AC 2008-1505: INVESTIGATING AND ADDRESSING LEARNING DIFFICULTIES IN THERMODYNAMICS

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Investigating and Addressing Learning Difficulties in Thermodynamics

Abstract

Study of thermodynamic principles forms a key part of the basic curriculum in many science and engineering fields. However, there are very few published research reports regarding student learning of these concepts at the college level. 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 at a large Midwestern university. The total sample size was over 1800 students in the physics courses alone, and approximately 90% of these students were engineering majors. Part of this work included examination of learning difficulties encountered by physics and engineering students enrolled in an upper-level (junior/senior) thermal-physics course. We used a combination of free-response diagnostic questions administered in written form, and hour-long clinical interviews with individual students in which they explained their reasoning while solving problems. We found that up to 80% of the introductory students were unable to make practical application of the first law of thermodynamics in problem solving even after instruction had been completed, and many had a seriously flawed understanding of the meaning of heat and work. In addition, a large majority retained significant confusion regarding the role of entropy within the context of the second law of thermodynamics. In many cases, part of the difficulty could be traced to interchanging the roles of state functions on the one hand with process-dependent quantities on the other, to overgeneralization of conservation principles in inappropriate contexts, or with confusion regarding the meaning of commonly used terms such as “system” and “surroundings.” We found that a majority of the upper-level students at the beginning of their course retained most of the specific learning difficulties seen among the introductory students. We have attempted to address these difficulties through learning strategies that emphasized working in small groups on research-based guided-inquiry worksheets. Our experience in probing and addressing these learning difficulties may provide insights into analogous pedagogical issues in upper-level courses in engineering which focus on the theory and applications of thermodynamics.

Introduction

For the past eight years, my research 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. A large majority of the students in the introductory course were engineering majors, and thus for most of them this course was their first detailed exposure to thermodynamic concepts. Our experience in addressing students’ learning difficulties in thermodynamics may provide insights into analogous pedagogical issues in upper-level courses in engineering 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 a large Midwestern state university, where the introductory course is populated primarily by engineering majors. (A substantial portion of the work presented here has been published in other venues,[1] but it has not yet been collected together and presented as an integral whole.)

Assessment Data: First-Law Concepts

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.

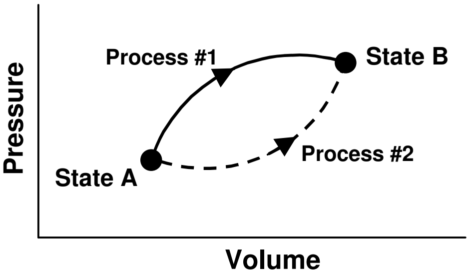
We administered a short set of written questions, after instruction, to 653 students in the introductory general physics course over a three-year period. In the fourth year, we carried out individual interviews (also after instruction) with 32 volunteers drawn from the students enrolled in that same course. (It was not possible to do such interviews in the other years.) This latter group, referred to below as the "Interview Sample," consisted of all those students who agreed to participate in an interview in return for a $10 payment. The names of those who volunteered were unknown to the course instructor and so their participation could have no effect on their course grades; this latter point was made explicit in the consent form given to the volunteers. This group 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. In this sense, the Interview Sample represents above-average students in the class; we anticipate that any difficulties they might have with learning of the course material would be difficulties shared by the average student in the class. Moreover, it seems reasonable to assume that the proportion of students in the Interview Sample manifesting a specific conceptual difficulty would not be greater than the proportion of students in the class as a whole who would manifest such a difficulty.

The students in the Interview Sample responded to the same set of written questions as had been given previously in written form to the 653 students; in addition, they responded to other related questions. The same 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.

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 (25%, 26%, and 35% in 1999, 2000, and 2001, respectively), and also by 22% of the students in the 2002 Interview Sample. Similarly, 21% of the students in the thermal physics course gave this answer (performances on this question in 2003 and 2004 were statistically indistinguishable).

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.”

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.*

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 $Q_1 > Q_2$).

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 might seem as if 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, such a conclusion would not be correct, for these questions *required* students to furnish explanations of their reasoning. When considering only correct answers that 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; the latter had consistently poor performances of 14%, 10%, and 10% (correct with correct explanation) in 1999, 2000, and 2001, respectively, compared to 30% overall in the Thermal Physics course. (Results in the 2004 Thermal Physics course were very similar to those in 2003. The Interview Sample also had performance numerically superior to the broader sample of introductory students, although with such a small sample size this difference is not statistically significant [$p = 0.16$].)

Although the upper-level students had performance superior to that of the introductory students, their correct-response rate of less than one-third would probably not be considered adequate, by most physics instructors, for a group that is supposed to be beginning study of statistical mechanics. In a typical upper-level physics course instructors ordinarily assume that most of the enrolled students have mastered first-law concepts, and so proceed quickly to discuss microstates, macrostates, ensembles, distribution functions, and other relatively sophisticated ideas. Our results suggest that the typical assumptions made regarding students' conceptual background may not be valid.

TABLE 1. Responses to Diagnostic Question #2: Heat Question. The courses were given at Iowa State University.

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

In analogy to the explanations offered for the Work question, the most popular incorrect response on the Heat question 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.

The introductory students in our interview sample had the opportunity to respond to numerous additional questions on related first-law-type questions.[1(a)] These included a set of questions regarding an ideal-gas system that undergoes a cyclic process including an isobaric compression and an isothermal compression. These interviews extended over an hour or more, and students were under no time pressure to formulate their responses. Our results demonstrated quite consistently that most of these students retained serious confusion regarding certain central concepts. Among these conceptual difficulties were (1) most students believed that, over the course of the cyclic process, the net work done by the system and the net heat transfer to the system had to equal zero; (2) most students did not realize that heat transfer away from the system had to occur during the isothermal compression; (3) nearly a third of the students believed that the total kinetic energy of the ideal-gas molecules would have to increase during an isothermal compression; (4) about one third of the students believed that positive work is done *on* the system by the surrounding environment during an isobaric expansion.

At the beginning of the upper-level thermal physics course, students were given the opportunity to respond to the same set of questions answered by the interview sample in the introductory course. (Some of these data have been reported in Ref. 1[b].) Remarkably, even these more advanced students retained most of the same conceptual difficulties found among the introductory students who volunteered for interviews. There was little or no significant difference in performance among the two groups on most of the questions and thus the impression, given by the data in Table 1, was sustained: even among students beginning advanced-level undergraduate courses, a majority was unable to make effective use of key first-law concepts in problem-solving. This included the sample of engineering majors and physics/engineering double-majors who were enrolled in the upper-level physics course. Results from a small sample of physical chemistry students at a northeastern university were entirely consistent with these findings.

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[3] that portrays students in an advanced physical chemistry course finding a significant challenge in working similar problems based on P-V diagrams.

Assessment Data: Second-Law Concepts

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.

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** [$S_{\text{surroundings}}$] *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 [$S_{\text{system}} + S_{\text{surroundings}}$] *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*.

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.[4]

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

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

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

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

[c] 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.

A more detailed analysis of these data[5] shows that both before and after instruction, most students tend to think of entropy as a quantity that is conserved. Responses to both the question shown in Fig. 2 above and to a closely related question set in a different context were very similar. (This other context incorporated an object in an insulated room containing air, in which the object and the air are at different initial temperatures). About two thirds of the students before instruction, and between half and two thirds of the students after instruction stated that the total entropy of the system plus that of its surroundings would be unchanged during a naturally occurring process. Most of the students followed a clear line of "conservation"-type reasoning, stating either that the entropy changes of the system and surroundings would cancel each other out exactly, or that these entropy changes were in themselves not determinable but that their sum would nonetheless have to equal zero.

In an attempt to address these conceptual difficulties regarding entropy, we have developed a guided-inquiry tutorial worksheet in which students are led to analyze the entropy changes in a system consisting of two very massive, insulated metal cubes at different temperatures, connected only by a thin metal pipe of negligible heat capacity. Since the two cubes act as thermal reservoirs it is easy to calculate their entropy changes using the relationship $\Delta S = \frac{Q}{T}$. Students are guided to realize that although the net energy of the system is indeed conserved, the net entropy must increase.

Students are asked to consider the magnitudes and signs of heat transfers to the two blocks; they are led to recognize that these heat transfers are equal in magnitude and opposite in sign, and that net energy change is zero. Students are then asked to consider the relative magnitudes and signs for the entropy changes of each block, as well as the net change in entropy. Students are guided to realize that the entropy increase of the cooler block is larger in magnitude than the entropy decrease of the warmer block, and so the *net* change in entropy is positive. Extensive details regarding these worksheets along with sample pages are provided in a forthcoming publication.[5]

We have tested this tutorial worksheet in courses at two different state universities and have so far obtained results which are promising, but by no means definitive. A significantly larger proportion of students who had used the worksheets gave correct answers on several diagnostic questions (such as those in Fig. 2) when compared to students in a course that had not used the worksheets. Specifically, we found that in a course at a large Midwestern university that did not make use of the worksheets, only 5% of all students (N = 127) responded correctly, before instruction, to all three questions shown in Fig. 2. After instruction, that proportion rose only to 8%. By contrast, in a nearly identical course in which the worksheets were used (in conjunction with interactive lectures enhanced with some of the worksheet strategies), 55% of the students gave correct answers to all three questions (N = 191). This contrasted sharply with the pre-instruction proportion of correct responses in that same course of only 6%. Similarly, in an analogous course at the University of Washington that made use of the tutorial worksheet, 63% of students gave all-correct responses on the set of three questions compared to only 13% before instruction.[5] Testing and refinement of the materials is still underway, in addition to development of other, related instructional materials.

Issues Associated with Engineering Students in the Upper-Level Course

Although there were some notable exceptions, it seemed that the majority of the engineering students (and physics-engineering double majors) were relatively less familiar or comfortable with the course requirement that they 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 methods (sometimes called "plug-and-chug") of simply substituting numbers into equations without providing required explanations of reasoning. Some students attempted to defend this process as being the more appropriate method for an upper-level science course, despite the fact that the course instructor had made very clear that expectations were different for this particular class. Some students demonstrated a persistent and inappropriate tendency to employ notations and specific algebraic expressions learned in engineering courses, even when they had been pulled out of context and therefore conflicted directly with those used in the thermal physics course. (This sometimes extended to an unwillingness to express algebraic answers using the symbols employed in the text, notes, lectures and homework assignments of the thermal physics course.) In general, overt *expressions* of dissatisfaction with the course and the "interactive-engagement" instructional methods[6] (though not necessarily dissatisfaction itself) seemed more common among the engineering students. To be fair, our sample of such students was quite small, there were some very notable exceptions to the general pattern, and we certainly draw no implication that the students were accurately representing the *intent* of the instructional methods in upper-level engineering courses.

Implications for Teaching Chemical Engineering Courses

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,[3,4] and with the results from our small sample of physical chemistry students. Although we have not tested it explicitly, one might suspect that students in chemical engineering thermodynamics courses might be subject to the same conceptual difficulties found among students in our sample. 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 and, perhaps, in chemical engineering thermodynamics courses as well. 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.

A somewhat contrasting view might be adduced from consideration of the long-standing tradition in engineering thermodynamics textbooks to incorporate definitions of quantities and statements of relationships (e.g., "entropy balance") that explicitly require students to consider entropy changes due *both* to heat transfers to the system *and* to intrinsic irreversibilities of the process itself. Since entropy changes due to heat transfer are directly linked to the entropy change of the surroundings, this formulation might lead students to appreciate more clearly the idea of "total" or "net" entropy change. It is possible that highlighting and distinguishing explicitly these various entropy changes might allow students to learn and apply second-law concepts more effectively than we have observed to be the case. However, there does not yet seem to be any published research examining this possible learning effect. For instance, in compiling an exhaustive bibliography of over 230 peer-reviewed papers dealing with student learning of thermodynamics concepts,[7] we have yet to find a report of a research investigation that probed student learning of these specific second-law issues in an engineering context.

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.

Conclusion

This report has focused much more on difficulties encountered by students in learning certain concepts than on possible solutions for addressing and remedying these difficulties. Although we and others have made extensive efforts toward the goal of improving instruction in thermodynamics, our assessment of progress to date shows results that are inconsistent and unsatisfying.[1,2] One conclusion is that making progress in improving learning in this field is far from easy and that substantial additional efforts will be needed, along with careful assessment of outcomes from efforts to improve instruction.

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