2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #32903

Students' Transfer of First Law Concepts Across Engineering and Science Discipline-Specific Contexts

Dr. Alexander P. Parobek, Purdue University at West Lafayette (COS)

Dr. Alex Parobek is a graduate student and chemistry education researcher pursuing a Ph. D. in Chemistry at Purdue University. He previously received a Ph. D. in Chemistry at Yale University for work on single-molecule infrared absorption spectroscopy before transitioning into discipline-based education research. His current research interests center around investigating students' transfer of knowledge across the disciplines of science, engineering, and mathematics. He is a published author in Chemistry Education Research and Practice (CERP) and has served as a reviewer for both CERP and the Journal of Chemical Education.

Mr. Patrick M. Chaffin, Purdue University at West Lafayette (COS)

Mr. Patrick Chaffin is a Ph. D. graduate student at Purdue University conducting chemistry education research. His research interests are focused on exploring the dynamics of student-tutor interactions and students' transfer of knowledge across the disciplines of STEM. He is a published author in Chemistry Education Research and Practice.

Dr. Marcy H. Towns, Purdue University at West Lafayette (COS)

Dr. Marcy H. Towns is the Bodner-Honig Professor of Chemistry and Director of General Chemistry at Purdue University. She is a Fellow of the American Association for the Advancement, a Fellow of the American Chemical Society (ACS), a Fellow of the Royal Society of Chemistry. In 2019 she received the Nyholm Prize in Education from the Royal Society of Chemistry. She received the 2017 ACS Award for Achievement in Research for the Teaching and Learning of Chemistry and the 2017 James Flack Norris Award for Outstanding Achievement in the Teaching of Chemistry from the Northeast Section of the ACS. She has been recognized with Purdue University's most prestigious honors for teaching. Her research has focused undergraduate chemistry laboratory including the development and implementation of digital badging to assess hands-on skills, argumentation practices, student understanding of mathematics in chemistry in thermodynamics and kinetics, and student understanding of the chemistry of climate science. Trained as a physical chemist, she developed a passion for research at the interface between mathematics and chemistry that continues to inspire her to this day. She is a member of IUPAC's Committee on Chemistry Education and was an author on the IUPAC technical report that contributed to the landmark decision to redefine the mole. She served as an Associate Editor for the Journal of Chemical Education for 7 years, focusing on manuscripts pertaining to chemistry education research. Towns began her career as secondary math and chemistry teacher after graduating from Linfield College with a BA in chemistry and mathematics. She received a Jefferson Award for her engagement in activities surrounding food insecurity in her community. She holds an M.S. and Ph. D. from Purdue University in Chemistry having carried out research in chemistry education (masters) and physical chemistry (doctorate).

Students' Transfer of First Law Concepts Across Engineering and Science Discipline-Specific Contexts

Abstract

The first law of thermodynamics plays a crucial role across engineering and science classrooms by allowing students to interpret and predict the evolution of energy and matter throughout a thermodynamic process. Despite the interdisciplinary relevance of the first law, few studies to date have explored the reasoning employed by students across disciplines when addressing this central thermodynamic principle. A qualitative research study was undertaken to investigate students' reasoning approaches to first law problems across the disciplinary contexts of engineering and science. Undergraduate student participants were recruited from engineering, chemistry, and physics introductory courses and interviewed while evaluating a set of disciplines-specific first law problems. The dynamic transfer framework provided a theoretical and methodological lens for interpreting the ontological and epistemological basis for students' reasoning as it evolved dynamically over the course of the interview. Classroom observations were undertaken in each course of interest to inform findings derived from the interview portion of the study. Analysis revealed that students in each course appeared to adopt different approaches when framing the first law to address the interview tasks. Engineering and physics students appeared to rely heavily on physical mapping in order to interpret the provided descriptions and equations, while chemistry students relied more heavily on conceptually interpreting the provided descriptions to reason about changes in energy. In particular, engineering students demonstrated a preference for reasoning approaches that involved the application of the mathematical formulation of the first law of thermodynamics and often in manners that were unproductive in the problem-solving context. The variation of students' reasoning approaches and framing of the first law has implications on the effects of discipline-specific instruction of thermodynamics in engineering and science classrooms. Suggestions are made to practitioners on how to go about varying problems to assist students in developing an interdisciplinary skillset for applying and understanding the first law.

Introduction

Motivation

Traditional silo-ed approaches to teaching STEM have been deemed outdated given the inherent collaboration required among STEM experts of various disciplines to solve real world problems [1]. A call to action has been made to develop and support new educational programs for the revision of STEM education into a more integrated model [2], [3]. To this end, guiding frameworks are necessary for identifying what concepts must be incorporated into such models to effectively teach STEM in an interdisciplinary manner. In particular, the Next Generation Science Standards (NGSS) outlines the "crosscutting concepts" as the common tools and lenses shared across disciplines that may be used to bridge into alternative contexts [4], [5]. The NGSS further distinguishes "energy and matter" as a crosscutting concept with relevance across the fields of science and engineering. The first law of thermodynamics serves as a critical principle to understanding how energy and matter evolve during physical processes. This study seeks to support more integrated models of STEM education by exploring the effects of discipline-specific instruction on students' understanding of the first law of thermodynamics.

When studying the impact of instruction on a students' proficiency with crosscutting concepts, the extent to which a student can use crosscutting concepts to bridge or "transfer" ideas across disciplinary contexts is of paramount importance [4]. Transfer of learning may be defined as the process a student engages in when applying a concept learned in a familiar context to a new context [6]. Modern approaches to transfer of learning research advocate that addressing a new context inherently involves the transfer of ideas in a manner that is either "productive" or "unproductive" [7], [8]. We adopt a similar perspective of transfer given the importance of adopting a student-centered viewpoint when exploring the experiences and factors that influence students' transfer of learning [9].

Background

Previous research has been performed to explore students' transfer of energy and matter and energy ideas across disciplines. Chemistry students have demonstrated difficulty in bridging new chemistry content with first law concepts previously learned in physics instruction [10]. Similarly, the application of chemically-relevant energy concepts into a biological context has been shown to be a challenge for biology students [11]. Research suggests that the different discourses used to discuss energy and matter across disciplines may impact or even drive these difficulties [12]. Innovative curricula have been developed in recent years to integrate disciplinary discourse regarding energy to support students' transfer of energy and matter across disciplinary contexts [13], [14]. More broadly, multidisciplinary, interdisciplinary, and transdisciplinary teaching initiatives leveraging chemical concepts have shown promise in improving students' academic achievement when compared to traditional curricula [15].

While previous research has revealed energy and matter to be a challenging topic, more work is needed to determine the effects of disciplines-specific instruction on students' transfer of energy and matter. A thermodynamics textbook study by Christiansen and Rump [16] revealed that the fields of chemistry, engineering, and physics all adopt different paradigmatic conceptions of fundamental thermodynamic concepts and the first law of thermodynamics. Despite these differences in the conceptualization of thermodynamics across disciplines, little work has been carried out to date to explore students' understanding of fundamental thermodynamic concepts across discipline-specific curricula [17]–[19]. Meltzer [17] investigated chemistry, engineering, and physics students' approaches to thermodynamics problems at multiple levels of instruction. Findings derived from this study revealed that engineering students tended to rely more heavily on "plug-and-chug" methods of calculation, while chemistry students encountered difficulties when addressing standard physics notation. A study by Clark and colleagues [19] similarly found that mechanical engineering students prefer arithmetical approaches to solving thermodynamics problems when compared to chemical engineering and physics students. These findings may align with previous studies that suggest calculation-intensive instructional methods, often characteristic of the engineering classroom, erode retention by favoring procedural knowledge over conceptual knowledge [20], [21]. While these general trends across disciplines are informative, further work is necessary to uncover the different ways in which students conceptualize the first law across the fields of science and engineering.

Therefore, this study was implemented to explore chemistry, engineering, and physics students' conceptualization of the first law and the potential impacts of field-specific instruction on students' ideas. In particular, this report focused primarily on students' conceptual and arithmetical interpretations of the first law as guided by the following research question: *How do chemistry, engineering, and physics students frame the first law of thermodynamics when addressing discipline-specific first law problems?*

Dynamic transfer framework

Investigating the process of transfer as it occurs during an interview requires a theoretical and methodological basis for how transfer may evolve during discourse and how to structure interview questions to monitor this process. The "dynamic transfer" framework by Rebello and colleagues [22] provides the theoretical lens and methodological approach for monitoring the process of transfer in this study as it dynamically unfolds during the course of an interview. Students' transfer of ideas is understood according to a generic model in which a student processes an external stimulus to associate ideas stored in long-term memory (Figure 1). The dynamic transfer framework contextualizes this process by providing definitions and evidence for distinct types of ontological and epistemological ideas that students use to interpret an interview prompt.

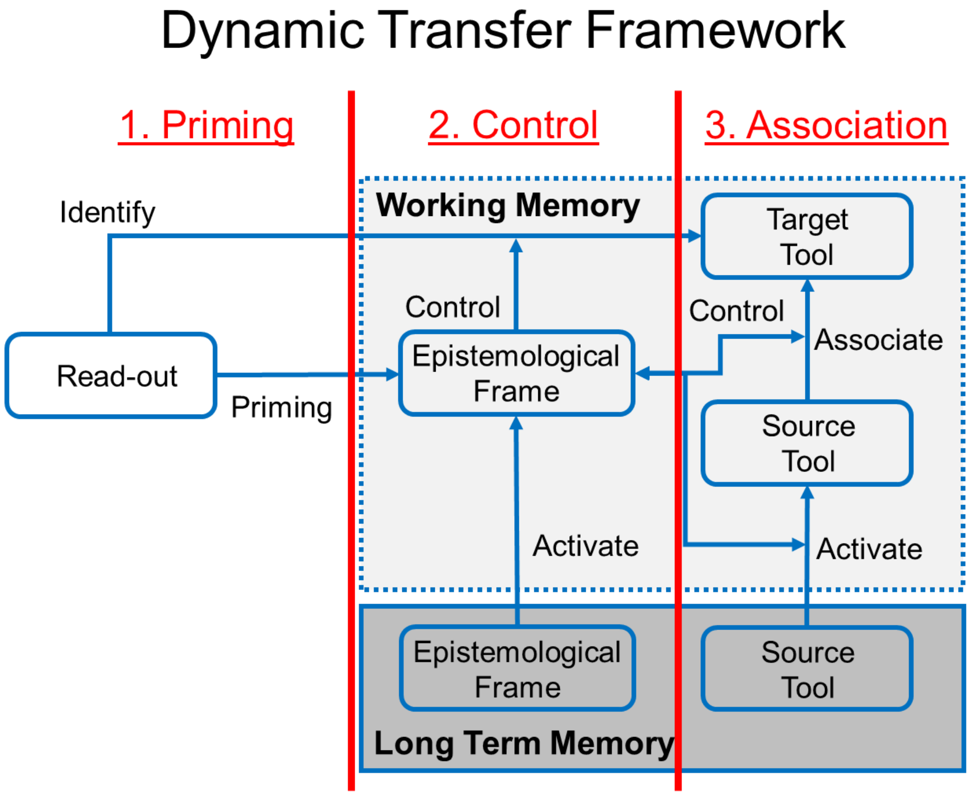

Figure 1: Dynamic transfer framework schematic adapted from Rebello and colleagues [22]. Transfer within the interview setting may be viewed as being comprised of three stages: (1) Priming, (2) Control, and (3) Association. Information read out from an interview prompt or question is used to identify the "target tool" the participant uses to "know with." Additionally, the read-out information primes the student to adopt a certain epistemological frame that shapes their expectations and controls the activation and association of ideas or "source tools."

First, a participant "reads out" an external input to identify the "target tool" or the portion of the prompt that the student uses to "know with." This read-out simultaneously primes the adoption of certain epistemic meta-tools, or frames, that control and mediate how thoughts are activated downstream. Finally, a student activates source tools, or conceptual ideas, to associate with the target tool. Previous research has demonstrated that a student may shift between epistemological frames leading to the association of productive or unproductive source tools with the target tool [23]. The two previously characterized epistemological frames "knowledge as propagated stuff" and "knowledge as fabricated stuff" describe whether a student's personal epistemology relies on transferring knowledge from authoritative sources or from the dynamic construction of knowledge respectively [24]. Additionally, students have also been found to adopt certain epistemological frames when addressing problems that involve physical equations and notations [25]. The "calculation" epistemological frame distinguishes when students deem numerical information and arithmetical approaches to be relevant to solve a problem involving mathematical relationships. Conversely, a student adopting the "physical mapping" frame assesses the relationship or "goodness of fit" between physical observations and mathematical expressions to derive a result.

Methods

Interview prompts

Three conceptual problems that focused on the first law of thermodynamics were developed to serve as interview prompts. These three interview prompts were generated by constructing the same base conceptual first law problem but with different systems [26], language [27], and mathematics notation [28] specific to each discipline studied. Chemistry, engineering, and physics textbooks were used to develop each prompt and the instructor of each course verified the relevance and form of each prompt to their specific classroom environment. Each prompt provided a mathematical formulation of the first law in addition to descriptions of processes involving a piston-cylinder system (Table 1). The choice of a piston-cylinder system was based upon the important role such model systems play in instruction across all three disciplines. Students were tasked with determining how the internal energy of the system changed based upon selecting one of three multiple choice answers: (A) the internal energy increases, (B) the internal energy decreases, or (C) cannot determine based on the information provided. While these first law formulations were included to assist students in reasoning about the first law, no numerical values were provided for computation and all prompts could be evaluated conceptually.

Table 1: Mathematical relationships provided in each discipline-specific prompt

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

The interview protocol was broken up into three separate stages (Figure 2) that progressively investigated students' interpretations of the first law and the provided interview prompts. To start, participants were asked open-ended questions about the first law of thermodynamics to better understand how they conceptualized the first law prior to any further prompting. Afterwards, students proceeded to separately address one in-discipline and one out-of-discipline interview prompt. Interview questions during the second stage were modeled after the dynamic transfer framework [22] by first asking questions that primed students to identify relevant target tools and to reflect on their expectations about the problem before solving the problem. Any identified difficulties with the disciplinary contexts encountered structured the interview questions during the scaffolded transfer interview phase. During this final stage, students were asked to compare the previously evaluated prompts and were scaffolded to recognize differences between both prompts to aid in transferring ideas across disciplinary boundaries.

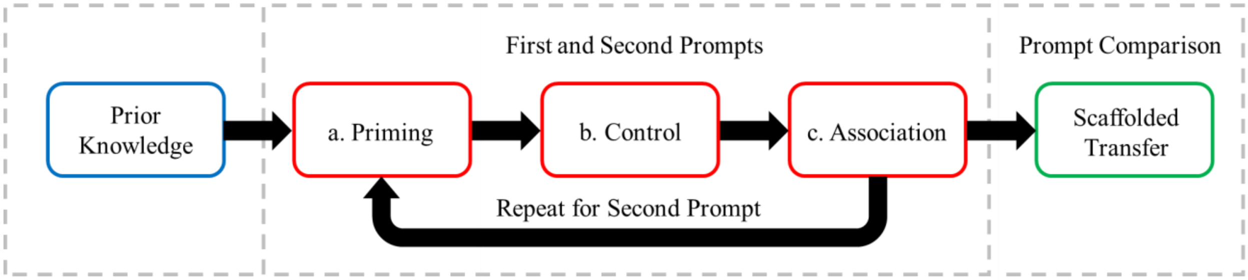

Figure 2: Structure of interview protocol divided into three distinct stages by the grey dashed lines.

Data collection and analysis

The study was conducted at a large engineering-intensive midwestern university. Approval was obtained from the Institutional Review Board at the institution to implement the applied recruitment and data collection procedures. Participants (n = 40) were recruited from chemistry-, engineering-, and physics-major courses that each represented the first instance of instruction on the first law of thermodynamics at the college-level for each respective discipline. While engineering encompasses a wide host of sub-disciplines (civil engineering, mechanical engineering, etc.), engineering was considered a single discipline in the context of this study because the institution of interest provided a single introductory thermodynamics course for many of the engineering majors. Students were provided with a $20 gift card as a financial incentive for participating in the study. A post-interview questionnaire was utilized to monitor the extent of students' prior experiences in coursework across chemistry, engineering, and physics. Audio and writing generated by participants was recorded with a Livescribe pen. All interview transcript data were de-identified and pseudonyms were assigned to each interview participant such that the first letter of each name starts with a "C," "P," and "E" corresponding to the disciplines-specific course in which each student was enrolled. The out-of-discipline prompt selected for each student was selected based upon the traditional course sequences in each respective discipline. As such, engineering students (n = 20) addressed both chemistry and physics prompts, while chemistry and physics students (n = 10, each) did not address the engineering prompt. Therefore, four unique prompt combinations were applied, and each combination had an equal number of participants that began with an in-discipline and out-of-discipline prompt. In addition to the interview study, classroom observations were performed in each course of interest to better understand how students were drawing upon discipline-specific information when interviewed.

A general inductive analysis approach was utilized to code and categorize interview transcript data generated during the interview phase [29]. The analysis was grounded in the dynamic transfer framework by distinguishing emergent codes according to the structural elements of the framework [22]. In the case of this report, the findings are specific to the associations students made in reference to the first law of thermodynamics to answer the question posed by the interview prompt. Transcribed interview data was organized and processed using a NVivo 12 software package. A subset of interviews (n = 8) were coded by the first and second authors to assess the reliability of the findings through the calculation of a pooled Cohen's kappa statistic [30]. Interrater reliability calculations resulted in a 0.82 pooled Cohen's kappa value indicating sufficient agreement in the coding scheme [31].

Results

Analysis of students' interpretations of the first law resulted in the emergence of three distinguishable reasoning approaches: direction-oriented, magnitude-oriented, and process-oriented reasoning (Table 2). These distinct types of reasoning represent distinguishable approaches students used to frame the first law when tasked with the conceptual first law problems provided in this study. The nature of these three reasoning approaches and their dependence on disciplinary background are utilized to address the posited research question of this study.

Table 2: Summarized definitions for the three emergent first law reasoning approaches

Reasoning Approach	**Summarized Definition**
Direction-oriented	The provided descriptions or interpretation of the given system is associated with a particular sign of work and heat in the provided equations.
Magnitude-oriented	The numerical values or magnitude of the work or heat terms in the provided equations or of contributing changes in internal energy is suggested to be relevant to the prompt.
Process-oriented	A change in internal energy is interpreted based upon any provided or inferred system properties and associated processes without reference to the provided equations.

All three identified reasoning approaches were found to emerge from students across the disciplinary backgrounds studied, but to varying degrees and often with different character. Figure 3 summarizes the average percent coverage of each reasoning approach for students in each respective disciplinary course sequence. Engineering students demonstrated a preference for direction-oriented and magnitude-oriented reasoning, while chemistry students favored direction-oriented and process-oriented reasoning over magnitude-oriented reasoning. Averaging the percent coverage across all physics students resulted in a notably even distribution of reasoning approaches. For the purposes of exploring the content and character of these reasoning approaches, three representative interviews were chosen for analysis and discussion.

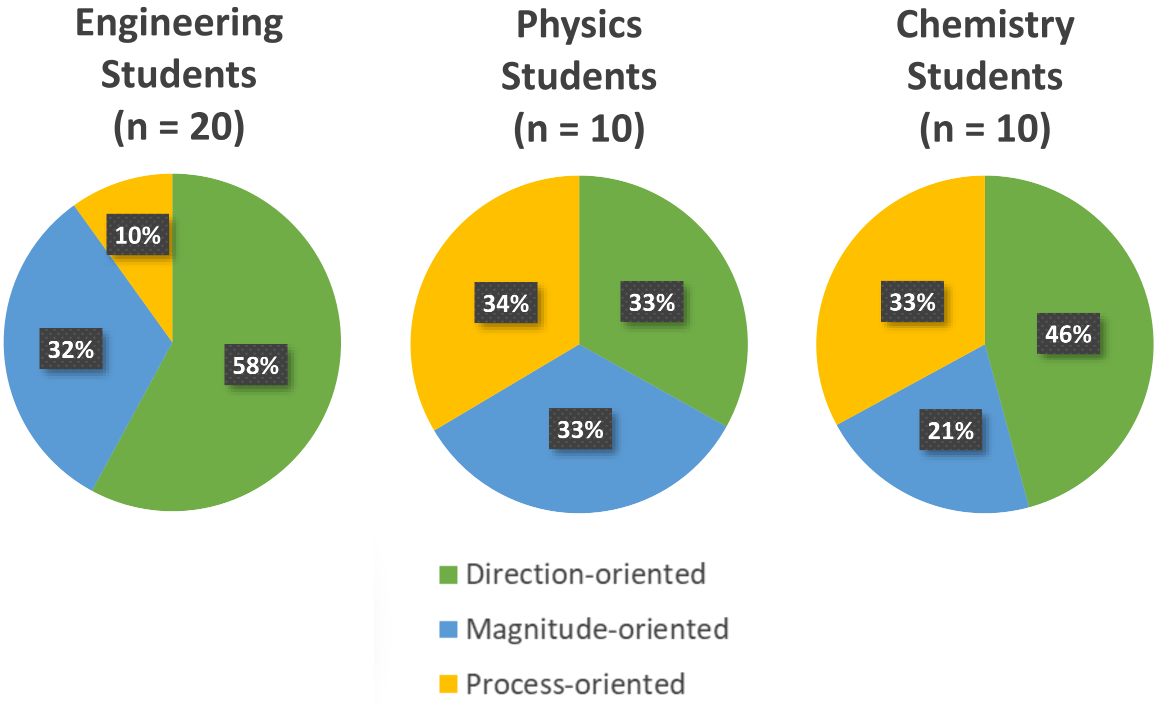

Figure 3: Average percent coverage of each reasoning strategy calculated via NVivo analysis software for each discipline-specific course of interest. Percent coverage values were calculated by (1) normalizing the percent coverage of each reasoning strategy by the total percent coverage of all reasoning strategies per interview, (2) averaging the percent coverages for each interview according to disciplines, and (3) dividing by the total number of interviews for each respective discipline.

Direction-oriented reasoning

Many students utilized the provided first law of thermodynamics equation to physically map the described processes to reason about how the internal energy would increase or decrease. Eli demonstrated a heavy preference for applying direction-oriented reasoning regardless of the provided disciplinary prompt. Consider the following statements by Eli when addressing the engineering prompt:

> Interviewer: “All right, so to start, what descriptions in this question, if any, do you feel are relevant to the first law of thermodynamics?”
>
> Eli: “Uh, it moves out of the, uh, the piston, the piston is pushed further out of the cylinder means that there is a boundary work, uh, cylinder-. The fact that it's allowed to thermally equilibrate by being surrounded by an c-, col-, I, what I assume is a colder surrounding. So I would assume that there is, um, a heat transfer, a negative heat transfer.

> And, yeah, those are the two things. […] Uh, so as I said earlier, heat transfer is um negative because you have, heat, um, there's, there's, there's transfer of heat from the system to the surroundings. Yeah. And uh, so, that's Q-. Boundary work is positive, so that would, that would be negative, positive W equals Delta-U and K-E and P-E are negligible in this problem, so that would be that. Um, which would be negative Q minus W will always be a negative value.”

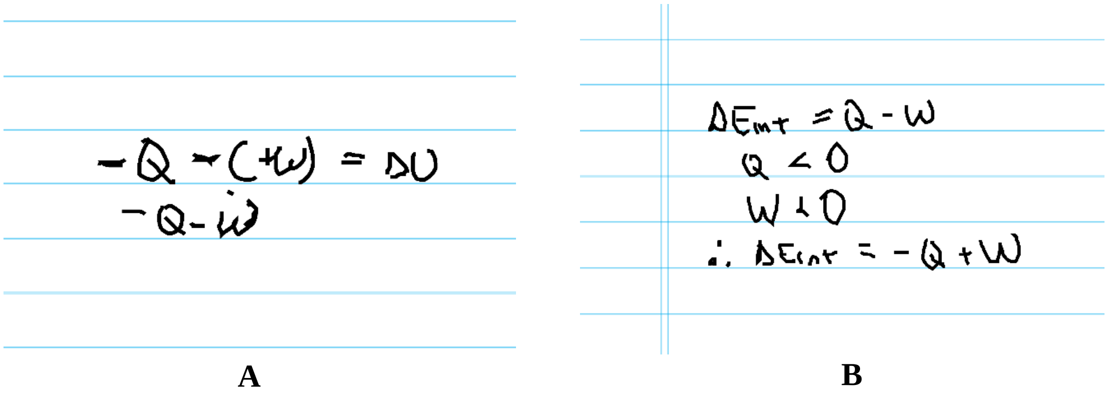

Figure 4: Eli’s written work when evaluating the engineering prompt (A) and the physics prompt (B). Direction-oriented reasoning was most commonly accompanied by sign insertions into the first law equation as demonstrated above by Eli.

Eli drew directly upon provided statements about heat transfer and boundary work to reason about the signs associated with the Q and W terms in the first law equation. It is important to note that Eli referred directly to the variables in the first law equation to evaluate the problem. Therefore, the first law equation itself is established as the target tool that the student uses to know about changes in internal energy. Ideas about the relationship between the provided descriptions and the target tool are then used to evaluate the prompt. Similar to other students that adopted direction-oriented reasoning, Eli justified his responses by re-writing the first law equation with accompanying sign insertions based upon interpretations of the provided descriptions (Figure 4).

Direction-oriented reasoning may be viewed from the dynamic transfer framework as the identifying of the first law equation as the target tool and associating the equation with ideas about the equation’s dependence on the provided description. Figure 5 summarizes the connectivity of these elements and demonstrates how a physical mapping epistemological frame may be used to describe how a student frames the first law to solve the problem. In direction-oriented reasoning, the student reads out description that is physically relevant to the first law and this in turn primes the adoption of a physical mapping frame that then controls the identification of the first law equation as the target tool [25]. The physical mapping frame adopted then guides students to draw upon ideas that allow them to assess the goodness of fit between the provided descriptions and the first law equation.

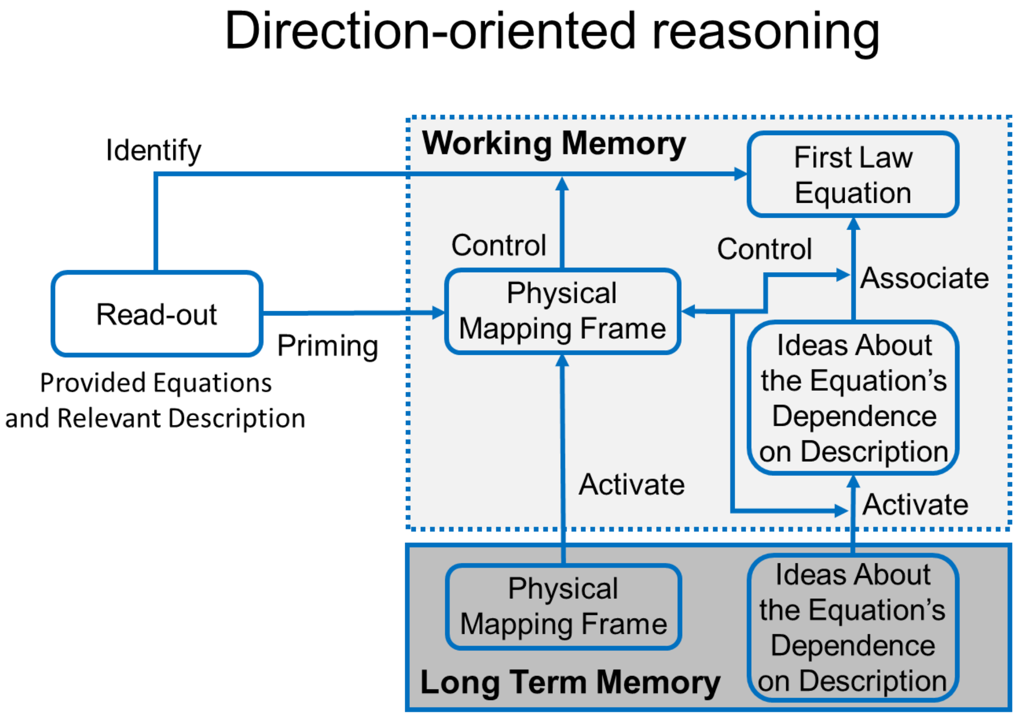

Figure 5: Dynamic transfer [22] schematic of direction-oriented reasoning. In direction-oriented reasoning, a student reads out the provided equations and relevant description to associate ideas that relate the provided equations and description. The physical mapping frame mediates this reasoning approach by allowing such ideas to be made available to the student when evaluating the problem.

Magnitude-oriented reasoning

Participants at times indicated that the magnitude of the work and heat terms associated with the provided first law equation were essential to solving the problem. Such instances were designated as “magnitude-oriented reasoning” given the emphasis placed upon using the first law equation to determine the change in internal energy through some anticipated arithmetic. In the case of this interview study, magnitude-oriented reasoning was most often unproductive given that the conceptual problems provided did not include numerical values. While magnitude-oriented reasoning was identified across disciplines, engineering and physics students demonstrated a preference for magnitude-oriented reasoning especially during the earlier stages of the interview (Figure 3).

Evan strikingly adopted only magnitude-oriented reasoning throughout the duration of his interview. When first asked what the relevant pieces of the engineering prompt were, Evan cited attributes that he would expect to be known based on his prior experiences:

> Evan:” Um, so I'm gonna have to know the final temp, well not necessarily. Um, I think that the final temperature of the, the gas after placing into the ice bath will be critical and also the mass of the cylinder. Also the volume of the initial and final gas. Well, yeah, the volume of the gas before and after placing into the ice bath.”

> Interviewer: “I see. And could, could you provide your own explanation as to why you feel these pieces are relevant?”

> Evan: “Um, well, first of all, in almost all of my homework and exam questions, we are, we are asked to find, or we were, we were given the volume of the gas before and after the change, as well as the temperature of the gas before and after the change.”

Evan’s perception that the values of properties such as temperature, volume, and pressure were critical to solving the problem ultimately led him to conclude that the change in energy could not be determined for either prompt. When coming to this conclusion, Evan cited further expectations on what information he would expect to be provided to come to an alternative answer:

> Evan: “Well, at this point I would say it's definitely C, because I don't know any of the numerical values or the, uh, the property table of nitrogen. So I would choose C at this point.”

The referral to “property tables” by Evan was a common theme unique to engineering students that adopted magnitude-oriented reasoning:

> Edwin: “Uh, but other things that you'd want to like understand within this, there's like a lot of things, like you get a lot of values from, uh, thermo tables, thermodynamic tables and you could get those values based on the state that your system is with-, is in.”

> Eugene: “Well often what we do in classes, we have our, our thermo tables, which they mainly describe the properties of the compressed liquid, saturated liquid-vapor mixture and superheated vapor states of different substances and if I had either that or some form of information from one of those I would just be would, I would use that to find the um, the change in heat energy, the heat energy put into the system.”

Students adopting magnitude-oriented reasoning tied the need for values to the variables provided in the first law equation (Figure 6). Therefore, similar to direction-oriented reasoning, magnitude-oriented reasoning relies on associating ideas with the first law as a target tool. However, adopting magnitude-oriented reasoning involves associating ideas about numerical values with the target tool and so students drew upon ideas of what numerical values they perceived necessary to evaluate the problem. The reliance of students on numerical values when adopting magnitude-oriented reasoning may be understood when considering the role of the epistemological calculation frame in controlling the target tool and the ideas that are made available to the student [25].

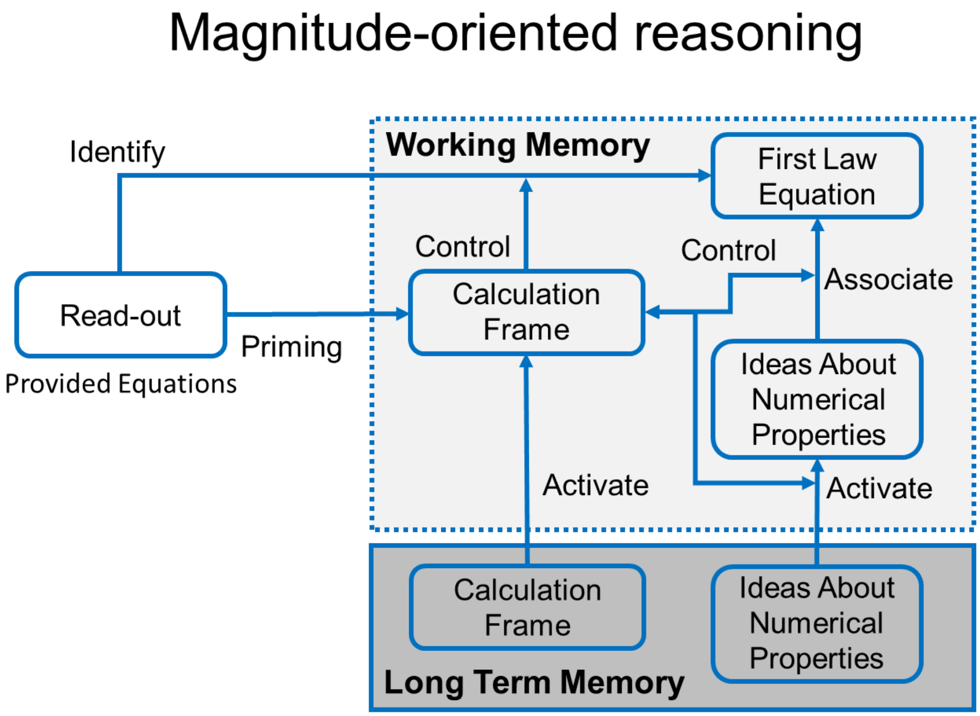

Figure 6: Dynamic transfer [22] schematic of magnitude-oriented reasoning. In magnitude-oriented reasoning, a student reads out only the provided equations to associate numerical properties that are expected to help evaluate the problem. The calculation frame controls this process allowing only the activation of ideas about numerical properties.

Generally, most engineering students were able to eventually adopt direction-oriented reasoning but only after notable transitions in their reasoning often accompanied by moments of cognitive dissonance:

> Eugene: “Main problem is even though I know where, where the work's being done, where the, where the, where the heat energy, where the compression work is being done. Unfortunately. I just don't know. I don't just don't, don't have any values to give them. […] Yeah what am I saying? I mean of course I can, of course I'm going to tell the internal energy is going to increase, such is the power of forgetting that you've actually read the question and already have kind of a base idea of what's your answer might be.”
>
> Emmett: “But it's still, it's still doesn't tell me exactly what those initial and final volumes were. So I still can't, that still doesn't really help with my analysis. Oh actually. Mmm. Okay. Okay. Cause, cause you can get pressure from um, sorry, I'm just kind of going through it right now. Yeah. Okay. You can definitely find pressure using tables and then, and okay. It's not asking for a specific answer for it. Um, so I guess it can be B because if I know that the final volume is greater than the initial volume, I know that the uh, uh, Delta-V term will always be positive and there is a way to find pressure.”

The stark transitions in these statements provide evidence for an epistemological shift in how students approach the problem through calculation and physical mapping frames. Shifts from magnitude-oriented to direction-oriented reasoning were most pronounced for engineering students, while most chemistry and physics students utilized magnitude-oriented reasoning to add upon ideas previously activated and associated through alternative reasoning approaches.

Process-oriented reasoning

Some participants appeared to draw upon perceived energy changes based directly on the described processes without reference to the provided equations, process-oriented reasoning. For example, when Cynthia was asked to interpret any descriptions that she felt were particularly relevant to the first law, she stated:

> Cynthia: “Um, it kinda is just because if the space is decreasing after, once you're pushing the piston down, then you still can't lose energy as that piston is being pushed down. It has to kind of stay in there or else it wouldn't, it would create energy or it would destroy energy and you can't do that.”

Cynthia refers to how the described process would result in a loss of energy and relates this back to their conceptual understanding of the first law as a principle that energy cannot be created or destroyed. Students adopting process-oriented reasoning, like Cynthia, did not draw upon the provided first law equation but instead discussed how the energy would change or transfer based on the read-out processes. When evaluating the physics problem, Cynthia went on to describe why they do not need to account for the provided equations:

> Cynthia: “Um, yes, probably because you don't really need to know like numbers or anything to solve it. You just kinda need to know the basics of the first law.”
>
> Interviewer: “I see. And, um, could you expand upon what you mean by the basics of the first law?”
>
> Cynthia: “Like, if you know that the energy cannot be created or destroyed then you should be able to solve the problem and know what the energy of the open space is going to do.”

When pressed further about what Cynthia meant by “what the energy of the open space is going to do,” Cynthia drew upon the ideal gas law and collision theory in order to determine that compressing the gas would in turn increase the energy in the system:

> Cynthia: “Well, when you're learning about the ideal gas law, you kind of learn about the pistons and how when you press down on the piston then you're going to get more pressure and more heat, and it's just going to overall give more energy to the system because there's less space for the gases to move around.”

Mechanistic explanations such as this were common for students adopting process-oriented reasoning as a justification for why such reasoning was valid. Relating the described macroscopic processes to molecular phenomena however requires a student to draw upon knowledge that cannot be directly interpreted from the prompt. More importantly, it requires a student to be comfortable with the notion that they can fabricate an explanation based on alternative principles they have previously learned. Process-oriented reasoning therefore may be viewed as being mediated by the epistemological frame “knowledge as fabricated stuff” [24] wherein the target tool is an underlying energetic process that a student identifies based upon the read-out of energy-relevant description (Figure 7). In effect, this approach frames and applies the first law as a conceptual principle to address the question posed by the interview prompt. Within this dynamic transfer model, the student can make ideas about energetic processes available by utilizing “knowledge as fabricated stuff” to bridge expectations about how energy should change and transfer across macroscopic and molecular scales.

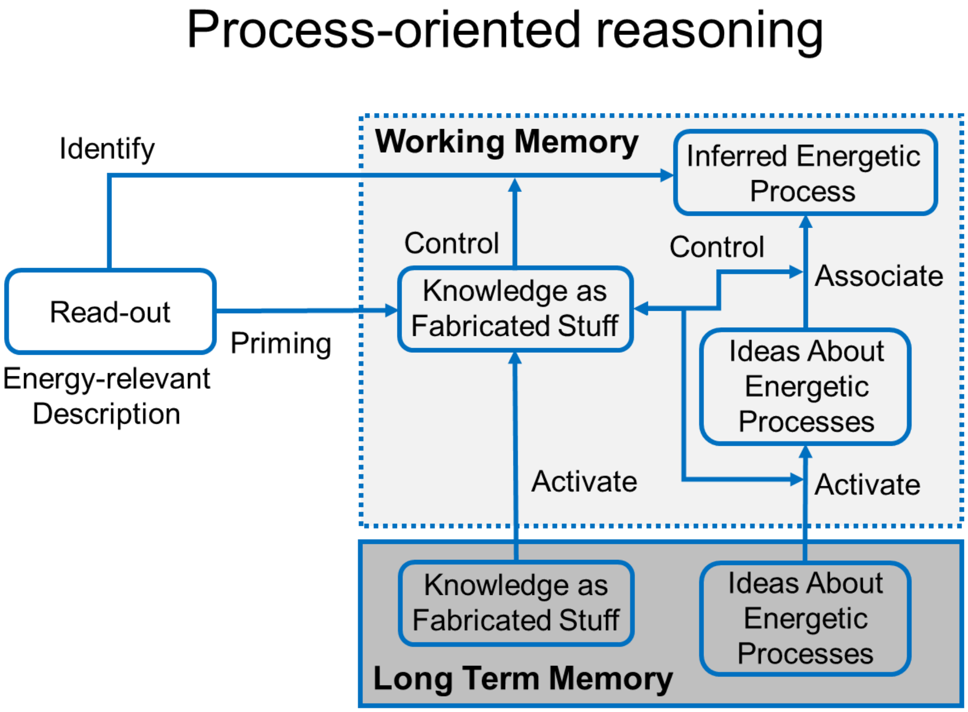

Figure 7: Dynamic transfer [22] schematic of process-oriented reasoning. In process-oriented reasoning, a student reads out energy-relevant description to establish a perceived underlying energetic process as the target tool. Next, a student associates ideas about energetic processes with the recognized energetic process based upon their conceptual understanding of how the first law describes changes in energy. This reasoning is controlled by the “knowledge as fabricated stuff” frame because associated ideas about energetic processes are discussed through causal-mechanistic explanations that are constructed by the student.

Discussion

The three emergent reasoning approaches identified were observed across disciplines; however, the frequency and character of these reasoning strategies did appear to depend on a student’s disciplinary background. For example, engineering students demonstrated a notable preference for reasoning approaches that designated the first law equation as the target tool (Figure 6) and exhibited abrupt transitions from magnitude-oriented reasoning into alternative reasoning approaches. The difficulty in engineering students’ transitions is believed to be in part due to the different ways in which thermodynamics was taught and framed across the three disciplinary tracks studied.

Classroom observations within the engineering classroom revealed that the vast majority of problems were numerical. Engineering students were often tasked to draw upon information contained in thermodynamic tables or graphs relevant to characteristic types of systems (such as superheated vapors, condensed liquids, etc.) Physics students also addressed predominately numerical problems, but in a manner where the first law was generalized as an overarching "energy principle." Problems and examples in the physics classroom demanded students to consider how to apply the energy principle according to the unique properties of the system in question. The emphasis on numerical problems in both the engineering and physics disciplinary tracks studied may aid in explaining the preference of both disciplines in designating the first law equation as a target tool, while the framing of the first law as a principle in the physics classroom may assist students in avoiding abrupt transitions in their reasoning.

Conversely, chemistry students evaluated a small number of numerical problems with the full functional form of the first law. Instruction instead emphasized causal-mechanistic discussions of how pressure and temperature changes resulted in changes in energy for a chemical system of interest. These differences in instruction are reflected in the preference of chemistry students to adopt process-oriented reasoning in comparison to engineering and physics students (Figure 3). However, it is important to note that the emphasis on the conceptual nature of the first law in the chemistry classroom did not necessarily make chemistry students flexible when it came to the formulation of the first law. Cynthia drew upon process-oriented reasoning to first address the physics prompt and then direction-oriented reasoning for the chemistry prompt. Cynthia commented upon the differences in her reasoning during the scaffolded transfer phase:

> Cynthia: "Well, in Problem 1, I don't really know how the equations relate to the problem, whereas in question number or Problem #2, I'm more know how the, how those equations relate to the problem. So I drew on those problems rather than a law I knew, I guess."

The reformulation of the first law provided in each of the prompts (Table 1) was notably difficult for chemistry students to address and may in part arise from limited experience in utilizing the first law in its functional form. Engineering students did not encounter these difficulties to the same degree and almost all engineering students that initially adopted magnitude-oriented reasoning were able to eventually transition into a more productive reasoning approach (8 of 9 students). The potential benefits of teaching the first law as an arithmetical and conceptual tool was demonstrated by some physics students who moved seamlessly between each form of reasoning to further nuance their interpretations of the provided prompts. However, it is unclear whether instances in which students moved freely between each reasoning approach was the result of their integration of concepts across multiple classroom environments or an effective assimilation of concepts presented in their discipline-specific course.

Conclusions and implications

Analysis of interview and observational data obtained in this study revealed that students across the fields of chemistry, engineering, and physics appear to adopt different reasoning approaches when addressing conceptual first law problems. In particular, three distinct reasoning approaches emerged from the dataset that have each been described within the theoretical underpinnings of the dynamic transfer framework. These findings demonstrate that the ways in which each discipline frame the first law impact the approaches that students adopt to solve first law problems across disciplinary contexts. However, the critical role of the first law as a guiding principle for the crosscutting concept of energy and matter suggests that limiting students' interpretations of the first law along discipline-specific boundaries is undesirable. Indeed, the apparent benefits and drawbacks of the reasoning approaches adopted by participants appears to align with this sentiment. We therefore suggest that practitioners focus on adapting teaching materials across disciplines to demand the epistemological frames needed to invoke direction-, magnitude-, and process-oriented reasoning. While each discipline will always incorporate a certain degree of systems, language, and notation specific to that discipline, it is critical that all practitioners recognize and teach to the variety of ways in which the first law can be interpreted and applied to solve problems across the many disciplinary contexts of STEM. Findings derived from this study are nongeneralizable beyond the classrooms studied and the relevance of the implications derived from these findings will depend on the nature of the discipline-specific curricula offered at a given institution.

References

[1] Office of Science and Technology Policy, *Summary of the White House Release Event for the 2018 STEM Education Strategic Plan*. Washington, DC: The White House, U.S. Government Printing Office, 2018.

[2] National Research Council, "Convergence is informed by research areas with broad scope," in *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*, Washington, DC: National Academies Press, 2014, pp. 43–58.

[3] Massachusetts Institute of Technology, "Recommendations for accelerating the convergence revolution," in *Convergence: The Future of Health*, Cambridge, MA: MIT, 2016, pp. 66–77.

[4] M. Cooper, "The crosscutting concepts: Critical component or 'third Wheel' of three-dimensional learning?," *J. Chem. Educ.*, vol. 97, no. 4, pp. 903–909, 2020.

[5] NGSS Lead States, *Next Generation Science Standards: For States, By States (Appendix G – Crosscutting Concepts)*. Washington, DC: The National Academies Press, 2013.

[6] M. K. Singley and J. R. Anderson, "The study of transfer," in *The Transfer of Cognitive Skill*, Cambridge, MA: Harvard University Press, 1989, pp. 1–41.

[7] J. D. Bransford and D. L. Schwartz, "Rethinking transfer: A simple proposal with multiple implications," *Rev. Res. Educ.*, vol. 24, no. 1, pp. 61–100, 1999.

[8] J. Lobato, "How design experiments can inform a rethinking of transfer and vice versa," *Educ. Res.*, vol. 32, no. 1, pp. 17–20, 2003.

[9] J. Lobato, "The actor-oriented transfer perspective and its contributions to educational research and practice," *Educ. Psychol.*, vol. 47, no. 3, pp. 232–247, 2012.

[10] L. C. Hadfield and C. E. Wieman, "Student interpretations of equations related to the first law of thermodynamics," *J. Chem. Educ.*, vol. 87, no. 7, pp. 750–755, 2010.

[11] K. P. Kohn, S. M. Underwood, and M. M. Cooper, "Energy connections and misconnections across chemistry and biology," *CBE Life Sci. Educ.*, vol. 17, no. 1, pp. 1–17, 2018.

[12] L. M. Hartley, J. Momsen, A. Maskiewicz, and C. D. D'Avanzo, "Energy and Matter : Differences in discourse in physical and biological sciences can be confusing for introductory biology students," *Bioscience*, vol. 62, no. 5, pp. 488–496, 2012.

[13] E. F. Redish *et al.*, "NEXUS/Physics: An interdisciplinary repurposing of physics for biologists," *Am. J. Phys.*, vol. 82, no. 5, pp. 368–377, 2014.

[14] M. Cooper and M. Klymkowsky, "Chemistry, life, the universe, and everything: A new approach to general chemistry, and a model for curriculum reform," *J. Chem. Educ.*, vol. 90, no. 9, pp. 1116–1122, 2013.

[15] J. G. Hardy *et al.*, "Potential for chemistry in multidisciplinary, interdisciplinary, and transdisciplinary teaching activities in higher education," *J. Chem. Educ.*, vol. 98, no. 4, pp. 1124–1145, 2021.

[16] F. V. Christiansen and C. Rump, "Three conceptions of thermodynamics: Technical matrices in science and engineering," *Res. Sci. Educ.*, vol. 38, no. 5, pp. 545–564, 2008.

[17] D. E. Meltzer, "Investigation of student learning in thermodynamics and implications for instruction in chemistry and engineering," *AIP Conf. Proc.*, vol. 883, pp. 38–41, 2007.

[18] B. R. Bucy, "Investigations of student understanding of entropy and of mixed second-order partial derivatives in upper-level thermodynamics." Ph.D. dissertation, The University of Maine, Orono, ME, 2007.

[19] J. W. Clark, J. R. Thompson, and D. B. Mountcastle, "Investigating student conceptual difficulties in thermodynamics across multiple disciplines: The first law and P-V diagrams," in *ASEE Conf. Proc.*, 2014, pp. 1–17.

[20] J. Engelbrecht, C. Bergsten, and O. Kågesten, "Conceptual and procedural approaches to mathematics in the engineering curriculum: Student conceptions and performance," *J. Eng. Educ.*, vol. 101, no. 1, pp. 138–162, 2012.

[21] J. Engelbrecht, A. Harding, and J. Du Preez, "Long-term retention of basic mathematical knowledge and skills with engineering students," *Eur. J. Eng. Educ.*, vol. 32, no. 6, pp. 735–744, 2007.

[22] N. S. Rebello *et al.*, "Dynamic transfer: A perspective from physics education research," in *Transfer of Learning from a Modern Multidisciplinary Perspective*, J. P. Mestre, Ed. Greenwich, CT: Information Age Publishing, 2005, pp. 217–250.

[23] M. C. Wittmann and R. E. Scherr, "Student epistemological mode constraining researcher access to student thinking: An example from an interview on charge flow," *PERC Proc.*, pp. 1–4, 2002.

[24] D. Hammer and A. Elby, "On the form of a personal epistemology," in *Personal Epistemology: The Psychology of Beliefs About Knowledge and Knowing*, B. K. Hofer and P. R. Pintrich, Eds. Mahwah, NJ: Lawrence Erlbaum Associates Publishers, 2002, pp. 169–190.

[25] T. J. Bing and E. F. Redish, "Analyzing problem solving using math in physics: Epistemological framing via warrants," *Phys. Rev. ST Phys. Educ. Res.*, vol. 5, p. 020108 (18 pp.), 2009.

[26] W. L. Hall, "A qualitative study of the ways students from the biological and life sciences solve calculus accumulation tasks." Ph.D. dissertation, North Carolina State University, Raleigh, NC, 2017.

[27] L. J. Bracken and E. A. Oughton, "'What do you mean ?' The importance of language in developing interdisciplinary research," *Trans. Inst. Br. Geogr.*, vol. 31, no. 3, pp. 371–382, 2006.

[28] F. R. Yeatts and J. R. Hundhausen, “Calculus and physics: Challenges at the interface,” *Am. J. Phys.*, vol. 60, no. 8, pp. 716–721, 1992.

[29] D. R. Thomas, “A general inductive approach for analyzing qualitative evaluation data,” *Am. J. Eval.*, vol. 27, no. 2, pp. 237–246, 2006.

[30] H. De Vries, M. N. Elliott, D. E. Kanouse, and S. S. Teleki, “Using pooled kappa to summarize interrater agreement across many items,” *Field methods*, vol. 20, no. 3, pp. 272–282, 2008.

[31] K. A. Hallgren, “Computing inter-rater reliability for observational data: An overview and tutorial,” *Tutor. Quant. Methods Psychol.*, vol. 8, no. 1, pp. 23–34, 2012.