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Investigating Student Conceptual Difficulties in Thermodynamics Across Multiple Disciplines: The First Law and P-V Diagrams

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1 Introduction

Thermodynamics is a core part of the curriculum in physics and many engineering fields. While individual courses in each discipline appear to cover many of the same topics at some level, the emphasis, applications, and many representations are idiosyncratic to the discipline. Education researchers in both disciplines have studied thermodynamics learning and teaching. In everyday common language heat and temperature are often used synonymously. This has led to well documented conceptual confusion among middle- and high school students.[1,2] These difficulties, along with others relating to thermodynamic work, have also been documented among students enrolled in introductory and upper-division physics courses.[3,4] Similar difficulties have been documented by engineering education researchers as well as difficulties specific to engineering contexts, such as steady state vs. equilibrium processes among upper-division engineering students.[5,6] Difficulties have also been identified with canonical representations such as P-V diagrams.[7,8]

An open question is the extent to which discipline-specific research findings apply across disciplines. Previous work in physics education research[9,10] has explored student difficulties with thermodynamics and statistical mechanics in upper-division physics courses. We have recently broadened the scope of our own investigation to include mechanical and chemical engineering courses, to see whether similar difficulties are present in these disciplines and how certain instructional pedagogies may affect student learning. At our institution, thermodynamics is not covered in the introductory physics course sequence, so for most students the discipline-specific thermodynamics course is their first formal encounter with the topic.

Using students in physics, mechanical engineering and chemical engineering thermodynamics as our study population, we are pursuing three broad research questions:

1. What are the similarities and differences in student understanding of thermodynamics concepts between different disciplines?

2. To what extent do students use appropriate concepts and tools when solving thermodynamics problems?

3. What can we learn from pedagogical approaches in each discipline to improve instruction within and across disciplines?

Our initial focus is on the First Law of Thermodynamics and its constituent elements, as this topic is fundamental to all the courses of interest. We have administered written, free-response questions to students at various points before and/or after instruction. The questions discussed here require interpretation of graphical information about thermodynamic processes using modified versions of a task developed by Meltzer.[11]

2 Research design

To address our research questions, we have designed a study that includes students enrolled in courses offered in multiple disciplines and taught by multiple instructors. The initial phase of our investigation uses only questions drawn from physics education research.

2.1 Study populations

We have collected data from five different courses in three departments, including both introductory calculus-based physics courses. The preparation of students entering the thermodynamics courses of interest vary between departments, so brief descriptions of the courses are required. For all these thermodynamics courses, the introductory calculus-based physics sequence and calculus I (differential) are prerequisite; most students have also completed calculus II (integral). Data were generally collected early or late in the semester. In some cases data were collected shortly after some relevant instruction but before all instruction or learning opportunities, such as completing homework or an examination covering that material. These cases are labeled as “Mid” in Table 1.

	Early		Mid	Late		
Course	Sym	Asym	Asym	Sym	Asym	Total
Chem Eng			26	41	26	93
Mech Eng - X	12	45			25	80
Mech Eng - Y			32		42	74
Physics	8	12		27	11	58
Thermodynamics Total	**20**	**57**	**58**	**68**	**102**	**305**
Intro Physics I					202	202
Intro Physics II					195	195

Table 1: Total count of task responses organized by course, instructor, task type and timing. In cases where multiple instructors taught different sections of the same course we have identified the students by their instructor (X, Y). Data were collected over multiple semesters and/or years. Not all students in participating courses chose to participate in the study.

2.1.1 Mechanical engineering thermodynamics

The mechanical engineering program has a two-course sequence covering introductory thermodynamics content. We have collected data in the first course, which is offered both semesters, but is usually taken in the fall semester of the sophomore year. This course covers energy and energy transformations, the First and Second Laws applied to systems and control volumes, thermodynamic properties of systems, and availability of energy. Calculus III (multi-variable) and introductory chemistry are typically taken concurrently, so these students would have had no prior formal, college-level exposure to thermodynamic concepts. This course has two or three sections each with 30-50 students in the fall semester taught by different instructors. One section of the first course is also offered in the spring semester.

2.1.2 Chemical engineering thermodynamics

The chemical engineering program also has a two-course sequence in thermodynamics. We have collected data in the first course, which covers applications of the First and Second Laws, equations of state for ideal and real gases, heat and energy relationships in chemical reactions, elementary phase equilibria, and heat and power cycles. Calculus III is a prerequisite of the course, as is a fundamentals of process engineering course, which covers the Zeroth and First Laws, energy and mass balances for closed and open systems, P-V-T relationships, heat capacity and heat of reactions. This course has one section of 30-60 students with the same instructor.

2.1.3 Physical thermodynamics

Unlike many physics departments that offer a one-semester thermal physics course, which combines the topics of thermodynamics and statistical mechanics, our physics curriculum has separate semester-long courses in each subject. This thermodynamics course is not specifically required by physics or engineering physics majors, but a number of students take it to satisfy a restricted elective in the fall semester of the junior or senior year. Calculus III is a prerequisite and most students have also completed differential equations. The course takes a theoretical perspective on the structure and concepts of equilibrium thermodynamics. Topics covered include P-V-T relationships, the First and Second Laws, properties and phases of matter and analysis of processes and practical applications. Enrollment varies but is typically in the 7-12 range.

2.1.4 Introductory calculus-based physics I & II

The main sequence of introductory calculus-based physics I and II is taken in the fall and spring semesters of the freshman year respectively, although both introductory courses are offered each semester. The off-sequence courses are taught by a different instructor than the main-sequence courses. Calculus I is a co-requisite of physics I and most students in the main sequence take calculus II concurrently with physics II. The first course covers mechanics and the second course covers electricity & magnetism and optics. Data in both courses were collected at the end of the fall semester only, with enrollment around 300 each.

2.2 Methods

We have collected data using two methods. The first is the administration of written, short-answer questions, given before and/or after relevant instruction to different populations. The second method involves classroom observation with data collected in the form of field notes. The field notes provide nearly complete transcription of text written on the board, descriptions of sketches and schematics, and fairly close transcription of instructor and student statements. A general description of classroom activity was also included when it deviated from the norm. The field notes were used in conjunction with the written student responses to generate and strengthen claims, especially in cases where the student work made little sense to researchers not present in the classroom.

Each survey question asks for an answer and an explanation. The coding scheme for student reasoning was developed using an approach in the spirit of grounded theory.[12] A true grounded theory approach makes no *a priori* assumptions and allows the data to drive the formation of a theory rather than using data to confirm an existing theory. The approach has four stages of analysis: codes, concepts, categories, and theory. As part of the first stage of this process, we have reviewed our existing data to see what lines of reasoning students used and then iteratively added and removed codes until we felt we had distinct, descriptive codes. While we had an awareness of potential codes and categories from previously documented student difficulties,[3,11] we have used this information as a confirmation of our own findings rather than as a guide for what to look for in our data. The second level groups several codes together into thematically similar clusters. This part of the process has been guided by our knowledge of the correct answer and reasoning to the survey questions asked of students and is explained in more depth below. As this paper describes research in progress, we have not yet advanced to the last two stages of the grounded theory approach.

2.3 Tasks

The original thermodynamics task[11] shows a *P*-*V* diagram with two states of an ideal gas connected by two different processes, represented by different, but symmetric, paths (see Fig. 1). The student is asked to compare three thermodynamic quantities for each process: 1) work done by the system, 2) heat transfer to the system, and 3) change in internal energy of the system. No additional information is provided as to what type of processes these might be (e.g., adiabatic, isothermal, reversible, etc.). Correctly answering these questions requires knowledge of state and path dependent functions, the integral definition of work, graphical representations, and the First Law of Thermodynamics. Our research began by using this task. However, we made small modifications to the diagram due to disciplinary conventions as well as to follow up on findings from the initial version.

The relevant form of thermodynamic work is defined by $W = \int PdV$ in both the physics and mechanical engineering courses. Since this is a *P*-*V* diagram, the work is represented graphically by the area under the curve, which is clearly larger for Process 1 shown in Fig. 1. A small number of students said that the works were the same using reasoning relating to "distance traveled" and/or the symmetry of the paths. A new version of the task was subsequently developed in which the two process paths were asymmetric (see Fig. 1) to separate students that correctly recognize that work was path dependent but were confused as to what was meant by "path" in this graphical representation. Finally, chemical engineers use a sign convention for work in which the work done *on* the system – rather than *by* the system – is positive. This means that an expansion, as both previous versions of the task were, results in negative work. The different sign convention leads to a complication with the work comparison, since a more negative value of work is less than a less negative value. To avoid this issue, a third version, based on the asymmetric task, was created

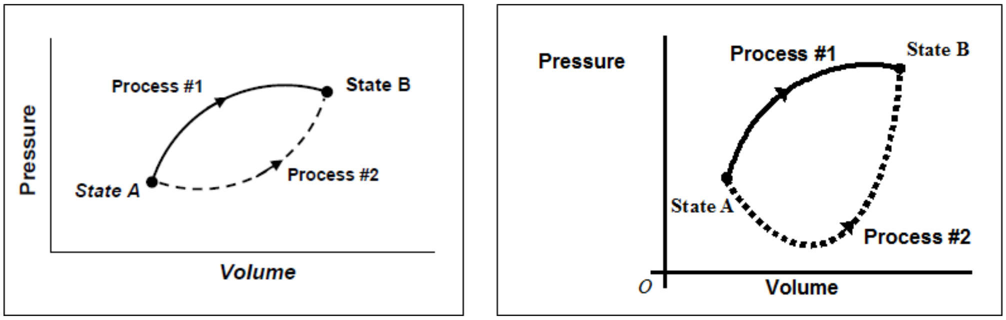


Figure 1: (Left) The original, symmetric comparison task figure developed by Meltzer[11] and used for all data collection prior to 2009. (Right) An asymmetric version was developed in 2009 and has been modified in small ways since.

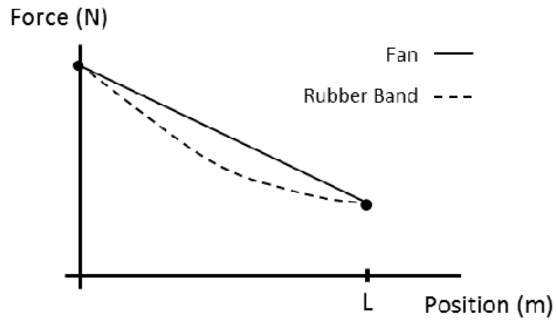
in which students were asked to compare the work magnitudes rather than the work values, and finally a fourth version was created in which the processes were compressive rather than expansive, and students were again asked to compare the (now positive) work values. The third and fourth versions were only used with chemical engineering students.

The first version of the task only asked about heat and work; the question about the change in internal energy was added later to probe students' knowledge of state and state-function concepts.[13] When it was introduced, it asked more generally about the change in the "total energy of all the atoms in the system." Since both processes start at state A and end at state B, the changes in state variables, including internal energy, must be the same. We altered the language to the formal term "internal energy" in the Fall 2013 semester. As a reminder, the heat transfer cannot be directly determined from a *P*-*V* diagram. This part of the task requires students to use the First Law, $\Delta U = Q - W$, and knowledge of the work and internal energy comparisons from the other sections of the task.

We have also created a one-dimensional work task (see Fig. 2) appropriate for students in our introductory courses. In this task, students compare the net work done in propelling a cart the same distance using two different propulsion methods. We have also altered the phrasing from a question to a statement. This task differs in two main ways from the *P*-*V* task. First, the variables aren't state variables. We would need to use tension and extension to get the equivalent one-dimensional task and our students are far more familiar with force and distance. Second, the initial point is at $x = 0$. This was chosen because while students have a good grasp of starting from a non-zero volume and expanding to a larger volume, many textbook problems place the origin of a position axis at the first point in the problem.

3 Results and discussion

The thermodynamics task has three parts, each of which asks for an answer and an explanation. We are interested both in how students perform on each part and on the whole task. Given the lack of completeness in many explanations, our coding scheme gives the students the benefit of the doubt. Therefore our results probably represent an upper bound on student knowledge. Consider-



Two methods of propelling a cart are being tested. The first uses a stretched **rubber band** while the second uses a **fan.** The graph below shows the size of the net force experienced by the cart as it travels away from the start point along a track of length L.

The net work done on the cart propelled by the **fan** in traveling the length of the track is

a. greater than,

b. less than,

c. equal to

the net work done on the cart propelled by the **rubber band**.

(Please briefly explain your reasoning.)

Figure 2: Task and prompt used in introductory physics to probe student ideas about work only.

ing each part individually offers insights into specific difficulties students have with each concept. Considering the task as a whole represents a more global integration of many concepts, which is an important step in progressing through any course of study. We present the analysis of each question in turn and finish with the complete task.

3.1 Student ideas about thermodynamic work

The students were asked to compare the works done in two different processes connecting the same initial and final states. They were also asked to provide an explanation. We believe the explanation is the more important aspect. We have found that students use a number of different lines of reasoning to explain or justify their answers and that the level of detail provided varies significantly. We provide three examples of student work and our interpretation of each in turn.

> 1) "$W = \int PdV$, The area under the curve is larger for process $\#1$, and this represents work"

This student appears to have a complete concept of work, from its mathematical definition to its graphical representation on the *P*-*V* diagram, and clearly describes the relationship.

> 2) "since work $= P(\Delta V)$ and the change in volume is the same, Process 1 does more work because its P values are greater at all times."

The second student appears to be equation-oriented and has extracted information from the graph to compare each term of the equation for the two cases. While the isobaric form of the work equation is inappropriate, the student has shown some knowledge of thermodynamic work and the ability to extract relevant information from a graph. We regard this as a partially correct explanation.

> 3) "Higher pressure"

The third student has provided, at best, an incomplete response. It is possible this student was thinking along the same lines as the second but the student did not feel the need to be more complete and descriptive in his answer. Our coding scheme gives students the benefit of the doubt and does not distinguish between this response and the more complete one provided by the second student.

We have grouped student reasoning into four broad categories. The first is correct or partially correct and includes students reasoning using *area*, *higher pressure*, and the *integral* definition of work. The explanation provided by the first student shown above includes both *integral* and *area* reasoning and to avoid counting this student twice we created a *multiple correct* reasoning code. Essentially all students that used a correct or partially correct line of reasoning also chose the correct answer for the comparison. The second set of reasonings ascribe state variable properties to work, as students said the works were equal because only the *end points* matter, or specifically that work was *path independent*. While a number of students use both of these reasonings in combination (*multiple equal*), showing that they understand these to be synonymous, we are keeping the categories distinct for students that only used one pending further, more conclusive data that a majority of students use the terms interchangeably. Third, there were a small number of students who explicitly stated that work was a *state variable* or *state function*; we have kept these separate from the previous category, despite the mathematical equivalence. The reason for doing this becomes more clear in the analysis of internal energy question and will be discussed further in section 3.3. The last category is *shape* and is comprised of reasoning that relates to the length, steepness, or concavity of the line. While these describe features of the line that are more distinct from each other than the *path independent* and *end point* reasoning, they are all irrelevant, although salient, features of the process path that lead students to the same incorrect conclusion regarding the work comparison. Lines of reasoning used by fewer than 5% of students were grouped into a general category of *other* and some students provided *no reasoning* at all.

Analysis of our data shows that we may predict a student's answer to the work comparison question by knowing only their reasoning in over 85% of samples. Some students used multiple types of reasoning. In some cases, as in the first example above, multiple reasoning types were classified in the same larger group. In the very few contradictory cases, such as when a student mentions both the end points and the area, we used their comparison answer to determine which feature was more important to the student and coded singly for the most appropriate reasoning to avoid double-counting students.

The work pretest data (see Fig. 3) show that fewer than 25% of students were able to correctly compare the quantity of work, and fewer than 20% used correct or partially correct reasoning. As it was a pretest, i.e., before instruction, this was not unexpected, but it provided a baseline for comparison with the post-test data. We note that a majority of students in physics and mechanical engineering and a third of students in chemical engineering determined that the works were equal and justified their answer using *path independent* or *end point* reasoning, as if work were a state function. This is most likely an overgeneralization of work done by conservative forces (e.g. gravity) covered in previous coursework.

Data collected at the end of physics I and II using a one-dimensional work task on a *F*-*x* graph (see Fig. 2) offers insight as to the initial high rates of *end point* and *path independent* reasoning of students in thermodynamics. At the end of physics I, 66% of students correctly compared the work done in two different processes, while 20% said the works were equal because the processes had the same *end points*. This general idea of work is reinforced in physics II when work is most often defined in terms of the change in electric potential, $W = -q\Delta V$, which inherently depends only on the end points. At the end of physics II, only 35% of students correctly compared the works while 46% used *end point* or *path independent* reasoning. While the physics students are typically two years removed from their introductory E&M experience, many have recently completed junior level E&M. Thus the most recent instruction on work, in an electrostatic context, seems to be influencing the responses of the upper-division thermodynamics students.

Another possibility is a lack of understanding of how to extract information from a graphical representation. Most students can integrate a clearly defined mathematical function but have difficulty determining which aspect of the graph to attend to when evaluating a definite integral.[14] The students may be recalling that a definite integral is evaluated at the end points, but failing to also recall that it is the end points of the antiderivative and not the function itself. Also, when students learn about path integrals in calculus III, they start attending to the length of the line instead of the area bounded by it and do worse than students in calculus II on a similar, but purely mathematical, version of this task.[8] While this interference effect exists in the context of the mathematics class, it's not clear how much may transfer to other contexts.

The post-test results show that by the end of the course, 75% of the students in physics and in chemical engineering correctly answer the question with correct or partially correct reasoning. However, the mechanical engineers have a strong persistence of *end point* reasoning. We suggest three possible reasons for the different outcomes. First, differing prior coursework may be important. Chemical engineers have completed at least one more semester of calculus and physics students generally have completed differential equations. While more calculus may be reducing performance on the pretest, it is reasonable to suggest that after practice applying calculus in the context of thermodynamics that a greater foundation in calculus results in better learning overall. Also, these groups have completed introductory chemistry, while mechanical engineers typically take it concurrently. A second possible explanation relates to pedagogy. Field notes show that both the physics and chemical engineering students participated in student-centered, small-group worksheet activities specifically related to graphical interpretation of mathematics. Also, while one of the two mechanical engineering instructors routinely drew *T*-*v* and *P*-*v* diagrams on the board to represent states and processes in example problems, the students were not actively engaged in the activity. While our early data suggest a difference in performance between students taught by these two instructors, we do not have sufficient samples sizes to have statistical significance. Third, we found that the two groups of students that were more successful by the end of the semester spent more time using the integral definition of work. The integral definition is really only useful for *calculating* work if there is a reasonably well-behaved function that can be integrated. Physics students spend most of the course treating the ideal gas case. The chemical engineers also spent more time on gases, both real and ideal, than mechanical engineers did. However, the integral definition is always useful in graphical applications for *comparing* work in different processes with any working fluid in a closed system.

3.2 Student ideas about heat

The question about heat transfer was the most difficult part of this task for our students. Three new lines of reasoning appeared in this question that were not present in the work data. The first involves the *First Law* and was generally written by students as $\Delta U = Q - W$. Students used their answers to the work and internal energy questions to evaluate Q. Nine students either incorrectly

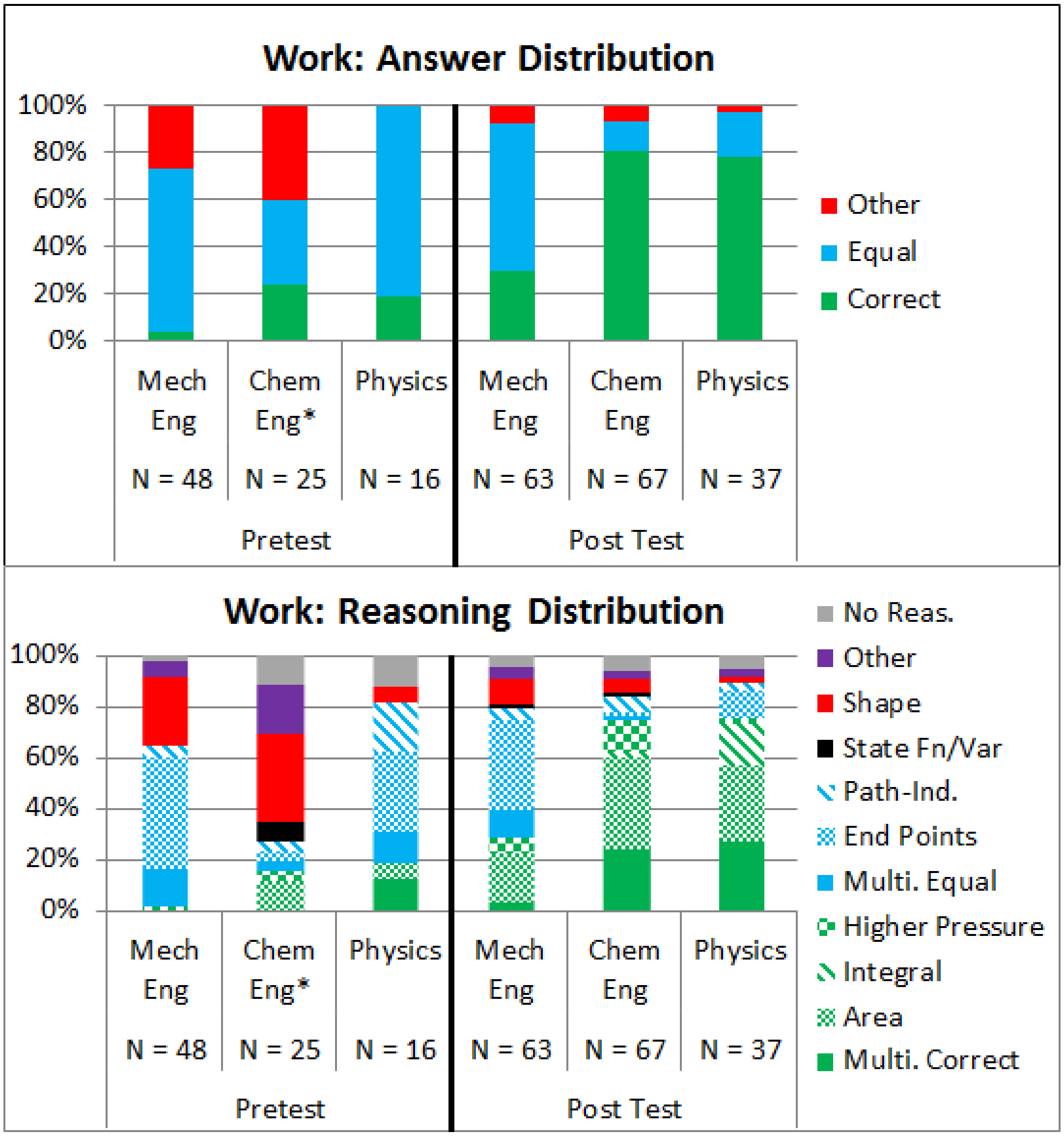


Figure 3: The answer (top) and reasoning (bottom) distributions to the task prompt "Is the work done by the system during process 1 greater than, less than, or equal to the work done by the system during process 2? Explain." The correct answer is $W_1 > W_2$; "Other" refers to the opposite inequality. Correct or partially correct reasoning codes are indicated by green. *The chemical engineering students have had a small amount of instruction on thermodynamic work, so it is not a true pretest.

compared the work or made a sign error leading to an incorrect heat comparison, but since they were reasoning using the First Law we have treated these students as if they had answered the heat comparison correctly. The second was the idea that heat transfer was *proportional to work*. While in this case, since the changes in internal energy are equal, heat transfer is indeed proportional to work, this is not generally true. We do include this as partially correct reasoning since student explanations are often not sufficiently detailed to know if the student was simply choosing to write fewer words or really doesn't know that this was a special case. The third related heat transfer to *temperature* and appears most commonly in the pretest.

On the pretest, we found that fewer than 30% of students correctly compare the heat transfers and even fewer use acceptable lines of reasoning. A few students invoked the *First Law*. At this point, we assume this represents the small fraction of the class that had either read ahead, were re-taking the class, or recalled it from a previous chemistry course. We also note that despite instruction on energy balances in a prerequisite course, the chemical engineering students do no better than the other groups on the pretest.

The post-test results were mixed. First, we had two distinct groups of chemical engineering students. Generally, we have been able to collapse our data sets across multiple classes since the outcomes were not statistically different. However, in this single instance that was not possible (answer distribution $\chi^2 = 11.6$, $p < 0.01$). At this time we have no explanation as to why one group was so different. Among the rest of the chemical engineering and physics students, 70% or more gave the correct comparison while among mechanical engineers, only 26% gave the correct comparison. When reasoning was considered, the percentage of students correct dropped to 51%, 60%, and 17% for physics, chemical and mechanical engineering students respectively with only one mechanical engineer using the *First Law*. While there is no clear explanation for why mechanical engineering students found this part of the task so difficult, we suggest several possibilities. First, this represents one class, so it may have just been an exceptional class in the same way as one of the chemical engineering classes was different. Second, the students may not think of equations as useful tools for comparing quantities relative to each other without having numeric values to plug in and explicitly evaluate. Third, it is also possible there is something inherent in our instrument in the phrasing that is confusing to these students. However, when the instructors were shown the task they did not suggest that they felt their students would find this task difficult to understand.

3.3 Student ideas about internal energy

Internal energy was the only state variable asked about in this task. It was also the only one for which an explanation was not specifically asked for in most versions of the task. We note that as many as 40% of students in each group consequently did not provide reasoning; this hampered our ability to assess student knowledge. The answer distributions for both students that did and did not provide reasoning was not statistically significantly different ($p > 0.1$). Because of this, we have assumed that students who did not provide reasoning used the same reasonings in the same proportions as those that did provide reasoning, and have thus excluded the *no reasoning* category from Fig 5 to better represent the proportions of reasoning lines that were used by the students.

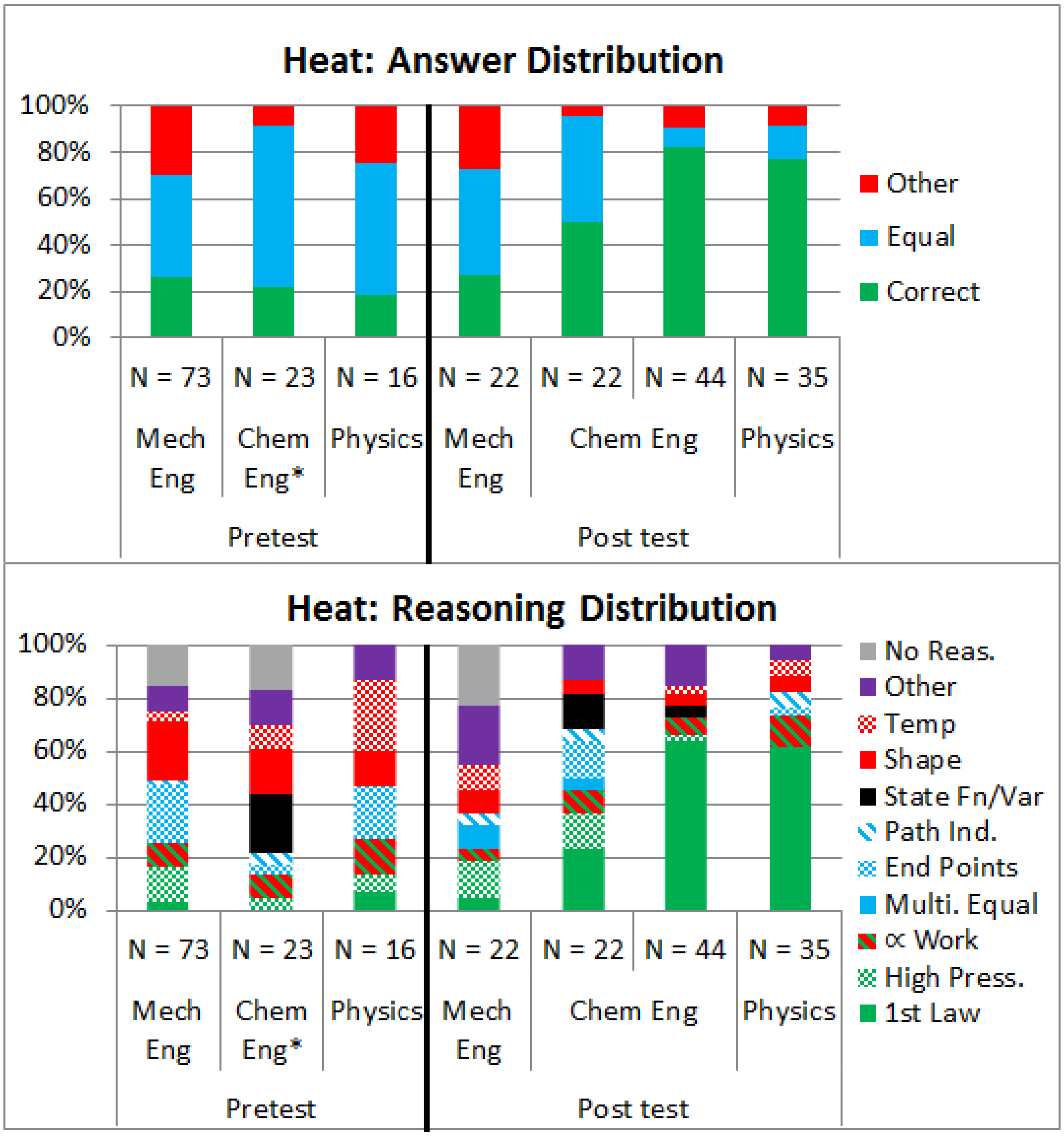


Figure 4: The answer (top) and reasoning (bottom) distributions to the task prompt "Is the heat transferred to the system during process 1 greater than, less than, or equal to the heat transferred to the system during process 2? Explain." The correct answer is $Q_1 > Q_2$. Correctly answering this question must involve the First Law as heat transfer cannot be directly read off the graph. Correct and partially correct reasoning codes are indicated by green. *Chemical engineering students had received instruction on energy balances in a prerequisite course.

Unlike the work and heat questions where the success rate on the pretest was less than 25% overall, we had 70% or more students correctly identify the changes in internal energy as equal. However, we do not believe this necessarily indicates a good understanding of internal energy, or state functions in general, because many of these students also identified the works as equal using *path independent* or *end point* reasoning. This suggest that these students may not recognize the distinction between a state function and a process-dependent quantity, and were treating most energy quantities as state functions. The answer distribution for mechanical engineers and physics students actually gets slightly, but not statistically significantly, worse ($p > 0.1$) on the post-test. Chemical engineering students most frequently used language specifically mentioning that internal energy was a state variable on the post-test; in this case, we believe this was meaningful as they also answered the work question correctly.

3.4 Whole task

Students rarely got the work question correct without also using correct or partially correct reasoning although the results are less good for the heat and internal energy questions (see Table 2). This indicates that these students have a reasonable, if not complete, conceptual understanding of work and at least some understanding of heat and internal energy. For the internal energy question in particular, we see high initial success and only a minor change in explanation among mechanical engineering and physics students from pretest to post-test, which makes it difficult to determine the extent of the students' understanding of this idea. The significant vocabulary change used in the explanations by the chemical engineering students, from *path independent* and *end point* to *state fn/var*, suggests that these students differentiate between state and path variables and can identify internal energy correctly. Overall, students that used *path independent* or *end point* reasoning on the internal energy question were statistically more likely ($p < 0.01$) to conclude that the works were equal than those that used *state fn/var* reasoning. This suggests that students that describe internal energy specifically as a state variable have a deeper conceptual understanding of the difference between state and process variables.

Students in chemical engineering and physics started below the chance level of 33% on the work and heat comparison questions and ended above 75%. Mechanical engineers also improved on the work question, but to a lesser degree. Observation of the classrooms during instruction shows that all students were presented with the information necessary to complete this task so we surmise that there was another issue present than lack of knowledge. Perhaps the success of the chemical engineers might be simply explained by their previous course dealing with part of the content (state functions and energy balances) if it were not for the fact that the physics students do just as well without having any prior course focused on thermodynamics. Prior exposure differences do not appear to explain the differences in performance of chemical engineering and physics students compared to mechanical engineering students. Another significant feature was that the mechanical engineers take the thermodynamics course earlier in their college careers than chemical engineers and physics students. Since there is clearly a maturation of students from the first year to the senior year, it is reasonable to assume that even a relatively small difference of a single semester might be significant. Chemical engineers and physics students both have more calculus

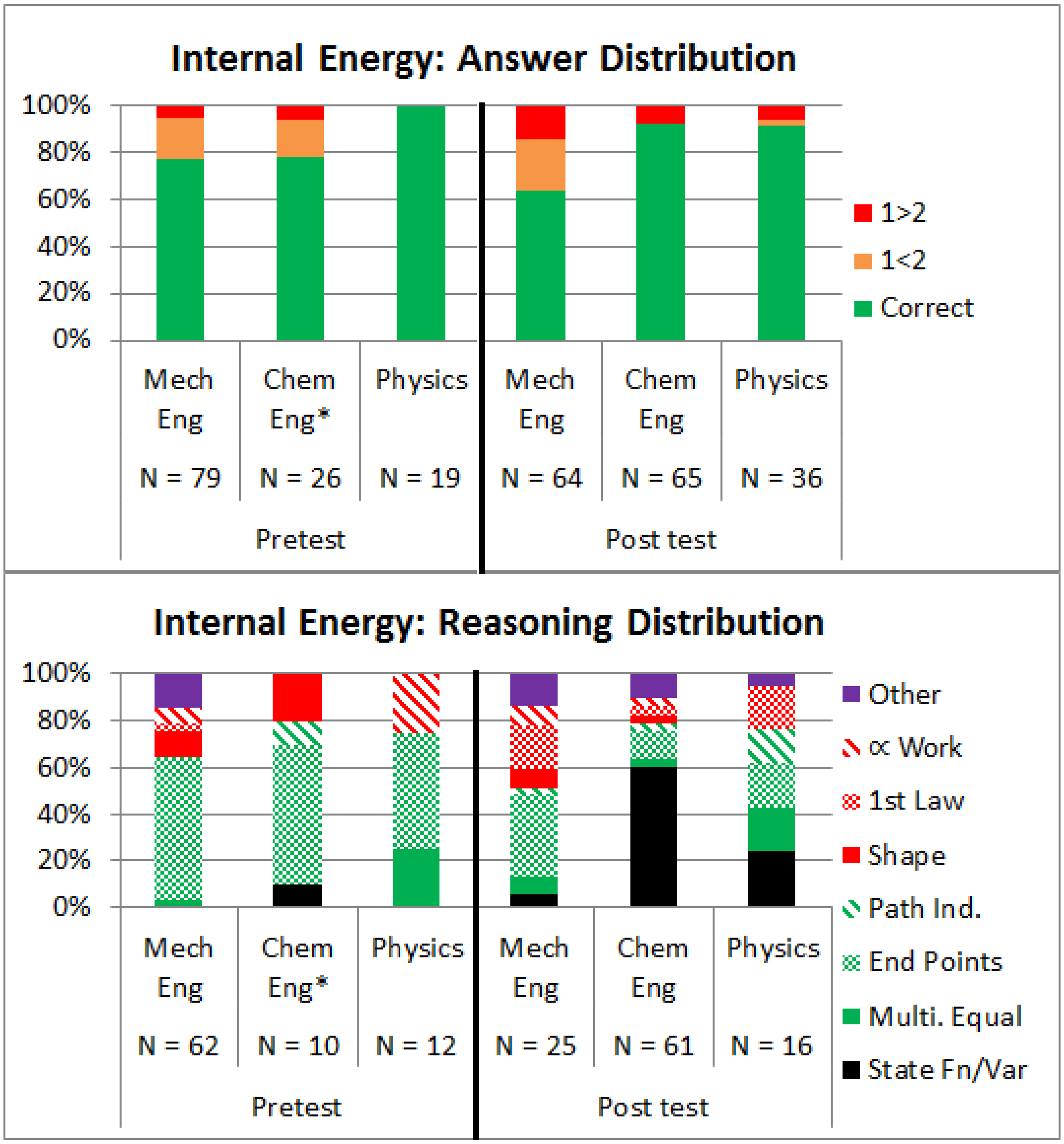


Figure 5: The answer (top) and reasoning (bottom) distributions to the task prompt "Is the change in internal energy for process 1 greater than, less than, or equal to the change in internal energy for process 2?" The correct answer is $\Delta U_1 = \Delta U_2$. The best and most complete answer, that internal energy is a state function, is indicated in black. Partially correct reasoning codes are indicated by green. The *no reasoning* category has been excluded from the lower graph to better illustrate the proportions of reasoning lines used by students that did provide reasoning. *Chemical engineering students had received instruction on state functions, including internal energy, in a prerequisite course.

and general experience with being college students in a challenging major. While more calculus could actually reduce performance on the task initially, it is reasonable to speculate that additional calculus brought to bear on the disciplinary content with attention to the representations is one way to address that concern.

We also note that the ordering of the questions on the task may have caused some students to incorrectly approach each step along the way as they may have become accustomed to progressing through problems in a linear manner. In most textbooks, this heuristic works well, but most real-world problems require assessing at each step whether there is sufficient information to proceed or whether more must be gathered. We have only recently altered the order of the questions to see if this makes a difference; we do not yet have sufficient data to determine whether the question order is significant.

Table 3.4 shows how consistently correct students were across the whole task. Over 90% of students that participated in any part of the task compared all three quantities. However, while the success rate of the comparison was over 70% correct among chemical engineers and physics students on each part of the task individually, only 58% and 43% respectively made correct comparisons across all three parts. The individual success rate for mechanical engineers was already significantly lower than the others, but we were surprised to find that none were successful on all comparisons. When we include reasoning, the success rate drops even more to 45% and 24% for chemical engineers and physics students respectively. This suggests that the task, as a whole, was difficult and required students to bring together many ideas and use them in concert.

	Course	Work (%)	Heat (%)	Internal Energy (%)	All Three (%)
Answered comparison	Mech E	96	96	100	91
	Chem E	100	99	97	96
	Physics	97	95	97	92
Correct answer	Mech E	39	26	70	0
	Chem E	81	70	90	58
	Physics	78	73	89	43
Correct answer and reasoning	Mech E	35	17	22	0
	Chem E	75	60	72	45
	Physics	76	51	43	24

Table 2: Breakdown of responses to all parts of the post test task by discipline, question and completeness and correctness of answer. While each question was individually answered by a high percentage of students, it was not consistently the same student across the whole task. The task was attempted by 23 mechanical engineering, 67 chemical engineering, and 37 physics students, but not all answered each question or provided correct reasoning.

4 Conclusion

In this study, we investigated student conceptual knowledge of the First Law of Thermodynamics, its constituent elements of work, heat and internal energy, and graphical interpretation of a *P-V* diagram. Returning to our three broad research questions concerning student difficulties, use of concepts and tools when solving problems, and instructional practices, we find some answers.

With regard to disciplinary specificity of student understanding and student difficulties, students across chemical and mechanical engineering and physics share some conceptual difficulties when they enter thermodynamics. We have found no specific difficulty unique to a discipline but the prevalence does vary between disciplines. The most prominent difficulty was the idea that work depends only on the end points or is path independent. This functional treatment of work as a state variable is consistent with earlier literature in physics education research.[3,7,11] While previously speculated by these earlier researchers, we have provided evidence that this idea arises quite reasonably from introductory physics instruction, in which many of the forces treated extensively (e.g., gravitational, elastic, electrostatic) are conservative forces. On a pedagogical note, we found that the groups that most successfully overcame this difficulty engaged in active-learning activities and spent more time applying the integral definition of work. We also found that chemical engineering students were far more likely to describe internal energy explicitly as a state variable at the end of the course.

As for our second research question, we found that students do not use the same concepts and tools when approaching the same problems. On the work question, very few mechanical engineers even wrote down the integral definition of work: of the four students that explicitly used the integral definition of work, one connected that definition to the *area* (*multiple correct*) and the other three mentioned aspects of the process curve (*shape*). This indicates potential difficulties with mathematics or graphical interpretation may persist with mechanical engineering students. We also found that few mechanical engineers used the First Law when approaching the heat question. We are confident that these students were familiar with the First Law, as they had successfully completed homework and test questions in which it was needed, so it remains a question as to why so few recognize its applicability to this situation. Since the homework questions were purely quantitative applications of the First Law, this result is consistent with physics education research findings[15] that quantitative proficiency does not imply conceptual or qualitative proficiency.

Finally, students in courses where they were more actively engaged performed better on all parts of our task. At this time it is unclear whether that is due to having work sheets on content similar to our task or if the out come would be similar without those specific activities. We also note that even when time was not spent on work sheets, instructors in chemical engineering and physics often posed questions to the class and waited until they were answered, encouraging at least some students to engage regularly.

References

[1] Eileen Lob Lewis. Conceptual Change Among Middle School Students Studying Elementary Thermodynamics. *Journal of Science Education and Technology*, 5(1), 1996.

[2] Shelley Yeo and Marjan Zadnik. Introductory Thermal Concept Evaluation: Assessing Students' Understanding. *The Physics Teacher*, 39(November):496–504, 2001.

[3] Michael E. Loverude, Christian H. Kautz, and Paula R. L. Heron. Student Understanding of the First Law of Thermodynamics: Relating Work to the Adiabatic Compression of an Ideal Gas. *American Journal of Physics*, 70(2):137 – 148, 2002.

[4] Christian H. Kautz, Paula R. L. Heron, Michael E. Loverude, Lillian C. McDermott, and Peter S. Shaffer. Student Understanding of the Ideal Gas Law, Part I: A Macroscopic Perspective. *American Journal of Physics*, 73(11):1055, 2005.

[5] Ronald L. Miller. Misconceptions About Rate Processes: Preliminary Evidence for the Importance of Emergent Conceptual Schemas in Thermal and Transport Sciences. In *American Society for Engineering Education Annual Conference*, 2006.

[6] Christian H. Kautz and G Schmitz. Interactive Lecture Questions as a Research and Teaching Tool in Introductory Thermodynamics. In *Proceedings of the 2006 SEFI Conference*, number June, pages 1–9, 2006.

[7] Evan B. Pollock. Student Understanding of P-V Diagrams and the Associated Mathematics. Master's thesis, University of Maine, 2008.

[8] Thomas M. Wemyss, Rabindra A. Bajracharya, John R. Thompson, and Joseph F. Wagner. Student Understanding of Integration in the Context and Notation of Thermodynamics: Concepts, Representations, and Transfer. In *14th Annual Conference on Research in Undergraduate Mathematics Education*, volume 4, pages 220 –234, 2011.

[9] Trevor I. Smith, Warren M. Christensen, and John R. Thompson. Addressing Student Difficulties with Concepts Related to Entropy, Heat Engines and the Carnot Cycle. *AIP Conference Proceedings*, 1179:277–280, 2009.

[10] Warren M. Christensen, David E. Meltzer, and C. a. Ogilvie. Student Ideas Regarding Entropy and the Second Law of Thermodynamics in an Introductory Physics Course. *American Journal of Physics*, 77(10):907–917, 2009.

[11] David E. Meltzer. Investigation of Students' Reasoning Regarding Geat, Work, and the First Law of Thermodynamics in an Introductory Calculus-based General Physics Course. *American Journal of Physics*, 72(11):1432–1446, 2004.

[12] Juliet Corbin and Anselm Strauss. *Basics of Qualitative Research (3rd ed .): Techniques and Procedures for Developing Grounded Theory*. 1990.

[13] David E. Meltzer. Student Reasoning Regarding Work, Heat, and the First Law of Thermodynamics in an Introductory Physics Course. In *Physics Education Research Conference 2001*, pages 107–110, 2001.

[14] Rabindra A. Bajracharya. Student Understanding of Definite Integral Using Graphical Representations. Master's thesis, University of Maine, 2012.

[15] Lillian C. McDermott. Oersted Medal Lecture 2001: "Physics Education Research—The Key to Student Learning". *American Journal of Physics*, 69(11):1127, 2001.