Students' interpretations of disciplinary convention with the first law of thermodynamics

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The transfer of knowledge within and across disciplines remains a compelling challenge for modern STEM education and further research is needed to expand on the student-exhibited cognitive and affective gains achieved by innovative cross-disciplinary STEM instructional techniques. This study seeks to support cross-disciplinary STEM instruction and learning by investigating how students use the first law of thermodynamics, a crucial principle to the crosscutting concept of energy and matter, to bridge across disciplinary boundaries. An interview study was undertaken wherein chemistry-, engineering-, and physics-major students addressed a common set of conceptual prompts written with different field-specific conventions. This report focuses on students' interpretations of the provided forms of the first law and work equations between prompts. Emergent findings demonstrate field-specific interpretations of arbitrary differences in convention and strong barriers to transfer. Derived implications inform suggestions for scaffolding across such disciplinary differences and for future work in this area.

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I. INTRODUCTION

Modern education research at the undergraduate level has demonstrated the positive impact that multidisciplinary, interdisciplinary, and transdisciplinary instructional approaches can have on students' learning and attitude towards learning STEM [1–3]. Supporting progressive teaching models should therefore be a major focus of education research and should be guided by a cross-disciplinary set of frameworks. The Next Generation Science Standards outlines the crosscutting concepts (CCCs) as the common tools and lenses used to bridge across the disciplines of STEM [4,5]. Despite the critical role of the CCCs in defining the topics which bridge the disciplines of STEM, little work has been conducted to date on the CCCs at the undergraduate level [5,6]. This interview study seeks to support such integrated models of STEM education by investigating students' abilities to apply the first law of thermodynamics, a crucial principle of the CCC of energy and matter, across the fields of science and engineering. In particular, the findings summarized herein focus on students' conceptualization of differences in disciplinary convention when addressing the first law equation.

Bridging from one disciplinary context to another may be viewed as transfer of learning [7]. A student-centered transfer of learning framework is applied in this study given the notable advancements of such frameworks in modeling and supporting transfer [8]. Recent studies have highlighted the critical role that epistemology plays in governing whether transfer emerges in a productive or unproductive fashion [9,10]. Addressing epistemology in the classroom is particularly challenging given that discipline-specific epistemic viewpoints emerge across traditional course environments and these messages may conflict depending on the context [11,12]. Therefore, building students' productive epistemic performance should be a major focus of future cross-disciplinary research [13].

Within the physics education research literature, significant advances have been made to understanding the guiding epistemologies that impact students' applications of mathematical representations. Redish & Gupta [14] introduced a seminal model for physical modelling that highlights four key skills that a scientist must engage in to effectively describe the physical world with mathematics. When engaging in modeling, students have been shown to commonly encounter barriers when applying only a limited set of modeling skills [15,16]. Such barriers are highlighted by students' stated reasons or "warrants" for adopting certain skills and the analysis of these warrants has revealed distinct guiding epistemologies in how students frame equations in a problem-solving context [17]. Unproductive guiding epistemologies often emerge from perceived authority [18] and the resulting trust in such authority over intuition in certain contexts [19]. However, flexibility in navigating between different epistemic viewpoints is notably desirable and the mark of expert-like modeling behavior, especially in the case where the modeling context is counterintuitive [20].

This study seeks to build on prior transfer and physical modeling research by examining how students leverage disciplinary differences in convention, when addressing the first law of thermodynamics, to bridge across disciplinary boundaries. For the purposes of this study, "disciplinary boundary" is defined as the set of systems [21], language [22], and notation [23] used to frame a problem-solving context. An interview study was conducted to engage students in solving a set of common conceptual first law problems for which the systems, language, and notation were varied across the sample of disciplines studied. Data analysis was focused on identifying how students realized the different disciplinary conventions to know about the first law problem-solving scenario. The guiding research question for the applied analysis was: "How does notational convention impact students' approaches to solving problems pertaining to the first law of thermodynamics?"

II. METHODS

A. Framework

The Dynamic Transfer (DT) framework [24] served as the methodological and theoretical basis for the applied methods and analysis. As a student-centered transfer of learning framework, DT models the process by which a student is primed by an interviewer to make knowledge available to themselves within an interview setting. A students' problem-solving expectations, the context they identify, and the ideas they use are all viewed as fine-grain knowledge elements or *tools*. The distinction of tools within DT is consistent with a manifold ontology of knowledge and the resources framework [25,26]. Where DT differs and expands upon these foundational perspectives is the structure of the model as it pertains to the unique context of the interview setting. The role of the interviewer in "priming" students to adopt a particular epistemology and the process of using the provided context to construct knowledge may all be modelled through this lens. As such, the application of DT in the case of this study may be viewed as an epistemic game [15] whereby the applied methods investigate "how" students access what knowledge they have rather than ascertaining "what" knowledge they have.

B. Interview prompts and protocol

Three discipline-specific interview problems were developed that tasked students with determining the change in internal energy for a piston-cylinder system following described heat and work processes. The developed problems were printed on paper and students were asked to draw a picture of the described system and to solve the problems in a think-aloud style. Each prompt had the same base structure as summarized:

1. Description of the system
2. Draw the system
3. Heat and work process descriptions
4. Determine the internal energy of the system
5. Provided first law and work equations
6. Problem question and MC answer choices

For each prompt, the systems, language, and notation defining the context were varied to incorporate the disciplinary conventions of thermodynamics in chemistry, engineering, and physics instruction. Therefore, each interview prompt may be viewed as variations of the same thermodynamics problem with arbitrary alterations in disciplinary context that provide the "task distance" for this transfer experiment [27]. Prompts were developed by first drawing from relevant textbook materials in each field and then vetting the prompts to align with classroom-specific practices. This report focuses on students' interpretations of the various disciplinary conventions associated with the first law and work equations across each prompt (see Table I).

Table I. Provided equations for interview prompts.

Prompt	First Law Equation	Work Equation
Physics	$\Delta E_{int} = Q - W$	$W = \int_{V_i}^{V_f} pdV$
Chemistry	$\Delta E = q + w$	$w = -P\Delta V$
Engineering	$Q - W = \Delta U$ $+\Delta KE + \Delta PE$	$W = \int pdV$

All students addressed one in-discipline and one out-of-discipline prompts (order varied) in succession. Afterwards, students engaged in a scaffolded transfer phase. During this phase, both prompts were placed side-by-side and students were asked to compare the similarities and differences between both prompts. The purpose of the scaffolded transfer phase was to support students transfer into an unfamiliar disciplinary context by prompting their attention towards the common application of the first law of thermodynamics in each prompt.

C. Sampling and analysis

A total of n = 40 students were recruited from introductory thermodynamics courses for majors in chemistry (n = 10), engineering (n = 20), and physics (n = 10). All participants were recruited from the same large institution which offered discipline-specific course sequences in each field of interest. Chemistry and physics students only addressed the physics and chemistry out-of-discipline prompts respectively. Analysis was conducted via a previously reported general inductive approach [28,29]. Validity and reliability were established by iterative interrater coding mediated by theoretical discussion.

The relative lack of notational differences between the engineering and physics prompts was reflected in the minimal activation of ideas associated with these differences. Therefore, the discussion of this report will focus on the portion of engineering students who addressed the chemistry prompt (ENG-C) and the remaining interview sample (n = 30 total). Participant quotations have been designated by an alphanumeric code denoting their discipline and interview number (C1, P3, etc.) and the stage of the interview (chemistry as first prompt: C1, scaffolded transfer phase: ST).

III. RESULTS/FINDINGS

A. Interpretations of first law equation

Disciplinary inconsistencies in the capitalization of heat and work symbols in the first law equation was the most frequently noted attribute that distinguished the chemistry prompt from the physics and engineering prompts (17 of 30 interviews). Most notably, engineering students, such as E7 below, indicated that the lower case heat and work terms of the chemistry prompt suggested that those variables were being considered on an extensive basis:

> E7.C1: *"I actually, actually it might be the fact that Q and W are actually lower case because usually in class you see them with that means is the, there would be the heat transfer and the work done per unit mass."*

E7's conjecture was common among engineering students and reflects the distinct use of intensive and extensive notation via letter case in the engineering course studied when compared to the chemistry and physics courses of interest.

Conversely, chemistry and physics students expressed confusion when encountering unfamiliar letter case. Both classroom environments implemented a different letter case convention when describing heat and work. However, capitalization rarely altered students' work on the provided problems as exemplified in P4's analysis of the unfamiliar chemistry notation:

> P4.C2: *"Um, it's kind of unusual that Q and W are lower case, kind of weirds me out a little bit, cause I'm so used to seeing them as capital Q and capital W, but I'm just, I'm kind of also assuming that they're just the same variables."*

Here P4 recognizes an irregularity in the letter case used for heat and work, but P4 eventually treats heat and work in the same way as they would if it were upper case. This recognition and approach was mirrored by chemistry students who had similar reactions to the upper case heat and work terms of the physics prompt. Ultimately, the distinguishing factor between students that did or did not associate meaning with the letter case of heat and work was reflective of whether their classroom environments communicated intended physical information through the purposeful use of letter case.

Students' problem-solving appeared to be more sensitive to their perception of what dependent variable was used to describe the expression. While each prompt was defined in terms of internal energy, some chemistry students (2 of 10 interviews) read the energy-internal term of the physics prompt to encode for some unfamiliar term that was distinct from the term provided in the chemistry prompt. C3 demonstrates this point below showcasing how unfamiliarity with the energy-internal term and the work equation impacted their interpretation of the equations in the context of the problem:

> C3.ST: *"Well in Problem 1 the E has I-N-T after it like in the subscript, which means internal normally. And then in the second one it just has Delta-E with no internal, and that equation I know does not deal with just internal. And I haven't seen Problem 1's equation before, at least for the W, which makes me think it's probably only for internal energy."*

Interestingly, C3 appears to be confident that the energy term of the physics problem (Problem 1) signifies the internal energy when reading out the subscript and uses this to infer that the more familiar chemistry term does not signify "just" internal energy (Problem 2). C3's perception of the dependent first law variables is critical to consider given that 8 out of 10 chemistry students ultimately came to an unproductive assessment of the physics prompt. A previous report has summarized chemistry students' tendencies to rely on causal-mechanistic reasoning when approaching the physics prompt [28]. Similar instances of uncertainty in declaring distinctions between the dependent variables of the provided first law equations were absent from physics and engineering students' reflections.

B. Interpretations of work equation

Students across the disciplines reflected on the different forms of the work equation employed in the chemistry problem when compared to the engineering and physics problems (20 of 30 interviews.) As suggested by C3 in the prior section, the general form of the boundary work equation was unfamiliar and tended to lead chemistry students to differentiating the corresponding first law equations across prompts. Conversely, engineering and physics students demonstrated expanded mathematical aptitude when addressing these different forms of the work expression. Engineering students, such as E8 below, commonly pointed out (4 of 10 interviews) that the connection between the two forms of the expression lie in a constant pressure assumption that would allow the pressure to be pulled "out of the integral:"

> E8.C2: *"[…] because, um, when we're solving problems, we always have to write basic equations and every time for work, the basic equation is integral of P times D-V. And if, if we ever want to make the equation just P-Delta-V we have to be able to pull the pressure value out of the integral."*

E8 discusses the connections between the simplified and general work expression without inferring any new information about the problem. Instead, E8 reflects on their prior experiences in approaching thermodynamics problems and how they always start from the more general form of the expression.

Physics students contrasted from engineering students in their notable tendency to infer attributes of the provided problem and described processes based on the provided work equation (3 of 10 interviews). Consider P3's comment below when comparing the chemistry and physics prompt equations:

> P3.P2: *"Again, pay attention to the fact that this work is given as an integral and not just P-Delta-V because it implies that P changes, cause of P does change. P-Delta-V wouldn't work, that's why they changed the form, that's why they changed the equation."*

Unlike E8's discussion, P3 suggests that pressure is implied to change within the physics prompt given the more general form of the expression provided. This distinction between E8 and P3 signifies a difference in the student-realized meaning of the provided prompts when comparing the students across disciplines.

C. Problem-dependence of equations

During the scaffolded transfer phase, students that used the provided equations to evaluate the problems were asked whether they felt the equations were only relevant to the provided problem or if they could be applied to both problems. Students' responses were binned into two mutually exclusive coding definitions included in Table II to distinguish whether students saw the equations as dependent or independent to the problem-solving context. Frequencies of each code across the interview sample is included for reference. The sum of these frequencies does not reach n = 10 for each discipline given that not all students utilized the first law equation to solve the provided interview problems.

The "problem as equation dependent" code was observed across the engineering and chemistry sample and was absent from the physics student sample. Most notably, student interviews for which the problem as equation dependent code emerged encountered unproductive barriers within the scaffolded transfer phase (5 of 6 interviews). Each case was marked by an unwillingness to productively apply the more familiar first law and work expressions to solve the out-of-discipline prompt. Only a small portion of students indicating problem as equation independent encountered similar barriers during the scaffolded transfer phase and all were chemistry students (3 of 20 interviews). Chemistry students, during the scaffolded transfer phase, would often cite a lack of familiarity with the equations provided in the physics prompt and would then indicate previously outlined features of the equations as reasons for this uncertainty:

Table II. Problem-dependence of equation codes and frequency.

Code	Definition	Count by Discipline		
		Chem	Phys	Eng-C
Problem as equation dependent	Statement that the provided equations in a prompt is specific to that prompt when comparing the equations provided in both prompts.	3	0	3
Problem as equation independent	Statement that the provided equations in a prompt can be applied in either prompt when comparing the equations provided in both prompts.	7	7	6

C9.ST: *"Um, well Equation #1 or 2 in Problem #1 is more difficult to solve than the problem, than Equation #2 in Problem #2 and again, and the, um, the variables are a different capitalization so they might not even mean the same thing."*

The quotation by C9 above demonstrates how their inherent uncertainty with the provided first law and work expressions impacts their perceived relevance of the more familiar first law and work equations. Of the eight chemistry students which avoided using the provided physics equations, only one chemistry student (C7) came to evaluate the problem with the more familiar first law and work equations after reconciling the differences between both problems:

C7.ST: *"Like I was taking the, um, idea that from Problem 2, I was taking Equation 2, and from that I was saying that work was positive and then I was taking it and applying it to Equation 1 in Problem 1, which you can't do, you can't mix and match like that because work is found in different ways in both of the columns."*

C7 ultimately comes to a productive assessment of the physics prompt due to similarities they read out between the two prompts during the scaffolded transfer phase. Achieving this outcome notably required C7 to recognize how their ideas about work relate to the first law equations provided in the chemistry and physics prompts.

IV. CONCLUSIONS

The arbitrary alterations in notation across the chemistry, engineering, and physics prompts of this study are shown to seed different student-realized interpretations. In particular, trends were identified in what interpretations students across these disciplines make when encountering an unfamiliar context. Chemistry students were notably keen to express uncertainty when addressing unfamiliar forms of the first law and work expressions and to refrain from applying equations they felt more familiar with. Engineering and physics students, while more able to interpret the provided differences, sometimes associated additional ideas with these expressions such as deducing that an integral work expression was provided to signify a changing pressure.

Most importantly, the inclusion of the scaffolded transfer phase in this study did not appear to significantly sway students from the most prevalent unproductive approaches to evaluating the provided problems. Of the eight chemistry students that were unproductive when addressing the physics prompt, only one chemistry student shifted to productively applying the equations provided on the chemistry prompt to the physics prompt. The shortcomings of this stage may be understood when considering the critical role of epistemic agency [30] in governing to what degree students are able to build knowledge in a learning space. A student may encounter a barrier when evaluating a problem out of discipline if they conclude that signs of ambiguity or unfamiliarity are the result of a personal lack of understanding. While metacognition on what one has learned and needs to learn is useful [31], the arbitrary variation of systems, language, and notation in the case of this study provides evidence for the emergence of an epistemic barrier derived from perceived authority.

These findings further support the previously outlined call to vary instruction of the first law of thermodynamics across disciplinary environments to emphasize the conceptual, mapping, and arithmetical power of this fundamental energy and matter principle [28,29]. Furthermore, this report suggests that building productive epistemic performance [9,13] with CCCs may require a general shift towards preparing students both to conceptually grapple with cross-disciplinary topics and to recognize the capacity of physical mathematical relationships, which serve as guiding principles to CCCs, to model reality [17,24]. Future work is needed to better understand the ways in which disciplinary acculturation has impacted students' abilities to leverage CCCs for the purposes of transfer.

Findings derived from this study are non-generalizable beyond the unique classroom environments that were investigated. The application of the Dynamic Transfer framework in this study restricts the findings to exploring how students realize the provided disciplinary context and does not track how ideas that students activate in these contexts became incorporated into long-term memory.

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