Overview

The goal of this project is to carry out a coordinated program of research and research-based curriculum development, both in introductory general physics courses and in advanced-level undergraduate courses, on the learning and teaching of a broad variety of topics in thermal physics. We will build on work we have carried out over the past several years that has focused on research and curriculum development targeted at student learning of calorimetry and the first law of thermodynamics, and on the role of diverse forms of representation in student learning of physics. We will extend our investigation of students' reasoning to a range of topics selected from among the following:

1) entropy and the second law*
2) heat engines and refrigerators*
3) free energies and thermodynamic potentials
4) phase transitions (first-order and continuous)
5) fundamentals of statistical physics*
6) relationship between microscopic and macroscopic view of thermodynamics*
7) interpretation of standard representations* (e.g., "inexact"differentials $đQ$ and $đW$; 3-D phase diagrams; partial derivative notation; P-V and S-T diagrams; etc.)

Among advanced students, all of these topics may be targeted. Among students enrolled in introductory general physics courses, a more limited selection (marked with an asterisk *) will be targeted.

We will extend our investigation of students' reasoning on representation-related issues, building on our previous work examining introductory students' understanding of P-V diagrams in a limited number of contexts. We will look closely at the role of standard representations in learning of key thermal physics topics in introductory general physics courses and in the junior-senior level courses in thermal physics, examining such things as P-V and S-T diagrams, "heat-flow" representations of heat engines and refrigerators, phase space diagrams, energy bar charts to represent thermodynamic quantities, partial-derivative notation, notation for "inexact differentials," mnemonic diagrams (such as those used for Maxwell relations), three-dimensional phase diagrams, etc.

Project Staff

The lead PI, David E. Meltzer, is Assistant Professor of Physics at Iowa State University (ISU); he has had more than twelve years of experience in research and curriculum development in physics education. He has been PI on seven education-related projects funded by NSF, and has published extensively and given more than 40 invited presentations on physics education research. After receiving a Ph.D. in theoretical condensed matter physics from SUNY Stony Brook in 1985 and completing six years of post-doctoral work at the University of Tennessee and the University of Florida, he turned his focus to physics education research. Since 1998 he has been director of the Iowa State University Physics Education Research Group. He is lead author on the *Workbook for Introductory Physics*, a CD-ROM compilation of over 400 pages of class-tested active-learning curricular materials. He has also taught more than 20 different physics courses, including nearly every course in the undergraduate curriculum.

The collaborating PI, John R. Thompson, is an Assistant Professor of Physics and Cooperating Assistant Professor of Education at the University of Maine. After completing a Ph.D. in experimental surface physics at Brown University, he spent three years as a post-doctoral research associate with the Physics Education Group directed by Prof. Lillian McDermott at the University of Washington. There he engaged in a variety of physics education research projects and was an instructor in many graduate and undergraduate courses employing research-based curricular materials and instructional methods. He was on the faculty at Grand Valley State University for two years, and in 2002 joined the faculty at the University of Maine, where he is co-director of the Physics Education Research Laboratory. He has broad-ranging experience in physics education research, development of research-based curricular materials, and instruction with inquiry-based teaching methods.

Synopsis of Previous Research on Students' Reasoning in Thermal Physics and Related Topics

Review of the literature

Given the fundamental importance of thermodynamics, it is surprising and ironic that there has been so little research into student learning of this subject at the university level. Although there have been literally hundreds of investigations into student learning of the more elementary foundational concepts of thermodynamics (heat, heat conduction, temperature, phase changes, etc.) at the secondary and pre-secondary level, the total number of published studies that focus on university-level instruction regarding the first and second laws of thermodynamics is on the order of ten, of which only two were devoted to physics students at U.S. universities. (We have compiled a world bibliography of over 220 publications in five languages; it is posted at http://www.physics.iastate.edu/per/current/index.html.) Research studies probing student learning of more advanced thermal physics concepts (such as statistical physics) are essentially nonexistent.

The multitude of investigations referred to above has demonstrated convincingly that pre-university students face enormous obstacles in learning to distinguish among the concepts of heat, temperature, internal energy, and thermal conductivity. Instructors at the university level have often noted similar ideas among their own students as well (Arons 1997; Knight 1998), and investigations that probed university students' thinking about these concepts have recently appeared (Yeo and Zadnik 2001; Jasien and Oberem 2002; Cochran 2003).

A few investigations have been reported that examined pre-university students' understanding of the entropy concept and the second law of thermodynamics (Kesidou and Duit 1993; Shultz and Coddington 1981; Duit and Kesidou 1988; Ben-Zvi 1999). Several reports have examined student learning of thermodynamics concepts in university chemistry courses (Cullen 1983; Granville 1985; Beall 1994; Kaper and Goedhard 2002; van Roon *et al*. 1994; Banerjee 1995; Thomas and Schwenz 1998; Thomas 1997; Greenbowe and Meltzer 2003); some of these studies have touched upon both first- and second-law concepts in addition to topics more specific to the chemistry context. Among investigations directed at university-level physics instruction, one in France focused on oversimplified reasoning patterns used by students when thinking about thermodynamics, particularly when explaining multivariable phenomena with reference to the ideal gas law (Rozier and Viennot 1991; Viennot 1996). A German study examined the learning of basic thermal physics concepts by students preparing to become physics teachers (Berger and Wiesner 1997). There was also a very brief report of a survey of entrants to a British university (Warren 1972), and a study related to U.S. students' concepts of entropy and the second law of thermodynamics (Pushkin 1995).

It seems that the first detailed investigation of university physics students' learning of heat, work, and the first law of thermodynamics was that of Loverude, Kautz, and Heron published in 2002 (Loverude *et al*. 2002). (Additional details are in Loverude's dissertation [Loverude 1999].) This study, incorporating extensive data collected from observations at three major U.S. universities, documented serious and numerous learning difficulties related to fundamental concepts in thermodynamics. It was found that many students had a very weak understanding of the work concept and were unable to distinguish among fundamental quantities such as heat, temperature, work, and internal energy. Only a small proportion of students in introductory courses were found to be able to make use of the first law of thermodynamics to solve simple problems in real-world contexts.

The report by Loverude *et al.* represents the first detailed examination of the effectiveness of standard university-level instruction in thermodynamics with regard to student learning of the first law of thermodynamics and related concepts. More recent work by the University of Washington group has begun to focus on such topics as the second law of thermodynamics, although only preliminary results have been reported so far.

Although there have been a great many discussions in the literature of possible approaches to teaching various topics in advanced undergraduate thermal physics (e.g., Marx 1983; Lewins 1985; Velarde and Cuadros 1995; *American Journal of Physics* 1999),virtually none of the published reports provide any substantial degree of documentation regarding the degree of student learning resulting from the proposed teaching methods. (A recent exception is Starauschek 2002). There is also remarkably little discussion of specific pedagogical problems observed among students during actual classroom instruction on these topics. Thus, both basic research on student reasoning regarding these topics, and detailed documentation of student thinking in reaction to curricular innovations in thermal physics, is lacking from the published literature. This goal of this project is to begin to fill in some of these gaps by carrying out in-depth investigation of student reasoning on thermal physics topics, and by assessing and documenting the degree of actual student learning that results from use of research-based curricular materials that we develop.

Previous work done by ISU Physics Education Research Group (PERG)

The investigations carried out by our group at Iowa State include independent examination of some of the same research questions analyzed by Loverude *et al.*, as well as several areas not addressed by their study. A preliminary report of our work appeared in 2001 (Meltzer 2001), and a comprehensive report has been submitted to the *American Journal of Physics* (Meltzer 2003). A related report of our investigations on student understanding of thermochemical concepts was recently published in the *International Journal of Science Education* (Greenbowe and Meltzer 2003). This work has been supported by an NSF grant through the Division of Undergraduate Education, and a parallel investigation of the role of diverse representations in student learning has been supported by a separate grant through the Division of Research, Evaluation, and Communication (see Biography pages for grant titles and numbers).

The findings of our investigation include several previously unreported aspects of students' reasoning about introductory thermodynamics. In contrast to at least one previous report, it was found that students tend to have a reasonably good grasp on the state-function concept in the specific context of internal energy. However, students' understanding of process-dependent quantities was found to be seriously flawed, as sizeable numbers of students persistently ascribe state-function properties to both work *and* heat. This is associated with a strong tendency to believe that net work done and net heat absorbed by a system undergoing a cyclic process are both zero. Interview data disclosed unanticipated levels of confusion regarding the definition of thermodynamic work, and heretofore unreported difficulties with the concept of heat transfer during isothermal processes.

Taking into account the work of Loverude *et al.* and the corroboration and amplification offered by our investigation, as well as further corroboration in the literature by researchers in several different countries, it seems very probable that a large proportion of students in introductory university physics courses fail to master the basic concepts of thermodynamics. It is ironic that students' apparent ability to comprehend the concepts of state and state function actually may contribute to their confusion regarding process-dependent quantities such as heat and work. Students learn to become very well aware that there exist quantities that are independent of process, and that energy of a state 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.

It would be hard to overestimate the magnitude of the learning obstacle generated by a misunderstanding of the process-dependent nature of heat transfer and thermodynamic work. Heat engines, refrigerators, and analyses based on the second law of thermodynamics crucially depend on the non-zero net heat transfer to, and net work done by, a thermodynamic system during a cyclic process. It is precisely this concept that was among the most poorly understood among the students in our investigation, and that was directly traceable to a confusion regarding the fundamental properties of heat and work. The results both of our investigation and those of others previously reported strongly suggest that most students emerge from introductory physics courses with little functional understanding of the first law of thermodynamics and related concepts.

Current work by ISU PERG

The lead PI (Meltzer) is currently teaching the junior-level course in thermal physics at Iowa State University (Physics 304). This course is providing the opportunity to class-test preliminary versions of the curricular materials created as a result of the research described above. This testing is providing considerable valuable insight into student thinking on various key concepts in thermal physics that will aid in formulating diagnostic test instruments for further research, and in drafting revised versions of the curricular materials. For example, this class testing has disclosed persistent student confusion – despite continual emphasis during instruction – regarding (1) the equality of net changes in state functions during reversible *and irreversible* processes linking common initial and final states; (2) the requirement of net increase in entropy of system *plus surroundings* (in contrast to considering solely changes in system entropy) during spontaneous, irreversible processes; (3) the implications of the second law of thermodynamics in relation to net work done by, and net heat flows into and out of a system during a cyclic process.

In addition to the ongoing work with the advanced students in the thermal physics course, we are continuing to carry out interviews with students in the general physics course in connection with our work in probing student thinking on calorimetry and the relationship between temperature and internal energy.

Proposed Research Plan for this Project

We will begin by developing and testing a variety of diagnostic instruments designed to assess student understanding of the concepts on our target list. Test questions will always be administered to at least two separate student samples – usually three or more – generally in two different course offerings or in recitation sections taught by different instructors.

We will carry out research simultaneously on two distinct student populations: (1) students enrolled in the introductory general physics courses, with a focus on the calculus-based course taken by engineering students; (2) upper-level students enrolled in the junior-senior level thermal physics course, populated primarily by physics majors. In the general physics course, we will administer both multiple-choice and free-response diagnostic questions as quizzes, practice quizzes, and on exams, with cooperation from the course instructors. We will solicit students currently enrolled in the courses to volunteer for one-on-one clinical interviews. We will carry out in-class testing of curricular materials that we develop based on our research, and we will carry out controlled experiments to assess the effectiveness of the materials by utilizing them in randomly selected recitation sections, at the same time that other sections use ordinary instructional techniques on the same topics. Pre- and post-testing through quizzes and exams will provide a measure of the relative effectiveness of the newly developed materials.

It is important for us to emphasize here that *all of research methods described in the paragraph above have been, and are currently being employed, in our ongoing work at Iowa State University.*

Similar methods have been used at the University of Maine (UMaine). The research at UMaine will primarily take place in *PHY 462: Physical Thermodynamics*, which is offered annually in the fall with a population of approximately 5-10 students each year and is normally taken as a junior or senior elective by students in the sciences or engineering. The instructor, Donald B. Mountcastle (Senior Personnel on this proposal), is involved in the activities of the UMaine Physics Education Research Laboratory (PERL), and has had experience implementing research-based instructional strategies in the laboratory setting at the introductory level. Mountcastle is eager to allow research activities to occur in his class. Other courses (for example, *PHY 463: Statistical Mechanics,* also taught by Mountcastle, and the graduate-level *Statistical Mechanics* course) may be probed as the research progresses. At the University of Maine, we have a unique opportunity to pursue extensive research on student learning throughout the entire physics major sequence. There is strong departmental support for physics education research (as carried out by the PI), and instructors are eager to bring innovations in teaching and assessment into their courses.

In the upper-level courses, we will primarily employ free-response written instruments in which students are required to explain their reasoning. Multiple-choice instruments would not be needed in these courses since enrollments are typically less than 20. Clinical interviews may be employed in the form of oral quizzes, possibly for extra credit, a method that we have used in the past in small-enrollment courses. Additional, clinical interviews may be carried out with students who have recently completed these courses.

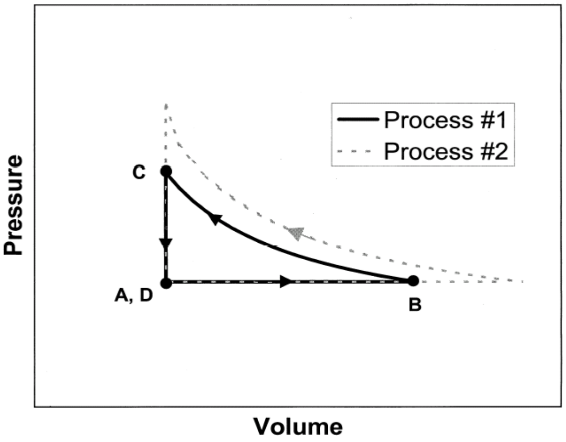
Research Methods

(1) One-on-one clinical interviews with students

The most deeply probing – and at the same time most time-consuming and laborious – data-gathering method in PER is the one-on-one interview with student volunteers. These interviews (known as "clinical interviews" in the education literature) usually require up to an hour or more, are recorded on audiotape, videotape, or both, and allow for very detailed analysis of students' thinking. Often they are carried out as "individual demonstration interviews," a format practiced at the University of Washington for over twenty years. In this type of interview, students are presented with appropriate pieces of apparatus for demonstration purposes. Students are asked to predict, define, or describe various physical phenomena. Interviewers probe student responses through extensive questioning. Results from a single interview are analyzed for models of reasoning and issues of consistency. Results from multiple interviews are compared, with researchers seeking common reasoning themes within the student population. The former give insight into the spectrum of student reasoning; the latter give insight into the prevalence of student ideas.

We will carry out a set of detailed individual interviews with students before and after instruction to assess their understanding of the material.

We have also carried out many interviews in which, for logistical reasons, no actual apparatus or equipment was available. In this format, students are asked to consider a hypothetical experiment that is described in detail using diagrams and printed text. For example, in our thermodynamics work we developed a series of questions describing an ideal-gas system in a cylinder surrounded by a water-filled container undergoing a cyclic process. The process is represented in this *P-V* diagram (a diagram that was ***not*** shown to the students):



A *P-V* diagram (not shown to students) of the processes (Process #1 and Process #2) discussed during interviews.

The process was presented to the students in the form of text and diagrams. For instance, the *B* to *C* segment was described to the students as follows, accompanied by the diagram below:

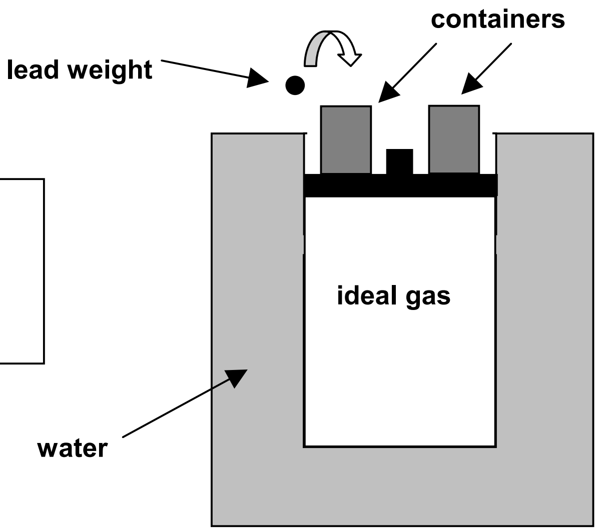
Step 2. Now, empty containers are placed on top of the piston as shown. Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly. While this happens, the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*. (That is, it remains at the temperature it reached at time *B,* after the water had been heated up.)

Step 3. At time *C* we stop adding lead weights to the container and the piston stops moving. (The weights that we have already added up until now are still in the containers.) The piston is now found to be at *exactly the same position it was at time **A***.

weights being added

Piston moves down slowly.

Temperature remains same as at time *B*.



Over the course of the one-hour (or longer) interview, students were given plenty of time to consider the complete cyclic process, answer a series of questions related to it, and explain their reasoning in detail. We were able to carry out interviews with 32 student volunteers from a single offering of the same calculus-based general physics course in which data had been collected during previous years [to be described in subsection (2) below]. The results of the interviews strongly confirmed our previous observations regarding student reasoning about heat and work, and provided important new data regarding student thinking about cyclic processes, isothermal processes, *P-V* diagrams, and a variety of other concepts.

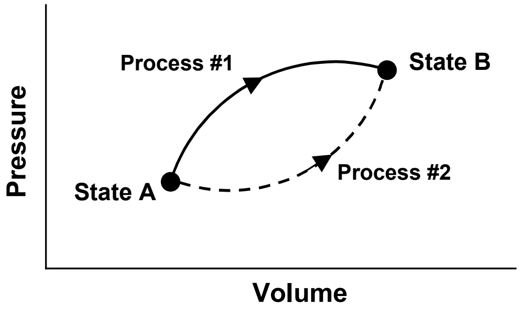
In the present project, one-on-one clinical interviews with students will form a major part of the data-gathering process. Reviewing the audio and/or video recordings, transcribing portions of the interviews, and analyzing and comparing the resulting data will be a major component of the time spent both by faculty members and graduate students on the project as a whole.

(2) Students' written explanations of their reasoning

An extremely useful probe of student thinking is a question, or a series of related questions, in which students are asked to explain their reasoning. Although it is not as revealing as a one-on-one interview, it is far more efficient in terms of the amount of data that may be collected and analyzed in a given time period. The development of good written questions will require an extensive knowledge of student reasoning, which will be provided by interviews, and/or data from multiple choice questions. Based on interview results, free-response written questions will be designed to obtain a larger set of data.

Here is an example that we have used in our previous thermodynamics research:

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.
3. Which would produce the largest change in the total energy of all the atoms in the system: ***Process #1, Process #2,*** or ***both processes produce the same change?***

These questions (or ones very similar) were administered over a two-year period to over 600 students in three separate offerings of the second-semester calculus-based general physics course. The questions were administered as a practice quiz during the last week of the course, after all instruction on the thermodynamics topics addressed in the questions was completed. All of the students' answers and explanations were carefully read, categorized, and tabulated. This allowed us to determine that a very substantial proportion of students believed that either heat or work – or both – behaved as state functions. That is, more than 50% of all students answered "equal to" on either question #1 or #2, and many explained their answer by asserting that heat absorbed and/or work done by the system was independent of process and depended only on the initial and final states. The results were very consistent from one year to the next, were consistent with responses from the 32 interview subjects discussed above, and (as discussed in the section below) were also consistent with results on a very similar multiple-choice final exam question. Although the process of collecting, analyzing, and checking the data collected with this instrument was extremely time consuming, it provided an enormous amount of insight into students' reasoning on fundamental concepts in thermal physics, as well as on the prevalence of various student views.

We expect that the data obtained from administering written examinations will provide feedback for other elements of our research. For example, finding a specific consistent issue in student reasoning will lead to appropriate interview studies and classroom observations. Student reasoning will most likely be context dependent (Brown *et al.* 1989) so finding the broadest possible range of studies in which to investigate an issue will provide the broadest understanding of student thinking.

(3) Responses on multiple-choice questions

Questions having an emphasis on qualitative reasoning and posed in multiple-choice format allow efficient data collection from large numbers of students. Statistical analysis of students' responses (both correct *and incorrect* responses) can offer valuable insights into student thinking, and may also serve as a check on data gathered in other formats from smaller student samples. We do not attempt to use data gathered from multiple-choice instruments in isolation, but only in a context with data from other types of instruments in which the overall consistency of response patterns may be assessed.

The development of a multiple-choice survey can be either the first or the last step in the research-question development process. In addition to creating questions first in multiple-choice format, we intend to develop questions for the topics being discussed based on the results of interviews and responses to written questions. Many multiple-choice surveys of this type have been developed through a similar research process, and we plan to make use of those that are relevant to our needs. At the moment, however, few deal with the physics content we seek to investigate. Therefore, we have had to develop a variety of such questions during the course of our previous investigations.

For example, the following question was administered on a final exam in a second-semester calculus-based general physics course at ISU, with responses from 407 students as shown (note that there was *no* diagram included in this question):

> A system consisting of a quantity of ideal gas is in equilibrium state "A." It is slowly heated and as it expands, its pressure varies. It ends up in equilibrium state "B." Now suppose that the same quantity of ideal gas again starts in state "A," but undergoes a **different** thermodynamic process (i.e., follows a different path on a *P-V* diagram), only to end up again in the same state "B" as before. Consider the net work done by the system and the net heat absorbed by the system during these two different processes. Which of these statements is true?
>
> A. The work done may be different in the two processes, but the heat absorbed must be the same.
> B. The work done must be the same in the two processes, but the heat absorbed may be different.
> C. The work done may be different in the two processes, and the heat absorbed may be different in the two processes.
> D. Both the work done and the heat absorbed must be the same in the two processes, but are not equal to zero.
> E. Both the work done and the heat absorbed by the system must be equal to zero in both processes.
>
> ***Responses* (*N* = 407):**
> **(A) 28% (B) 14% (C) 33%**
> **(D) 20% (E) 3% No response: 2%**

Responses to this question served as a check on results that had been gathered from the set of free-response questions described in subsection (2) above. The questions on the free-response instrument required students to explain their reasoning, and analysis of those data were extremely laborious and time-consuming. An attempt to analyze the multiple-choice data in isolation would have very risky, having the potential for false or misleading conclusions regarding student reasoning on heat and work. However, in the context of the results on the other instrument in which hundreds of student explanations were analyzed, we were able to confirm that students' tendency to write explanations in which both heat and work were treated as state functions (or as having state-function properties) carried over to their responses on a related question posed in multiple-choice format. (That is, the large number of students selecting responses A, B, and D in the question above is consistent with the similarly large proportion who, on the free-response question, claimed that in two different processes with common initial and final states, the heat absorbed must be the same in both processes, and so must be the work done by the system.) In our project, we will continue to develop, administer, and analyze multiple-choice questions of this type to deepen our picture of students' reasoning patterns.

Research Methodology and Data Analysis

Categorization of responses: Students' written and/or oral responses are categorized according to the major themes identified in the data, generally reserving separate categories for responses attributable to least 5% of all students in the sample; responses corresponding to less than 5% of all students are amalgamated in a category titled "Other responses." We usually find that it is not possible to predict in advance the major categories of student responses, although certain hypotheses are developed in the course of instructional experience. Often tentative categories are developed and students' written responses and interview transcripts are then reviewed to determine the appropriateness of the proposed categories.

Need for repeated data runs: Due to the large number of hard-to-control variables in educational research (instructor characteristics, course logistics, student demographic variations, etc.), we believe that a single data run is never adequate to provide convincing evidence of any given pattern in student thinking. A minimum of two, and preferably three or more administrations of a diagnostic instrument, or implementations of a controlled experiment, are needed to indicate both the probable mean and approximate dispersion in student responses.

Having parallel tracks of research, curriculum development, and implementation at ISU and UMaine will allow the work to proceed at a much more rapid pace than if either PI did the work alone. The proposed collaboration will essentially provide a feedback loop to allow for multiple iterations of curriculum during one teaching cycle.

Development and Assessment of Research-based Curricular Materials

Initial draft and in-class test

Initial drafts of curricular materials based on research and instructional experience undergo a first stage of testing simply by using them in a classroom situation or with student volunteers. This gives an indication of confusing or ambiguous language, areas of particular conceptual difficulty, and the appropriateness of the overall conceptual level of the material. In large-enrollment courses with numerous recitation sections, several revised drafts may often be tested within the same week. After the initial class test of the first draft, rapid revisions are carried out and immediately put to use in other recitation sections.

Another valuable method of preliminary testing is to use the draft materials in a one-on-one interview setting, carefully monitoring students as they work through the materials and simultaneously explain their reasoning.

Controlled test of revised drafts

Advanced drafts of the curricular materials are tested in a controlled fashion by using them in randomly selected recitation sections at the same time that most recitation sections use standard instruction on the same topics. Pre- and post-testing helps to determine whether any measurable differences between the two groups are observed. This is carried out by having both experimental and control sections respond to one or more common quiz or exam questions, with one set being administered before special instruction using the new curricular materials, and another set being administered afterwards. In the advanced courses, due to their much lower enrollments, repeated testing must often wait for the next semester or year in which the course is taught again. Occasionally, it will be possible to recruit student volunteers from the general population of physics majors or advanced engineering students to test materials in an interview setting.

Third-party assessment

Once the materials have reached a relatively mature stage of development at the home institution after repeated testing, they are provided to collaborating instructors at other institutions to test in their own courses, occasionally with minor local modifications. This provides a much more stringent test of the portability of the materials to diverse institutions and student populations.

Collaboration with Colleagues in Related Areas of Instruction

At Iowa State University, the Physics Education Research Group has carried out a long-term, highly productive collaboration with the Chemistry Education Research Group led by Prof. Tom Greenbowe. In particular, our work in probing student thinking and developing curricular materials in calorimetry and thermodynamics has been carried out jointly in both physics and chemistry courses, and papers have been published both on the physics work and the chemistry work. We expect that work on this proposed project will also proceed in close collaboration with our colleagues in chemistry, in particular through investigations targeted both at the introductory general chemistry course and at the advanced-undergraduate physical chemistry course.

At the University of Maine, acting through the UMaine Center for Science and Mathematics Education Research, the collaborating PI has generated interest among faculty in both Chemistry and Geological Sciences to collaborate with this project in some fashion. This will provide an additional venue both for collection of research data and for testing of curricular materials that will be developed.

Specific Research Questions

The general theme of our investigation revolves around the following central research questions:

> To what extent do students understand fundamental concepts of thermal physics at the advanced undergraduate level?

> How can research into student understanding help improve student learning of this topic?

Below we give examples of specific concepts to be probed during our investigation.

Entropy and the Second Law of Thermodynamics

Entropy is arguably one of the most abstract concepts in undergraduate physics, and yet it is fundamental to appreciating both the nature of spontaneous "irreversible" processes, and the constraints imposed on cyclic processes. We will investigate the dynamics of students' reasoning regarding these concepts, and in particular will consider these questions that our current work has already identified as potentially significant: (1) To what extent is an increase in entropy of the "universe" confused with an increase solely in entropy of the system? How may that confusion be minimized in instruction? (2) What are the instructional implications of the often-overlooked necessity of using heat transfer in a *reversible* process when applying the definition $\Delta S = Q_{\text{reversible}}/T$? (3) How well do students make the connection between the second law of thermodynamics and the constraints regarding heat flows and work performed during cyclic processes (*i.e.,* the "efficiencies" of engines and refrigerators)?

Reversible vs. Irreversible Processes

Appreciating the often-subtle distinction between reversible and irreversible processes is frequently difficult and yet is crucial to an understanding of the principles of thermal physics. What are the pedagogical issues involved in communicating this concept, and how might it be made more concrete for students? How do students interpret the role of "dissipative" work, and the meaning of "spontaneity"? How well do students make the connection between macroscopic and microscopic interpretations of irreversible processes?

Free Energies and Thermodynamic "Potentials"

The introduction of the Gibbs and Helmholtz functions and the relations among thermodynamic potentials often appear ad hoc and arbitrary. How well do students appreciate the connection between minimization of free energies in spontaneous processes and the implications of the second law of thermodynamics regarding entropy changes? Is the meaning of "stable" and "unstable" equilibrium communicated to students during instruction? How clear is the relationship between changes in the Helmholtz and Gibbs free energies and constraints on the maximum work (total work or "non-PdV" work) performed by a system during a process? Do students appreciate the relevant constraints that must be imposed when applying these various relationships (*i.e.,* zero net change in temperature and pressure, or temperature and volume, etc.)?

State Variables and State Functions

The distinction between state functions and process-dependent functions is fundamental to thermal physics. In what contexts are these distinctions clear to students, and in which contexts is the confusion most prevalent? Our previous work has suggested that while great confusion exists regarding the process-dependent nature of heat and work, students seem better able to appreciate the state-function property of internal energy. What is the nature of students' reasoning regarding this distinction for other common thermodynamic variables (*e.g.,* entropy, enthalpy, free energy, etc.)?

Various Standard Representations Used in Instruction (graphs, diagrams, etc.)

To what extent do the various representations – graphs of processes on various sets of axes (two- and three-dimensional), mathematical and verbal representations of thermodynamic processes, relations between variables as partial derivatives or integrals – help (or hinder) student learning of the concepts? Are there particularly helpful representations?

For example, it is common in introductory courses, or when first discussing cyclic processes at a more advanced level, to show a Carnot cycle process on a graph of temperature *vs.* entropy, so that the cycle traces out a rectangle; the area inside the rectangle is the net heat transfer during one cycle. While the T-S rectangle is the generic icon of any and all Carnot cycles, is this representation helpful for students in more than a superficial way? What are the pedagogical issues involved in interpreting and drawing P-V diagrams accurately, and translating between such diagrams and other forms of description of thermodynamic processes (*i.e.,* descriptions using equations and/or words)? Our current work has identified many areas of concern that merit additional investigation, such as difficulty in relating work done to area under the curve, inability to translate distinct thermodynamic processes into distinct segments on a P-V diagram, confusion in interpreting diagrams of cyclic processes, etc.

What role do the mathematical representations of some of these laws, especially those that involve partial derivatives or differentials, play in student learning? Are the various mnemonic devices for remembering the Maxwell relations useful in promoting conceptual understanding? To what extent are students able to *interpret* the meaning of a partial derivative or of a differential in physical terms and explain it with reference to actual physical processes? This is a crucial investigation in thermodynamics, since (a) a great deal of information is provided in each Maxwell relation involving partial derivatives, (b) entropy is defined thermodynamically by its differential, and (c) the First and Second Laws are often expressed in differential form.

A controversial issue is the use of notation for "inexact" differentials such as $đQ$ and $đW$; many recent texts avoid this notation. We will investigate students' interpretation of this notation in courses in which it is used, and try to probe the extent to which increased confusion regarding the process-dependent nature of heat and work may or may not outweigh possible advantages of the notation in expressing differential relationships.

Statistical Thermodynamics

Probability

Do students understand the distinction between the use of probabilistic descriptions in statistical thermodynamics, and that in quantum mechanics (a practical necessity in the first, but an irreducible aspect of the theory in the second)?

Macrostates and Microstates

What are the issues involved in understanding the distinction between macrostates and microstates, and the meaning of the multiplicity of states? How do students interpret the "fundamental postulate" regarding equal probability of accessible states?

Statistical Interpretation of Entropy and the Second Law

How do students interpret entropy in terms of the often-used analogy of "disorder"? (This has been a controversial issue in the literature; see, *e.g.,* Bohren and Albrecht 1998). Are students able to connect the microscopic interpretation of entropy and the second law to the macroscopic description of the tendency toward equilibrium?

Boltzmann Factor; Canonical Ensemble; Partition Function; Distribution Functions for Classical and Quantum Systems

Can students develop an understanding of these quantities sufficient to explain them with reference to physical processes in a variety of contexts, and not simply in mathematical form? How may current textbook discussions be improved to increase student understanding of these concepts?

Other Issues

Another interesting aspect of this research is to find out if it might provide a context in which to investigate the applicability of different models of student learning and understanding, *e.g.,* phenomenological primitives (diSessa 1993), facets (Minstrell 1992), resources (Hammer 2000; Hammer and Elby 2002), and conceptual change (Strike and Posner 1985). We will explore the extent to which each model can explain the empirical results, and perhaps even predict outcomes of various experiments. A secondary outcome of this research will be to better understand the role and applicability of various models, especially for student learning of more advanced topics.

Physics Education Research at Iowa State University

The Physics Education Research Group at Iowa State University was initiated in 1998 when David E. Meltzer joined the ISU faculty. Graduate students in the group take the same courses and meet the same academic requirements as all other graduate students in the Department of Physics and Astronomy. Since 1998, two students working in the group have graduated with Masters degrees, another is very close to finishing a Masters degree, and a fourth has passed the Ph.D. qualifying exam and is preparing to begin his thesis research for a Ph.D. in Physics Education Research. The group has been funded by over $440,000 in grants from the National Science Foundation (through five separate grants), and has also been supported by over $40,000 in grants from the ISU Center for Teaching Excellence. Since 1998, the group has maintained a close and highly productive collaboration with the long-established ISU Chemistry Education Research Group directed by Prof. Thomas Greenbowe. Meltzer and Greenbowe have collaborated as PI and Co-PI, respectively, on two NSF-funded projects, and have published a joint paper in the International Journal of Science Education. A measure of the productivity of the ISU Physics Education Research Group is its more than one dozen papers either published or submitted to refereed journals, or published (or in press) as a result of invitation from editors of journals, books, or proceedings. In addition, more than 30 invited presentations and over 45 contributed presentations have been made by the group over the past five years, and seven workshops have been given. The group has also produced the CD-ROM *Workbook for Introductory Physics*, a compilation of over 400 pages of class-tested active-learning curricular materials. Most of the papers and presentations produced by the group are available for download at its website, http://www.physics.iastate.edu/per/index.html.

UMaine Context for Research and Curriculum Development

The University of Maine hosts a Physics Education Research Laboratory (PERL), which is jointly supported by the Department of Physics & Astronomy and the College of Education and Human Development (CoEHD). The collaborating PI is co-director of the UMaine PERL, and has an appointment in Physics & Astronomy as well as a cooperating appointment in the CoEHD. The UMaine PERL presently consists of two full-time faculty, two additional faculty members in Physics & Astronomy who are interested and involved in activities to varying extents, and six graduate students – four seeking doctoral degrees in physics, and two seeking terminal Master's degrees, one in physics and one as a Masters of Science in Teaching (MST). Two of the doctoral students are also earning an MST.

Having parallel tracks of research, curriculum development, and implementation at ISU and UMaine will allow the work to proceed at a much more rapid pace than if either PI did the work alone. The proposed collaboration will essentially provide a feedback loop to allow for multiple iterations of curriculum during one teaching cycle.