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Toward an Analytic Framework of Interdisciplinary Reasoning and Communication (IRC) Processes in Science

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Students need to think and work across disciplinary boundaries in the twenty-first century. However, it is unclear what interdisciplinary thinking means and how to analyze interdisciplinary interactions in teamwork. In this paper, drawing on multiple theoretical perspectives and empirical analysis of discourse contents, we formulate a theoretical framework that helps analyze interdisciplinary reasoning and communication (IRC) processes in interdisciplinary collaboration. Specifically, we propose four interrelated IRC processes—*integration*, *translation*, *transfer*, and *transformation*, and develop a corresponding analytic framework. We apply the framework to analyze two meetings of a project that aims to develop interdisciplinary science assessment items. The results illustrate that the framework can help interpret the interdisciplinary meeting dynamics and patterns. Our coding process and results also suggest that these IRC processes can be further examined in terms of interconnected sub-processes. We also discuss the implications of using the framework in conceptualizing, practicing, and researching interdisciplinary learning and teaching in science education.

Keywords: *Interdisciplinary reasoning and communication (IRC); Interdisciplinary knowledge management; Integration; Translation; Transfer; Transformation*

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Introduction

Collaborative research involving multiple disciplines is pervasive in many science fields in the twenty-first century (Rhoten & Parker, 2004). Many scientific and technological innovations occur at disciplinary boundaries (Leonard-Barton, 1995). This trend mandates science education to prepare students to develop an interdisciplinary habit of mind. The US Next Generation Science Standards (NGSS Lead States, 2013) supports this philosophy by emphasizing core scientific and engineering practices (e.g. modeling) and crosscutting concepts (e.g. energy) that transcend disciplinary boundaries. Even discipline-based education emphasizes the interdisciplinary nature of science and students' ability to communicate and collaborate with other disciplines (American Association for the Advancement of Science, 2011). However, there are many barriers in the current educational system that prevent students from becoming successful interdisciplinary thinkers and doers (Czerniak, 2007): for example, typical assessments in science classes focus on specific disciplinary topics; school teachers are not prepared to implement interdisciplinary curricula; there is no consensus concerning what interdisciplinary science education means. As a result, students not only develop fragmented understanding in science, but they are also reluctant to think beyond disciplinary constraints.

Importance and challenges aside, little empirical research has been conducted to establish a theoretical and/or analytic framework of interdisciplinary learning and interaction (Boix Mansilla & Duraising, 2007; Czerniak, 2007). This paper aims to propose such a framework that can capture the key processes of interdisciplinary reasoning and communication (IRC) instantiated in interdisciplinary collaboration. We bundle reasoning and communication together to stress the intertwined nature of the cognitive and social processes in interdisciplinary interactions. Accordingly, we take an integrated perspective (Bransford et al., 2006) on learning that infuses cognitive perspectives (e.g. Piaget, 1970; Singley & Anderson, 1989) and sociocultural perspectives (Star & Griesemer, 1989; Vygotsky, 1978). In the long run, we hope that this framework can be used not only to help analyze interdisciplinary reasoning and interactions, but also to guide the development of curricular materials, instructional approaches, and assessment items that target students' IRC. Although we contextualize the study in natural sciences, we are hopeful that the framework can shed light on conceptualizing interdisciplinary learning and teamwork beyond natural sciences.

The work presented in this paper was based on a project that aimed to improve college students' interdisciplinary understanding by developing innovative assessments on the topic of osmosis (Shen, Liu, & Sung, 2014). The project was accomplished by an interdisciplinary team consisting of faculty members and graduate students coming from multiple science disciplines and science education. The team strived to establish a framework of interdisciplinary learning because understanding how students learn is central to the development of high-quality assessments (Pellegrino, Chudowsky, & Glaser, 2001).

To develop the framework, we drew perspectives from the learning sciences (Sawyer, 2006) and information processing and knowledge management (Carlile, 2002, 2004; Carlile & Rebentisch, 2003), and reflected on the progress of our own project. To refine the framework, we applied the initial framework to analyze two project meetings. As theory building is an iterative process, our understanding of interdisciplinary learning and interaction has evolved over time. Therefore, we stress that the elaboration and refinement of the framework should be viewed as a retrospection and reconstruction process.

Before we proceed to the IRC processes, we would like to clarify what we mean by *interdisciplinarity* here. First of all, we focus on academic disciplines in natural sciences such as physics, chemistry, and biology in this paper. Instead of a unified system, different taxonomies of discipline are often presented based on practical needs. For instance, the NGSS considers disciplinary core ideas in physical sciences, life sciences, earth and space sciences, and engineering, technology, and application of science, as these are the major disciplines in K-12 science education (NGSS Lead States, 2013). A discipline often has sub-disciplines or branches. For instance, physiology, zoology, and molecular biology are common branches of biology. These branches can be considered as individual disciplines in various contexts. The development of an academic discipline is dynamic and a new discipline may emerge from the intersection of multiple disciplines (e.g. biophysics). An established academic discipline has a relatively stable community of people who share a set of foundational ideas and common methods, develop new ones through collaboration in related projects, disseminate progress in professional conferences and academic journals, and train the next generation of scholars and workforce for the discipline.

Besides ‘interdisciplinary’ approaches to education and research, there are many other terms commonly used to denote the involvement of more than one discipline, such as *multidisciplinary*, *transdisciplinary*, and *integrated* approach. A multidisciplinary approach draws ideas and methods from individual disciplines while acknowledging clear disciplinary boundaries. This approach does not make special efforts to make purposeful connections or impose unification among the disciplines (Drake & Burns, 2004). A transdisciplinary approach focuses solely on addressing the holistic problem or issue that involves multiple disciplinary knowledge and expertise. Transcending disciplinary constraints, a transdisciplinary approach starts from and ends in the problem space without any *a priori* disciplinary lenses (Klein, 2008). An integrated approach is often used in an educational context. Lederman and Niess (1997) defined it as an approach in which ‘different subject matters form a seamless whole’ (p. 57) and no clear distinction exists among the disciplines. Acknowledging many overlaps with all these terms, we use the term ‘interdisciplinary’ in this paper in agreement with Lederman and Niess (1997) in the sense that it keeps the integrity of the disciplines involved on the one hand, and emphasizes the application of the integrated knowledge in resolving real-world problems on the other.

In the following, we first introduce the IRC framework that encompasses four interconnected processes: *integration*, *translation*, *transfer*, and *transformation*. We then present an empirical investigation in which we applied the framework to analyze the discourse contents of two meetings in the project. Through the empirical analysis, we hope to demonstrate the analytical potential of the framework in discerning patterns of interdisciplinary learning and interaction and further distill some key aspects of the framework.

Initial Theoretical Consideration

As established disciplinary knowledge is often at stake at disciplinary boundaries, interdisciplinary interactions challenge the ways in which people manage and communicate knowledge. Drawing on the literature on information processing and knowledge management, Carlile (2002, 2004) proposed a framework that captures the dynamics of knowledge management across specialized domains when innovation is desired. He explored the interactions among different functional groups in an automobile company during a new product development, which is analogous to our situation in which faculty members from multiple disciplines work together to generate new assessment items. In the framework he matched three critical processes (transfer, translation, and transformation)[1] with three types of boundaries (syntactic, semantic, and pragmatic) for knowledge management across domains: that is, establishing a common lexicon for *transferring* knowledge at the *syntactic* boundary, developing common meanings for *translating* knowledge at the *semantic* boundary, and establishing common interests for *transforming* knowledge at the *pragmatic* boundary. He also emphasized the importance of mediating these knowledge management and communication processes through *boundary objects*, defined as shared and shareable items used across different problem-solving contexts (Carlile, 2002; Star & Griesemer, 1989). More on this will be discussed later.

Carlile's (2002, 2004) framework illuminated the types of social interactions and associated constraints among people from different disciplinary contexts, but did not examine the cognitive processes involved in these interactions. For instance, there has been much work on transfer from a cognitive perspective (e.g. Klahr & Carver, 1988; Singley & Anderson, 1989) in addition to a social perspective (e.g. Lave, 1987). Furthermore, we aim to clarify the connections among these processes and examine the sub-processes that Carlile did not spell out. In brief, we intend to propose a framework that integrates both social and cognitive perspectives to paint a richer picture of the complex IRC processes. In the following, using examples related to osmosis we explain one by one each of the four processes in our initial consideration.

Integration

Integration seems a natural starting point when learning interdisciplinary topics is considered because intuitively, interdisciplinary learning involves integrating knowledge from multiple disciplinary sources. It also denotes a common mechanism of how expertise from multiple disciplines is managed and coordinated in interdisciplinary collaboration. For instance, Boix Mansilla and Duraising (2007) defined interdisciplinary understanding 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, emphasis added). A particularly relevant framework in science education is knowledge integration (KI) developed by Linn and her colleagues (for more details, see, Linn, 2006; Linn & Eylon, 2011). The KI framework emphasizes students' abilities in establishing various types of connections among scientific ideas (Shen & Linn, 2011).

Linking ideas across disciplinary boundaries is desired and encouraged to support KI. For instance, integration is involved when explaining 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, one needs to integrate knowledge in chemistry (e.g. solvation), cell biology (e.g. selectively permeable membrane of a cell), and physiology (e.g. structure and function of organs).

Translation

With the dominance of specialized professions nowadays, it is critical to effectively *translate* disciplinary knowledge to audiences who 'do not speak the same language' (Boix Mansilla & Duraising, 2007). In order to communicate effectively in this kind of contexts, people need to develop sufficient language to converse on a topic that involves multiple domains, ability to distinguish and translate terminologies between parties, and sensitivity regarding distinctive interpretations with certain words (Nikitina, 2005). Likewise, students who develop IRC 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 the cumulative high fluid retention in the brain cells. These two discipline-bounded terms are similar, as they present two concrete examples of osmotic pressure (Sung et al., 2015). A student who has developed IRC of osmosis should be able to translate between these terms.

A key distinction between translation and other processes is that it focuses on the linguistic aspect of the interaction between disciplines. In theory, a person can translate one term at a time by establishing the one-to-one correspondence for the term between two disciplines. In practice, it is more effective if one could translate terms *en masse* to build more systematic connections.

Transfer[2]

Students are expected to constantly *transfer* what they have learned from one situation to another (e.g. from school to real-world situations). Successful transfer fosters deep learning by enabling students to reactivate the knowledge acquired previously. Many factors contribute to or hamper students' knowledge transfer, including learners' prior knowledge, context of learning, scope of transfer, problem representations, and opportunities to develop deep understanding, to name a few (Bransford & Schwartz, 1999; Chin & Brown, 2000; Engle, 2006; Haskell, 2001; Klahr & Carver, 1988; Larsen-Freeman, 2013; Lave, 1987; Singley & Anderson, 1989). When encountering a novel situation or a real-life problem students with adequate disciplinary frames of information may retrieve and apply information more quickly (Hammer, Elby, Scherr, & Redish, 2005; National Research Council [NRC], 2000, 2012).

Interdisciplinary transfer, therefore, refers to the process when students successfully apply explanatory models, concepts, methods, and skills learned from one disciplinary context in order to understand phenomena or solve problems in another disciplinary context. One criterion is the ability to recognize the core structure of the system under study—matching the parallel elements or parts along with their connections within the two systems in a structurally and semantically valid way. This falls into the category of 'deep transfer' (e.g. Chin & Brown, 2000).

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. When the student is asked to explain the function and process of osmosis in a plant cell, s/he may be able to transfer his/her knowledge learned from the U-tube situation to recognize the similar system components, such as the two solutions with different solute concentrations that are separated by a selectively permeable membrane and the conditions for the water movement to reach equilibrium.

One difference between transfer and translation is the following. Since transfer focuses on the base structure (e.g. an explanatory model) that is being transferred from one discipline to another, the same set of terminologies may be used in both disciplines. In contrast, translation between two disciplines aims to establish the correspondence between two sets of terminologies, as the semantics of these terminologies has been established independently in each discipline.

Transformation

The fourth process in our IRC framework concerns *transformation*. This construct was partially drawn from Piaget's (1970) genetic epistemology: At the phylogenetic level of knowledge, the evolution of human knowledge is a process of a continual transformation and reorganization; at the ontogenetic level, the operative aspect of thinking can be expressed as transformation between states, including actions (transforming materials) and intellectual/mental operations (transforming knowledge structures). Shen and Confrey (2007), for instance, delineated a case on how transformations among representations and models helped a learner change her concepts. The idea of transformation is also embedded in the goal of a typical interdisciplinary collaboration project—generating new knowledge and/or making new products (Carlile, 2004; Carlile & Rebentisch, 2003).

In an interdisciplinary context, transformation involves the application of explanatory models, concepts, tools, and methods learned from the original disciplinary field to physically or conceptually *change* a system typically considered in a different field. An example in this category is reverse osmosis, a process that is frequently used in food engineering to purify water.[3] The design for reverse osmosis technology was first proposed by Hassler in 1949 at University of California, Los Angeles, borrowing ideas of osmosis from cell physiology and physical chemistry, and later was further refined and developed to change the ways in which seawater is purified (Glater, 1998).

It is important to note that these four processes, as characterized above, are intertwined and non-exclusive to each other in complex interdisciplinary interactions. For instance, interdisciplinary integration often co-occurs with translation, as a learner or a team has to acknowledge and understand the different languages used in different disciplines in order to integrate them; transformation often includes transfer because it requires the application of knowledge learned in one discipline to another.

Empirical Analysis

In the following, we describe how we applied the initial framework to analyze and interpret the discourse contents in two interdisciplinary meetings. Through the analysis, we further refine our framework by laying out the subthemes and their connections with the hope to improve the analytic potential of the IRC framework.

Background and Data

From Spring 2011 to Fall 2012, a group of faculty members and graduate students from different science disciplines (physics, chemistry, biology, and veterinary medicine) and science education worked together on a project to create interdisciplinary assessment items to be used in introductory science courses in physics, chemistry, and biology (Shen et al., 2014). These meetings presented great IRC opportunities for the participants, content experts nonetheless, as they encountered alternative views and argued about both the science and instruction related to osmosis. The

Table 1. The two meetings analyzed in the study

Meeting	Date	Duration (relevant portion)	Theme
1	03/03/2011	38 min	Discussed a group generated concept map on osmosis
2	04/28/2011	92 min	Discussed the formula that calculates osmotic pressure derived from ideal gas law

team met approximately once every other week. The meetings were audiotaped and transcribed.

In this study, we chose two meetings for analysis (Table 1) as our intention of this paper was theory building, as opposed to analyzing in detail the patterns and trends of all the meetings. These two meetings were chosen because they represented different phases in the project and covered different IRC processes. The first meeting was held on 3 March 2011 that was still early in the project. The relevant conversation lasted about 38 minutes (the rest of the meeting was about logistics). The second meeting was held on 28 April 2011 when the team had developed a good rhythm to discuss relevant issues. This meeting lasted about 92 minutes.

During 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.[4] The conflicting views made these content experts eager to defend their own understanding and learn other disciplinary perspectives. Therefore, we expected to see many dynamic interdisciplinary learning and interaction instances in this meeting and decided to start our analysis with this one. The second meeting focused on the construction of interdisciplinary assessment items and the inappropriate usage of the osmotic pressure formula that was derived from the ideal gas law.

Coding

Our unit of analysis was coherent statement, defined here as one or more sentences that deliver a stand-alone meaning. There were two layers of codes we applied to each statement. The first layer of codes emerged from reading the transcripts and concerned the topics of the statement. That is, we first decided if a statement fell into one of the following categories:

- A *concept-specific* statement involves specific scientific concepts and terminologies such as diffusion 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 included two topics, then we further divided it into two separate statement units. If a statement did not belong to any of the three categories or is unintelligible or irrelevant to interdisciplinary discussion, we categorized it as *irrelevant*.

In a sense these categories represent the types of boundaries in interdisciplinary interactions as Carlile (2004) suggested. Specifically, concept-specific statements often occur at the semantic boundary as many of these statements assert and clarify the meaning of scientific terms; meta-level statements at the syntactic boundary as many of these statements contain abstract rules and principles implied in interdisciplinary teaching and learning; and instructional statements at the pragmatic boundary as many of these statements touch upon practical considerations of what needs to be done instructionally.

Next, if a statement did fall into one of the three topic categories, we then applied the second layer of codes, that is, the four IRC processes—*integration, translation, transfer, transformation*, and *other* (did not fall into any of the four processes). There were statements involving more than one IRC process. To simplify the coding, we restrained a maximum of two IRC processes applied for the same statement. If that happened, we assigned an equal weight to each code. For instance, if a statement within the concept-specific category involves both translation and transfer, we then assigned ½ for each process.

We coded each statement in the context of utterance. On many occasions we had to infer the reference of a pronoun as well as the components omitted by the speakers. Depending on a continuation of context carried in the previous statements, a statement could be coded as concept specific even without spelling out 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 by another speaker. This was coded as concept specific.

We employed an iterative coding process that took several cycles. The first author initiated the coding framework and trained two coders, the second author (from a biology background), and the third author (from a physics background). The two raters coded all the statements independently. In each cycle, the coders coded a number of statements (varying from 30 to 50 statements) 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. In each cycle, the inter-rater reliability was calculated using the joint probability of agreement (i.e. the ratio of the number of statements with agreed codes over the total number of statements coded). Furthermore, if one rater coded a statement as involving two IRC processes but only one of them coincided with the other rater's code, the agreement count was 0.5 in this case. As the number of coding categories was big (a total of 16 categories of codes combining the two layers), the chance of coincidence due to random coding was small. This process repeated for several cycles during which the reliability reached an adequate level (>.85). All inconsistent codes were resolved through discussion.

Results

In the following, we first present some meeting excerpts to illustrate the four IRC processes. We then report the descriptive statistics of the coding results and discuss the patterns observed. To help the reader interpret these excerpts, the home departments of the speakers included in these excerpts are as follows (pseudonyms are used in the paper): Carson and Leo—Physiology and Pharmacology; Jamie—Plant Biology; Jo—Science Education (with physics background); Riley—Large Animal Medicine; Sam—Physics.

Instances of the IRC processes in the meetings. The objective of the first meeting was to discuss the group concept map on osmosis, compiled by the first two authors from the individual concept maps created by the team members during the previous meeting. Much of the discussion was on a number of osmosis-related concepts that were used inconsistently across the disciplines, such as osmotic pressure (Sung et al., 2015). The first eight minutes of the meeting focused on the meta-level aspect, while the rest was much more concept specific. The meta-level comments touched upon the structure of the concept map that the team created. Excerpt 1 at the beginning of the meeting focused on how people from different disciplines would visualize the connections among concepts on osmosis:

[Excerpt 1. Transcripts 03/03/2011: 00'49''–02'35''.]

Sam: It's like a physicist is focusing on one area of the concept map almost to the exclusion of the other, which is (starting) 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 (compared to that for the physicist).

…

Jamie: I think one of the big benefits of this project is that you give people the translation, because ultimately you're talking about the same thing. But in physics (we are) looking from angles as biologists do, not because we impose physicists to teach [in a] biological way, but you need to give something that you can approach this from a background of physics.

Carson: Sounds like a Venn diagram to me … . you know biology and physics (have different concepts on their own), and you got (an) overlap in the middle, and you got that core, and the perspectives that give you insight to that, am I right?

Jamie: I personally would never draw a diagram like that, but … 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.

In this excerpt, the discussion focused on meta-level integration and translation as the group members were reflecting on the structure of the group concept map. Sam started with a comment on how a physicist and a biologist would approach a concept map from different angles. Although she saw 'eventually mixing those connections' between the disciplines, she emphasized the different interests that were represented in different regions on the map. Jamie focused on the translational issue in teaching: in this context, he saw people from different disciplinary backgrounds were 'talking about the same thing,' and a disciplinary context could provide a (linguistic) tool for someone with that disciplinary background to approach the same phenomenon. Carson, echoing what Sam started with, described the visual representation of related concepts from multiple disciplines as a Venn diagram and emphasized the 'overlap in the middle'. In this sense, the 'overlap' or the 'core' represents the cross-cutting concepts shared by different disciplines, an integration mechanism that links distinct disciplines. Commenting on this, instead of using Venn diagram, Jamie expressed his preference on integrating different concepts using yet another type of visualization, a hierarchical structure.

Later in the meeting, when the team members 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, as shown in Excerpt 2 that was triggered by an initial comment made by Jamie involving the term of solute potential:

[Excerpt 2. Transcripts 03/03/2011: 09'03''–10'24''. The italicized words in the excerpt refer to scientific terms.]

Carson: *Solute potential*, I've never heard (of it).
Jo: Ok, so I just cross that out (in the map)?
Riley: What does that mean?
Jo: I don't know. It's on the map.
Jamie: Oh, well, wait wait wait, that should be over here for *plant cell*.
Jo: *Plant cell*?
Jamie: Yeah, in *plant cells* when you talk about *water potential* … you have two components, one is *solute potential*,
Riley: Sorry, you said in *plant cell* what?
Jamie: ….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 (osmotic pressure due to) the *solute concentration* except it's backwards, if you look at the numbers. And the other part is the *pressure potential*, which in essence represents the *cell wall* where the *pressure* starts building up, results in *turgor pressure* … .

This excerpt showcased the high frequency of concept-specific translation in this particular meeting. The term *solute potential*, raised by Jamie, was alien to several team members. Having taught plant physiology, Jamie translated the term for others by using the context of plant cells and relating it to other terms such as solute concentration, water potential, and pressure potential.

Similar discourse exchanges recurred in the rest of the discussion when the team members used the term *osmotic pressure* in different ways to describe osmosis. The difference was magnified later in the discussion when the plant biologist saw no

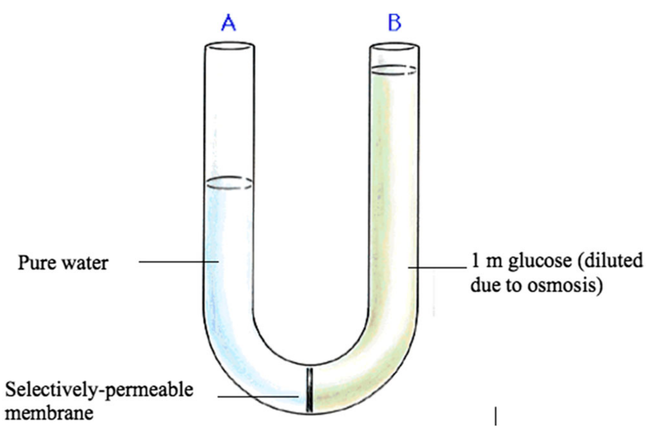

Figure 1. The U-tube scenario

'osmotic pressure', but the animal physiologists all contended its existence in a typical U-tube scenario (Figure 1). In order to situate all the discussants on the same page, Jo drew the U-tube scenario on the white board and asked specifically where exactly the osmotic pressure was in this context. The conversation as in Excerpt 3 followed:

[Excerpt 3. Transcripts 03/03/2011: 20'40''–21'50''.]

Jo: … is this part osmotic pressure [pointing to the raised column of solution (B) in the U-tube]?

Jamie: (Yes,) 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.

Carson: In my mind, do you only have a potential until … equilibrium?

Sam: No, you only have a difference in potential until (equilibrium). The potential is still there.

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

Jamie: Yes.

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

Sam continued to elaborate on the meaning of chemical potential from a thermodynamics perspective: the change of free energy when a particle of the same species is added to the system.[5]

In this excerpt, we witnessed two instances of transfer. Jamie connected the physical U-tube scenario to a plant context and attempted to apply the idea of turgor pressure from plant physiology to make sense of osmotic pressure in the U-tube scenario. He noticed that in the plant context a closed system was considered, whereas in the U-tube scenario an open system was present. This comparison led him to believe that there was no osmotic pressure in the U-tube scenario. Sam on the other hand, applied a thermodynamics perspective and compared the concept of chemical potential with osmotic potential. In both cases, the speaker applied a concept with which they are familiar to interpret the new concept (osmotic pressure): for Jamie, the familiar idea was turgor pressure; for Sam, the familiar idea was chemical potential. The group did not reach agreement on how to reconcile the different definitions of osmotic pressure at the end of this meeting. The problematic nature of the term has been documented elsewhere (Sung et al., 2015).

We did not find any statement that could be categorized in transformation in the first meeting (Table 2). This may be due to participants' unfamiliarity with the subject matter from an interdisciplinary perspective. Furthermore, given the time limit, the participants had not fully captured the inconsistent views. This drove us to code the second meeting, which took place almost two months after the first one (there were four other meetings in between).

The second meeting started with the discussion on incorporating animations in assessment, and then quickly shifted to the conceptual aspect of osmosis, specifically the incongruent understanding of how solvation impacts osmosis and the formula that is used to quantify osmotic pressure. Although the second meeting was much

Table 2. Number of statements in the coding categories for the first meeting

	Integration	Translation	Transfer	Transformation	ID other	Total (%)
Concept specific	4	165.5	19.5	0	11	200 (74)
Meta-level	23	10.5	2.5	0	24	60 (22)
Instructional	5.5	1	1.5	0	4	12 (4)
Total (%)	32.5 (12)	177 (65)	23.5 (9)	0	39 (14)	272 (100)

Note: A total of 26 irrelevant statements were excluded from the frequency count.

longer than the first one, the coding for the second one took much less time. This was because much effort had been devoted to establish and clarify the first three IRC processes when analyzing the first meeting. In the following, to avoid repetition we chose excerpts from the second meeting to illustrate the transformation aspect only.

The first few minutes in the second meeting instantiated the instructional aspect of interdisciplinary transformation. The team was trying to figure out a practical way to embed computer animations in assessment items targeting students' interdisciplinary understanding:

[Excerpt 4. Transcripts 04/28/2011: 1'30''–2'50''.]

Jamie: The more real (the embedded animations) you get, the more complex and the more confusing and overwhelming for students at different levels. So we have to have a sliding rule I think at some point, what we want them to get and what potential or missions do we make in this.

Jo: Right, and regarding the animation and assessment, … as you said, we can start with very simple, maybe one solute, no external pressure, maybe horizontal tube, something like that, very simple one to see whether students get that. And the next step is adding more and more things to the simulation, right? Maybe at some point we say these are optional if you want to study more advanced topics.

Sam: For example, when we're thinking about the animations, I don't personally feel like it's important for the animations, at least at the lower levels, to show something like the solvation and the free water.

In Excerpt 4, Jamie started by pointing out that osmosis is a complex process and therefore, the animations the team was trying to embed in the assessment had to be at an appropriate level for the students. Following this line of reasoning, Jo spelled out some specific constraints for an assessment item and the corresponding animation such as one solute (simplified chemistry aspect) with no external pressure (simplified physics aspect), and proposed the idea of 'horizontal tube' as the context. Sam then added additional constraints for easy items without showing the solvation process and the free water. Sam's idea of leaving the portrayal of important chemical process out in the animation, from a physicist's stand point, quickly brought an

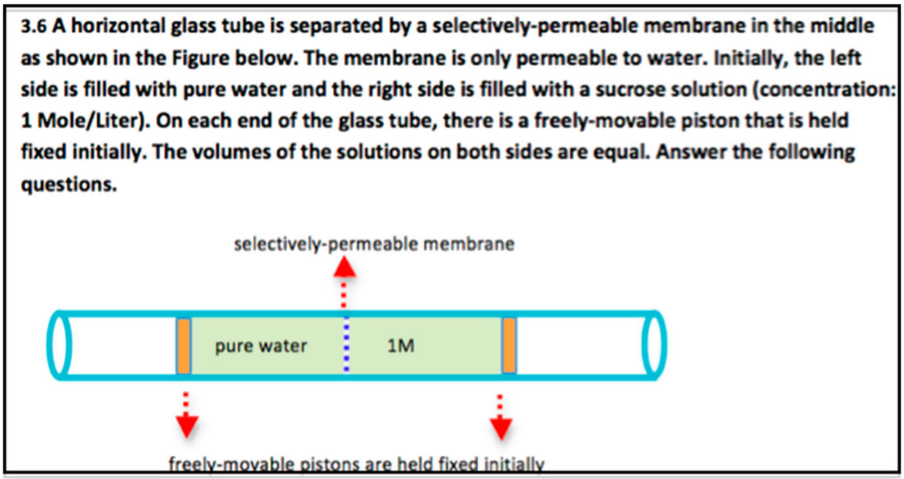

Figure 2. The horizontal-tube assessment stem emerged from the meetings

intense debate among the team members with regard to the underlying mechanism of osmosis. This pattern of discourse dynamics is typical for these meetings: moving from instructional (the second meeting) or meta-level (the first meeting) discussion to concept-specific discussion triggered by some concepts or terminologies either unfamiliar to some team members or inconsistently used across disciplines.

What we want to highlight here is that the discussion sparked Jo's idea of using a horizontal tube as a scenario for an assessment item on osmosis, a remarkable transformation of a conventional assessment item (the U-tube scenario) to exclude the factor of hydrostatic pressure (typically a matter considered in physics). A few meetings later, the team was able to exploit this initial thought and created the new assessment item horizontal tube, as shown in Figure 2. The driving force, instructionally speaking, was to break down (i.e. *disintegrate*) a complex interdisciplinary problem into multiple simpler (disciplinary) aspects in order for students to comprehend the problem step by step. In summary, as a result of the interdisciplinary discussion, a new assessment item was proposed, revised, and operationalized.

Many transformation statements coded in the second meeting were attributed to the creation and revision of thought experiment, a common strategy scientists use to reason and communicate about abstract scientific theories or situations that are difficult to perform physical experiments (Sorensen, 1992; Velentzas & Halkia, 2013). For example, the discursive exchange in Excerpt 5 occurred after the team started to dig deep into the solvation process and one member initiated a thought experiment:

[Excerpt 5. Transcripts 04/28/2011: 13'44''–17'01''.]

Sam: The thing is, we want to say that the sucrose has been hydrated, but really? I mean, are we saying that because we want to have water molecules around it (sucrose) or just we want it to be in a solution rather than sitting on the bottom of the beaker (in the animation)?

Jamie: No, that's the whole justification why osmosis occurs, right? If that wouldn't happen, if you wouldn't have attraction of water molecule (to solute particles which results in) reducing the free water, it would lose the concentration gradient of free water, right?
Sam: … I go back to the ideal gas model, which is a very very bad model for what happens in liquid. I admit that. But you can get the equivalence of osmosis with a purely ideal gas model. So osmosis is (the selective diffusion of) 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. You would get a net flow of gas A from the pure gas A side to the mixture side, and that's true even if, say gas A and gas B don't interact, don't bond with Van der Waals' forces or anything like that.
Jamie: I'm just missing the connection, sorry, because that's just diffusion of two things rather than osmosis, right? But, what am I missing here?
Jo: So basically you're saying, instead of sucrose, you say, A and B, right? [start to draw a diagram on the board; see Figure 3] Molecules A, and these big molecules, B [pointing to the diagram].
Sam: And they're all gases, and the B molecules don't attract A molecules at all, they don't interact.
Leo: Are they the same volume, the two sides?
Sam: They're just hard-sphere collisions sort of thing, permeable to A, but not to B.
Riley: Then why doesn't A go from right to left?
Jo: Because of the (partial) pressure—you have two partial pressure.

At the beginning of this excerpt, in response to Sam's question about the importance of showing hydration in the animation, Jamie initiated a thought experiment—what if the water molecules behave differently (i.e. no hydration) in an imaginary world? This indicates that, Jamie, in his head, transformed the real situation into an imaginary, different situation. Following Jamie's proposal, Sam quickly constructed an analogous system using the ideal gas model that was very familiar for her to entertain the thought experiment. Here, Sam's transformation process (i.e. construction of the thought

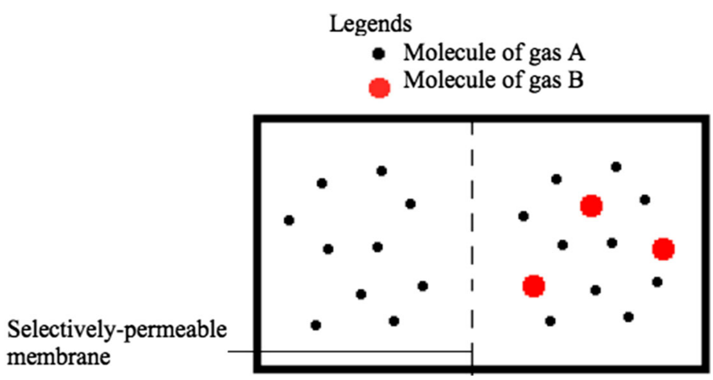

Figure 3. The ideal gas model described by Sam: the two compartments contain the same amount of gas A (analogous to solvent) separated by a selectively permeable membrane that is only permeable to gas A; Gas B is then added to one compartment

experiment) was accompanied by analogical transfer (using the familiar ideal gas model to reason about the ongoing thought experiment about osmosis).

Jamie was immediately confused by Sam's ideal gas model. Jamie thought that Sam was talking about the diffusion of two species of gas molecules, which could not explain the diffusion of water (osmosis). To help visualize what the model looks like, Jo started to draw on the white board. This visualization helped the team to further specify more details about the model (e.g. the types of interaction between the two species of gas molecules, the volume of the two compartments). Riley (and Jamie later, quotes not included here) had an incorrect prediction that gas A would move from right to left (Figure 3) because the total pressure on the right side was higher (which entails more particle collisions with the membrane). Analogously, this would be contradictory to osmosis (in which water moves from the region with lower solute concentration to the region with higher solute concentration). Jo responded by bringing up the term of partial pressure.[6] Although there was no consensus concerning the connection between the ideal gas law and the quantitative formula of osmosis (i.e. van Hoff's Law) at the end of the second meeting, clearly, the thought experiment (and the analogy of the gas model) initiated by Sam was powerful to help the team generate richer interdisciplinary communication and deeper understanding.

We found in our analysis that the transformation process requires a whole new level of reasoning that involves integration of relevant disciplinary knowledge, translation of terms if needed, and transfer of what one knows to predict what would happen in a new system. As a result, the transformations made in these thought experiments became a catalyst for the team to resolve the burning questions under discussion. In this particular case, later in the meeting, the team realized that some information presented in the textbooks was misleading and discussed practical ways to test the thought experiment using real experiments (which they did after the meeting).

Coding results for the meetings. Tables 2 and 3 list the frequencies of the coding results. There were a total of 272 relevant statements in the first meeting and 464 relevant statements in the second meeting. Our analysis focused on these relevant statements.

Table 3. Number of statements in the coding categories for the second meeting

	Integration	Translation	Transfer	Transformation	ID other	Total (%)
Concept specific	42	234	18	34	42	370 (80)
Meta-level	5	6	2	2	17	32 (7)
Instructional	11.5	12.5	2.5	4.5	31	62 (13)
Total (%)	58.5 (13)	252.5 (54)	22.5 (5)	40.5 (9)	90 (19)	464 (100)

Note: A total of 34 irrelevant statements were excluded from the frequency count.

In terms of topics, the team in both meetings was more engaged in *concept-specific* discussion (as illustrated in Excerpts 2, 3, and 5): A total of 74% of the relevant statements in the first meeting and 80% in the second one fall in the concept-specific category. Overall, compared with the first meeting, the percentage of meta-level statements decreased from 22% to 7% but the instruction-related statements increased from 4% to 13%. This is reasonable because the second meeting focused on a particular aspect of instruction—assessment.

In terms of the IRC processes, the team in both meetings was mainly engaged in *translation* for each other (as illustrated in Excerpts 2 and 3). For the first meeting, 65% of the relevant statements fall in the translation process, compared to 12% in integration, 9% in transfer, 0 in transformation, and 14% in other; for the second meeting, 54% in translation, 13% in integration, 5% in transfer, 9% in transformation, and 19% in other. It implies that overcoming concept-specific terminology barriers through *translation* was a practical priority for these meetings. Specifically, it is also noted that in the first meeting, when the team members talked about interdisciplinary education at the meta-level or on the instructional issues, they emphasized integration over the other processes (relatively high frequency of integration statements within the meta-level or instructional statements; see Table 2). However, as the team members debated about the concepts involved and spent much time on translation in both meetings, they realized the importance of translation at the meta-level or in instruction (increased relatively high frequency of translation statements within the meta-level or instructional statements; see Table 3). Furthermore, the percentage of the translation statements declined about 10% from the first to the second meeting. This suggested that although still facing the challenge of communication, the team did improve on language use over time. This may partially explain the increase in the transformation statements: As the team had reached some common ground, they were able to allocate time for more complex reasoning.

Discussion and Further Consideration of the Framework

Our analysis revealed some interesting patterns of the two meetings as described above. In this section, we further discuss the refinement of the IRC framework. We first discuss some new insights related to the IRC (sub-)processes (Figure 4). We then turn to the construct of boundary object that is critical in interdisciplinary reasoning and interactions.

Differential Integration and Commonality Integration

Two kinds of interdisciplinary KI emerged from the coding. The first type, *differential integration*, is about organizing concepts from different disciplines into a connected whole. As such, differential integration demands a great deal of interdisciplinary translation to avoid confusion due to discipline-specific languages. When the team members discussed the concept map in the first meeting, they pointed out that there were concepts bounded by different disciplines on the map. In other words,

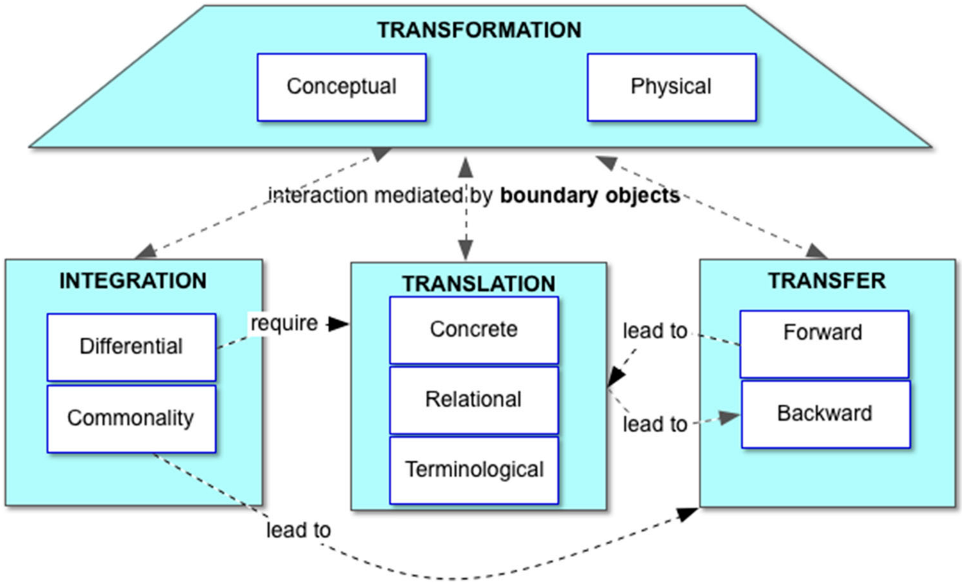

Figure 4. The refined IRC framework

capable interdisciplinary integrators are not only more competent in providing comprehensive explanations by incorporating multiple discipline-based concepts and/or tools, they are also more conscious about the discrepancies and differences in distinct disciplinary knowledge.

The second type of interdisciplinary KI, *commonality integration*, emphasizes the common set of knowledge across disciplines. On several occasions, the members in the meetings talked about a shared 'core' when thinking of an interdisciplinary topic such as osmosis, as Carson described in the first excerpt. In these references, the 'central core' is an integrated set of concepts or big ideas in a way similar to the crosscutting concepts proposed in the new science standards (NGSS Lead States, 2013). These crosscutting concepts can be used to describe the underlying processes applicable to different disciplines. They can be visually represented in different ways such as the shared region in a concept map, the overlapping area in a Venn diagram, or the upper-level concepts in a hierarchical diagram.

Interdisciplinary integration can be easily confused with interdisciplinary transfer. Three distinguishable properties are discussed here. First, in interdisciplinary integration the ideas are compared and contrasted across disciplines, and these disciplines are put at the same level of priority. In contrast, in interdisciplinary transfer, one takes an idea or an explanatory model from a primary discipline and applies it to other disciplinary contexts. In this sense, the primary discipline is prioritized. Second, interdisciplinary integration can involve a competing flavor while interdisciplinary transfer does not. In our framework, integration includes two types. Differential integration is about organizing ideas from different disciplines into a connected whole. Therefore, it emphasizes the complementary aspect.

Commonality integration, however, aims to single out the common set of knowledge across disciplines. Therefore, it includes the competing aspect that begs the question which concepts from each discipline enter the core. In comparison, interdisciplinary transfer does not seem to involve a competing element. Third, commonality integration will often lead to interdisciplinary transfer. As long as one develops a deep understanding of the integrated common core, one can subsequently transfer it to different disciplinary contexts. In reality, these processes are often intertwined. For instance, when the team compared and contrasted the ideal gas model with osmosis (Excerpt 5), both differential and commonality integration occurred when the members emphasized the differences (e.g. gas vs. liquid, no inter-molecular interactions vs. hydration) and similarities (e.g. the direction of the flow of the 'solvent' particles), and interdisciplinary transfer happened when the members applied the ideal gas law to explain osmosis.

Levels of Translation

More than half of the relevant statements in both meetings focused on concept-specific translation. These statements were mainly cued by the terms used in different disciplines to describe osmosis. This indicates the group's passionate engagement in reaching semantic and syntactic consensus regarding concepts and terminologies used to describe the same phenomenon. It also highlights the importance of the translation process in IRC, which may be easily neglected in science education as students and teachers may assume that all scientific terms are used consistently across disciplines.

Different levels of interdisciplinary translation emerged from our data analysis. First, one may simply introduce the terms (e.g. in the second excerpt, Jamie introduced the terms solute potential, pressure potential, and water potential). We call this *terminological translation* (surface level). Next, one may extend the translation by describing the relations of the terms from a disciplinary perspective (e.g. Water potential is the sum of solute potential and pressure potential). We call this intradisciplinary (i.e. within the disciplinary boundary) *relational translation*. However, this discipline-oriented strategy may not be effective in interdisciplinary communication. For instance, when Jamie elaborated on the two components of water potential, it did not help the group further develop their understanding of that term at the time. Finally, in *concrete translation*, one may provide concrete examples to contextualize the terms. These examples are typically drawn from common experience to which the audience can relate (e.g. the U-tube scenario). As such, concrete translation may draw on commonality integration. Compared to terminology translation, which is at the surface level, relational translation and concrete translation are considered deep translation, as they provide a mechanism for a person to make connections among ideas. Interdisciplinary deep translation may be simply called explanation within an interdisciplinary context. What we emphasize here is that the speaker has to keep in mind that the audience is from a different disciplinary background, and therefore s/he needs to attend to the terminologies used. In these translation processes, one also expects the listener to integrate and transfer the newly translated terms and internalize them.

Directions of Interdisciplinary Transfer

A transfer process may occur in two opposite directions with regard to disciplinary boundary crossing. When a person draws ideas from his or her own discipline to explain a scenario considered in a different disciplinary context, we term this process *forward transfer*. For instance, as shown in the third excerpt, Jamie was transferring his knowledge in plant physiology to explain why there was no osmotic pressure in the physical U-tube setting. Most of the transfer processes occurred in the meetings fell under this category. In a less common fashion, a person applies ideas conventionally introduced in a discipline other than his or her own to explain a phenomenon in his/her discipline. We call this *backward transfer*. These instances only occurred a few times in our meetings after a long translation process. For instance, the animal physiologists applied the idea of solute potential to explain osmotic pressure after a long conversation on the former concept.

Most of the time in our meetings, a member brought up a *forward* transfer instance in order to help explain the scenario from his or her own disciplinary perspective. Given that the team members came from different disciplines, these forward transfer processes initiated long translation processes as other team members were puzzled by the speaker's disciplinary perspective. As a result, confusion easily arose in our coding when *concrete translation* overlaps with *forward transfer*, especially when the speaker was applying disciplinary ideas to explain concrete, everyday examples in order to translate for others. These statements were coded as deep translation because the speaker was forward transferring knowledge within his or her own discipline for the purpose of interdisciplinary communication.

Transformation Built upon Integration, Translation, and Transfer

Transformation occurs when a person or a group mentally or physically modifies an existing system to explain new phenomena, solve new problems, or engineer new products. We did find transformation statements scattered in the second meeting because constructing innovative assessment items was the objective of the meeting and the creation of innovative assessment items could not be achieved without transformation of the traditional ones. These statements fostered a more dynamic and diverging discussion among the team members. Being instructors of college-level science courses, the team members began to realize the constraints of disciplinary perspectives and gradually developed an interdisciplinary understanding of osmosis after iterative integration, translation, and transfer processes. These transformation instances were also great learning experience for the team members themselves. Exercising transformative processes drastically encouraged conceptual refinement and innovative experiments in our team (e.g. the team created a set of physical experiments that demonstrated the errors found in many college science textbooks with regard to the underlying mechanism of osmosis).

It is relatively easier to distinguish transformation from other IRC processes because it is usually found when an individual (or a group) encounters incompatible and incongruent views that require him/her to change the existing schema. This process requires the execution of the other processes when needed, as one has to be able to integrate, transfer, and translate an old system in order to reconstruct and change it in a meaningful way. The process of transformation, however, goes beyond the mere sum of the other three processes.

One characteristic that can be easily attached to transformation is creativity. That is, the transformed product is a departure from its old form. The creative transformation may not be a groundbreaking discovery or innovation in one try. People may create a new entity or provide innovative reasoning through a combination of interdisciplinary integration, transfer, and translation that is built upon existing disciplinary knowledge and practices. Previous research supports that a series of small steps of transformation may lead to surprising creations (Latour, 1990; Shen & Confrey, 2007).

Note that in our coding, once a transformation process was completed (e.g. resulting in a mature thought experiment), the follow-up statements referring back to the same transformed product (e.g. a thought experiment) were not coded as transformation because there was no more need of qualitative conceptual shift (i.e. transformation) in describing the created scenario.

Many transformation instances in our second meeting highlight the importance of thought experiments. For instance, in the fifth excerpt, Jamie used the 'if' clause to propose an imaginary scenario in which hydration would not occur. This is the *reduction* approach of thought experiment: that is, hypothetically taking out an element in a system to see what would happen in order to understand the nature of that element within the system. There are many other types of thought experiments (Sorensen, 1992; Velentzas & Halkia, 2013). Understanding the nature of these thought experiments may contribute directly to understanding of the transformation process.

Developing and Sharing Boundary Objects

One recurrent theme found in the coding of the meeting discourse, especially on transformation processes, is that the IRC processes are intertwined with the generation of and discourse about *boundary objects*, an analytic tool developed by Star and Griesemer (1989) to interpret how actors from different parties worked together (in their case, at the Museum of Vertebrate Zoology at the University of California, Berkeley during its early years). They defined a boundary object as something that:

> … inhabits several intersecting social worlds … and satisfy the information requirements of each of them. Boundary objects are objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. … The creation and management of boundary objects is a key process in developing and maintaining coherence across intersecting social world. (Star & Griesemer, 1989, p. 393)

This construct has since been further developed and used to analyze and interpret how experts from different communities share and disseminate their ideas (e.g. Carlile, 2002; Henderson, 1991).

In our research, we studied how people with different scientific backgrounds reasoned and communicated in order to create interdisciplinary science assessment items. Our framework and analysis provided hints about how the boundary objects were created, utilized, and refined in association with the IRC processes. Instead of analyzing in detail the evolution of these boundary objects, which would be a different paper, here we enumerate four types of boundary objects that correspond to the four IRC processes to further illuminate our framework (for other taxonomies, see, Carlile, 2002; Star & Griesemer, 1989).

The first type of boundary objects includes symbolic meta-representations that are used to facilitate integration. The co-constructed concept map was a boundary object in this category where key information on osmosis was shared and conflicting ideas were confronted among the team members (e.g. Excerpt 1). Boundary objects of this type are filled with intention for integration of foundational ideas in an interdisciplinary project. In our case, the team members constructed and conversed about the map in order to reach or maintain a conceptual coherence for osmosis. Nonetheless, the map was inherently heterogeneous, a common characteristic of all boundary objects (Star & Griesemer, 1989): the team members proposed different organizational structures for the map (e.g. Excerpt 1) and different positions for certain concepts (e.g. where to put solute potential, see Excerpt 2).

The second type of boundary objects includes specific abstract concepts that demand translation. This was instantiated in the abstract concept of osmotic pressure in our case. This kind of boundary objects is used in, different disciplines, but is interpreted in different ways due to historical or practical reasons (Sung et al., 2015). As a catalyst, it stimulated much of the team discussion in need of a significant effort for translation (e.g. Excerpt 3).

The third type of boundary objects includes familiar or commonly understood models that are used to support analogical reasoning or interdisciplinary transfer. An example in our study was the ideal gas model, initially developed in chemistry and later applied in the description of osmosis (see Excerpt 5). Its mathematic form, $\mathrm{PV} = nRT$, is analogous to the van't Hoff law, $P_{\mathrm{osm}} = MRT$, which states that the osmotic pressure (P_{osm}) of a dilute solution is the product of the universal gas constant (R), the absolute temperature (T), and the molar concentration of the solute (M) (Whitten, Atwood, & Morrison, 2010).

The fourth type of boundary objects includes newly constructed objects that mediate the interactions between transformation and the other IRC processes. The horizontal-tube assessment item (Excerpt 4) and the thought experiment (Excerpt 5) are instances of this type. These objects are newly created, revised, and shared through a truly interdisciplinary and collaborative effort.

Conclusion, Implication, and Future Direction

In this paper, we propose a framework on IRC in science that has four interrelated processes: *integration*, *translation*, *transfer*, and *transformation*. The analytical potential of the framework is instantiated in the corresponding codes and analysis we applied on two interdisciplinary meetings that focused on improving college-level science education and assessment. Our analysis revealed interesting patterns in these meetings (e.g. both meetings spent much time on conceptual translation but the translation proportion dropped overtime), and suggested a refined understanding of the framework.

The current validation for the IRC process framework seems a tedious and labor-intensive process; however, with the increasing demand to provide interdisciplinary education to students, efforts to define and evaluate interdisciplinary learning are necessary and valuable. Our earlier attempt of developing interdisciplinary assessments (Shen et al., 2014) used *integration* as the overarching construct. The refined framework we propose here suggests the further development of interdisciplinary assessments that attend to the intertwined IRC processes. For instance, our analysis suggests that some IRC sub-processes may be hierarchical in nature (e.g. from surface translation to deep translation). This may inform the development of multi-dimensional, construct-based assessments (NRC, 2014). As an early exploration, Sung (2013) has built an assessment instrument tapping for students' interdisciplinary understanding of energy focusing on the integration and transfer processes.

We believe that our work has significant implications when rethinking interdisciplinary or multidisciplinary teaching and learning and associated research in this area. First of all, promoting interdisciplinary science education does not mean discarding disciplinary approaches (Boix Mansilla & Duraising, 2007; Zhang & Shen, 2015). In fact, the IRC framework assumes learners developing strong disciplinary foundations. Our results hint that interdisciplinary activities can reinforce disciplinary understanding. For instance, to practice interdisciplinary KI, students need to distinguish knowledge from individual disciplines. Being aware that certain concepts are rooted in specific disciplines is a strong indicator of deep disciplinary knowledge, a prerequisite to true interdisciplinary integration. Moreover, deep interdisciplinary translation pushes students to interpret disciplinary terminologies using concrete examples.

Our work has demonstrated the complexity and complementarity of the IRC processes. Constantly engaging students in teamwork that requires a combination of all the IRC processes may help them realize the full potential of interdisciplinary learning. We stress that translation is often overlooked in interdisciplinary learning activities. Our team members, content experts on the topic nonetheless, took a significant amount of time and effort in seeking terminology consistency across disciplines. If content experts encounter difficulties in communication in an interdisciplinary context, we shall not expect our students to execute these processes successfully on their own. Students need appropriate scaffolds as our analysis showed that there were multiple levels of translation involved in interdisciplinary interactions; instructors need to be mindful of the diverse disciplinary perspectives and vocabularies and potential disciplinary biases. Collective efforts are needed in the science education community to create practical support (e.g. freely available charts showing the different interpretations of crosscutting concepts in different disciplines).

In terms of interdisciplinary teaching and learning sequence, the IRC framework cautions that a series of activities encompassing integration, translation, and transfer need to be carried out before transformation activities can truly occur in a meaningful and practical way. In our case, the team experienced a significant amount of translation before other processes took place successfully. However, exactly how to sequence interdisciplinary learning activities based on the IRC processes is still an open question and calls for more empirical research.

Recognizing the important role of boundary objects in IRC processes may help instructors develop better tools to facilitate students' interdisciplinary learning. Many practical questions need to be investigated: for example, when do we ask students to develop their own boundary objects and when do we provide these objects to facilitate students' interdisciplinary learning? To what extent do different types of boundary objects help or hinder students' IRC processes?

Although our framework portrays the complex IRC processes and their relationships, it leaves out many other important aspects including the causes of these processes (e.g. why do these processes happen?), which call for further empirical investigation. Only two particular meetings concerning osmosis were analyzed in the study as a way to clarify and refine our framework. We expect the framework to further evolve if more empirical data are inspected. We situated our study of interdisciplinarity within the scope of natural sciences, but extending this framework to other domains is conceivable.

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Notes

1. Carlile (2004) used these terms differently from ours. For instance, he used the term 'transfer' in the context of knowledge movement in organizations (e.g. Argote, 1999). It denotes the process in which knowledge is mobilized from one locale to another: for example, from one department within a company to another. We use the term 'transfer' to denote the process of (a person) applying the source knowledge to a new context. See our definitions below.
2. The idea of (interdisciplinary) transfer is closely related to analogical reasoning, often defined as comparison and transferring of information from a source analogous to the target (e.g. Gentner, 1989; Glynn, 2008; Singley & Anderson, 1989). Thagard (1992) framed analogical thinking as satisfaction of pragmatic, semantic, and structural constraints when mapping between the analog and the target. These different types of constraints also apply in interdisciplinary transfer

processes. However, analogical reasoning and interdisciplinary transfer are conceived as two different processes in our framework. While analogical reasoning attends to linking familiar and new contexts in a broad sense, interdisciplinary transfer emphasizes the distinctive *disciplinary contexts* between the source and the target. Another difference in educational setting is that in analogical reasoning, the learning focus is more on the target as the source analog is already familiar to the learner (e.g. understanding a new science phenomenon such as electric current using everyday experience such as water flow), whereas in transfer, the learner pays more attention to the source knowledge (e.g. a scientific principle such as Ohm's law) in order to better understand, apply, and map it in the new situation.

3. Reverse osmosis is achieved by applying additional pressure to the higher solute-concentrated side, resulting in retaining solute molecules and ions on the pressurized side of the membrane, forcing solvent to pass to the other side.
4. In a previous meeting, each team member was asked to draw an individual concept map on the topic of osmosis without much specific guidance. Before that, the group had discussed concept mapping in general and had seen examples of concept maps (Novak & Cañas, 2008). The first two authors then made a compiled map based on the individual maps.
5. The term *chemical potential* causes much confusion for many students. Historically, it has been treated differently between physics and chemistry. For more interpretation and clarification of the term, see, for example, Baierlein (2001) and Job and Herrmann (2006).
6. Riley's (and Jamie's) prediction would be correct if gas B is identical with gas A. The phenomenon of 'osmosis' of the gas model proposed by Sam would only happen if the volumes of the two compartments could change: for example, the far ends of the two compartments are installed with freely movable pistons. In that case, adding gas B to the right compartment will increase the total pressure of the mixed gas, which will lead to an increase of its volume. As a result, the partial pressure of gas A in the right compartment will decrease, which will lead to a net movement of gas A flowing from left to right.

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