Investigation of Student Reasoning Regarding Concepts in Thermal Physics

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Decades of research have documented substantial learning difficulties among pre-university students with regard to heat, temperature, and related concepts.[1] However, it has not been clear what implications these findings might have with regard to the learning of thermodynamics. Studies reported in several European countries in recent years have indicated significant confusion among university students regarding fundamental concepts in thermal physics.[2] The recent investigation of Loverude *et al*.[3] strongly suggested that a large proportion of students in introductory university physics courses emerge with an understanding of the fundamental principles of thermodynamics that is insufficient to allow problem solving in unfamiliar contexts. In related work, the Iowa State University Physics Education Research Group has been engaged since 1999 in a research and curriculum development project aimed at improving thermodynamics instruction in the introductory university physics course. In this short report I will summarize some of the initial findings of our ongoing investigation into students' reasoning regarding concepts in thermodynamics.[4]

Our data for this initial phase of the investigation were collected during 1999-2002 and were in two primary forms: (1) a written free-response quiz that was administered to a total of 653 students in three separate offerings of the calculus-based introductory physics course; (2) one-on-one interviews that were conducted with 32 student volunteers who were enrolled in a fourth offering of the same course. All testing and interviewing was done after students had completed their study of the relevant topics. Results of all the various data sources were quite consistent with each other.

We found that students' understanding of process-dependent quantities was seriously flawed, as substantial numbers of students persistently ascribed state-function properties to both work *and* heat. Although most students seemed to acquire a reasonable grasp of the state-function concept in the context of internal energy, it was found that there was a widespread and persistent tendency to improperly over-generalize this concept to apply to both work and heat. This confusion was associated with a strong tendency to believe that the net work done and the net heat absorbed by a system undergoing a cyclic process are both zero.

The written quiz consisted of a *P-V* diagram on which curving lines represented two separate expansion processes involving a fixed quantity of ideal gas. The initial and final states of the two processes were identical, but the areas under the curve differed in the two cases. Students were asked to compare the amount of work done by the system during the two processes, and also the amount of heat transfer to the system during the same two processes. About 30% of all students asserted that the work done would be equal in the two cases, although the areas under the curve were clearly different. Similarly, 38% of all students claimed that the heat transfer to the system would be the same in both processes, although a straightforward application of the first law of thermodynamics shows that the heat transfer must be different in the two cases. (This incorrect response regarding heat was almost equally popular among students who gave the *correct* answer to the work question, as it was among those who claimed that the work done was equal in the two processes.)

During the interviews, students were shown diagrams portraying a three-step cyclic process involving a cylinder containing a quantity of ideal gas. The diagrams showed an isobaric expansion followed by an isothermal compression, followed finally by a constant-volume cooling. (The net work done by the system and the net heat transfer to the system during the complete cycle were negative.) After slowly and methodically working through and discussing this process (the typical interview lasted over one hour), 75% of the students asserted with great confidence that either the net heat transfer to the system during the complete cycle, the net work done by the system during the cycle, or both of those quantities, would have to be equal to zero. The interviews also disclosed unanticipated levels of confusion regarding the definition of thermodynamic work, as well as difficulties in recognizing the existence of heat transfer during isothermal processes involving volume changes.

Consistent results over several years of observations involving both written quizzes and oral interviews enabled us to make a high-confidence estimate that approximately 80% of students in the introductory calculus-based physics course emerged with only a very weak ability to apply the first law of thermodynamics to solving problems in unfamiliar contexts. This result was consistent with findings of Loverude *et al*.

Although it is not entirely clear *how* students arrive at their ideas regarding thermodynamics, some of the more widely shared ideas seem to have an understandable basis. It seems that a fundamental conceptual difficulty is associated with the fact that heat transfer, work, and internal energy are all expressed in the same units, and all represent either energy or *transfers of* energy. Many students simply do not understand why a distinction must be made among the three quantities, or indeed that such a distinction has any fundamental significance. One of the subjects in our interview sample, when invited to explain what he found particularly confusing about the heat-work-energy relationship, offered this comment: "How is it acceptable for something called 'work' to have the same units as something called 'heat' and something called 'energy'?"

Part of this confusion stems from the ubiquitous and well-documented difficulty students have in making a clear conceptual distinction between a quantity and the *change* or *rate of change* of that same quantity (for example, that between velocity and acceleration).[5] Many students do not learn that heat transfer and work both represent *changes* in a system's internal energy, and that they therefore are not properties associated with a given state of a system but rather with the transition between two such states. This problem is exacerbated by the use in colloquial speech of the terms "heat" or "heat energy" to correspond to a concept that is actually closer to what physicists would call "internal energy". However, our findings corroborated those of Loverude *et al*.[3] that an even more significant difficulty was that related to mastering the work concept in a *mechanics* context, let alone within the less familiar context of thermodynamics. Significant difficulties in understanding work persisted from students' studies of mechanics, and hampered their ability to master the related ideas in the context of thermodynamics.

Students do learn well that there exist quantities that are independent of process, and that (internal) energy of a system is one of these quantities. Perhaps due to their already weak grasp of the concepts of heat and work, many students improperly transfer, in their own minds, various properties of state functions either to heat, or work, or both. Certainly, the fact that mechanics courses frequently highlight the path-independent work done by conservative forces may contribute to this confusion, as may extensive use of the equation $Q = mc\Delta T$ in calorimetry problems.

Another area of confusion might be traced to the limiting approximations frequently – and often tacitly – invoked regarding idealized processes. Experienced physicists automatically "fill in the dots" when describing, for instance, an isothermal process and the meaning of a thermal reservoir. The overwhelming majority of textbook discussions treat these and similar idealized processes only very cursorily; our data suggest that for most students, such treatments are inadequate.

Implications for Instructional Strategies

Loverude *et al*. have pointed out that a crucial first step to improving student learning of thermodynamics concepts lies in solidifying the student's understanding of the concept of work in the more familiar context of mechanics, with particular attention to the distinction between positive and negative work.[3] Beyond that, it seems that little progress can be made without first guiding the student to a clear understanding that work in the thermodynamic sense can *alter* the internal energy of a system, and that heat or heat transfer in the context of thermodynamics refers to a *change* in some system's internal energy, or equivalently that it represents a quantity of energy that is being transferred from one system to another.

The instructional utility of employing multiple representations of physics concepts has been demonstrated.[6] The results of our study suggest that significant learning dividends might result from additional instructional focus on the creation, interpretation, and manipulation of *P-V* diagrams representing various thermodynamic processes. In particular, students might benefit from practice in converting between a diagrammatic representation and a physical description of a given process, especially in the context of cyclic processes.

Our results demonstrate that certain fundamental concepts and idealizations often taken for granted by instructors are very troublesome for many students (for example, the relation between temperature and kinetic energy of an ideal gas, or the meaning of thermal reservoir). The recalcitrance of these difficulties suggests that it might be particularly useful to guide students to articulate these principles themselves, and to provide their own justifications for commonly used idealizations.

It is worth noting another one of our observations that corroborated reports from other researchers. We found that students often used microscopic arguments both as a basis and as a justification for incorrect reasoning regarding thermodynamic phenomena. (This is identical to a finding reported in Ref. 3, and in other references cited in both Refs. 3 and 4.) The extent to which this faulty student reasoning was actually initiated or catalyzed by instruction involving microscopic concepts is uncertain. However, our research serves as a caution that merely incorporating a strong instructional emphasis on the microscopic, molecular viewpoint in thermal physics is unlikely, *in itself*, to dramatically impact students' understanding. Indeed, our ongoing research indicates that many key concepts emphasized in a microscopic approach are very challenging even for physics majors in their third and fourth years of study.[7]

Acknowledgments

This material is based on work supported by the National Science Foundation under Grant Number DUE-9981140 (Co-Principal Investigator: T. J. Greenbowe), and Grant Number PHY-0406724. The thermodynamics curriculum project is a collaboration with the ISU Chemistry Education Research group directed by T. J. Greenbowe.

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