Three Diagnoses of Why Transfer Across Disciplines Can Fail and Their Implications for Interdisciplinary Education

Eric Kuo, Stanford University, Stanford, CA 94305, erickuo@stanford.edu
Danielle Champney, California Polytechnic State University, San Luis Obispo, CA 93407, dchampne@calpoly.edu

Abstract: One goal of interdisciplinary educational efforts is to increase students' ability to transfer knowledge from one disciplinary context to another. The approach taken to foster this transfer depends on the diagnosis of why this transfer can fail in the first place. Although a common diagnosis focuses on content knowledge and problem features as explanatory, there exist other, less prevalent diagnoses for why transfer across disciplines fails. In this paper, we show how one student responds differently to two similar problems set in physics and calculus problem contexts. We argue that beyond a *content knowledge diagnosis*, an *epistemology diagnosis* and an *accountability diagnosis* can also plausibly contribute to an explanation of why this student approaches these two similar problems differently, presenting additional considerations in fostering interdisciplinary transfer.

How Approaches to Interdisciplinary Education Imply Diagnoses of Why Transfer Fails

The transfer of content knowledge across different disciplines is one goal of a multidisciplinary education system. A typical curriculum for an undergraduate STEM major is designed with the expectation that students can and will, in any particular course, apply knowledge and skills learned in other disciplinary courses – for example, the typical undergraduate physics curriculum is designed expecting that students can and will transfer knowledge learned in prerequisite math courses into those physics courses; similarly, engineering courses expect students can transfer-in knowledge from math and physics courses.

Although these various courses are largely designed independently from one another, some interdisciplinary course reform efforts have developed, aiming to bolster transfer across the disciplines. The most common interdisciplinary approach is to align the content between two courses in order to construct content connections across the disciplines (e.g. Al-Holou et al., 1999; Dunn & Barbanel, 2000; Plomer, Jessen, Rangelov, & Meyer, 2010). Common goals of these efforts include avoiding haphazard coverage of related content across disciplinary courses as well as highlighting content connections between disciplines to decrease compartmentalization of knowledge and encourage future transfer to different disciplinary problem contexts.

Approaches such as these reveal (either explicit or implicit) views that poor content knowledge generalization and problem-specific surface features are explanatory in understanding why transfer across disciplines can fail. This *content knowledge diagnosis* is aligned with classical views of transfer that found reduced spontaneous transfer of a learned problem solution when the surface features of transfer problems were made more dissimilar from the initial training cases (Gick & Holyoak, 1980; Reed, Ernst, & Banerji, 1974). Such transfer is improved when multiple training cases were used, supporting the development of a more general solution schema not tied to the surface features of any one particular case (Gick & Holyoak, 1983; Reeves & Weisberg, 1994). In the same way, the alignment and co-presentation of content in interdisciplinary efforts aims, in part, to prevent the content knowledge from being tied to any one disciplinary context while also providing practice in applying that content knowledge in multiple disciplinary problem contexts.

We argue that there exist other possible diagnoses for why transfer across disciplines fails, which are not as prevalent as the *content knowledge diagnosis*. In this paper, we present one student, Will, who reasons differently on two similar problems set in physics and calculus disciplinary contexts. Investigating why his reasoning differs on these problems leads to two additional diagnoses of why he applies different ideas and approaches in each case: an *epistemology diagnosis* and an *accountability diagnosis*. We conclude with the possible implications of these alternative diagnoses for interdisciplinary education efforts.

Two Problems Asking "What Counts as a Good Approximation?"

As part of a larger study, we designed a set of problems to investigate how students might reason with similar mathematical content in different disciplinary problem contexts. This paper will include an in-depth discussion of one student's reasoning on two of these problems. The two problems, PENDULUM and ARCTAN, ask about approximations and infinite series in physics and calculus problem contexts, respectively:

> <u>*PENDULUM (includes a figure of a pendulum with angle, length, and mass labeled)*</u>*: You have a pendulum made of a metal ball on a string. The string is 1 meter long and the metal ball has a mass of 1 kg. You might know that the approximation for the period of a pendulum*

for small oscillations is: $T = 2\pi\sqrt{\frac{l}{g}}$ *, where T is the period of the pendulum, l is the length of the pendulum, and g is acceleration due to gravity (9.81 m/s²). This equation only holds for small angle oscillations of the pendulum. For larger angles, the period of a pendulum can be found with the following equation:* $T = 2\pi\sqrt{\frac{l}{g}}\left(1 + \frac{1}{16}{\theta_0}^2 + \frac{11}{3072}{\theta_0}^4 + \cdots\right)$*, where* θ_0 *is the angle of displacement of the pendulum from vertical in* radians*. You want to calculate the period of oscillation for this pendulum. How big can the angle of displacement of the pendulum be before the equation for small oscillations isn't a good approximation of the period?*

TAYLOR SERIES (note: since both problems relate to Taylor series and infinite series, for clarity, we refer to this problem in this paper as "ARCTAN"): The Taylor series about x = 0 for arctan(x) is: $arctan(x) = x - \frac{1}{3}x^3 + \frac{1}{5}x^5 - \frac{1}{7}x^7 + \cdots$*. How big a value can x be before stopping at the second term is a bad approximation?*

Each problem contains two mathematical expressions, one an approximation of the other. In both problems, these two expressions are exactly equal when the relevant parameter is zero ($\theta_0 = 0$ in PENDULUM and $x = 0$ in ARCTAN). However, as these parameters increase, the two expressions become more different. The interviewee's task is to determine how large the parameters can get before the two expressions are so different that one is no longer a good approximation for the other. Although the specific mathematical expressions were not identical across both, these two problems deal with a similar issue of how to judge "what counts as a good approximation?" for an infinite series expression. Because the idea of what counts as a "good approximation" is not precisely defined here, tasks such as these reveal how interviewees might make these judgments differently in different disciplinary problem contexts.

Will's Reasoning on PENDULUM and ARCTAN

The interview with Will was conducted in the summer of 2011 by the first author. At the time, Will was a rising sophomore at a large, public east coast university and was planning on declaring a mechanical engineering major. In his freshman year, Will had completed two semesters of calculus (which covered infinite series and Taylor series) but had only taken one semester of physics (which did not cover pendulum oscillations). However, he had taken physics in high school and commented that he had seen the small angle approximation equation for the period of a pendulum before. The interview session lasted about 90 minutes. In the interview, Will reasoned about PENDULUM first (from 00:02:25 – 00:45:22), then ARCTAN (00:45:22 – 01:15:16), and then reflected on his work on the two problems (01:15:16 – 01:27:12).

The data collection and analysis were driven by two research questions: 1) "How do students approach these approximation problems similarly/differently in the different problem contexts?" and 2) "What factors plausibly support this similar/different reasoning?" The interview was semi-structured in that the interviewer was free to ask follow-up questions and probe deeper into unclear statements or interesting emergent topics. To address the research questions, we analyzed the entire video with corresponding transcript and written work to characterize Will's approaches to these problems as well as his thoughts and reflections on those solutions. Once we had these initial characterizations, we performed more careful, line-by-line analysis through key sections of the transcript, looking for confirmatory or disconfirmatory evidence of our characterizations.

Through this analysis, we argue that one difference between Will's approaches to the two problems is that he attempts to *make sense of and explore* possible analytical solutions on PENDULUM, while he instead attempts to *recall ideas* from calculus on ARCTAN. Then, we argue for three possible diagnoses of why such different approaches were taken: a *content knowledge diagnosis,* an *epistemology diagnosis*, and an *accountability diagnosis*. In conclusion we argue that these diagnoses have implications for how transfer of reasoning across the disciplines is supported.

Will's Approach to PENDULUM: *Making Sense and Exploring*

Will starts his work with PENDULUM by noting that he has not seen this problem before, and he reads the text carefully to make sense of what it is asking. Although unfamiliar to him, Will is able to make sense of the expressions and notes that being a good approximation means the two expressions for the period are equal to each other. He notices that the two expressions are the same except for the addition of $2\pi\sqrt{\frac{l}{g}}\left(\frac{1}{16}{\theta_0}^2 + \frac{11}{3072}{\theta_0}^4\right)$ in the series expression, and that each progressive term in the series gets smaller and smaller. He says that this additional term is added to "make up for the error that occurs…when the angle gets too big." He goes on to explain that for small angles, the additional term is small, and so the two expressions will be approximately equal, but for larger angles, the additional term is large, so the two expressions will not be equal.

Will takes two approaches to trying to answer the problem: setting common-sense, physical bounds on the angle and attempting to set up and solve an equation that will produce a value for θ_0. In both approaches, he uses his physical understanding of the motion of the pendulum in order to evaluate the reasonableness of the answers. In setting an upper bound on the angle, he looks at the picture and declares that the upper bound is 90 degrees, because he feels that motion past that would no longer be that of a typical pendulum. While attempting to manipulate the equations to find values of θ_0 within the limits of a good approximation, one approach Will tries is to set the two expressions equal to each other to solve for θ_0. While the interviewer points out that $\theta_0 = 0$ would satisfy this mathematical relation, Will argues that is not a reasonable answer, because when the angle is zero the pendulum is not swinging at all. As Will says, "You can't really have a period when it's just sitting there not moving."

We label Will's approach here as *making sense and exploring*. Will starts by making sense of how two unfamiliar mathematical expressions are similar and different. Throughout the problem, he uses his understanding of the physical motion of a pendulum to make sense of the bounds on the angle. Without a sense of what the correct approach must be, Will tries to set up an equation and solve for θ_0, using his physical understanding to evaluate his results. Independent of his final answer here, this overall approach of *making sense and exploring* stands in contrast to his approach on ARCTAN.

Will's Approach to ARCTAN: *Recalling Formal Knowledge*

In contrast to making sense of an unfamiliar problem on PENDULUM, Will starts ARCTAN by pointing out that he does not remember the general method for finding the Taylor series of a function and by recognizing this problem as the kind he has done before in calculus class.

Throughout ARCTAN, Will fixates on certain pieces of knowledge he learned in his math classes that he believes are relevant and attempts to recall them. He mentions that arctangent has asymptotes, but he can't remember what they are. He cues in on the phrase "about $x = 0$" as being important and tries to remember what it means and how it is relevant for this problem. He also tries to remember common Taylor series expansions, such as those for sine and cosine, as well as the general formula for generating Taylor series.

As with PENDULUM, Will attempts to set bounds, on $\left(x - \frac{1}{3}x^3\right)$, for which the approximation is good. He vaguely remembers that some parameters have to be less than 1 in certain series convergence tests in calculus, and he uses this remembered fact to set the bounds as $0 < \left(x - \frac{1}{3}x^3\right) < 1$, although he recognizes that this is a guess and is not the "right way to do it." Later, the interviewer supplies two pieces of information at Will's request: the graph of arctangent with asymptotes labeled ($y = \pi/2$ and $y = -\pi/2$) and the general formula for Taylor series. Will uses the asymptotes of arctangent to change the bounds to $-\frac{\pi}{2} < \left(x - \frac{1}{3}x^3\right) < \frac{\pi}{2}$. He does not use the general Taylor series formula in his final answer.

Although he produces bounds for what counts as a good approximation in both PENDULUM and ARCTAN, his approaches are very different. Throughout his work on ARCTAN, rather than attempting to make sense of the relevant equations and ideas or trying to manipulate expressions to solve for x, Will seeks to *recall formal knowledge* from his calculus class. At the end of the interview, Will articulates his awareness of these two different approaches:

> [01:17:00] W: [On ARCTAN] I was thinking from the top down in that, "What's a Taylor series? What are the equations related to it? Uh, what's the information that I was once told relating to this subject that I would need in order to find basic numbers, the number that I need." So it was actually a complete opposite way of looking at it. [On PENDULUM] I immediately read it and tried to, *pssh*, clear my mind and, alright, what am I looking for? Basics. [On ARCTAN] I immediately read it and I was filled with, "What's Taylor series again? How do you find the equation for approximations?"

Three Diagnoses of Why Will Does Not Take the Same Approaches to These Problems

How can we explain why Will attempts to *make sense and explore* on PENDULUM but tries to *recall formal knowledge* on ARCTAN? Here, we present three possible diagnoses.

1) A *Content Knowledge Diagnosis*

Attention to the content knowledge used and differences in specific problem features offers several specific diagnoses of why Will takes different approaches to these two problems, suggesting possible treatments for supporting alignment of Will's reasoning across these problems:

I) Although both problems involve infinite series, ARCTAN contains many explicit cues to Taylor series (i.e. explicit mention of "Taylor series" and the phrase "about $x = 0$"). On PENDULUM, Taylor series are never explicitly mentioned. If PENDULUM similarly contained these explicit cues to Taylor series ideas, Will may have sought to *recall formal knowledge* of Taylor series on PENDULUM as well.

II) Because $arctan(x) \approx \left(x - \frac{1}{3}x^3\right)$ includes transcendental and polynomial terms, it is not as easy to manipulate this equation to solve for x as it is in PENDULUM, where the analogous equation contains only polynomial terms. This difference in the mathematical structure of the two problems could explain a difference in Will's approaches. If $arctan(x)$ was changed to a different expression, such as $(1 - x)^{-1}$, Will may have also have sought to solve for x algebraically on ARCTAN.

III) In PENDULUM, the diagram of the pendulum cues the physical motion, providing a way to determine the bounds on the angle, whereas ARCTAN contains no such diagram. Although not cuing the same type of intuitive knowledge about physical motion, a graph of $y = arctan(x)$ given in the problem statement (rather than given later by the interviewer) could provide similar visual cues for *making sense and exploring* bounds.

Here, the intention is not to present all possible such diagnoses. Rather, the above examples are meant to illustrate what we take to be a *content knowledge diagnosis*: differences in reasoning on these problems stem from different content knowledge being cued by different problem features. We have argued that this type of underlying diagnosis is common in interdisciplinary course design efforts. For example, Dunn and Barbanel's (2000) co-taught multivariable calculus/electricity & magnetism course develops the mathematics and physics in parallel, with common language and notation. The hope is that content knowledge will be learned in a way that isn't compartmentalized to particular disciplinary contexts or problem cues, fostering transfer of that knowledge across disciplines.

2) An *Epistemology Diagnosis*

Providing an alternative to the content-focused perspectives on transfer, another perspective focuses on knowledge activation and transfer as related to individuals' *epistemologies* (or views on the nature of knowledge and knowing.) Hammer, Elby, Scherr, and Redish (2005) argue that what has been described as transfer is the activation of similar knowledge resources in various situations, and that this activation depends not only on content knowledge and problem features, but also on epistemological stances towards what kinds of knowledge are appropriate in different situations. For example, they describe two students taking different approaches to answering the question of how a scale reading of a person's weight changes in a moving elevator. Hammer et al. argue that one student's epistemological stance supported a formal computational approach to this problem, because she started by listing all the numerical quantities in the problem, apparently preparing for a calculation. Another student interrupted by asking, "Do we even need to do all that calculation?" and proceeded to describe her physical sense of how the elevator floor is falling away from the person as an elevator is accelerating downwards. This second student's interjection was a challenge not to the correctness of the numerical values listed, but to whether this *kind of approach* was necessary. Hammer et al. argue that this second kind of approach to the question stems from a different epistemological stance towards what kind of knowledge will be useful or productive here.

While this example might suggest that these students have fixed epistemologies that can only support one type of reasoning or activity, other research shows that individuals have access to many different epistemological stances, of which different ones can be cued in different moments to support different kinds of reasoning (Hammer & Elby, 2003; Rosenberg, Hammer, & Phelan, 2006). In this section, we argue that Will's different epistemological stances towards the two problems support his two different approaches.

"Logical Reasoning" Is Useful on PENDULUM

In evaluating his work on PENDULUM, Will recognizes that he would not get full credit for this explanation if it were an answer on a test, because he expects that problems on a physics test would require precise, learned methods, not just guesses at the bounds. In spite of this, he still thinks that he would get some partial credit, because the "logical reasoning" that he demonstrated is valued:

[00:42:26] W: A lot of teachers, if you put something down that sort of makes sense, if you put something down, and you show logical thoughts and sort of show how you got to a semi-close answer, they'll give you like a point or two and be like, "Alright, nice try, but not even

557 close.” Um, and it's a big difference again between this stuff and, like, history. This kind of
558 stuff you can, even if you don't know it, you can use logic and you can, uh, make connections
559 and rationalize certain things and know that they're true just by looking at what you are given.
560 You don't need to know, I mean you've learned it over the years, but you don't need to know a
561 specific date or a specific event to answer a question. If they ask you, you know, “What's the
562 Battle of Hastings?” and you don't know anything about the Battle of Hastings, you're not,
563 you can't just be like, “There were swordsmen. They fight.” You can't say that. But this one
564 you could say, “Alright I don't know what this equation really means, but I'm told, and I've
565 never seen it before, but I do know that T should equal T when the number of, when the, um,
566 degree of displacement of the oscillation is correct.” And you can show stuff like that. And I
567 think if you show that you're willing to do that, they'll give you a little bit.

Here, Will’s statements provide evidence of an epistemological stance that values “logical reasoning:” making sense of unfamiliar ideas, building connections, and providing evidence of rational thinking. Importantly, Will’s statements are epistemological in that he is reflecting not only on his approach to PENDULUM, but also on *what kinds of approaches are appropriate* on this type of problem. This is reflected especially in contrast to the types of reasoning that are appropriate for historical questions, such as, “What’s the Battle of Hastings?” which Will says cannot be reasoned through and requires specific prior knowledge.

Will’s epistemological stance here is aligned with and plausibly supports his approach to PENDULUM. If he views “logical reasoning” as appropriate on this problem, then it is reasonable that Will would try to *make sense of and explore* this unfamiliar content rather than seek formal knowledge required to solve this problem. As a specific example, Will rejects $\theta_0 = 0$ as a possible answer to the problem, arguing that this answer must be wrong, not through a learned fact or procedure, but rather because of an intuitive physical interpretation that makes that answer violate common sense. In this way, Will’s intuition-based evaluation of $\theta_0 = 0$ aligns with his epistemological stance that such “logical reasoning” is appropriate.

The “Pure Mathematical Reasoning” in ARCTAN Cannot Be Reasoned Through

While attempting to recall ideas from his calculus class, Will reflects on what is difficult about ARCTAN, revealing his epistemological stance that the reasoning required for this problem is “not normal reasoning:”

773 [01:03:14] W: Um, but yeah. It's 'cause I, I just don't remember those, uh, that information. I
774 don't think that, and I couldn't, this is, I hate, it's, that's why I hated these problems so much,
775 that I couldn't reason through them. I couldn't think, “Oh well, infinity, you know, this
776 happens.” I just can't, it doesn't make any sense.
777 I: It's not like the previous problem, is what you're saying?
778 W: No, not at all. That's like concrete. That's like, ok, pendulum moving. I can see that.
779 That's why I hated Taylor series so much, is 'cause you can't see it. It's, it's just, it's like pure
780 mathematical reasoning that's, like, not normal reasoning. It's, you think about it a different
781 way. You can't just think as a person like, “Oh yeah, it's, pendulum swings to a certain point,
782 this happens.” You have to think about it in terms of, like, infinity and what happens when
783 you go to infinity. That's like, I don't think that's like in, humans don't think like that
784 naturally, so you have to learn it.
785 I: Ok.
786 W: So I wouldn't be able to really, I, like, I couldn't get partial credit on this problem.

Here, Will describes an epistemological difference between appropriate approaches on PENDULUM and ARCTAN. The “pure mathematical reasoning” here is described in contrast to the “logical reasoning” on PENDULUM (lines 778 to 784). For Will, ARCTAN requires unnatural, formal, mathematical ways of thinking. Again, in comparison to PENDULUM, this means that Will would not expect to get any partial credit on this problem (line 786), because he cannot replicate the canonical reasoning from calculus class. In this way, Will’s epistemological stance here is more similar to the one he takes towards a history question like “What’s the Battle of Hastings?”

Will’s epistemological stance towards ARCTAN aligns with *recalling formal knowledge*. It does not make sense to attempt “logical reasoning” as he does on PENDULUM if the mathematical content on ARCTAN is unnatural and cannot be reasoned through. Instead, the only productive approach would be to recall facts from calculus class. An epistemological stance that rejects “logical reasoning” as productive also helps explain why even after his initial failures to recall the relevant ideas he seeks, Will persists in recalling formal knowledge, instead of attempting the kind of *making sense and exploring* that he does on PENDULUM.

Importantly, the *epistemology diagnosis* suggests one reason why content or problem feature alignment alone may not be successful. Aligning only the content features of two problems as prescribed by the *content* *knowledge diagnosis* may not be successful in fostering similar approaches to those problems if in working on those problems one takes different epistemological stances to what knowledge and approaches are useful.

3) An *Accountability Diagnosis*

Another approach to transfer focuses on the importance of motivational aspects: achievement goals, interest, and self-efficacy (Pugh & Bergin, 2006). In attending to these factors, we found how a sense of accountability to knowing and being able to recall relevant facts and approaches (and the related negative affect and feelings of low self-efficacy when he can't remember) can help explain Will's persistence in trying to *recall formal knowledge* on ARCTAN.

Will Does Not Feel Accountable for Knowing the Canonical Way of Solving PENDULUM

We argue that Will does not feel accountable for such canonical knowledge on PENDULUM, likely supporting his *making sense and exploring* on PENDULUM. Through the initial interaction with the interviewer, Will's focus shifts from knowing the "right way" to solve the problem to expressing his own understanding and seeking a solution that makes sense to him.

At the start of working on PENDULUM, Will reads the problem silently for about 80 seconds, pausing only to confirm with the interviewer that he is not required be familiar with this type of problem already. After reading, Will confirms his understanding of the two expressions with the interviewer. He then starts asking about what the problem wants him to do:

48 [00:04:26] W: Ok. [pause] So you don't want me to calc-, you just want me to answer the
49 question, right? I don't have to do anything?
50 I: Uh, yeah. Yeah, I mean, does it make sense, what they're asking?
51 W: Yeah, it makes sense. I mean, I can understand what they're trying to say.
52 I: Ok.
53 W: I haven't done oscillations, but I can understand the idea that they're trying to get through.

Here, the interviewer's redirection from what Will should be doing on the problem (lines 48 to 49) to Will's understanding of the problem (line 50) may help shift the focus to what Will understands. The interviewer's answers to Will's earlier clarification questions may also support an interpretation of the activity as the interviewer helping him make sense of the unfamiliar problem rather than testing what he already knows. Furthermore, the uninterrupted time spent silently reading could contribute to a feeling that Will has the opportunity to make sense of an unfamiliar problem, rather than immediately having to recall an answer. In line 53, he indicates that he has not "done oscillations," positioning himself as not accountable to this content.

After this excerpt, Will again spends one minute silently reading and thinking about the problem, after which he again starts to ask the interviewer if his understanding of the question is correct:

54 [00:05:47] W: Well, I would guess that these T's should be equal, right? If they're going to
55 be, they're both going to be accurate approximations.
56 I: Ok.
57 W: So at a certain point, when they're no longer roughly approximate is when your angle is
58 getting too big that this one [the small angle approximation] breaks down, and this is the one
59 [series equation] you have to use. Is that correct?
60 I: Um, well I mean, I mean, I just sort of want to figure out how you would think about it.
61 W: Ok.
62 I: So whether or not it's correct.
63 W: Ok, so you want me to explain how I would think about it.
64 I: Yeah.

After this except, Will's talk switches from asking confirmatory questions about the problem (as in lines 54 and 59) to stating his understanding of the question and how he would answer it. This shift in Will's talk suggests a corresponding shift in Will's interpretation of the interview situation, from an evaluation of his knowledge to one where his ideas are important and worth exploring.

This interpretation of the interview situation aligns with *making sense and exploring* on PENDULUM. If the purpose of the interview is to hear how Will would think about the problem, not holding him accountable to particular canonical ways of understanding and approaching this problem, then this would provide space and support for the *making sense and exploring* in which Will ultimately engages.

Will Feels Accountable for Recalling Ideas from Calculus Class on ARCTAN

Unlike the start of his reasoning on PENDULUM, Will does not initially approach ARCTAN by reading and making sense of the problem. Instead, he immediately indicates familiarity with this kind of problem:

> [00:46:18] W: Um, I, don't you need to know how to formulate the Taylor series for, I don't know, you don't, I guess. I don't even know how to formulate the Taylor series, so it's a good thing they kind of gave it to me. Um, ok, I absolutely hate this stuff, but I have done this one before. I have taken, like, calc 2, so I have done this before [Will reads the problem to himself again].

Throughout the problem, Will signals that he feels accountable for remembering the relevant calculus content by indicating both his frustration at not being able to recall those facts as well his lower self-efficacy:

> [00:58:28] W: And it's annoying, this one's really annoying, because I definitely have done this or something like it, so I should know how to do this one. It's been in my mind before, um, but I did get a 40 on this test, so, didn't know it that well. Uh, [laughs] let me think.

Unlike on PENDULUM, here the interviewer does not intervene to suggest to Will that he is not necessarily expecting him to recall facts from class, possibly because Will doesn't directly ask a question to the interviewer during ARCTAN. Instead, after Will attempts to recall information and work on the problem, the interviewer asks Will what information he would look up or ask someone, given the chance. This likely supports an interpretation by Will that prior knowledge is important, supporting his feelings of accountability. Similarly, receiving that knowledge later on may tacitly signal that this information was crucial.

At the end of Will's work on the problem, Will presents his answer, reflecting on how he feels about his answer:

> [01:11:52] W: Um, but yeah, this one [ARCTAN] is more upsetting to me than the other one [PENDULUM], because I did actually do these kinds of problems before. And like, I don't really have, or see how to do these right, but that's how I would do it at this point, not remembering much.

Will's sense of accountability towards knowing the canonical and correct methods and the associated feelings of frustration, displayed throughout his work on ARCTAN, provide another plausible support for why Will continues to seek to *recall formal knowledge*, even if that formal knowledge is not obviously useful for the problem. For example, throughout the problem he attempts to remember the general Taylor series formula, as well as the series expansions of sine and cosine, even though these are not necessary for solving the problem. A *content knowledge diagnosis* would suggest that cuing Taylor series simply cued the recall of other Taylor series ideas. An *accountability diagnosis* suggests that, on top of this, the goal of recalling facts that he learned in his calculus class in order to demonstrate competence and relieve frustration may support persistence in *recalling formal knowledge*. At the end of the interview, Will supports this interpretation when he explains why he tried to recall the general formula for Taylor series even though he did not use it in his answer: "I know I'd done it before. It was just frustrating me that I didn't remember the basic idea of it."

Importantly, this diagnosis differs from an *epistemology diagnosis*, because it looks beyond what kinds of knowledge and reasoning Will thinks the task requires. An *accountability diagnosis* also considers feelings of being accountable for that knowledge, such that not being able to remember those ideas leads to feelings of frustration and low self-efficacy, driving persistence in attempting to recall formal knowledge.

Implications of These Alternative Diagnoses for Interdisciplinary Education

Although research into transfer has opened up possibilities beyond the *content knowledge diagnosis*, it remains a common diagnosis in interdisciplinary efforts. In this paper, we raise the plausibility of other such diagnoses, namely an *epistemology diagnosis* and an *accountability diagnosis*, arguing that efforts that focus solely on alignment of content and problem features are incomplete. Here, we discuss some possible implications of each alternative diagnosis for interdisciplinary education efforts.

The *epistemology diagnosis* implies that instructors should also want students to view certain different disciplinary problems as requiring similar kinds of knowledge and approaches. Some interdisciplinary efforts have started incorporating the *epistemology diagnosis* into their course goals – for example, some recent physics courses aimed at life sciences students have the explicit epistemological goal of helping students see physics concepts and the associated mathematical reasoning as relevant and useful for understanding biology and have showed preliminary success in achieving these goals (Meredith & Bolker, 2012; Redish et al., in press). Although these courses do align particular topics to build connections between physics and biology content knowledge, they simultaneously aim to help students view physics knowledge and ways of reasoning as productive for understanding biological problems, to support future transfer of physics into biology.

We have also shown that, for Will, feelings of accountability, with the associated low self-efficacy and negative affect, lead to brittle transfer of prior knowledge from his calculus class and persistence in unproductive approaches on ARCTAN. Although there have not been similar interdisciplinary reforms in response to an *accountability diagnosis*, some related research offers possible treatments. Elliott and Dweck (1988) mitigated the negative affect and low self-efficacy associated with "helplessness" by emphasizing the learning goals of an activity over goals of demonstrating competence. This led to both increased willingness to make public mistakes and improved performance over time. It is possible that deemphasizing performance goals could have similarly helped Will try different approaches on ARCTAN related to *making sense and exploring*. Interdisciplinary courses could aim to emphasize learning goals over performance goals, in order to counter low-risk/performance-oriented attitudes that may impede novel transfer across disciplinary courses (as well as to counter feelings of low self-efficacy, frustration, and helplessness that can impede learning more generally).

Our goal is to raise awareness of these multiple diagnoses of why transfer across disciplines may fail. Although we advocate for the inclusion of alternate diagnoses, we do not wish to downplay the importance of the *content knowledge diagnosis*, nor do we mean to suggest that these diagnoses are mutually exclusive. Surely, instruction that attends to *only* epistemology or *only* the low self-efficacy and negative affect related to feelings of accountability will be as incomplete as sole attention to content knowledge. Rather, enriching our understanding of the multiple reasons why transfer across disciplines can fail has the potential to lead to improvements in current interdisciplinary efforts. Additionally, it is possible that these multiple diagnoses can enrich our understanding of why *current* interdisciplinary efforts succeed, illuminating epistemological, affective, or motivational benefits of approaches derived purely from content considerations.

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