Investigation Of Student Learning In Thermodynamics And Implications For Instruction In Chemistry And Engineering

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Abstract. As part of an investigation into student learning of thermodynamics, we have probed the reasoning of students enrolled in introductory and advanced courses in both physics and chemistry. A particular focus of this work has been put on the learning difficulties encountered by physics, chemistry, and engineering students enrolled in an upper-level thermal physics course that included many topics also covered in physical chemistry courses. We have explored the evolution of students' understanding as they progressed from the introductory course through more advanced courses. Through this investigation we have gained insights into students' learning difficulties in thermodynamics at various levels. Our experience in addressing these learning difficulties may provide insights into analogous pedagogical issues in upper-level courses in both engineering and chemistry which focus on the theory and applications of thermodynamics.

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INTRODUCTION

For the past seven years, my group has been investigating student learning in thermodynamics in physics courses at both the introductory and advanced levels. Through this investigation we have probed students' learning difficulties at different points in their undergraduate training. Our experience in addressing these learning difficulties may provide insights into analogous pedagogical issues in upper-level courses in both engineering and chemistry which focus on the theory and applications of thermodynamics.

A particular focus of our work has been to examine the learning difficulties encountered by physics, chemistry, and engineering students enrolled in a junior/senior-level thermal physics course that included many topics also covered in physical chemistry courses. In this paper I will compare the initial knowledge (before instruction) of students enrolled in this course with the post-instruction knowledge of students finishing the introductory calculus-based general physics course. (Both courses were taught at Iowa State University, where the introductory course is populated primarily by engineering majors). I will also compare these results with data from a physical chemistry course taught at the University of Maine.

ASSESSMENT DATA

We [1] and others [2] have recently reported results which indicate that students finishing introductory university physics courses emerge with significant learning difficulties related to fundamental concepts in thermodynamics, such as heat, work, cyclic processes, and the first and second laws of thermodynamics. Some of these data, previously reported, will be repeated here in order to compare with student response data from the upper-level thermal physics and physical chemistry courses.

We administered a short set of written questions, after instruction, to 653 students in the introductory general physics course over a three-year period. In the fourth year, we carried out individual interviews (also after instruction) with 32 volunteers drawn from the students enrolled in that same course. This group, referred to below as the "Interview Sample," had course grades far above the class average; half of the Interview Sample had grades above the 81st percentile of the class as a whole. The students in the Interview Sample responded to the same set of written questions, in addition to other related questions.

The set of written questions (along with other questions) was administered on the first day of class to a total of 33 students enrolled in the upper-level thermal physics course during 2003 and 2004. Some of the questions were also administered in a physical

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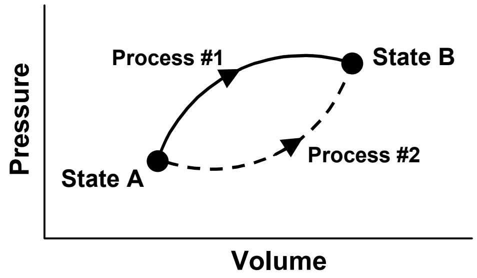
chemistry course during 2005 at the University of Maine; in that case, students responded to the questions after they had already received instruction on those topics in the physical chemistry course.

Two of the questions that were administered to all of the students are shown in Figure 1. The first question (the “Work” question) may be answered by examining the area under the curves representing Process #1 and Process #2, respectively. Since the area under the curve representing Process #1 is the larger, the work done by the system during Process #1 is greater than that done during Process #2. Interpretation of curves drawn on *P-V* diagrams in similar problems is often a focus of study in introductory physics courses; most instructors would probably consider this question to be relatively simple. Nonetheless, we found that a significant proportion of students in all samples responded by claiming that the work done by the system in both Processes #1 and #2 was the same. This response was given by 30% of the 653 students who responded to the written questions, and also by 22% of the students in the Interview Sample. Similarly, 21% of the students in the thermal physics course gave this answer. In the physical chemistry course at the University of Maine, six out of the eight students enrolled also gave this response, even after the relevant material had been discussed in that course.

The explanations offered by the students indicated that many of them believed that work done by a system during a thermodynamic process either is, or behaves as, a state function. Some of the explanations stated that idea explicitly, while others used words and phrases that carried the same implication. Examples of such explanations are these: “Equal, path independent; “Equal, the work is the same regardless of path taken.”

A correct response to the second question (the “Heat” question) required some understanding of the first law of thermodynamics. Since the change in internal energy is the same in both processes but more work is done by the system in Process #1, the system must absorb more energy in the form of heat in Process #1 in order to reach the same final state (so we will have $Q_1 > Q_2$).

This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:



[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

1. Is *W* for Process #1 ***greater than***, ***less than***, or ***equal to*** that for Process #2? Explain.
2. Is *Q* for Process #1 ***greater than***, ***less than***, or ***equal to*** that for Process #2? Please explain your answer.

FIGURE 1. Two of the questions posed to students in both introductory and upper-level physics courses. Answers: (1) *greater than*; (2) *greater than*.

The results we obtained on this question are shown in Table 1; 2003 and 2004 results are combined. If one neglects consideration of students’ explanations, it seems that both the students in the high-performing interview sample and the upper-level thermal physics students performed more poorly than did the introductory students who gave written responses. However, when considering only correct answers that

TABLE 1. Responses to Diagnostic Question #2: Heat Question. The Physical Chemistry course was given at the University of Maine; all other courses were given at Iowa State University. (Figures in the last column are rounded to the nearest 5%.)

	1999-2001 Introductory Physics Written Sample (Post-test) *N* = 653	**2002 Introductory Physics Interview Sample (Post-test) *N* = 32**	**2003-2004 Thermal Physics (Pretest) *N* = 33**	**2005 Physical Chemistry (Post-test) *N* = 8**
$Q_1 > Q_2$	45%	34%	33%	15%
Adequate explanation *(Correct or partially correct)*	11%	19%	30%	15%

are accompanied by correct or partially correct explanations, it becomes clear that the thermal physics students actually had superior results compared to the broader sample of introductory students. (Results in 2004 were similar to those in 2003.) Nonetheless, a correct-response rate of less than one-third would probably not be considered adequate by most instructors for a group that is supposed to be beginning study of statistical mechanics.

In analogy to the explanations offered for the Work question, the most popular incorrect response was that $Q_1 = Q_2$, and the most popular explanation for that answer was that the heat transfer to a system during a process was independent of the path taken by the system during the process. Since the initial and final states were the same, many students argued, the heat absorbed also had to be the same. Thus we found that many students at both the introductory and advanced level, when referring to work and to heat, use words and phrases that are only used by textbooks and instructors when referring to state functions.

Students' responses on related problems [3] corroborated the finding that a majority of the upper-level students were unable apply the first law of thermodynamics effectively in problem solving. Similarly, among students enrolled in the physical chemistry course at the University of Maine, only one out of eight was able to respond correctly to the Heat question even *after* having studied the first law of thermodynamics and related topics in that course.

The fact that we obtained consistent results in three separate upper-level courses at two different universities suggests that a significant proportion of upper-division students beginning advanced study of thermodynamics, in both physics and chemistry, are still struggling with fundamental concepts of heat, work, and the first law of thermodynamics that are normally presumed to have been mastered in their introductory courses. This appears consistent with the report by Towns and Grant [4] that portrays students in an advanced physical chemistry course finding a challenge in working similar problems based on *P-V* diagrams.

We also explored students' understanding of the second law of thermodynamics and the principle of entropy increase during spontaneous processes. We illustrate our findings with the problem shown in Figure 2; the results we obtained are given in Table 2.

The results show several similarities and some differences between the introductory and upper-level students. The introductory students have a tendency to argue that the "system entropy" must always increase, even in cases where inadequate information is available to make such a determination. At the same time, these students are slow to accept the idea that the *total* entropy of system and surroundings must increase during naturally occurring ("spontaneous") processes. In contrast to the introductory students, the students in the thermal physics course readily accept the principle that entropy increases in naturally occurring processes. However, they share with the introductory students the tendency to assume that "system entropy" must always increase regardless of process and regardless of how the "system" is defined. This finding is consistent with results reported by Thomas and Schwenz in 1998 for students enrolled in a physical chemistry course [5].

For each of the following questions consider a system undergoing a naturally occurring ("spontaneous") process. The system can exchange energy with its surroundings.

A. During this process, does the entropy of the **system** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

B. During this process, does the entropy of the **surroundings** [$S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

C. During this process, does the entropy of the system *plus* the entropy of the surroundings [S_{system} + $S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

FIGURE 2. "Spontaneous Process" question posed to students in both introductory and upper-level physics courses. Answers: (a) *not determinable*; (b) *not determinable*; (c) *increase*.

TABLE 2. Proportion of correct responses to Spontaneous-Process question.[a,b,c,d]

Question	Course	Pretest	Post-test
A (S_{system})	Introductory	42%	40%
	Thermal Physics	50%	65%
	Physical Chemistry	--	75%
B ($S_{surroundings}$)	Introductory	42%	39%
	Thermal Physics	50%	75%
	Physical Chemistry	--	50%
C (S_{total})	Introductory	19%	30%
	Thermal Physics	90%	100%
	Physical Chemistry	--	25%

[a] Introductory: *N* (pretest) = 1184; *N* (post-test) = 255

[b] Thermal Physics: *N* = 12 , matched sample

[c] Physical Chemistry: *N* = 8

[d] Most popular incorrect response on question *A* was *increase* (Introductory: 26% on Pretest, 34% on Post-test; Thermal Physics: 50% on Pretest, 25% on Post-test.

In our own small sample, most of the physical chemistry students asserted that *total* entropy would not change, similar to assertions that were made by the introductory physics students.

ISSUES ASSOCIATED WITH ENGINEERING STUDENTS

Although there were some notable exceptions, it seemed that the majority of the engineering students (and physics-engineering double majors) were relatively unfamiliar and uncomfortable with the need to provide explanations for reasoning in problem-solving, in comparison to the majority of the physics majors. There seemed to be a greater tendency to favor "plug-and-chug" methods, and even to defend them as being the more appropriate method for an upper-level science course. Some students demonstrated a persistent tendency to employ notations and formulations learned in engineering courses, even when they conflicted with those used in the thermal physics course. In general, overt *expressions* of dissatisfaction with the course and the interactive-engagement instructional methods (though not necessarily dissatisfaction itself) seemed more common among the engineering students.

IMPLICATIONS FOR TEACHING CHEMISTRY

Based on the similar course preparation for chemistry and physics majors at the introductory level, it seems probable that students beginning upper-level physical chemistry courses would have the same or similar difficulties regarding fundamental concepts in thermodynamics as was noted among the physics students. This would be consistent with the findings reported by researchers in Chemical Education [4, 5], and with the results from our small sample of physical chemistry students. One implication that could be drawn from this is that there is a need for a strong focus on fundamental concepts—including qualitative reasoning—at the beginning (at least) of the standard physical chemistry course. We also noted that unfamiliarity with standard physics notations and conventions caused difficulties not only for some of the engineering majors, but for a chemistry major enrolled in the course. These difficulties were more persistent than anticipated. This suggests a need for additional attention to addressing confusions related to diverse notations and conventions when students from varied backgrounds are enrolled in an upper-level physics course.

METHODOLOGICAL ISSUES

In physics education research, a vital role is often played by researchers' interpretations of students' explanations as presented in both written and verbal form. Our experience in this course emphasized a need to take into account the different backgrounds and notational conventions of engineering students when analyzing, interpreting, and categorizing their responses to diagnostic questions. Our difficulty in following students' chains of reasoning was often increased by their adherence to non-standard (from the physics standpoint) notations and lines of argument.

Another potentially significant issue for researchers arises when a class under investigation—particularly an upper-level course—includes students from a diversity of majors. When a significant sub-group of a class has a background substantially different from the majority (e.g., engineering vs. physics), data that represent the "class average" can easily tend to obscure patterns that may correlate strongly with sub-group membership. This problem is compounded by the small sample sizes that typify research investigations in upper-level courses. It is likely that patterns in the data that correlate with sub-group membership, even if they do actually exist, may fail to show up as statistically significant with the small numbers of students typical in upper-level courses.

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REFERENCES

1. D. E. Meltzer, *Am. J. Phys.* **72**, 1432-1446 (2004).
2. M. E. Loverude, C. H. Kautz, and P. R. L. Heron, *Am. J. Phys*. **70**, 137-148 (2002); M. J. Cochran and P. R. L. Heron, *Am. J. Phys.* **74**, 734-741 (2006).
3. D. E. Meltzer, "Student Learning in Upper-Level Thermal Physics: Comparisons and Contrasts with Students in Introductory Courses" in *2004 Physics Education Research Conference [Sacramento, California, 4-5 August 2004]*, edited by J. Marx, P. R. L. Heron, and S. Franklin, AIP Conference Proceedings 790, American Institute of Physics, Melville, NY, 2004, pp. 31-34.
4. M. H. Towns and E. R. Grant, *J. Res. Sci. Teach.* **34**, 819-835 (1997).
5. P. L. Thomas and R. W. Schwenz, *J. Res. Sci. Teach.* **35**, 1151-1160 (1998).