribute to advancing interdisciplinary science education by revealing how learners' conceptualization of interdisciplinary problems is influenced by their disciplinary learning experiences, what strategies learners use to integrate different disciplinary knowledge, what attitudes learners possess toward general interdisciplinary approach, and how learners' training in specific disciplines affects their attitudes toward related interdisciplinary problems.

Theoretical Framework

Interdisciplinary Science Education

Human knowledge has long been classified and divided into various 'academic tribes and territories' (Becher & Trowler, 2001). Accordingly, knowledge has been taught and learned following the traditions and formats of disciplinary establishment and organization. Discipline-based education is efficient in helping people acquire knowledge and develop expertise in particular fields since it reduces the complexity of knowledge. However, knowledge developed from a disciplinary approach is often fragmented (Linn, 2006; Sternberg, 2003).

On the practical side, discipline-based education faces more and more challenges because increasingly complex societal problems (e.g. energy crisis, climate change) need to be solved by synthesizing knowledge and skills from multiple areas. Our society needs a sizable workforce whose members possess a diverse knowledge base and are able to communicate and integrate knowledge from multiple disciplines. In order to meet this challenge, many policy-making organizations call for efforts to promote interdisciplinary research and education (AAAS, 2011; NAE & NRC, 2014; NRC, 2005). Recently, Finland announced an educational reform that aims to replace subject-based curriculum with cross-subject, topic-based approach in schools (Beeson, 2015).

The educational benefits of interdisciplinary approach have been widely acknowledged (e.g. Bybee, 1997; McComas, 2009). McComas and Wang (1998), in their literature review, summarized these benefits from four perspectives: (a) from a philosophical perspective, through an interdisciplinary approach, students can learn holistic knowledge as knowledge in nature is a continuity; (b) from a psychological perspective, an interdisciplinary approach will enable students to see the connections of disciplines and decrease the 'psychological distance' among different fields; (c) from a pedagogical perspective, interdisciplinary education can increase teaching effectiveness since it allows students to break the constraints of disciplinary boundaries and connect knowledge with their personal lives in meaningful ways; (d) from a pragmatic perspective, a growing body of evidence supports the practical values of interdisciplinary education.

Although many researchers stress the advantages of interdisciplinary learning, its implementation faces many challenges. For instance, an interdisciplinary approach is typically more demanding than discipline-based learning because it requires not only mastering the knowledge of the involved fields, but also knowing the 'interconnected concepts' and synthesizing the knowledge (Schaal, Bogner, & Girwidz, 2010). In addition, students' expectations about their own disciplines may give rise to their negative feelings toward or even resistance to the incorporation of other disciplines (e.g. Gross, Brent, & Hoy, 2004; Watkins, Coffey, Redish, & Cooke, 2012). Moreover, the different epistemologies, inconsistent definitions, or even conflicting perspectives often lead to difficulties and confusions when studying interdisciplinary topics (Bracken & Oughton, 2006; Jacobs & Frickel, 2009; Sung et al., 2015).

To address these challenges, researchers have studied interdisciplinary learning from various perspectives. Some scholars have examined educators' teaching experience and ideas about interdisciplinary education. For instance, Boix Mansilla and Duraisingh (2007) established an assessment framework to pinpoint the problems of students' interdisciplinary understanding mainly by interviewing faculty members who teach interdisciplinary undergraduate programs. Other researchers have studied how students engage or collaborate in interdisciplinary science projects or courses. For instance, Gouvea, Sawtelle, Geller, and Turpen (2013) tried to find the effective ways of facilitating students' interdisciplinary learning by analyzing students' collaborative responses to interdisciplinary tasks. Redshaw and Frampton (2014) summarized the problems occurred in an interdisciplinary problem-based learning activity, provided possible solutions to cope with the problems, and explained how their suggestions may benefit science teaching and learning. But very little empirical work has been done to examine how individual students solve interdisciplinary problems.

Problem-Solving

Problem-solving is the process of 'moving from a situation in need of resolution to a solution, overcoming any obstacles along the way' (as cited in Taasoobshirazi & Glynn, 2009). There are many different types of 'situation in need of resolution', or simply put, problems. For instance, problems can be categorized into qualitative and quantitative ones based on whether they require numerical solutions (Taasoobshirazi & Glynn, 2009). They may also be labeled as well-structured or ill-structured according to whether the problems are well defined (Shin, Jonassen & McGee, 2003). In this study, we focus on the types of problems that move beyond disciplinary boundaries (Friman, 2010).

Problem-solving has been studied from many perspectives, among which the cognitive and affective aspects are two major themes (Taasoobshirazi & Glynn, 2009). From a cognitive perspective, problem-solving involves processes such as problem conceptualization (e.g. Bunce, Gabel, & Samuel, 1991; Chi et al., 1981; Smith, 1992) and problem reasoning (e.g. Cavallo, 1996; Lawson, 1987), and associated strategies and schemes (e.g. Anderson, 2005; Heyworth, 1999).

As a beginning step, problem conceptualization is critical for problem-solving because it has a direct impact on the follow-up steps such as attention distribution, decision-making, and schemata activation. Problem conceptualization consists of two closely related reasoning processes—problem categorization and representation. The former refers to how problem-solvers classify a problem into different types and the latter refers to how solvers construct the cognitive structure of a problem (Chi et al., 1981). Problem categorization and representation interact with each other and work together to help solvers conceptualize a problem. In addition, existing literature has indicated that experts and novices take different approaches to conceptualize problems: Experts tend to categorize and represent a problem according to the deep structure such as underlying concepts, laws, and theories, whereas novices' problem categorization and representation are often based on the surface features of a problem such as terms, objects, and configurations involved in the problem (Chi et al., 1981).

Strategy is another important cognitive aspect of problem-solving since it determines what procedures or skills solvers will adopt. For instance, it has been shown that both forward and backward strategies are used to solve science problems (Larkin, McDermott, Simon, & Simon, 1980; Sweller, 1988). Experts tend to employ the forward strategy, meaning that they usually analyze and reason problems from known to unknown. In contrast, novices tend to use the means-ends analysis, which is a backward strategy. To solve interdisciplinary problems, students need to develop knowledge integration strategies (Klein, 2008; Linn, 2006). The research in science education has indicated that discipline-based science education may lead to learners' fragmented understanding about science (Dreyfus et al., 2011). Therefore, learners may encounter difficulties in integrating ideas from different scientific areas.

Besides cognitive factors, affective factors, such as emotion, motivation, and self-efficacy, also influence problem-solving processes (e.g. Fredrickson, 2003; Pajares & Graham, 1999; Taasoobshirazi & Glynn, 2009). For instance, positive emotion will contribute to the development of problem-solving skills by broadening learners' 'momentary thought-action repertoires' (Fredrickson, 2003); motivation may exert influence on the transfer process of problem-solving strategies (Bereby-Meyer & Kaplan, 2005); self-efficacy influences the amount of effort and levels of persistence students will put in problem-solving (Dalgety et al., 2003). Furthermore, it has been shown that students hold positive or negative attitudes toward specific scientific disciplines. They often have their own ideas about the nature of disciplinary knowledge before they enter a science class. For instance, some biology students may repel the quantitative aspect because they believe that equations belong to physics and engineering (Gross et al., 2004; Watkins et al., 2012).

Methods

In this study, we examined how people perceive and reason about interdisciplinary problems. As an exploratory effort, we interviewed a purposeful and convenient sample and asked them to solve two interdisciplinary problems that involved three natural science disciplines—physics, chemistry, and biology. In the following, we describe our interview protocol, interdisciplinary problems, participants, and data collection and analysis methods.

Interview Protocol

We created a semi-structured interview protocol (Patton, 1990) based on the methods of clinical interview (Ginsburg, 1981) and self-report interview (Barker, Pistrang, & Elliott, 2002). The protocol consisted of the following four sections. The first section, 'Science Learning Experience', was about participants' majors and their college science courses that may be relevant to the problem context. The questions included the following:

- What is your major for your Bachelor/ Master /Doctoral Degree?
- Did you take any college-level physics/biology/ chemistry course?
- If you have taken any college-level physics/biology/ chemistry course, when did you take them?
- If you have taken any college-level physics/biology/ chemistry course, what were the courses?

The second section, ‘Think-aloud Protocol’, asked the participants to speak aloud when they reasoned about and solved two interdisciplinary problems on osmosis (Figure 1). These two problems were selected from an instrument (Shen, Liu, & Sung, 2014) targeting students’ interdisciplinary understanding within sciences. The instrument was designed by an interdisciplinary team consisting of members from multiple science disciplines and science education. The participants were also given a scratch paper in case they needed to write or draw things.

The third section, ‘Reflection Questions’ were asked after participants finished solving the problems. It aimed to invite participants to reflect on the (inter)disciplinary nature of the two problems (see section below) and the difficulties they had in solving

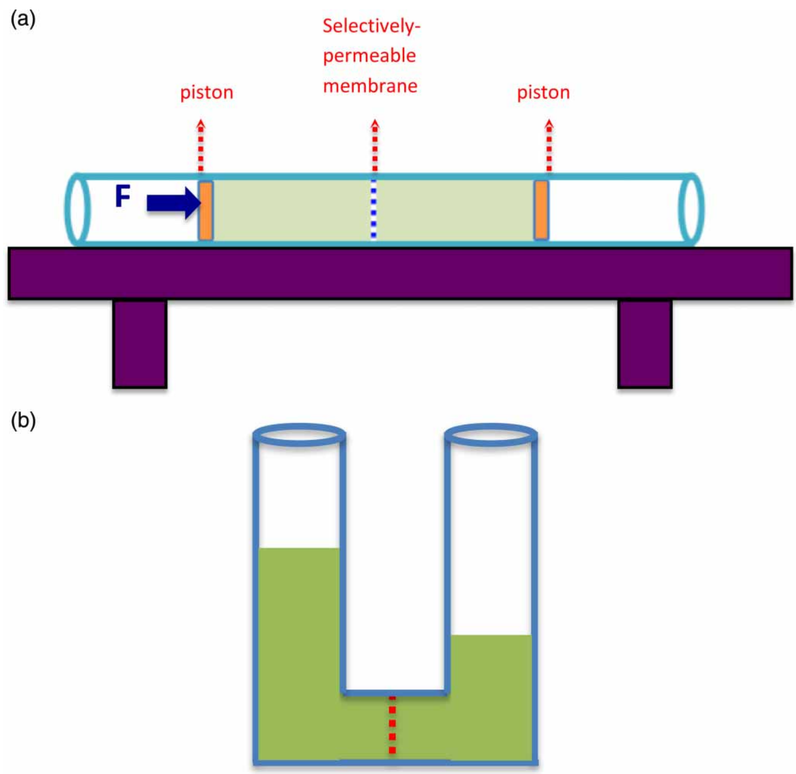

Figure 1. The horizontal-tube problem (a) and the U-tube problem (b) in the interview protocol. Note: A horizontal glass tube filled with a solution is fixed to a table (Figure 1(a)). The tube has a selectively permeable membrane that is only permeable to water in the middle. On each end of the glass tube, there is a freely movable piston that is held fixed initially. A constant external force is applied on the left piston as shown in the figure below. Ignore friction between the pistons and the tube. If the force is always present, where will the pistons be eventually? An empty U-tube is separated at the bottom by a selectively permeable membrane, which only allows water to pass through (Figure 1(b)). In an experiment, Jessie quickly poured some dilute sugar water into both sides of the U-tube so that initially, the left column is higher than the right column. Please explain what will happen to the solution in the two arms until a stable state is reached

them. Combining a think-aloud protocol with follow-up reflection questions is a common method used to reveal how students reason when solving science problems (Heyworth, 1999; Nehm, 2010). These reflection questions included the following:

- Do you think the two problems are interdisciplinary ones?
- If you think the two problems are interdisciplinary, what scientific disciplines are involved? Explain why.
- If you think the two problems are interdisciplinary, which one is more interdisciplinary? Explain why.
- What difficulties did you meet when you try to solve the two problems?

The last 'Attitudes' section probed into the participants' attitudes related to interdisciplinary problem-solving. Specifically, we asked the participants to self-report the following aspects:

- What is your attitude toward general interdisciplinary approach? Explain Why.
- What is your attitude toward Physics? Biology? Chemistry? Explain Why.
- If the interdisciplinary scientific problems involve the disciplines which you don't like, what is your attitude toward the problems? Explain why.

Interdisciplinary Problems on Osmosis

The two interdisciplinary problems (Figure 1) were developed based on the phenomenon of osmosis (Shen et al., 2014). Osmosis is the net, passive movement of water through a selectively permeable membrane from a region of higher water potential to a region of lower water potential. Osmosis is an interdisciplinary topic because it involves concepts from multiple science disciplines. Specifically, in the two problems, the physics component includes pressure and related concepts (e.g. hydrostatic pressure); the chemistry component includes solution and related concepts (e.g. solvent, solute concentration); the biology component includes the membrane and related concepts (e.g. functions of membrane).

The two problems have the same 'deep structure' but different 'surface features' (Chi et al., 1981). The deep structure of the two problems involves the following understanding: the dynamic equilibrium of the water movement crossing the selectively permeable membrane is under the influence of two competing factors—pressure gradient (water moves down the pressure gradient) and solute concentration gradient (water moves up the solute concentration gradient). In both cases, the two factors act against each other and the final equilibrium state is reached when they balance each other. In contrast, the two problems have different surface features: e.g. the shape of the tube and the way the pressure difference is introduced. These surface features will help us get more insights about how problem-solvers conceptualize interdisciplinary problems (Chi et al., 1981; Nehm, 2010).

The two interdisciplinary problems are qualitative in nature. We chose qualitative problems for two reasons. First, qualitative reasoning is the starting point to solve any problem (Heyworth, 1999). Second, we tried to reduce the confounding factor of quantitative reasoning, which is closely tied to yet another discipline, mathematics.

Participants and Recruiting

We recruited our participants through convenient but purposeful sampling (Coyne, 1997). First, we recruited participants who had a minimum of master's degree because we wanted to interview students who had sufficient disciplinary training and, therefore, had more insights in disciplinary and interdisciplinary learning. Second, we targeted students who were capable of articulating their ideas as we asked the students to speak aloud when they were solving the problems. This would give us more insights into their problem-solving processes. Third, we included participants with different content background with respect to the three disciplines involved (biology, chemistry, and physics).

As an exploratory effort, the first author invited classmates and friends from a public research university who met our criteria to participate in the study. We started with interviewing students who had had exposure to different degrees to all the three disciplines at the college level, this resulted in 11 participants. Then we expanded to include five more participants who had less or minimal exposure to the three disciplines at the college level in order to expand the spectrum of content background for our sample. Therefore, in a total 16 students volunteered to participate in the study. Table 1 lists the pseudonyms, the majors, and the college-level science learning experiences of the participants. Among the 16 participants, 11 had taken college-level courses in all three disciplines, two had taken courses in two of the three disciplines, and three only had taken courses in one of the three disciplines.

Data Collection and Analysis

The interviews were conducted by the first author in spring 2013. Each interview lasted for about 30–60 minutes and was audio-recorded. During each interview, the participants were allowed to sketch things on a piece of scratch paper while solving the problems, and the paper was collected after the interview. The first author also took brief field notes. These notes focused on the participants' train of thoughts when solving the two problems and notable observations that the audio records couldn't capture (e.g. the vacillation moments the participants experienced when they were trying to negotiate conflicting ideas and unconfident expressions when they made a decision).

All 16 interviews (557 minutes) were transcribed. First, we registered the first part of the interview transcripts regarding the information about the participants' majors, science backgrounds, and previous science learning experiences and organized this information in a table. Next, we analyzed the participants' responses to the remaining three sections of the interview protocol, following the inductive category development procedure (Mayring, 2000). Focusing on our research questions, we examined how participants conceptualized, solved, and felt about the problems from two angles:

Table 1. Participants' majors, college science learning experiences, and response quality scores

Name	Bachelor	Master	Doctor	PHYS	CHEM	BIOL	Score
Grace	Plant Protection	Plant Pathology		S	A	A	5
Hannah	Biology	Human anatomy and physiology	Science Education (Biology)	S	A	A	5
Lauren	Biology & Geology	Earth Science	Science Education	S	A	A	5
Luis	Biochemistry	Physical Chemistry	Science Education (Chemistry)	A	A	S	6
Sierra	Biology	Secondary Science (Biology)	Science Education (Biology)	S	A	A	5
Sophia	Science Education (Biology & Chemistry)	Science Education (Biology & Chemistry)	Science Education (Biology & Chemistry)	S	A	A	4
Brian	Science Education (Biology)	Science Education (Biology)	Science Education (Biology)	S	S	A	6
Gabrielle	Biology	Entomology	Science Education (Biology)	S	S	A	5
Jasmine	Mechanical Engineering	Biomedical Engineering	Science Education (Physics & Engineering)	S	S	A	5
Robert	Physics Teaching	Science Education	Science Education (Physics)	A	S	S	5
Victoria	Science Education (Biology)	Science Education (Biology)		S	S	A	6
Caleb	Physics	Science Education (Physics)	Science Education (Physics & Engineering)	A	S	N	5
Lily	Psychology	Psychology	Psychology	S	N	S	4
Jacob	Applied Mathematics	Statistics	Statistics	S	N	N	4
Jessica	Mathematics	Operational Research	Statistics	S	N	N	5
Tyler	Physics	Physics	Nanotech	S	N	N	4

Note: The PHYS, CHEM, and BIOL column indicate if the participant had No (N), Some (S), or Advanced (A) college-level learning experience in the discipline.

(a) a discipline-specific perspective and (b) a more holistic and interdisciplinary perspective. More specifically, for the problem conceptualization aspect, we derived two levels on which how students conceptualized the problem: from either a 'micro' or a 'macro' level. The former referred to how participants categorized problem elements into different disciplines and the latter was about how they represented the whole problem structure. For the problem-solving strategy aspect, we paid particular attention to strategies that may be discipline-specific or discipline-general. For the attitudes aspect, we scrutinized how their attitudes towards specific disciplines interacted with their attitudes towards interdisciplinary problems in general.

In addition, to evaluate the quality of students' responses, we applied a rubric that was specifically designed for assessing students' interdisciplinary understanding on the topic of osmosis (for details and design rationale of the rubric, see Shen et al., 2014). The levels of the rubric are: 0—showing no answer or off-task; 1—presenting simple statement with no apparent indication of relevant disciplinary ideas or presenting misconception; 2—presenting one relevant and correct disciplinary core idea or multiple but isolated ideas; 3—presenting two scientifically valid and relevant ideas that are from different disciplines and making meaningful connections between them; 4—demonstrating three or more scientifically valid and relevant ideas from multiple disciplines and making meaningful connections among them. The maximum total quality score of each student's response is therefore 8.

The scratch paper and field notes were used to help make references when analyzing the transcript data. We did the member checking (Lincoln & Guba, 1985) with all the participants via informal conversations, phones, or emails when we encountered questions.

Findings

Overall, all the participants were able to solve the two interdisciplinary problems to a certain degree; but none of them could solve them completely. The quality scores range from 4 to 6 and the average response quality scores for the participants who had taken courses in all three, two, and only one involved fields were 5.2, 4.5, and 4.3, respectively (See Table 1). This trend suggested that participants' discipline-based science courses did contribute to their ability of solving interdisciplinary problems (the reader should keep in mind the small sample size involved).

Our further analyses revealed complex patterns in how participants' disciplinary science learning experiences influenced their conceptualization of the problems, the difficulties occurred, and the strategies they used to integrate different disciplinary knowledge. It was also found that although the participants acknowledged the benefits of a general interdisciplinary approach and developed positive attitudes toward it, their prior disciplinary learning experience resulted in them having mixed feelings toward specific interdisciplinary problems. In the following, we report our findings in three sections, each addressing one research question.

Disciplinary Conceptualization of Interdisciplinary Problems

Two themes were induced on the participants' conceptualization of interdisciplinary problems. First, at a 'microscopic' level, the participants associated the individual elements (e.g. words, objects) in an interdisciplinary problem to different disciplines in a rather similar way. More specifically, the participants tended to link force (16 out of 16 participants) and piston (12/16) with physics, solution (13/16) and concentration (10/16) with chemistry, and the selectively permeable membrane (16/16) with biology. For instance, the following responses were elicited when the participants were asked to explain what made them think the problems were interdisciplinary in essence (italicized words/phrases indicate these associations):

> A *selectively permeable membrane* is something related to *biology* problem. The *solution* in the tube and the water being able to move across the tube make me think of *chemistry* and the makeup of the solution. Then I guess when I think about *piston and force*, they are more like *physics* to me. (Lauren, interview, March 20, 2013)

> I think that they [two interdisciplinary problems] both have the *chemistry* components of *concentration and solution*. There are also the *physics* components of *force and piston*, the difference of the height of the U tube. The *selective permeable membrane* is *biology* component. (Gabrielle, interview, March 6, 2013)

The participants' similar categorization of problem elements came naturally from their prior science education experience. All participants had taken multiple discipline-based science courses. In these courses, concepts or objects such as force and piston are often taught in physics, solution and concentration are generally covered in chemistry, and selectively permeable membrane usually appears on biology textbooks.

Second, although the participants had similar ways of associating individual problem elements with specific disciplines at the 'microscopic' level, they perceived the whole interdisciplinary problems from different disciplinary perspectives at the 'macroscopic' level. Apparently, participants' major science background knowledge affected how they conceptualized an interdisciplinary problem as a whole based on their familiar disciplinary contexts. Taking the first interdisciplinary problem as an example. Tyler, whose major science background was physics, thought it was a physics problem and could be solved by using the knowledge of oscillation. He said, 'the solution between piston and membrane will act like the mass in the Spring-Mass system and undergo simple harmonic motion'. Brian, whose science background was biology, mentioned that ' … I was thinking about biology because this one reminds me of blood vessels, stuff like that'. Hannah, who got her master's degree in human anatomy and physiology, said that, 'It could be physics and biology because I am thinking the force exerted by muscles on bones'. Besides major science knowledge background, the participants' particular learning experience also influenced how they viewed the whole problem. For instance, for the second interdisciplinary problem, Lauren said that it was more like a biology problem because she had seen an U-tube problem in a biology textbook: 'I guess this reminds me of a diagram I've seen in biology textbook. I know I've seen an example about U-tube before. When I think about the selectively permeable membrane, that makes me think of biology again as well' (Lauren, interview, March 20, 2013). In contrast, Brian believed that the second problem was more like a physics problem because he studied pressure in physics class. He said, 'when I see U-tube, I always think about physics because they [teachers] cover pressure topic in physics class' (Brian, interview, March 6, 2013).

Participants' conceptualization of interdisciplinary problems, at both the microscopic and the macroscopic levels, influenced how they related the two problems. When asked about which problem was more interdisciplinary, six participants said they were comparable because the elements of the problems (the surface features) were similar. For example, Robert and Tyler mentioned:

> I think that they are essentially the same level of interdisciplinarity. Because they're both essentially the same situation: a tube containing a semi-permeable membrane and a solution with a force being applied. (Robert, interview, February 25, 2013)

> They are similar interdisciplinary problems. Both them include physics, like force, piston, and pressure. They have selectively permeable membrane. That is biology. Solution and solute belongs to chemistry. (Tyler, interview, March 1, 2013)

In contrast, seven participants believed that one was more interdisciplinary than the other. For instance, Jasmine provided her rationale as the following:

> I would say question number two is interdisciplinary. What I can see is, you have physics there because it deals with the force … There is chemistry because they have concentration in the two [compartments]. I guess you can also say it is biology because there is membrane that can go across different concentration there. [Interviewer: So, you don't think the first problem is interdisciplinary?] That one I kind of see it as a fluid problem. I see it as a physics problem. (Jasmine, interview, February 27, 2013)

Only three participants recognized that the two interdisciplinary problems were the same in essence. Just as Victoria said: 'I feel like these [the two interdisciplinary problems] are the same question though'.

Integration Strategies for Solving Interdisciplinary Problems

Our results showed that the participants had difficulty in sorting out the two factors influencing the dynamic equilibrium of water movement in the problems. These factors could invoke distinctive disciplinary knowledge and experience for the participants, therefore, causing confusion or challenges in linking or integrating them in the same context. They used the words, like 'hard' and 'tricky', to describe the two problems. For instance, when reasoning about the U-tube problem, Gabrielle and Lauren experienced the difficulty of integrating two seemingly contradictory factors.

> Soon, that [gravity] will work to balance out so that the arms will even. But, if it does that, it has water flow across because the sugar can't. Which means, there will be a higher concentration of sugar on one side than the other. So, as soon as water will flow from the left to the right to even. See, I am not sure. The concentration of the sugar water must be the same … This is hard. It wants the equilibrium because it wants to stay that, the same concentration and also the same height. (Gabrielle, interview, March 6, 2013)

> If I move the water over, then I am going to have a much higher concentration of sugar in this [left side]. So, maybe the volume would be equal. But, the concentration would be much different most likely. Which is why this is tricky for me. Because I am not sure if for the solution, it would be better have an equal concentration which means uneven amount or to have an even amount of solution. But the solution would have uneven concentration. So, the problem is that I don't know enough to know which solution, which idea about the tube makes more sense. (Lauren, interview, March 20, 2013)

The participants did acknowledge that a problem should have a solution despite competing disciplinary perspectives. For instance, when responding to a follow-up question, Sierra said: 'If a physics perspective has a different answer [from a biological perspective], then I think there is a problem with the question because, eventually, you can't have different answers to the same problem' (Sierra, interview, March 25, 2013).

After failing to reason through the problem initially, the participants tried four follow-up strategies: (a) relying on mathematical formula; (b) doing experiments; (c) neglecting one competing factor to simplify the situation; and (d) applying a 'mixed strategy' to reconcile the two competing factors. The first two strategies pertain to the specific context of science, while the latter two pertain to interdisciplinary problem-solving.

When having a hard time solving the problem, seven participants started to write formula on the scratch paper, despite the two problems are qualitative in nature. For instance, Brian wrote $P = h^* d^* g$; Jasmine wrote $Pg+Pc = Pg+Pc$, $\sum F = 0$, and $F_1 + F_2 + F_3 = F_4 = 0$; Caleb wrote $F = PA$ and $P = \rho gh$. None of them wrote down van Hoff's law though. Lily even tried to assign some numbers to the problems and calculated those using equations (Figure 2). It is natural when people cannot complete conceptual reasoning, they would try to draw on mathematical formula (Bodner, 1987; Nakhleh, 1993). This is especially relevant in science as students have been trained to apply mathematical formula in solving science problems as routine practices.

In contrast to a theoretical approach, three participants mentioned they wanted to do experiments to see what would actually happen. For instance, Grace said that 'I

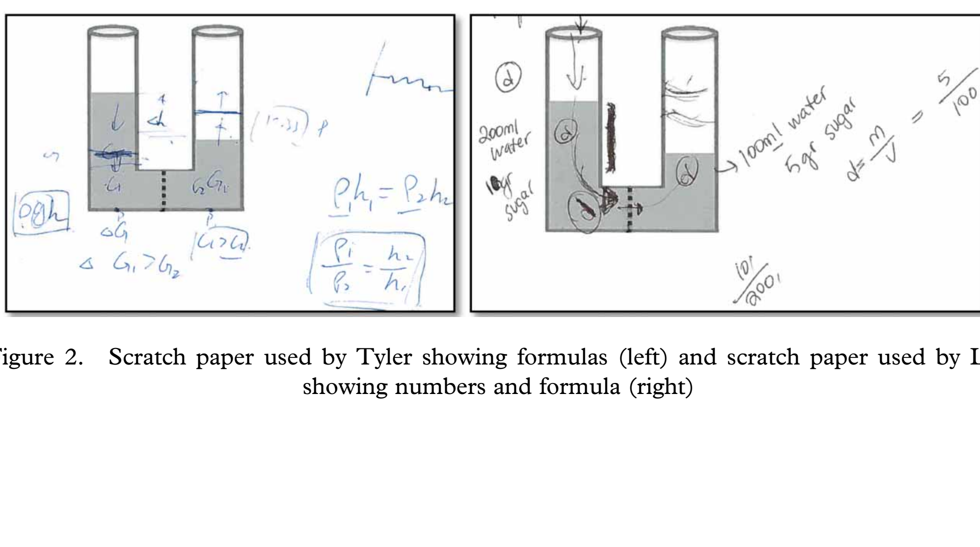

Figure 2. Scratch paper used by Tyler showing formulas (left) and scratch paper used by Lily showing numbers and formula (right)

think problems like these need to do experiments to see what actually happens'. Proposing experiments was a good thought because the scenarios presented in the problems were hypothetical, and seeing what actually happens would help one to reason through these phenomena.

Those who used mathematical formula or proposed experimental solutions could not predict the final state of water movement in the two problem scenarios. In order to come up with a final state, eight participants decided to neglect one of the two competing factors to simplify the problem, although they themselves felt uncomfortable about their reasoning. The participants' decisions about which factor they left out seemed to be related to their background knowledge and science learning experience. For instance, Robert, coming from a physics background, said the following when reasoning about the U-tube problem:

> In my mind, the physics perspective would win if this is big. I think most of the time, diffusion type of stuff, happening in a molecule level that is small stuff between cells. This is a big thing. This U tube is like something that I can hold in hands. So, it seems like basically gravity would win over diffusion. (Robert, interview, February 25, 2013)

In Robert's mind, physics was more tied to macroscopic phenomena, whereas biology had more to do with molecular-level phenomena. Therefore, in this case, water movement would be mainly determined by the hydrostatic pressure difference due to gravity (which implied that water movement due to concentration difference was negligible). In contrast, Hannah, who had a biology background, guessed that the pressure factor was negligible. She said:

> I am thinking about concentration and the pressure. I don't think there is enough pressure to make us observe a difference in where the levels are … I don't know how much pressure is pushing down. I don't think [difference in hydrostatic] pressure is goanna be significant enough to change the levels of the fluid. (Hannah, interview, March 27, 2013)

Hannah's guess was probably influenced by the osmosis scenario related to cells in biology textbooks. In these scenarios, gravity is often neglected or not mentioned at all. This was also echoed by Grace during the member checking.

Four participants tried to employ the 'mixed strategy' to solve the two interdisciplinary problems. That is, participants put two disciplinary perspectives side by side without integrating them successfully. For instance, when solving the horizontal-tube problem, Brian couldn't determine the competition result of the two disciplinary perspectives and concluded that the final state would be the same as the initial state because 'if the [external] force pushes that way, the osmosis will push back. So, it [the piston] will go back to the initial position'. Victoria, who failed to integrate the factors of pressure and concentration in the U-tube problem, concluded that the pressure and concentration factors would keep on competing with each other and the water movement through the membrane would never stop. When reasoning about the problem, Victoria stated the following:

> Initially, the left side is forced by gravity. So, the water on the left side will go toward right. And then, the water potential on right side will be stronger. Therefore, the water will go

> toward left again. And then, it will be the same situation with original point. So, the moving of water will repeat. Eventually, the water will never stop. (Victoria, interview, February 22, 2013)

Apparently, this reasoning was influenced by the model of oscillation. As a result, Victoria failed to see that the solution in the U-tube would reach a dynamic equilibrium state. This was probably because she could not reason through the water movement process at the molecular level, at which the mechanism of the water movement due to the two competing factors can be truly integrated.

Positive Attitudes toward General Interdisciplinary Approach and Mixed Feelings toward Specific Interdisciplinary Problems

Although 12 out of the 16 participants expressed negative attitudes toward one or two of the three involved scientific disciplines, all participants acknowledged the importance of an interdisciplinary approach in general and held positive attitudes toward it. Based on their self-reports, their positive attitudes toward an interdisciplinary approach can be attributed to epistemological, practical, or educational reasons.

From an epistemological perspective, four participants stressed that science knowledge, in essence, is integrated and cannot be separated, and boundaries between subjects are artificial. For instance, Tyler said, 'What is physics? I think all scientific knowledge is integrated eventually. We cannot distinguish which one is physics, which one is chemistry or biology at all'. Luis said, 'they [the scientific fields] are integrated. To understand the world, you need all of them. The knowledge itself is interrelated'.

From a practical perspective, seven participants emphasized that, in order to solve real-world problems, one needed to use scientific knowledge from different disciplines simultaneously. For example, Lily said, 'I think there is almost no real-world problem or research can be done only by [applying] one scientific discipline. All of them need helps from other disciplines'. Robert acknowledged that 'I think some more meaningful problems, like real problems, are interdisciplinary problems, especially when it starts to get into application type of stuff'.

From an educational perspective, participants submitted that an interdisciplinary approach could facilitate [science] learning in many different ways. For instance, it offers different perspectives in learning, as Luis mentioned, 'I think it is helpful for understanding because you get different ideas. Different people tend to look at things differently. Biology will look at a problem a little different from chemistry'. It also shows learners how different fields are connected with each other, as Sophia explained.

> I think it is a really way to get students to pull in lots of different science concepts. A lot of times, science is just very separated. You have biology, chemistry, and physics. They really don't talk about how the three are connected,even though, obviously, they are connected. (Sophia, interview, February 25, 2013)

Furthermore, seeing connections among different fields can help learners develop holistic understanding of science, as Sierra stated in the following:

> It helps students make more connection rather than think of biology,chemistry and physics as isolated subjects.So … interdisciplinary [problem] solving in learning is important because it helpsstudents see the concepts over and over, and in different areas to help themget more holistic understanding … They may actually start to see the big picture [of science]. (Sierra, interview, March 25, 2013)

Learners' holistic understandings, in return, can deepen their understanding of individual scientific areas, as Gabrielle said 'If I have learned all those subjects [physics, chemistry, biology] in this [interdisciplinary] way that you just asked the questions, then I would understand them a lot more better because I will understand the relationship between them'. Some also argued that interdisciplinary problems could provide learners with concrete and practical application contexts when learning abstract contents. For instance, Jacob mentioned 'Both physics and statistics have many abstract theories. I will feel bored if I only learn the theories. If there are some interdisciplinary problems that need to apply the abstract theories, I will recognize the significance of these theories'. Finally, according to the participants, an interdisciplinary approach can also help learners develop their interests in disliked areas, as shown in the quote by Hannah below.

> Physics is a mess to me. I don't like physics. It is just not interesting for me. It must have to do with the force generated by your muscles and your bones. That is interesting. I would say the same to biochemistry. It is also not that interesting to me. Again, with the muscle physiology, I really like it. Biology is my favorite. If I have had that sort of thing [interdisciplinary learning] in school, maybe, physics and chemistry will grade higher for me. (Hannah, interview, March 27, 2013)

It is worth noting that although all participants had positive attitudes toward an interdisciplinary approach in general, they also acknowledged some challenges. First of all, as some participants pointed out, an interdisciplinary approach is hard for learners. For instance, Hannah said that 'I think it [interdisciplinary approach] is so important. I also think it is so hard. I should put it on the top [of disciplinary approach] because it is so important. But I think I should be realistic'. In addition, participants mentioned explicitly that they needed specific scaffolds to feel comfortable with and increase confidence in an interdisciplinary approach.

> One problem with interdisciplinary learning and teaching is that, it is hard to adjust our thinking to do it. I would need somebody to help me understand how to do it before I could jump into it. We need to be presented the idea more often. We also have to practice it. We are goanna mess it up. But we need to keep practicing and we will get better. I think if I have support, I would use it more. (Hannah, interview, March 27, 2013)

As for attitudes toward specific interdisciplinary problems, it appears that the participants preferred the ones that included their favorite science subjects. For the interdisciplinary problems involving the disciplines that they were not good at or disliked, they would feel intimidated and lack of confidence. For instance, Lauren responded to interview's question about her attitude toward interdisciplinary problem:

> I guess it depends on what disciplines involved in it. [Interviewer: Just now, you mentioned that you dislike physics. So, how would you feel about the interdisciplinary problems if it involves physics?] I think if the problem involves physics, I would certainly try to do it. But I might be a little more intimidated than if it was a question that has biology and chemistry. (Lauren, interview, March 20, 2013)

This clearly shows that some participants' feelings about some scientific disciplines (in our sample, it was mostly physics) did influence their attitudes toward related interdisciplinary problems.

Summary

In brief, our study showed that a student's disciplinary foundation may help or hinder his or her interdisciplinary problem-solving. We investigated three aspects as shown in Figure 3.

The participants used different ways to conceptualize the interdisciplinary problems and diverse strategies to integrate different disciplinary knowledge. The conceptualization of interdisciplinary problems was based on both problem elements (micro level) and whole problem structure (macro level). When resolving the conflict between different disciplinary perspectives, the participants tried strategies that may be discipline general (e.g. relying on mathematical formula) or discipline-specific (e.g. prioritizing a disciplinary perspective). In terms of attitudes, there may be contradictory attitudes the participants had toward interdisciplinary approach in general and specific interdisciplinary problems. All participants recognized the importance of an interdisciplinary approach, held positive attitudes toward it, and were willing to engage in interdisciplinary science learning. Nevertheless, many of them had concerns about taking an interdisciplinary approach because it was harder than discipline-based

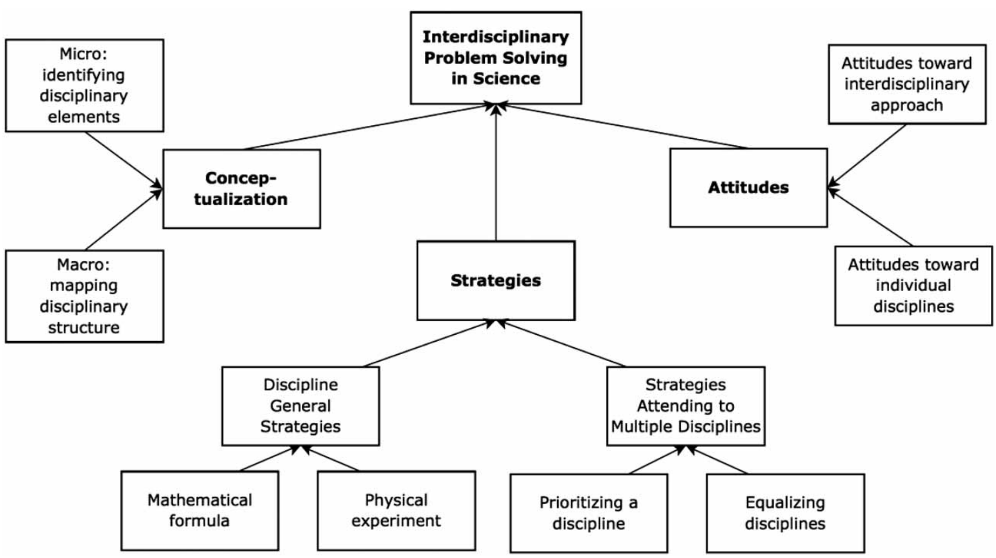

Figure 3. Major aspects influencing interdisciplinary problem-solving

science learning. Moreover, some participants held negative feelings toward some interdisciplinary areas because of their negative learning experience in or attitudes toward some of the involved disciplines.

Conclusion and Implication

We interviewed a convenient but purposeful sample of 16 graduate students coming from a variety of disciplinary backgrounds and asked them to solve two interdisciplinary science problems on the topic of osmosis. We also probed into their attitudes toward general interdisciplinary approach and specific interdisciplinary problems. We found that participants' prior discipline-based science learning experiences had both positive and negative influences on their interdisciplinary problem-solving. These influences were embodied in their conceptualization of the interdisciplinary problems, the strategies they used to integrate different disciplinary knowledge, and the attitudes they had toward interdisciplinary approach in general and specific interdisciplinary problems. Although we only interviewed a small number of students, we believe that the diverse student responses do shed light on interdisciplinary science problem-solving specifically and interdisciplinary learning in general. Here we highlight the following points.

First of all, we need to reconceptualize the relationship between interdisciplinary problem-solving (or interdisciplinary learning in general) and its disciplinary foundations: they are not in a simple linear relationship. As Figure 3 shows, we investigated three factors that may influence interdisciplinary problem-solving. Each factor contains competing elements that may contribute positively or negatively to interdisciplinary problem-solving. For instance, disciplinary knowledge and experience is necessary for interdisciplinary problem-solving, but it may result in biased problem conceptualization and solving strategy. One's attitudes toward interdisciplinary problems are complicated by the fact that one may possess different attitudes toward the individual disciplines involved. Therefore, we call for more empirical studies to further investigate the complexity that may lead to a better framing of the relationship between interdisciplinary learning and disciplinary foundations.

In order to implement successful interdisciplinary science learning, coherent and systematic coordination among instruction, curriculum design, and assessment is very much needed. We should not assume that learners are able to integrate different disciplinary knowledge naturally. This study showed that although in general, students recognize the significance of interdisciplinary approach and hold positive attitudes towards it, they lack systematic interdisciplinary learning experience. Without targeted instructional support that provides rich interdisciplinary learning experience, even for someone who possesses all relevant disciplinary knowledge, he or she may still face great challenges when solving an interdisciplinary problem, as shown in this study. This is not surprising, as interdisciplinary science problems require solvers to not only possess relevant knowledge base, but also be able to integrate knowledge and skills from different scientific areas. Interdisciplinary science learning has to been fostered through deliberate instruction, which calls for reforming of many existing science teacher preparation programs (since most of them are discipline-based, especially at the secondary level), or creating innovative professional development opportunities for inservice teachers to learn how to deliver interdisciplinary instruction.

Interdisciplinary learning is not an easy task and therefore, should be set as a long-term goal (i.e. throughout K-16 education). Students can start from basic integration and then increase the integration level so that they can have enough time to adapt to interdisciplinary thinking, reduce anxiety, and develop confidence and positive attitudes in interdisciplinary learning. For instance, students may simply start with connecting interdisciplinary subject matter through some surface features, and then pay more attention to the deep structure of the connection.

A first step toward making interdisciplinary learning a more long-term goal is to reexamine the national or local educational standards to see if they highlight making connections across disciplines in a consistent way. One example is the Next Generation Science Standards in the United States in that it integrates scientific and engineering practices and emphasizes crosscutting concepts across domains (NGSS Lead States, 2013). NGSS also makes explicit connections to the Common Core Mathematics and English Language Arts Standards. However, more efforts are needed to coordinate these guiding documents to make them more coherent across domains. For instance, the practice of modeling is highlighted in both NGSS and the Common Core Mathematics Standards (National Governors Association for Best Practices & Council of Chief State School Officers, 2010), but clearly they are portrayed very differently.

Successful interdisciplinary science education needs effective assessments to pinpoint students' difficulties and reflect their actual interdisciplinary reasoning ability. The problem conceptualization and solving strategies revealed by this study may give directions to interdisciplinary assessment development. For instance, conceptualizing interdisciplinary problems in a disciplinary way may be one of the reasons that lead to reasoning deadlocks. Therefore, interdisciplinary assessment designers need to carefully balance problem elements that people may easily associate with certain disciplines. Additionally, student responses to certain items that involve competing disciplinary factors may reveal different interdisciplinary reasoning levels. For instance, deliberately ignoring one disciplinary factor is probably at a higher level than not recognizing all the relevant disciplinary factors. Assessment items that are designed to elicit these nuanced responses with respect to interdisciplinary reasoning will provide instructors with more information, and therefore, enable them to provide more targeted feedback regarding how students connect knowledge across disciplines.

Limitation and Future Direction

This exploratory study has many limitations. In this study, we focused on the cognitive and affective factors that influence individuals' interdisciplinary problem-solving, but we did not examine how these factors interact with each to influence students' problem-solving. Future studies should look into the complex connections and interactions among these factors. Although we set certain criteria when recruiting participants, this study only interviewed a small sample. More systematic approach in sampling is needed in follow-up studies. Also, we focused on individuals in the study. As collaboration is a common approach in interdisciplinary work, more research is needed to probe into students' collaborative problem-solving from an interdisciplinary perspective.

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