Toward a Cognitive Framework of Interdisciplinary Understanding

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Abstract: Students need to think and work across disciplinary boundaries in the 21st century. However, it is unclear what interdisciplinary thinking means and how to assess students' interdisciplinary understanding. In this paper, drawing from multiple perspectives in the learning sciences, we aim to apply and refine a theoretical framework that helps define interdisciplinary learning in science. Specifically, we examine four cognitive dimensions of interdisciplinary understanding: integration, translation, transfer, and transformation (IT^3 framework). We apply the framework in analyzing the conversations among university faculty members from different science disciplines who strive to improve college level science education. We report our results and further discuss the implications of using our framework in conceptualizing interdisciplinary learning.

Introduction

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

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

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

Relevant Literature and The IT^3 Framework

The learning sciences literature has provided many useful perspectives for examining the issue of interdisciplinary understanding. Here, we highlight the ones that influenced our framework.

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). Recognizing that students develop fragmented understanding in science topics, Linn and colleagues developed the framework of knowledge integration (KI) that emphasizes students' abilities in establishing connections among scientific ideas (Linn & Eylon, 2011; Linn, 2006). The framework promotes coherent understanding by encouraging students to add new ideas, distinguish new and existing ideas, develop scientific criteria to reconcile ideas, and build coherent connections between a science phenomenon with their prior knowledge or experiences across different dimensions of knowledge (Liu, Lee, & Linn, 2011). In this paper, we further explore the role of disciplinarity in scientific knowledge integration.

Students constantly face the challenge of transferring scientific knowledge learned in one context to another, which includes transferring knowledge from one discipline to another (Bransford & Schwartz, 1999; Chin & Brown, 2000; Haskell, 2001). Research has shown that many factors contribute to or hamper student knowledge transfer, including prior knowledge and experience, opportunities to develop deep understanding, language, and context of learning (Klahr & Carver, 1988; Lave, 1987).

It is critical to communicate the knowledge and outcome of interdisciplinary work with audiences from different disciplines. In an interview from her study, Boix Mansilla and Duraising (2007) highlighted the importance for learners to communicate their disciplinary knowledge to "people who do not speak the same language" (p.224). Learners who are able to acquire sufficient language to converse on a similar topic or distinguish terminologies from another discipline are considered more competent in thinking across disciplines than those who require interpretation. Therefore, acquiring different terminologies used across disciplines is highly desired for students to achieve interdisciplinary understanding.

The IT^3 Framework

Building upon related literature, we argue that deep interdisciplinary understanding has four interconnected dimensions: integration, translation, transfer, and transformation (henceforth, the IT^3 framework) (Shen, Sung & Rogers, 2012). We elaborate on each dimension in the following using examples from osmosis, an interdisciplinary science topic.

Integration

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

Translation

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

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

Transfer

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

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

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

Transformation

The fourth dimension of interdisciplinary understanding is transformation. Students need to be able to apply explanatory models and concepts learned from one discipline to physically or conceptually transform a system typically considered in a different discipline into another novel system. An example in this category is reverse osmosis, a process that is frequently used in food engineering. Reverse osmosis is achieved by applying additional pressure to the higher solute-concentrated side. Because of the selectively permeable membrane, this process results in retaining large molecules and ions on the pressurized side of the membrane, forcing smaller molecules or ions to pass to the other side. Reverse osmosis is typically used to purify water. Since students have already acquired knowledge of regular osmosis process (existing system), they have to identify an additional system (pressure) in order to understand reverse osmosis (new system). The production of a new physical or conceptual system is a key feature of transformation, which is different from transfer.

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

Applying the Framework

Background and Data

In this study, we applied the IT^3 framework to analyze the discourse of an interdisciplinary faculty group meeting. The group of faculty members came from different science disciplines and worked together to create interdisciplinary assessment items to be used in introductory science courses in physics, plant physiology, animal physiology, and chemistry. The faculty met roughly once every two weeks. The meetings were audiotaped and transcribed. We chose one particular meeting (38 minutes) out of 13 meetings to demonstrate our analysis. We chose this segment to start with because in this meeting, the faculty members encountered different and sometimes conflicting disciplinary perspectives while they were discussing a concept map on osmosis that they co-constructed. The conflicting views made these content experts eager to learn another disciplinary perspective and develop their interdisciplinary understanding.

Coding

The unit of our analysis is a coherent statement, defined as one or more sentences that deliver a stand-alone meaning. The segment of the meeting we analyzed consists of 298 individual statements in total.

There are two layers of codes we apply to each statement (see Table 1 for sample statements). The first layer of codes emerged from the coding process—it concerns the topic of the statement. That is, we first decided if a statement falls into one of the following three categories:

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

If a statement does not belong to any of the three categories, we categorized it as *non-interdisciplinary other*. If a statement falls into one of the three categories above, we then apply the second layer of codes, i.e., the four dimensions of interdisciplinary understanding. If a statement falls into one of the three categories but cannot be coded as one of the four dimensions in the IT^3 framework, it is coded as *interdisciplinary other*. This process results in 16 different codes that may be applied to a statement. If a statement involves multiple codes, we assign equal weights to each code involved. For instance, if a statement involves both translation and transfer, we then assigned ½ for each.

We coded each statement in the context of the utterance. On many occasions we needed to infer the references of a pronoun as well as components omitted by the speakers. For example, in the stand-alone statement "I think they are the same," the pronoun *they* referred to osmotic potential and water potential in a prior statement of another speaker.

We employed an iterative coding process that took several cycles. The second author initiated the coding framework and trained two coders, one from a biology background (the first author) and the other from a physics background (the third author). The two coders independently coded all the statements. In each cycle, the coders coded a number of statements (30-50) and then compared their codes. The whole team then examined the inconsistent codes and discussed questions that arose in the coding until we reached agreement as a group. This process repeated for several cycles during which the interrater reliability (joint-probability of agreement) increased from 0.69 to 0.87. All inconsistent codes were resolved through discussion.

Table 1: Examples of the two layers of coding.*

	Content-Specific:	Metacognive:	Instructional:

Integration:	So that the water potential is being negated by the increase of osmotic pressure? (S157)	So now we have two sorts of approaches, one is the core and connect to different context, and somehow we can put some that are related to biology and physiology or related to physics. (S51)	Well, yeah, part of what Kathrin might be saying is that a biology student or biology instructor you know is also a physicist or whatever approaching this from a different perspective. (S3)
Translation:	Chemical potential? The change in internal energy of a system when you add another one of those particle into the system. Ok, that's the most general definition. (S97)	and maybe that's not what a biologist would say. In which case, there's a, are difference of language. (S182)	So I think at least for that part we could actually translate that into biological term so it's more intuitive for people who are teaching that. (S184)
Transfer:	I think it's actually maybe the problem I have, with the solute and pressure potential, because when people come to me and tell me well, that cell on its own in isolation has that pressure potential of that number and that solute potential. (S117)	If you understand the central core of osmosis, and you apply it in physics situation or biology situation, isn't there a central core that enables you to see the links between them? (S2)	And I found good students, that they learned things with a core, integrated knowledge, and then they extrapolate to physics, and biology. (S43)
Transformation:	N/A	N/A	N/A

*We did not include the *other* category in the table because statements falling into this category are usually situated in between the dialogue.

Results

Table 2 lists the frequencies for each code for this data set. In this conversation, in terms of topics, the faculty members were more engaged in concept-specific discussion (overall, 63% in this category, compared to 12% metacognitive and 3% instructional). In terms of the interdisciplinary dimensions, they were mainly engaged in translation for each other (overall, 60% translation, 11% integration, and 8% transfer).

Table 2: Frequencies of coding results.

	Integration	Translation	Transfer	Transformation	ID Other
Concept	4	165.5	19.5	0	11
Metacognition	23	10.5	2.5	0	24
Instructional	5.5	1	1.5	0	4
Non-ID Other	26				

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

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

> Clark: ….. It's like a physicist is focusing on one area of the concept map, almost to the exclusion of the other which is from one region and works his or her way out from there. Biologist might be starting from a different region, and eventually mixing those connections. But what's important in that concept map for the biologist is a lot of other stuff.
> Sam: So does it make sense what I heard from you is we could somehow incorporate … this region (on the concept map) is more physics related and this region is sort of biological context or physiological context.

Kate: I think one of a big benefit of that project is that you give people the translation, because ultimately you're talking about the same thing. But in physics (people are) looking from angles as biologists do, but not because we impose physicists to teach biological way but you need to give something that you can approach this from a background of physics.
Tim: sounds like a Venn diagram to me…. you know biology and physics, and you got overlap in the middle, and you got that core, and the perspectives that give you insight to that, am I right?
Kate: I personally would never draw a diagram like that, but that's again, that's personal. I'm a more hierarchical person, and I would start with what I'm really interested from the top, and then I would be more detailed of the big picture when I go down to the bottom.…

Later in the meeting, when the faculty brought up different terminologies on the concept map, they started a heated discussion on the specific concepts. That is why concept-specific discussion dominated the rest of the meeting.
Tim: Solute potential, I've never heard (of it)
Sam: ok, so I just cross that out?
Larry: What does that mean?
Sam: I don't know. It's on the map.
Kate: Oh, well, wait wait wait, that should be over here for plant cell.
Sam: Plant cell?
Kate: Yeah, in plant cells when you talk about water potential, … you have two components, one is solute potential,
Larry: Sorry, you said in plant cell what?
Kate: ….In plants the water potential is made up of two parts, … what triggers osmosis has two parts, it's the solute potential which is usually equivalent with the solute concentration except it's backwards, if you look at the numbers. And the other part it's the pressure potential, which in essence represents by the cell wall where the pressure starts to building up, results in turgor pressure ….

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

Discussion

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

Integration

Numerous studies had introduced much about knowledge integration in general (e.g., Linn, 2006). Here, we focus on *interdisciplinary* knowledge integration. From the meeting discussion, we see that two kinds of interdisciplinary knowledge integration were brought up. The first type, *differential integration*, is organizing concepts from different disciplines into a connected whole. When the faculty members discussed the concept map, they noticed that there were concepts bounded by different disciplines on the map (see the first segment of quotes on the previous page). Being aware that certain concepts are rooted in specific disciplines is a strong indicator of deep disciplinary knowledge, which we argue, along with other researchers (Boix Mansilla & Duraising, 2007), to be a prerequisite to true interdisciplinary integration.

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

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

Translation

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

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

Differentiating Translation and Transfer

Although our coders' interrater reliability improved significantly and reached a satisfactory level, we still encountered difficulties in determining whether a statement belonged to transfer or translation. Most of our disagreement resulted from the confusion between translation and transfer. This indicates that the two processes are probably more intertwined than the other processes and that there needs to be more clarification of the *transfer* and *translation* constructs. The following are some insights we gained through the data analysis process.

First, a transfer process may include intradisciplinary and interdisciplinary transfer. The IT^3 framework aims to address interdisciplinary understanding. Therefore, transfer in our framework only refers to *interdisciplinary transfer*.

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

Confusion may arise when concrete translation overlaps with intradisciplinary transfer, the process of applying concepts to concrete examples within a discipline in order to translate for others. Specifically, in the context of interdisciplinary conversation, if one elaborates on any term or principle by explaining how it is applied within one's own discipline in order to solve intradisciplinary problems by providing specific examples from one's disciplinary understanding, this statement was coded as translation—*deep translation*, instead of interdisciplinary transfer. For example, when a plant physiologist attempted to clarify pressure flow to faculty from other disciplines by saying, "That added sugar attracts water, and it comes out of the xylem, that's right next to the phloem and so you get all these water rushing in which builds up pressure", one might be tempted to code this statement as transfer; however, the speaker only provided this phenomenon from her discipline, so this statement was categorized as deep translation. Figure 1 represents the refined IT^3 framework based on the discussion above.

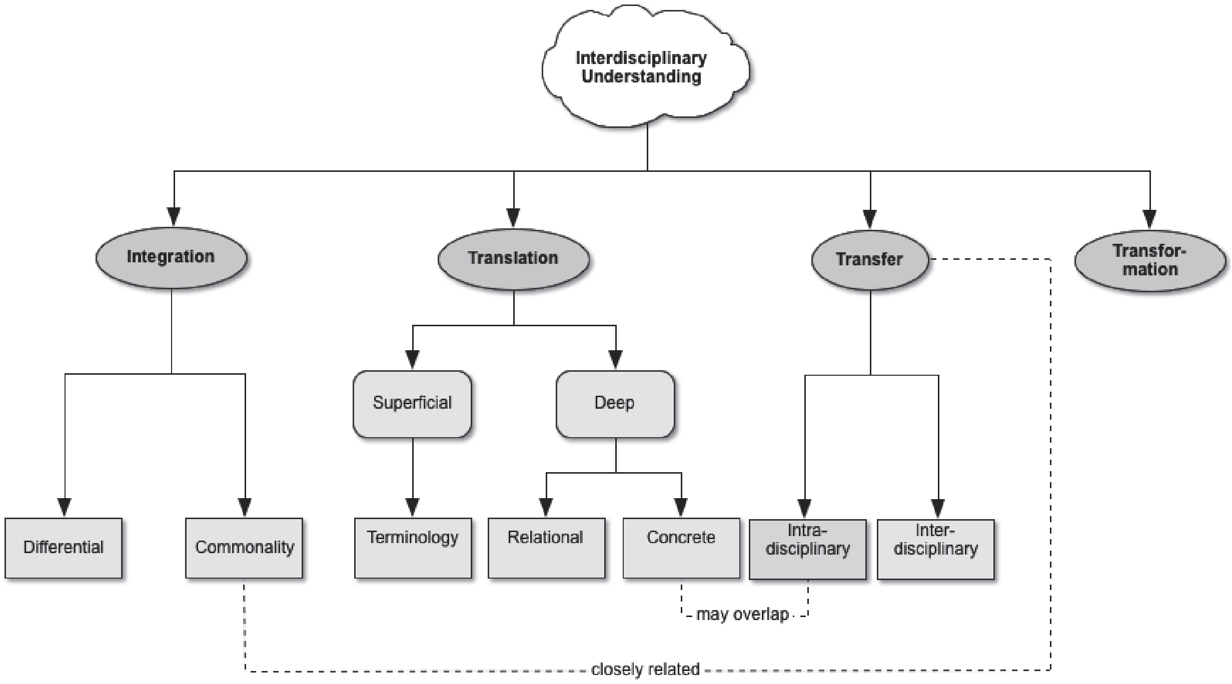

Figure 1. The refined ITTT framework.

Limitations

In this study, we only analyzed one meeting. This limits the insights we can gather from this empirical data set. For instance, there was no statement that qualified as transformation. This may be because within the time limit, the participants had yet to absorb the inconsistent views and develop a better understanding to reach the transformation stage. We will analyze more faculty meetings as the next step.

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

Conclusions and Implications

In this paper, we elaborated a framework on interdisciplinary understanding that has four interrelated dimensions: integration, translation, transfer, and transformation. Our framework provides a theoretical foundation to understand the construct of interdisciplinary understanding. We then developed corresponding codes using this framework to analyze a segment of an interdisciplinary faculty meeting, focusing on improving college-level integrated science education. We found that in this meeting, the faculty members spent most of the time discussing concept-specific issues and engaged in the process of interdisciplinary translation.

The faculty members who sought to resolve the inconsistent usages of terminologies across disciplines demonstrated and confirmed the importance of nurturing the ability to translate in order to communicate with people who speak another "language" (Boix Mansilla & Duraising, 2007). The most difficult terms causing extensive clarification, objection, and discussion among the faculty members in this study were potential, osmotic potential, and osmotic pressure; this has significant educational implications when re-thinking teaching the topic of osmosis. We currently are carrying out a content analysis study to investigate how these terms are interpreted from different textbooks in different disciplines.

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

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

References:

Boix Mansilla, V., & Duraising, E.D. (2007). Targeted assessment of students' interdisciplinary work: An empirically grounded framework proposed. *The Journal of Higher Education*, 78(2), 215-237.

National Research Council, (2000). *How people learn: Brain, mind, experience, and school (Expanded Edition)*. Washington, DC: National Academy Press.
Bransford, J. D. & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. In A. Iran-Nejad and P. D. Pearson (Eds.), *Review of Research in Education*, (pp. 61-100). Washington, D.C.: American Educational Research Association.
Chin, C., & Brown, D.E. (2000). Learning in science: A comparison of deep and surface approaches. *Journal of Research in Science Teaching*, 37(2), 109-138.
diSessa, A.A. (1993). Toward an epistemology of physics. *Cognition and Instruction,* 10(2&3), 105-225.
Engle, R. A. (2006). Framing interactions to foster generative learning: A situative explanation of transfer in a community of learners classroom. *Journal of the Learning Sciences*, 15(4), 451-498.
Haskell, J. P. (2001). The latitudinal gradient of diversity through the Holocene as recorded by fossil pollen in Europe. *Evolutionary Ecology Research,* 3, 345–360.
Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. In K. McGilly (Ed.), *Classroom lessons*, 51-74. Cambridge: MIT Press.
Klahr, D., & Carver, S.M. (1988). Cognitive objectives in a LOGO debugging curriculum: Instruction, learning, and transfer. *Cognitive Psychology*, 20, 362–404.
Lave, J. (1987). *Cognition in practice.* New York: Cambridge University Press.
Liu, O.L., Lee, H., & Linn, M.C. (2011) Measuring knowledge integration: Validation of four-year assessments. *Journal of Research in Science Teaching*, 48(9), 1079-1107.
Linn, M. C. (2006). The knowledge integration perspective on learning and instruction. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 243–264). New York: Cambridge University Press.
Linn, M. C., & Eylon, B.-S. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration*. New York: Routledge.
Mezirow, J. (2000). Learning to think like an adult—Core concepts of transformation theory. In J. Mezirow (Ed.), *Learning as transformation: critical perspectives on a theory in progress* (3-33). San Francisco: Jossey-Bass Inc.
Rhoten, D., & Parker, A. (2004). Risks and rewards of an interdisciplinary research path. *Science*, 306(5704), 2046-2046.
Shen, J., Sung, S., & Rogers, W. (2012). Assessing interdisciplinary understanding in science—The IT^3 framework. *Poster presented at the annual conference of the National Association for Research in Science Teaching (NARST). Indianapolis, IN.*

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