Student Learning In Upper-Level Thermal Physics: Comparisons And Contrasts With Students In Introductory Courses

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Abstract. We found that students in an upper-level thermal physics course were in general quicker than introductory students at grasping and applying fundamental concepts. Upper-level students seemed, in general, more receptive to employing qualitative reasoning using multiple representations, and capable of using it more effectively than introductory students. In addition, upper-level students were better able to utilize guided-inquiry curricular materials in the sense of reasoning with greater depth and grasping more subtle issues. However, although the overall level of preparation and ability was higher in the upper-level course, the broad range of preparation represented among the students presented various practical challenges to implementing active-learning instructional strategies. Moreover, even quite capable upper-level students would falter unexpectedly and unpredictably on various conceptual difficulties that are common among introductory students. The unpredictable and inconsistent nature of this effect demonstrated that instructors must always be prepared to detect and address such difficulties in upper-level courses.

INTRODUCTION

We have been engaged in an ongoing investigation of student learning of thermal physics in introductory courses [1-3]. In the course of this project, we have probed students' reasoning regarding heat, work, the first law of thermodynamics, calorimetry, and related topics. Based on this work, we have developed and tested preliminary versions of guided-inquiry curricular materials.

During Fall semester 2003, I taught a junior-level thermal physics course targeted at physics majors and other advanced students. In this course, many instructional methods were used that are often characterized as "interactive engagement" [4] or "active learning" [5]. Fourteen students were enrolled, mostly junior and senior physics majors along with several students majoring in chemistry or engineering. This course provided an opportunity to compare introductory and advanced students regarding learning of similar topics, using some identical curricular materials and methods. In this paper, I will discuss some of the main features of this experience.

METHODOLOGICAL ISSUES IN UPPER-LEVEL CLASSES

Students taking upper-level physics courses are certainly not representative of the overall student population enrolled in introductory general physics courses. Only a small percentage of students in the introductory course have a specific interest in physics as a major field, and most would be far more likely to take upper-level engineering courses than to enroll in advanced-level physics courses. For this reason, we must assume that observations regarding learning and transfer in advanced-level physics courses are characteristic only of a highly selected subsample of students enrolled in a typical introductory course. It is also important to remember that small class sizes (common in upper-level courses) are associated with a relatively high probability that any *one* particular class will not be fully representative of other, similar classes [6].

When evaluating students' performance in upper-level courses, two distinct factors come into play: (1) students' knowledge of material previously covered in introductory courses, and (2) students' *learning* of new

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material during the advanced course. In order to make some determination of students' knowledge of material learned in previous courses, it is essential to administer pretests on the relevant material to the students before those topics are covered in the advanced course. This poses a logistical challenge, because extensive pretesting ordinarily requires substantial amounts of class time. Because pretests are administered before instruction on the relevant topics, they can not be graded for course credit. Moreover, even when pretest data are acquired, an important dimension of student learning is missed, that is, the degree to which students may have increased their *readiness* to learn new topics as a result of their experiences in the introductory courses.

Although students may give incorrect answers or inadequate explanations on pretest questions related to specific topics, it may well be that their exposure to those topics in their previous courses had provided them with a basis for rapidly and effectively assimilating a second round of instruction on those same topics, as is often provided in advanced courses. Determining the students' state of "readiness" for new learning is an extremely challenging problem for researchers who develop and administer diagnostic pretests. Ordinary tests assess students' knowledge at a particular point in time and do not provide a measure of the rate at which such knowledge might be *changing*, nor of its *susceptibility* to change.

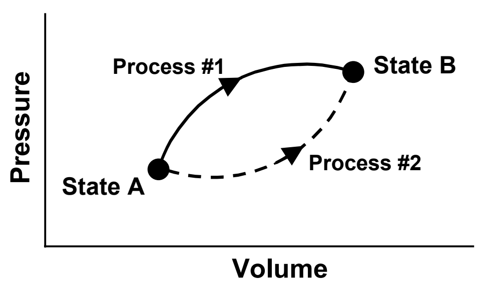
When considering "transfer" of learning from introductory courses, we are interested in two distinct (but hard to separate) factors: (1) *application* of knowledge previously learned, and (2) *synthesis* of new concepts based on knowledge elements learned or learning skills developed in previous courses. In the case of "application" of knowledge, we might try to determine the degree to which students can apply knowledge of concepts and techniques acquired in previous courses to the solution of more complex problems that make use of those same concepts or techniques. However, we have an equal or greater interest in the degree to which students can learn *new* concepts or techniques in the advanced course, and effectively apply those new concepts in problem solving. One assumes that an important product of instruction in introductory courses is the preparation of students for learning of new concepts in more advanced courses. However, it is probably much more difficult to determine students' ability to *learn* new concepts, than it is to determine their ability to *apply* previously learned concepts in new contexts.

STUDENTS' INITIAL KNOWLEDGE

On the first day of class, a small set of diagnostic questions related to calorimetry and the first law of thermodynamics was administered to provide information regarding students' initial knowledge. Overall performance on these questions was superior to the average post-instruction performance of students in the introductory physics courses reported in Refs. 1-3, although a broad range of knowledge levels was found.

During the present (Fall 2004) semester, I am again teaching the thermal physics course. On the first day of class, a larger set of diagnostic questions was administered to the students. Two (out of a total of 15) of these questions are shown in Fig. 1.

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*.

Most of the questions in this second diagnostic set had been administered (after instruction was completed) to students in the introductory calculus-based general physics course during the investigations reported in Refs. 1-3.

Among the 21 upper-level students responding to these questions, a wide range of initial knowledge levels was evident. Some students showed good ability to apply first-law concepts, while others showed little or none. On some questions, average performance was clearly superior to the post-instruction performance of students in the introductory course, while on other questions performance was virtually indistinguishable from that of students in the lower-level course.

On Question #1 shown in Figure 1 (the "work" question), about one quarter of students in both introductory and upper-level courses answered incorrectly that the work done by the system in Process #1 would be the same as that done in Process #2. By contrast, on Question #2 (the "heat" question), 38% of students in the upper-level course gave a correct or nearly correct answer with an acceptable explanation, compared to only 15-20% of students *after instruction* in the introductory courses. On questions related to cyclic processes, thermal reservoirs, and isothermal processes, performance of students in the upper-level course was comparable to the post-instruction performance of a self-selected sample of interview volunteers from the introductory course whose course grades were well above the class average [2].

COMPARISONS AND CONTRASTS WITH INTRODUCTORY STUDENTS

Students in the upper-level course demonstrated a number of important learning skills that were significantly better developed than among students in the introductory course. At the same time, even very able students in the advanced course periodically demonstrated a vulnerability to learning difficulties similar or identical to those found among students in the introductory course.

Upper-Level Students Demonstrated Superior Learning Skills

Learning skills displayed by upper-level students were superior in a number of respects to those of students in the introductory course. For example, they demonstrated an ability to make use of qualitative reasoning, multiple representations, and guided-inquiry curricular materials that was generally beyond that of the introductory students.

In covering similar material, upper-level students were quicker to generalize over specific contexts with a unifying concept. By contrast, introductory students tended to focus on pattern matching, recognizing commonalities among different problems without necessarily extracting a unifying physical theme. Despite having superior mathematical skills, upper-level students relied *less* on purely mathematical calculations and arguments than did introductory students in working identical problems. They were less likely to simply point to an equation as an explanation, and more likely to use arguments based on proportional reasoning.

Upper-level students found it easier than did introductory students to interpret the meaning of diagrams, bar charts, and other graphical material, even in novel contexts. They were more comfortable in making use of multiple representations (verbal, diagrammatic, etc.) to express their own thinking, and they showed less reliance on purely mathematical forms of reasoning. Even upper-level students with relatively less preparation demonstrated facility with multiple representations.

Upper-level students made effective use of guided-inquiry worksheets originally developed for use with introductory students. Typically, upper-level students worked through problems faster and more thoroughly, and required less guidance from instructors, than did students in the introductory course. Moreover, they were less likely to become bogged down in problem minutiae such as instructions or descriptions of apparatus, and they showed less confusion in interpreting instructions. These students worked well in groups, usually had productive discussions, and helped each other effectively. They showed a willingness to devote extra time to the resolution of confusing points.

Common Reasoning Difficulties Were Shared by Upper-Level Students

Even students receiving the highest overall grades would sometimes encounter conceptual difficulties that were the same as or similar to those observed among introductory students. The appearance of these learning difficulties among the upper-level students was intermittent and unpredictable, but recurrent (although the *same* difficulties did not generally recur). *Providing* they were addressed directly, these difficulties appeared to be resolved efficiently and thoroughly with few observable remnants.

Notable examples of conceptual difficulties encountered included the following: (1) Several students had substantial difficulty in applying the state-function property of entropy to conclude that ΔS would be equal for a free-expansion process and an isothermal process sharing identical initial and final states. In general, invoking state-function properties in contexts involving *entropy* seemed to be more difficult for most students than in the context of internal *energy* [7]. (A similar finding was recently reported by Kautz [8].) (2) Many students were slow in learning to compare engine and refrigerator efficiencies to the Carnot efficiency in order to check compliance with the second law. In addition, there were difficulties in making the correct identification of heat and work inflows *to* and outflows *from* the system in these problems. (3) When working through a guided-inquiry worksheet using diagrams that depicted a cyclic process, some students initially concluded that net work done by the system during the process had to be zero. Similar difficulties had been prevalent among students in the introductory course [2] and were evident among the upper-level students on the first-day pretest. (4) Many students displayed considerable difficulty in distinguishing between systems that had identical temperatures but different internal energies, and vice versa. (This is related to the classical confusion between heat and temperature, long recognized as a recurring learning difficulty in teaching thermodynamics to diverse student populations.)

Challenges and Difficulties

Consistent with observations made among students in introductory courses, both highly favorable and highly unfavorable reactions toward interactive-engagement techniques were displayed by upper-level students. The 10-15% unfavorable rating on evaluations matched that found in the introductory algebra-based course. Use of guided-inquiry worksheets during class (instead of in a separate recitation section) created logistical difficulties due to the broad range of speeds with which students worked. Insufficient pretesting and lack of previous relevant research made optimal course planning difficult.

SUMMARY

Students' performance on qualitative and quantitative problems throughout the course (on homework, quizzes, and exams) provided substantial evidence of effective learning in the context of this "active-learning" environment. There was some evidence of transfer of learning from previous courses, in that students seemed able to make use of (sometimes fragmentary) ideas acquired during previous instruction in the process of synthesizing an improved overall grasp of the subject. However, there was also substantial evidence suggesting that instructors must be attentive to sudden and unpredictable appearances of standard learning difficulties even among upper-level students.

When presented with unfamiliar concepts, upper-level students appeared to learn and apply them more efficiently than did introductory students. Experience with other advanced courses and a willingness to do substantial amounts of homework apparently contributed to significant learning gains. Upper-level students demonstrated, on the average, greater motivation; however, it is difficult to separate motivational factors from skill factors with respect to their relative significance in the production of observed learning gains.

The fundamental problem regarding analysis of transfer in the context of upper-level courses is the difficulty in answering this question: When learning is observed in upper-level courses, does it represent (a) transfer of *knowledge* acquired in introductory courses, (b) application of *learning skills* acquired in introductory courses, or (c) knowledge and/or skills possessed by the student all along, perhaps even before beginning introductory courses? (Or, perhaps, all three?) It is likely that extensive longitudinal investigation with diverse courses and student populations will be required to apportion the proper weights among the various relevant factors.

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