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Exploring the impact of disciplinary context on students' dynamic transfer of learning when addressing problems that apply the first law of thermodynamics

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ABSTRACT

A widespread call has been made to develop and support more integrated approaches to STEM education. The first law of thermodynamics serves as a guiding principle for the crosscutting concept of energy and matter. A qualitative interview study was undertaken to support integrated approaches to STEM education by exploring how chemistry, physics, and engineering students ($n=40$) transfer first law concepts across disciplinary contexts. Acquired interview data were analysed through the lens of the dynamic transfer framework to reveal the underlying contextual elements students used to know with. Emergent trends across the disciplines revealed how these applied reasoning approaches and epistemologies were realised by each discipline. Productive transfer is shown to be facilitated by the coordination of different disciplinary epistemologies. Suggestions are made to practitioners on how to support students in applying different reasoning approaches when addressing first law problems. The applied methods also serve as a promising methodology for future investigation of students' transfer of crosscutting concepts.

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Introduction

Motivation

There is widespread recognition that STEM education should be integrated across different disciplines in a way that allows students to make connections between concepts learned in separate disciplinary contexts (National Academies of Sciences, Engineering, and Medicine, 2018). This assessment is made with the recognition of the substantive collaboration within the STEM workforce (National Science and Technology Council, 2018) and the many career pathways undertaken by STEM graduates (National Science Board, 2015). However, STEM education is still often 'silo-ed' so that discipline-specific concepts are taught in separate course environments (Breiner et al., 2012). The implementation of integrated models of STEM education have revealed the potential benefits of multidisciplinary, interdisciplinary, and transdisciplinary teaching in the improvement

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of student achievement in and attitude towards STEM (Becker & Park, 2011; Hardy et al., 2021). Some researchers have even undertaken the design of innovative curricula to assist students in bridging across disciplinary boundaries within a content area of interest (Cooper & Klymkowsky, 2013a; Redish, Bauer, et al., 2014). While the benefits of integrated STEM education are apparent, additional guidance is needed to identify what content must be addressed through integrated instruction for students to make connections across disciplinary contexts.

The Next Generation Science Standards (NGSS) outlines the ‘crosscutting concepts’ or the common tools or lenses that are shared by the disciplines of STEM (Cooper, 2020; Next Generation Science Standards Lead States, 2013). The distinguished role of the crosscutting concepts within the NGSS model provides a useful set of guidelines for what topics should be instructed on in an interdisciplinary manner. In particular, ‘energy and matter,’ or the ‘tracking of fluxes of energy and matter into, out of, and within systems,’ is distinguished by the NGSS as a crosscutting concept (Next Generation Science Standards Lead States, 2013). Despite the critical role that crosscutting concepts play in bridging across disciplinary boundaries, crosscutting concepts have seen little attention in the research literature to date (Cooper, 2020). We seek to support the development of integrated STEM instruction by exploring the impact of traditional silo-ed instruction on students’ conceptualisation of the crosscutting concept of energy and matter.

Transfer of learning

The act of bridging across disciplinary boundaries by the recognition of a crosscutting concept may be viewed as transfer of learning across instructional environments. Transfer has traditionally been defined as the application of a previously learned concept to an unfamiliar context (Singley & Anderson, 1989). Traditional transfer of learning research involved monitoring students’ application of researcher-defined target concepts or skills between different instructional environments and often failed to reproduce transfer in an experimental setting (Detterman, 1993). Some researchers have posited that these trends are due to the fragmented nature of students’ knowledge and the resulting lack of coherence in the application of previously learned concepts (diSessa, 1993; Hammer et al., 2005). Other researchers have criticised the traditional transfer of learning research methodology and attributed its shortcomings to theoretical deficiencies in researcher-defined performance metrics and the conflation of context with task (Cobb & Bowers, 1999; Lave, 1988). To address these challenges, a major shift was undertaken in the learning sciences to develop student-centred models of transfer to interpret the cognitive processes students engage in when addressing unfamiliar contexts (Bransford & Schwartz, 1999; Greeno et al., 1993; Lobato, 2003). The application of these models has revealed that transfer occurs frequently in ways that may be distinguished as either ‘productive’ or ‘unproductive’ (Lobato, 2012; Schwartz et al., 2012).

Transfer studies are often distinguished across different dimensional aspects given the broad breadth and scope of transfer of learning research (Royer et al., 2005). The similarity of the contexts addressed and the extent to which students are asked to transfer is often distinguished accordingly as ‘near’ versus ‘far’ transfer (Dori & Sasson, 2013). Transfer of learning may also be viewed along cognitive dimensions based on whether the process of transfer involves a student mapping information onto a pre-existing mental framework,

‘horizontal’ transfer, or constructing a new mental framework, ‘vertical’ transfer (Rebello et al., 2007). The distinction between vertical and horizontal transfer further implies that transfer is inherently a learning process and that a student’s cognitive structure is altered by the process of transfer.

An area of expanding interest within transfer of learning literature is on the important role of a student’s underlying epistemology, or beliefs about the nature of knowledge within certain disciplines, on productive transfer (Greene et al., 2021; Redish, Sawtelle, et al., 2014). This expansion in transfer of learning research on epistemology has revealed that different disciplinary learning environments may provide students with differing and, at times, conflicting epistemological messages (Gouvea et al., 2019; Kohn et al., 2018). Research in this area has highlighted the need for instructors to emphasise the value of various field-specific epistemological viewpoints and approaches (Gouvea et al., 2019; Redish, Sawtelle, et al., 2014). This is especially challenging given recent studies that have suggested practitioners may have rigid epistemological views that translate heavily into their methods of instruction (Park et al., 2022; Vale et al., 2019). Building and monitoring apt epistemic performance across disciplinary contexts should therefore be viewed as a major goal of integrated STEM instruction and transfer of learning research (Barzilai & Chinn, 2018; Greene et al., 2021; Wu & Tsai, 2022).

Transfer of energy and matter knowledge within and across disciplines

Students’ transfer of energy and matter knowledge across disciplines is accompanied by the significant challenge of reconciling discipline-specific concepts and discourse learned across different science courses (Hartley et al., 2012; Lancor, 2014). An example of such interdisciplinary reconciliation is self-evident in students’ difficulties when discussing whether the breaking of a chemical bond releases or absorbs energy (Cooper & Klymkowsky, 2013b). The challenge of reconciling the energetic process of bond breaking may be understood when considering the unique contexts under which the fields of biology and chemistry use energy concepts and how the nature, history, and culture of these fields impacts the integration of energy into each discipline (Kohn et al., 2018). Similar difficulties have been documented when addressing the energy and matter topics of free energy (Geller et al., 2019; Wolfson et al., 2014), intermolecular interactions (Teichert et al., 2008), energy transformation (Macrie-Shuck & Talanquer, 2020), and the first law of thermodynamics (Ding et al., 2013; Hadfield & Wieman, 2010). In particular, Geller et al. (2019) demonstrated the importance of framing the content of an interdisciplinary physics course as building on students’ existing knowledge of disciplinary concepts and providing useful crosscutting tools for establishing explanatory coherence. Explicit scaffolding between discipline-specific examples of energy and matter processes has also been shown to help students make connections between foundational energetic systems within the disciplines of chemistry and physics (Nagel & Lindsey, 2015). While these studies have contributed greatly to our understanding of and techniques for reconciling energy and matter in singular classroom contexts, few studies have compared students’ transfer of energy and matter knowledge across the disciplines of STEM.

The laws and principles of thermodynamics that are essential to understanding energy and matter provide their own unique set of challenges to students attempting to navigate disciplinary boundaries. A textbook analysis conducted by Christiansen and Rump

(2008) demonstrated the unique paradigmatic conceptions of fundamental thermodynamics concepts employed by the disciplines of chemistry, physics, and engineering. A comparative study conducted by Meltzer (2007) examined the written work and interview responses of students recruited from a variety of chemistry, physics, and engineering courses to thermodynamics problems on the topics of heat and spontaneity. Student interviews revealed a tendency for engineering and physics-engineering double majors to rely on plug-and-chug methods to evaluate the provided problems. Conversely, chemistry students struggled with the physics notation in the interview problems despite being sampled from an upper-division course. Clark et al. (2014) extended these comparative findings by investigating chemical engineering, mechanical engineering, and physics students' answers to interview problems on the topics of heat, work, and internal energy. No unique difficulties were identified across disciplines; however, mechanical engineering students were found to struggle when making qualitative comparisons with the first law of thermodynamics.

Study overview

Further exploratory research is needed to document the effects of discipline-specific instruction on students' understanding of crosscutting concepts such as energy and matter. Obtaining meaningful results from a comparative interdisciplinary study requires a clear definition of disciplinarity and how it is both defined by the expert and realised by the student. Research materials developed to interview or survey students will inevitably incorporate disciplinary context given that science is organised according to the history and culture of each discipline. Therefore, we have strategically incorporated disciplinary features into the applied study design and materials by using systems (Hall, 2017), language (Bracken & Oughton, 2006), and notation (Yeatts & Hundhausen, 1992) commonly adopted within each discipline and unique classroom context studied. Exploring how a student's understanding and unique experiences interact with disciplinarity is further contextualised by the application of a student-centred transfer of learning framework. This approach was applied in this study to investigate students' understanding of the first law of thermodynamics given the crucial role of the first law as a guiding principle to the crosscutting concept of energy and matter. In this report, we choose to focus on how disciplinary context itself impacts students' reasoning by addressing the following guiding research question: 'How does disciplinary context impact students' approaches to solving problems pertaining to the first law of thermodynamics?'

Materials and methods

Data collection

All research participants were recruited from a large institution located in the Midwestern United States. This institution offers exclusive course tracks for chemistry-, physics-, and engineering-major students that run separate from non-major course tracks in each respective discipline. Each course selected for recruitment represented the first instance of discipline-specific instruction on the first law of thermodynamics and each course included an introduction to the first law as both a concept and mathematical relationship.

It is critical to emphasise that the courses selected were not viewed as isolated learning experiences but as critical junctures at which students were acculturated into their discipline-specific framing of the first law (see *supplemental information [A]*). We acknowledge that students may transfer ideas learned within non-majors' courses and this is viewed as being desirable given that the purpose of such courses is often to diversify a student's understanding as they are acculturated into their field of study.

A total of $n = 40$ interview participants were recruited during the fall semester of introductory chemistry ($n = 10$), physics, ($n = 10$) and engineering ($n = 20$) courses for majors in each respective discipline. Students volunteered to participate via an email sent out by the instructor of the course that contained an anonymous sign-up link. Interviews lasted for 75 min on average and students were financially compensated for their time in the form of \$20 in cash (USD). All audio and written information was recorded via a Livescribe® pen (Linenberger & Bretz, 2012), transcribed into a text document, and processed by NVivo 12 software for coding.

Dynamic transfer framework

The applied research materials, methods, and analysis procedures were methodologically structured and theoretically informed by the dynamic transfer framework (Rebello et al., 2005). As an applied theoretical framework, the dynamic transfer framework provides a student-centred model for the process of transfer as it dynamically evolves over the course of an interview (Figure 1). This model structures the process of transfer according to a manifold ontology of knowledge in alignment with the resources framework

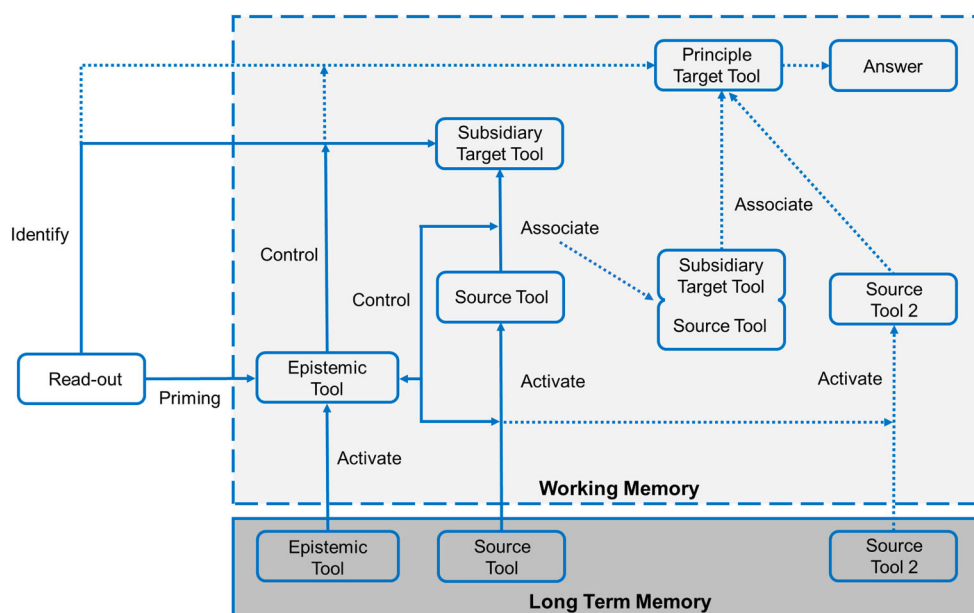


Figure 1. Dynamic transfer framework overview. The primary model underpinning the dynamic transfer framework (solid arrows) is extended to highlight how 'chaining' or successive transfer steps may be utilised to inform a new target tool with associations made in a previous instance of transfer (dashed arrows).

(Hammer et al., 2005) wherein fine-grain elements of knowledge are activated in response to a perceived context. Transfer of knowledge is viewed as the epistemological and ontological association of activated resources or *tools* from long-term memory with a contextual feature. Within this theoretical perspective, the interviewer is viewed not as an external observer but as an active agent that continually shapes the context that a student addresses. A student's approach to an interview question may therefore be influenced by *priming* the student to activate certain *epistemic tools*, or epistemological framings, that are used to *control* students' interpretations of the problem-solving context. This process engages the student to identify a realised contextual feature, or '*target tool*,' to reason with. A *target tool* may emerge in the form of student-identified surface features, affordances, deep structure, or states of affairs (Greeno et al., 1993). Finally, the identification of the *target tool* and its mediation by the activated *epistemic tool* result in the activation of a *source tool*, or pre-existing knowledge, that is then associated with the *target tool*.

While this model provides a structure to monitor transfer as it occurs during an interview, it is important to recognise that students' reasoning often does not involve the association of a single idea to an identified contextual feature but a 'chaining' of reasoning to evaluate a broader problem or question. The dynamic transfer framework addresses this concern by recognising that student-identified *target tools* are in themselves knowledge elements that may become intrinsically linked to pre-existing *source tools* within a student's working memory. Therefore, chaining may involve the association of a previously highlighted *target tool* – *source tool* pair, now acting as a new *source tool*, with a new *target tool* (Figure 1). The merging of *target tools* and *source tools* during chaining demonstrates how the dynamic transfer framework allows the researcher to monitor transfer as it occurs dynamically over the course of an interview.

Interview structure and prompts

The primary mode of data collection came in the form of recorded audio and writing derived from problem-solving interviews. Three discipline-specific interview problems were developed that incorporated a context relevant to the chemistry, physics, and engineering courses of interest. Instructors of each course were consulted to validate the relevance of the disciplinary features incorporated in each prompt prior to implementation. A pilot study ($n = 4$ students) was conducted in an introductory engineering course to improve upon the design of the prompt prior to the implementation of the full study. The final format for each problem resulted in a common general structure for each of the three prompts (Table 1) wherein the systems, language, and notation used to write each question were varied to define different disciplinary contexts. Intentional vagueness was incorporated in each interview prompt to allow for students to project their own goals and epistemological framing of the transfer scenario. All three problems lacked numerical values and could be solved conceptually by recognising the relevant heat and work contributions from the provided descriptions in the problem.

The interview protocol was divided into stages that were designed to follow the process of transfer as defined by the dynamic transfer framework (see *supplemental information [B]*). Each student addressed one in-discipline and one out-of-discipline interview problem. The order of prompts was maximally varied across the sample for each discipline. For the out-of-discipline prompts, chemistry and physics students both

Table 1. Interview problem structure summary.

Structure element	Chemistry example	Physics example	Engineering example
1. Physical system descriptions	Imagine a cylinder that is <i>filled halfway with carbonated water</i> above which rests a piston.	Consider a cylinder <i>filled with steam</i> in which one of the sides is a movable piston.	Envision a cylinder which has been <i>partially filled with nitrogen</i> held by a frictionless piston at room temperature.
2. Draw the system	Draw a picture of the described apparatus and label any components.		
3. Heat and work descriptions	Shortly afterwards, the cylinder is placed directly above the <i>flame of a Bunsen burner</i> .	Over time energy transfers between the cylinder and the <i>cold thermal reservoir</i> .	Afterwards, the cylinder is immediately placed in an ice bath and <i>allowed to thermally equilibrate</i> .
4. Provided first law and work equations (first law example)	$\Delta E = q + w$	$\Delta E_{int} = Q - W$	$Q - W = \Delta U + \Delta KE + \Delta PE$
5. Problem Question	Using the first law of thermodynamics, describe how the internal energy of the system will change.		
6. Answer choices and justification	(a) $\Delta E > 0$, the internal energy increases (b) $\Delta E < 0$, the internal energy decreases (c) Cannot determine based on the information provided Justify your answer below		

- Systems, language, and notation features that were planted as discipline-specific terms based upon textbook reference materials and course-specific instructor feedback are *italicised* above.
- This summary does not include every provided sentence/equation for each discipline-specific structure element.
- Similar answer choices for each prompt used an internal energy symbol that matched the symbol used to define the internal energy in the provided first law equation.

addressed physics or chemistry prompts respectively, while engineering students were equally divided between addressing chemistry and physics prompts. This design decision was made both to model the curricular tracks of the students in each discipline and to avoid redundancy between the similar physics and engineering prompts.

Classroom observations

Classroom observations were undertaken by the lead researcher on the project in each course of interest to complement the analysis of interview data. All observational data was recorded in the form of written or typed notes. Observations were limited to each course's instruction on the first law of thermodynamics and note-taking was focused on recording (1) how the first law was introduced in each course, (2) what the first law was used to accomplish, and (3) what systems, language, and notation was used to frame the first law. The primary objective of performing classroom observations was to inform what materials and experiences students were drawing upon from their discipline-specific coursework to understand and apply the first law of thermodynamics. As such, the classroom observations obtained inform the interpretation of trends observed during the interview study and allow for retroactive reflection on the potential consequences of traditional instruction of the first law in field-specific course sequences. A summary of classroom observation findings may be found in the *supplemental information* [C].

Analysis

A general inductive approach was adopted to funnel from a broader set of preliminary codes to summative themes (Thomas, 2006). Figure 2 pictorially summarises how a

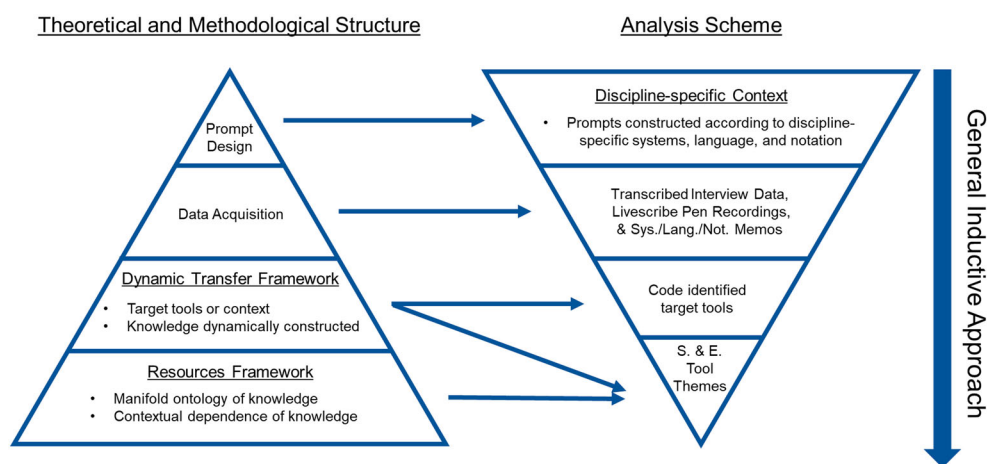


Figure 2. Analysis scheme. A pictorial summarisation of how the elements and frameworks of the study were used to drill down into summative source and epistemic tool themes via a general inductive approach (Thomas, 2006).

general inductive approach was applied in this study and how it was further informed by the dynamic transfer framework. Analysis began by coding for the relevant *target tools* that students defined when approaching each problem. These emergent *target tool* codes were then organised into categories. Examination of the general trends in these emergent categories was used to distinguish the different ways in which students used the provided interview context to know about the first law of thermodynamics.

Code definitions (see *supplemental information [D]*) were developed by the first two authors while engaging in iterative coding mediated by theoretical discussion and inter-rater reliability (IRR) calculation. The first author employed the general inductive approach to code the 40-interview data sample to identify relevant target tools. Concurrent to the full coding of the data sample, a total of eight interviews (20% of the data sample) were selected to be coded by the second author for the purposes of IRR evaluation and theoretical discussion. Interviews selected for IRR assessment were chosen purposefully to capture the full diversity of the emergent codes with equal representation from the three courses of interest. The iterative process of modifying coding definitions, recoding, and re-evaluating resulted in an average pooled Cohen's kappa statistic (de Vries et al., 2008) of 0.81 indicating substantial agreement in the coding scheme (Hallgren, 2012).

Results and discussion

This study focuses on examining the *target tools* students drew upon and how these were controlled by the applied epistemological framings of the first law, or applied *epistemic tool*, to evaluate the provided problems. A preliminary report on this same dataset and analysis (Parobek et al., 2021) revealed and defined three unique reasoning approaches adopted by participants: direction-oriented reasoning (DOR), magnitude-oriented reasoning (MOR), and process-oriented reasoning (POR). Each applied reasoning

Table 2. Summarised definitions for first law applied reasoning approaches previously identified.

Applied reasoning approach (ARA)	Summarised definition	Epistemic tool
Direction-oriented (DOR)	The provided descriptions or interpretation of the given system is associated with a particular sign of work and heat in the provided equations.	Physical mapping
Magnitude-oriented (MOR)	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.	Calculation
Process-oriented (POR)	A change in internal energy is interpreted based upon any provided or inferred system properties and associated processes without reference to the provided equations.	Knowledge as fabricated stuff

approach is defined contextually to the problem-solving scenario of this interview study and each approach is distinguished by the adoption of a different *epistemic tool* when addressing the provided thermodynamics problems (Table 2). This report expands upon these previous results by providing new insight into how students utilise *target tools* through ‘chaining,’ as mediated by their epistemological framing of the first law, to arrive at an answer.

For the purposes of discussion, the first law contextual feature each student used to solve a provided problem and arrive at an answer is designated as the ‘Principal Target Tool’ (PTT). Any *target tools* that precede the PTT and contribute to chaining are designated as ‘Subsidiary Target Tools’ or STTs. All research participants have been designated by an alphanumeric code comprised of a letter corresponding to the discipline of the course they were recruited from and an assigned participant number (e.g. E1, C8, P6, etc.). Interview quotes are labelled with this designation preceded by an abbreviation of what prompt or portion of the interview the quote was obtained from (e.g. chemistry second prompt: ‘C2,’ scaffolded transfer phase: ‘ST’).

Applied reasoning approaches when problem solving

In accordance with the guiding research question, the *epistemic tools* and *target tools* students used to solve the provided problems are the focus of this report. Here ‘applied reasoning approach’ is defined as the reasoning a student applied after being explicitly asked to solve the problem to arrive at an answer. As such, the *epistemic tools* and *target tools* of interest represent a subset of all the *tools* addressed by students during the interview that were selected by focusing on what ultimately drove students’ reasoning. The distribution of the applied reasoning approaches students adopted for the out-of-discipline and in-discipline prompts is provided in Table 3. Most notably, chemistry students demonstrated a preference for adopting POR when addressing the out-of-discipline prompt, while engineering students relied more heavily on DOR and MOR approaches. Physics students were comparatively split between adopting DOR, MOR, and POR approaches when addressing both the out-of-discipline and in-discipline prompt. For in-discipline prompts, a general preference for DOR and DOR/MOR approaches was observed across disciplines. Table S2 (see *supplemental information [E]*) provides the full distribution of applied reasoning approaches adopted by each student that gives rise to the summative trends outlined in Table 3.

Table 3. Distribution of applied reasoning approaches (ARAs).

ARA(s)	Out-of-discipline prompts			In-discipline prompts		
	Chemistry	Physics	Engineering	Chemistry	Physics	Engineering
DOR	-	0.50	0.40	0.60	0.10	0.70
MOR	-	0.10	0.05	-	0.20	0.05
POR	0.50	0.30	-	-	0.10	-
DOR and MOR	0.30	-	0.45	0.10	0.40	0.15
DOR and POR	0.10	0.10	0.10	0.30	0.10	0.10
MOR and POR	-	-	-	-	0.10	-
DOR, MOR, and POR	0.10	-	-	-	-	-

Note: The provided values represent the number of interviews in which the indicated applied reasoning approach was employed divided by the total number of interviews in that discipline.

The emergent trends in DOR, MOR, and POR across disciplines are further discussed by drawing upon the dynamic transfer framework and the outlined considerations for chaining (Figure 1). For the purposes of discussion, interview excerpts were selected that summarised the most common trends in observed chaining, the coordinating STTs and *source tools*, which emerged across each discipline's application of DOR, MOR, and POR. These trends are summarised by including one fully modelled example excerpt of each applied reasoning approach alongside additional excerpts which further contextualise the variability in how these common reasoning approaches were applied differently across each discipline. Modelled excerpts include bolded numbers that map the preceding statements of the participant onto the corresponding process suggested by analysis through the lens of the dynamic transfer framework.

First law equation as the principal target tool

The provided mathematical formulations of the first law and work equation in each interview prompt were used by students across the disciplines to solve the provided problems. DOR and MOR approaches applied the first law equation as the PTT and were mediated by different epistemological framings that shaped what *source tools* could be associated with the PTT to derive an answer.

Direction-oriented reasoning

Students across disciplines most often applied DOR to solve the provided problems by mapping the provided heat and work descriptions onto the provided first law equation. Students such as E8 below read out the provided work description to recognise a change in volume that was used to evaluate the sign of the work term.

The flame from the Bunsen burner (1), um, provides a heat transfer into the system (2), which indicates that Q is positive, um, and uh, um, based on W equals negative $P\Delta V$, um, [...], since the piston is pushing down (1) the final volume is less than the initial volume (2), which means ΔV is less than zero. [...] ΔE also has to be [greater than] zero cause you're adding two positive values (3). (E8.C2)

In this case, the provided piston-pushing description served as a STT that was associated and paired with a recognised property change, a *source tool*, to be associated with the first law equation, the PTT, to arrive at an answer (Figure 3). E8's assessment of a provided physical description and the reciprocal alignment of that description with a mathematical

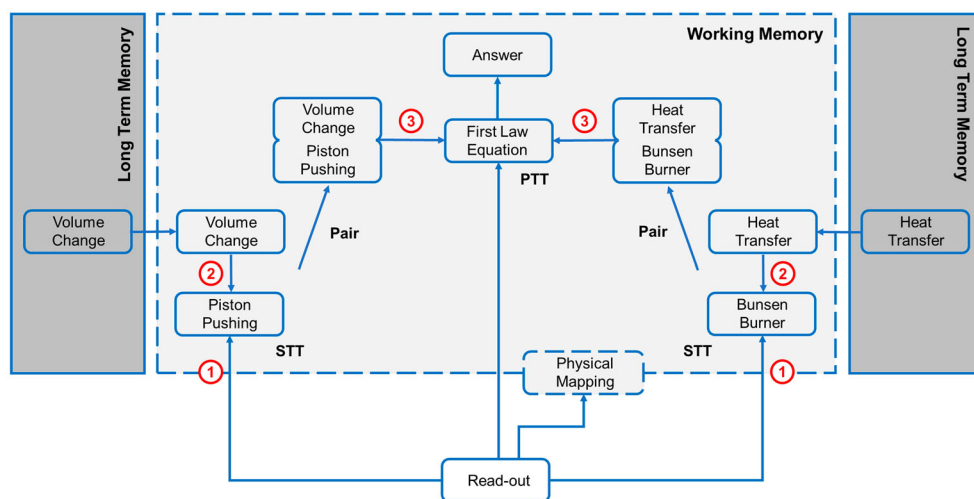


Figure 3. Dynamic transfer modelling of E8's DOR approach. E8's DOR approach involves the read out of relevant 'piston pushing' and 'Bunsen burner' statements provided in the prompt (1) to associate activated ideas about volume change and heat transfer (2) that were then associated with the first law Equation (3).

relationship justifies the application of a physical mapping frame (Bing & Redish, 2009) and DOR approach.

Chemistry students commonly inferred changes in pressure based upon the provided work description. The sign associated with these inferred changes in pressure were inserted into the provided work equation despite the lack of a ' Δ ' symbol on the constant pressure term provided in the PV-work equation. In this case, an inferred process, a state of affair, was read out that impacted students' interpretation of the work equation thereby influencing the ideas associated with the PTT. C1 was one such chemistry student that made inferences about changes in pressure that ultimately impacted their interpretation of the work equation:

So for, W still equals this, **but now the pressure has gone up because the piston has gone down, right?** [...] **So the pressure is now higher, it's a higher negative, but that gets cancelled out by the negative of the ΔV (work equation),** because the volume is getting lower. (C1.C2)

Here, C1 infers that the piston going down must simultaneously cause a pressure increase and a volume decrease, and unproductively associates the sign of this perceived change in pressure with the provided expression for PV-work. These inferences were found to be associated with a causal-mechanistic picture for how the pressure or energy of the system might change with volume as demonstrated in C1's earlier explanation for the physics prompt:

Besides the mathematical relationship, uh, I'm just kinda think **when you have a bunch of gas molecules moving about and you like close it, they move faster,** which means a different amount of energy than when it was a smaller volume. (C1.P1)

This flexibility in moving between mathematical first law and conceptual energy statements reflects the discussion and framing of the first law as energy conservation throughout the introductory chemistry course.

Physics students often adopted a similar approach but relied more directly on changes in energy supported by casual-mechanistic explanations without reference to changes in pressure. In either case, both approaches may be viewed as being driven by an inferred process, an underlying molecular mechanism, that acts as a STT to support the activation and association of *source tools* with the PTT.

The term ‘insulation’ greatly impacted the work that physics students generated when compared to chemistry and engineering students. Two physics students read out the lack of the term ‘insulation’ within the chemistry prompt to modify the provided first law equation to have an energy-escape term:

I don't think so because I think some part like, um, **some energy like might escape through the walls of the cylinder since it's not insulated. So I think I would need like one more variable, like how much energy escapes**, uh, through the walls of the cylinder to find out the change and the internal energy of the system. (P2.C2)

Attending to the absence of the term ‘insulation’ signifies a student's attention to deep structure and how this in turn impacts their interpretation of the PTT. In this case, the read out of the absence of insulation serves as a STT that prompts, through a physical mapping frame, the read out of an additional inferred energetic process, a second STT, that then is finally used to associate ideas about energy transfer to the provided first law equation (PTT). This approach by P2 exemplifies sophistication in mathematical modeling of physical processes (Redish & Smith, 2008). The ‘build-up approach’ to the instruction on the first law in the physics classroom studied mirrored the practice of modifying existing mathematical relationships to better model a described system.

Engineering students commonly mapped the provided heat and work descriptions directly onto the first law equation based on whether heat was transferred into or out of the systems and whether work was done on or by the system. Consider E11's interview excerpt below:

So we know that um Q is going from the, Q is going from this steam to the reservoir, so Q is going out of the system. **So, when Q is coming out of a system, we know that the heat transfer is negative.** So we have negative Q, and then we have our work, and the piston is being pushed onto the steam. **So we have a work being pushed onto the system. So when a work is on a system, that work is then negative.** (E11.P1)

The students that engaged in this approach were able to map read-out descriptions directly onto the first law equation without considering the provided work equation as part of the PTT. This approach was productive when the sign convention for work was defined in accordance with a student's expectations. However, some of the engineering students that mapped work descriptions directly onto the first law equation did so without recognising the changes in the sign convention of work when moving between the chemistry (+) and engineering (-) prompts. Participant E10 commented on how their expectations of work being done on the system impacts the provided work term when evaluating the chemistry prompt:

Um, so in this case, **I know ΔE is equal to Q plus W , and that we know, uh, work is negative in this case. Um, so the piston is doing work on the system.** Um, so we have a negative term and then we have a positive term. So I really can't say what the, uh, how the internal energy is going to change. (E10.C2)

Students that applied this approach immediately referred to 'work done on/by the system' based upon the provided description demonstrating how this source tool may be unproductively associated with the first law when addressing an out-of-discipline context.

Magnitude-oriented reasoning

MOR was often applied during the physics prompt across disciplines to reflect upon the usefulness of numbers in evaluating the prompt when considering opposing changes in heat and work recognised with DOR (DOR/MOR approach). In this manner, students applied MOR by recognising that adopting a separate *epistemic tool* would allow them to evaluate the expression by applying a perceived arithmetic if they were provided numbers to come to an answer other than Answer C.

However, some physics and engineering students initially read out the lack of numerical information provided in the prompt to mean that the problem could not be solved. This applied reasoning approach was often accompanied by a description of some anticipated arithmetic by which the student would numerically solve for the change in internal energy via the PTT, such as in the case of P4's interview (Figure 4):

So since Q is related to change in temperature, it's not clear (1) how the, what the magnitude of this change in temperature is (2). But it's also not clear (1) how large this cylinder is. So we know that the force is constant and that the dis-, but we also don't know how large this distance is (2). So to me, I'm not sure what this is either. Um, and so I'm, I think I'm going to, I'm going to have to conclude that we can't determine based on the information provided (3), so [Answer] C. (P4.P1)

It is important to point out that P4, and similar students adopting MOR approaches, cited specific variables they would anticipate to be given. This indication by P4 of an anticipated arithmetic in their explanation is in alignment with a calculation-based framing (Bing & Redish, 2009) and a MOR approach. The emphasis of calculation-based work in both the physics and engineering courses studied suggests that students unproductively drew upon MOR in this context because that is the *epistemic tool* they are accustomed to adopting in their own disciplinary environment. These findings align with and expand upon previous work which has postulated a connection between reduced qualitative proficiency in problem solving and receiving calculation-intensive instruction and assessments (Clark et al., 2014; Engelbrecht et al., 2007; Meltzer, 2007). The presence of an anticipated arithmetic was particularly evident for the engineering students adopting MOR, such as in the case of E6 below:

Um, so with those assumptions ΔU is Q minus W . And uh Q , well to get Q I will need, **um in general we have um, the table of uh, the vapor gas mixture. So from there we can get ΔT multiplied, uh, enthalpy, ΔH minus $P \cdot d \cdot V$.** So without the numerical values, I don't think I can proceed. (E6.E1)

E6 cites the need for property tables, a common resource drawn upon in engineering thermodynamics instruction, and highlights how this information may be used to

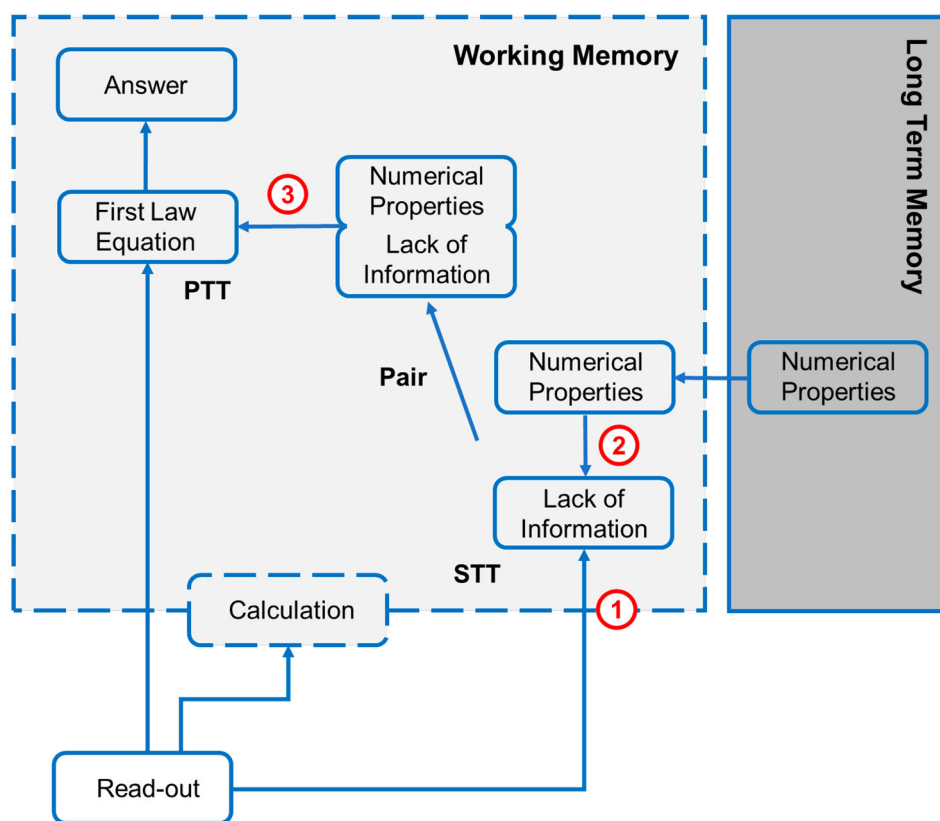


Figure 4. Dynamic transfer modelling of P4's MOR approach. P4's MOR approach begins with the read out of a lack of the information within the prompt (1) that only allows ideas regarding the numerical properties of the system to be made available to the student (2). The perceived absence of system-specific information leads to the determination that the first law cannot be used to solve the problem (3).

evaluate the relationship between the described processes and the provided mathematical formulations. Many students that initially adopted a MOR approach did so for both in-discipline and out-of-discipline prompts such that they indicated Answer C for both problems.

Inferred energetic processes as the principal target tool – process-oriented reasoning

Students adopting a POR approach identified an inferred energetic process as the PTT that was used to associate conceptual first law ideas with the problem to arrive at an answer. In general, an inferred process may be viewed as a state of affair the student identified to be relevant to a particular problem-solving context. The identification of an inferred energetic process as the PTT allows for the student to read out provided descriptions as STTs to activate and associate ideas about energy transfer with the PTT.

Most notably, chemistry students employed POR more frequently than engineering and physics students and preferably when addressing the out-of-discipline prompt

(Table 3). The interview excerpts by C5 below showcase how many chemistry students navigated the physics prompt by inferring that heat transfer would occur based on the high energy associated with a collection of steam particles in motion (Figure 5):

Yeah. I just think since there's steam (1), and like I thought of steams are gas particles and, and like if you think about the different states, like solids, liquids and gases, gases, they have the highest amount of energy because they, they move so fast (2). [...] So I feel like eventually over time that, um, um, what's inside the cylinder, like those same, um, particles would like lose some of the energy (3), so therefore that internal energy would decrease. (C5.P1)

Interestingly, many of the chemistry students that adopted POR during the physics prompt failed to account for any work contributions despite having productively evaluated the work equation via DOR in the chemistry prompt. Chemistry students' reflections on their previous work revealed that many applied POR to only reason about heat transfer due to a lack of familiarity with the provided physics and mathematics

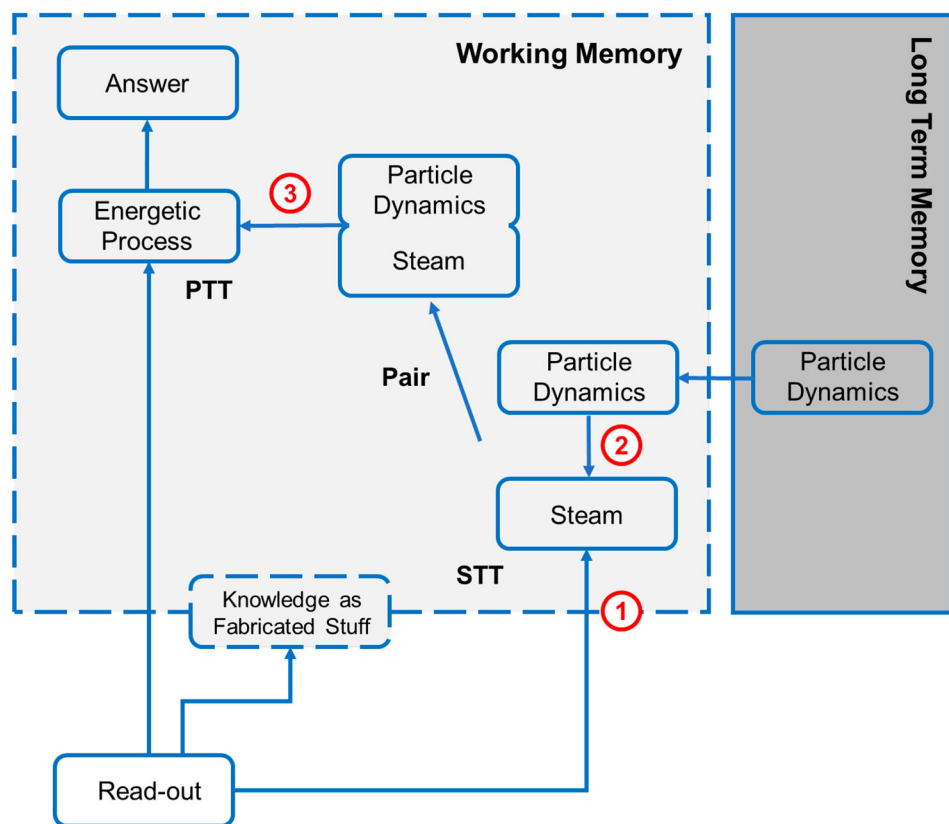


Figure 5. Dynamic transfer modelling of C5's POR approach. A model for C5's approach highlighting the recognition of an inferred energetic process that may be associated with the evolving particle dynamics within the system. The read out of the word 'steam' (1) activates ideas about particle dynamics (2) and how these dynamics may evolve and contribute to the recognised energetic process (3).

notation (Meltzer, 2007) for the work equation and/or an insufficient mathematical aptitude to interpret the provided work equation (Hoban et al., 2013).

The second equation of Question #1 (physics prompt), I just have no idea how to like even look at it, like to solve it. It's just, yeah, I don't know how to plug in, like even just think about, oh, what will I get for that if I just think about positive or negative signs. But for Question #2 (chemistry prompt) the two equations are straightforward, I have learned those in class so I know how to like kind of use them. (C5.ST)

Physics students employed POR approaches to assess perceived changes in energy based on the described processes. However, unlike the chemistry students, these inferences often did not refer to pressure or the first law equation and instead provided a more direct mapping of energetic changes to the provided descriptions. Consider the quote below by P5 when assessing the chemistry prompt:

I wouldn't really know how to write it down because, um, heat is being applied to the uh cylinder, **and because pretty much heat is energy, it just, it wouldn't create, or the carbonated water would absorb the energy provided by the heat.** And so, you know, internal energy in the carbonated water would increase. (P5.C1)

P5 makes a direct connection between the provided heat description and an associated change in energy for the system. Therefore, the provided description serves as a STT that then allows for *source tools* to be associated with the perceived energetic process, the PTT. In this case, the perceived energetic process does not result from inferences about pressure but by a more direct mapping consistent with the 'energy accounting' framing of the first law taught within the introductory physics course.

POR approaches were almost non-existent across the engineering student population for both the in-discipline and out-of-discipline prompts. The lack of POR within engineering students' interviews stemmed from the preference of engineering students for identifying the first law equation as the PTT and the tendency for engineering students to discuss heat and work contributions without references to energy.

Only two engineering students adopted POR and both did so to check work already assessed via a DOR approach. Consider the following quote by E4 as they assessed their answer to the engineering prompt:

So work is gonna be positive, uh number, you know, we'll call positive B. So when we get back to it, it's going to be some negative number, negative A minus, um. Actually not a B plus, that'd be plus, plus the (1), so actually no, because now sort of my last step in the problem is to think about it theoretically. Like if I had a gas and I expanded it and I cooled it down, what is going to happen to sort of what I think the internal energy would look like (2). And right now that's telling me that I probably made a mistake somewhere, so I should go back and look at my signs (3). (E4.E1)

Here E4 used POR as a means to assess the validity of the answer obtained via the previous DOR approach. A clear framing transition between DOR and POR approaches occurs as E4 indicates that the 'last step in the problem is to think about it theoretically.' The transition between *epistemic tools* by E4 allows them to assess the applied DOR approach by recognising the underlying energetic process as a PTT via POR (Figure 6). The ability for E4 to productively assess their initial DOR approach, a field-specific engineering tendency, via POR highlights the value of being flexible in applying

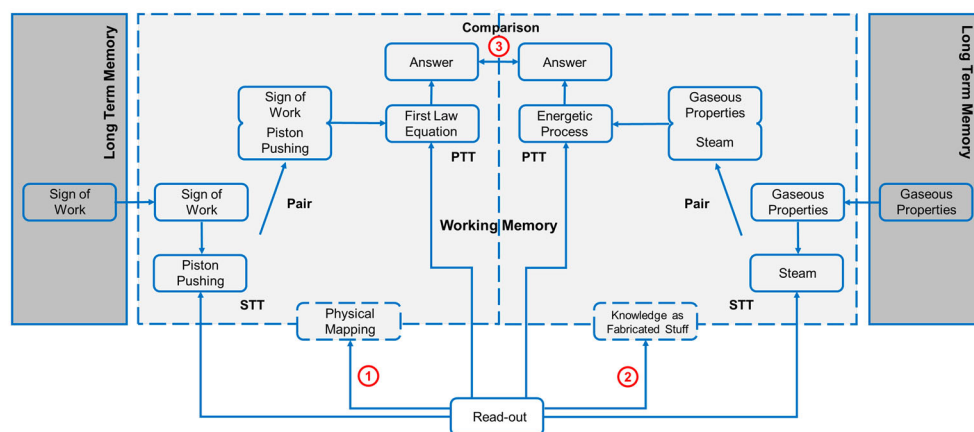


Figure 6. Dynamic transfer modelling of E4's transition between a DOR and POR Approach. E4's reasoning may be viewed, from a dynamic transfer framework perspective, as following the activation of separate sets of source tools as mediated by the epistemic tools 'physical mapping' (1) and 'knowledge as fabricated stuff' (2). The resulting comparison of answers derived from these two separate associations (3) indicates to E4 that there is a mistake somewhere in their work.

epistemological framings traditionally employed in different disciplinary contexts (Greene et al., 2021; Redish, Sawtelle, et al., 2014).

Conclusions and implications

The applied methods and analysis have revealed evidence for discipline-specific modes of transfer for students when considering the first law of thermodynamics across various disciplinary contexts. In particular, discussion and modelling of student excerpts through the dynamic transfer framework have provided key insight on the nature and character of the observed DOR, MOR, and POR trends for each discipline when addressing the in-discipline and out-of-discipline prompts (Table 3). The examination of students' approaches to the out-of-discipline prompts has demonstrated both productive and unproductive ways in which students bridged across disciplinary boundaries.

Transfer across disciplinary contexts was most facilitated by the application of multiple applied reasoning approaches and an awareness of the value of these methods in assessing the provided interview problems. This key finding further supports previous research that has reported the need to communicate to students the value of different disciplinary epistemologies (Gouvea et al., 2019; Redish, Sawtelle, et al., 2014) and provides clarification of how these epistemologies manifest themselves in the case of first law problem solving. Conversely, unproductive instances of transfer coincided with the exclusive application of *epistemic tools* and *source tools* commonly referenced in each classroom setting. Physics and engineering students' tendencies to address numerical problems within the classroom was reflected in the adoption of MOR approaches that, at times, led students to unproductively indicate that the problem could not be solved. Likewise, chemistry students' repeated exposure to POR approaches through casual-mechanistic reasoning was mirrored in their attempts to address the physics prompt.

These findings further emphasise the need for instructors to consider what applied reasoning approaches they are asking their students to exercise and to vary instruction on the first law of thermodynamics to incorporate DOR, MOR, and POR when problem solving. Additionally, highlighting different potential *source tools* that may be used to evaluate first law problems may be useful considering the potential role in repetitive problem solving on students' applied reasoning approaches. For example, scaffolding the separate approaches of evaluating the first law according to the sign convention of work and considering changes in volume in relation to a work equation may assist engineering students in critically evaluating their reasoning. Chemistry students on the other hand may benefit from more numerical calculations with the first law of thermodynamics and instruction on the differing notational formats and conventions adopted across the disciplines of science and engineering.

Furthermore, the application of the dynamic transfer framework in this study demonstrates how researchers may prepare interview prompts to study students' transfer across disciplinary contexts by purposeful incorporation of field-specific systems, language, and notation. This approach highlights the distinction between configuring an interview prompt with an expert-defined disciplinary context and disciplinary context as it emerges from a student-centred perspective through the recognition of what *target tools* a student uses to know with. The applied methods may be adapted to study other energy and matter topics and potentially other crosscutting concepts by considering how to incorporate discipline-specific context in a standardised conceptual prompt. Expanding our understanding of students' approaches to transferring crosscutting concepts may further support the development of innovative STEM curricula that teach students to communicate and collaborate across disciplinary boundaries.

Limitations

The results derived from this study were obtained from a single institution with a limited sample size making the results non-generalisable across different institutional curricula. Instructor-specific teaching practices may have uniquely contributed to the activation of certain *tools* within the context of the interview study. The applied dynamic transfer framework further limits the implications of these findings by focusing in on what ideas students make available to themselves during the interview study. Neither this framework nor do the findings derived from this study claim to definitively track how the *tools* students applied become incorporated within long-term memory.

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Ethics statement

This study was approved for implementation (IRB-2020-1265) by the Institutional Review Board at the university where the study was conducted.

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