Development of Active-Learning Curricular Materials in Thermodynamics for Physics and Chemistry

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Summary: This is a project to create new curricular materials for the study of thermodynamics, which would have a direct impact on instruction both in the Department of Physics and Astronomy, and the Department of Chemistry. We will utilize educational resources that are uniquely available at Iowa State University, combining the capabilities of the Education Research Groups in both Physics and Chemistry. By targeting the subject of thermodynamics – a field that lies precisely on the borderline between Physics and Chemistry – we will be able to bring to bear the extensive experience of both of our groups. We will create new instructional materials of immediate use both in Physics courses and in Chemistry courses. These materials center on "active-learning" worksheets, consisting of carefully structured and sequenced sets of questions and exercises. They are designed to elicit common conceptual difficulties, and then to guide students to confront and resolve the difficulties.

Statement of Purpose:

This is a project to create new curricular materials for the study of thermodynamics, which would have a direct impact on instruction both in the Department of Physics and Astronomy, and the Department of Chemistry. We will utilize educational resources that are uniquely available at Iowa State University, combining the capabilities of both the Physics Education Research Group (led by D. Meltzer) and the Chemistry Education Research Group (led by T. Greenbowe). By targeting the subject of thermodynamics – a field that lies precisely on the borderline between Physics and Chemistry – we will be able to bring to bear the extensive experience of both of our groups. We will create new instructional materials that will be of immediate use both in Physics courses (such as Phys. 222 and Phys. 304, total of over 800 students per year), and Chemistry courses (such as Chem. 165, 167, 178, and Chem. 321; over 1500 students per year). Due to the fundamental nature of thermodynamics we expect that the materials will have even broader usage, for example in the engineering curriculum where thermodynamics is a basic subject for mechanical and chemical engineers, and for those in the materials science and engineering program. Undergraduates in these fields devote much course time to basic and applied thermodynamics, e.g. in the course ME 330 (Thermodynamics). We also anticipate that the work to be carried out under this project will enable us to submit a very competitive grant proposal to the National Science Foundation (under the Course, Curriculum, and Laboratory Improvement Program) for further development of the curricular materials.

The students initially affected by this project include all engineering and most science majors enrolled in the full introductory sequences both in general physics and general chemistry – over 2,000 students per year. Subsequently, there will be an impact on intermediate level students taking Phys. 304 (Thermal Physics), as well as Chem. 321 (Physical Chemistry) – a notoriously difficult course combining physics, chemistry, and calculus.

The motivation for the creation of these new materials is the now very extensive research base into student learning both in introductory chemistry and introductory physics at the university level. An increasing body of evidence suggests that the traditional forms of instruction involving lecture classes and standard recitations and labs result in only very slight increases in students' understanding of fundamental concepts (Barrow, 1991; Black, 1993; Brooks, 1984; Hestenes, Wells, and Swackhamer, 1992). It has been pointed out by many experienced researchers that complex scientific concepts are not effectively communicated to students simply by lecturing about them – however clearly and logically the concepts may be presented (e.g., McDermott, 1991). For one thing, students taught exclusively through lecture-based curricula are inclined to short-circuit the highly complex scientific thought process (Reif, 1995). In other words, students do not absorb physics and chemistry concepts simply by being told (***or*** shown) that they are true. They must be guided continually to challenge their present state of understanding, and to resolve conceptual confusion through a process of "active engagement."

By providing new research-based curriculum materials for these courses, using a design model shown to be effective through extensive research (described below), this project will significantly strengthen introductory and foundation courses both in Physics and Chemistry. Because the development of these materials is an integral part of the research program carried out by the Physics and Chemistry Education Groups, this project develops new programmatic connections between undergraduate curriculum, and the research activities of the faculty. These materials are specifically designed to be used by students working in collaborative groups of two, three, or four – either in "recitation" sections, or during the lecture presentation itself. In this way, they provide small-group learning experiences for first-year students enrolled in the introductory sequences in Physics and Chemistry. By combining the resources of the Departments of Physics and Astronomy, and of Chemistry, this project promotes interdisciplinary collaboration for undergraduate curriculum development. The materials, both in their creation and further refinement, depend directly on student outcomes assessment, in the form of pre- and post-testing utilizing conceptual understanding diagnostics, as well as clinical interviews to assess student learning. Thus target areas #2, 4, 6, 7, and 8 are addressed directly by this project.

Description of the Project

The specific project we are proposing to carry out is the creation of materials for the study of thermodynamics – both at the elementary and intermediate level – in what is usually called an "active-learning" classroom. In such a classroom, students are required to carry out tasks designed to ***actively*** engage their creative abilities, far beyond merely sitting in a chair and listening to an instructor or teaching assistant. For instance, the students might explore phenomena using lab equipment, or work in groups to solve simple problems posed by the instructor. The materials we plan to develop can be described as guided-inquiry problem sets. These are *not* the same type as those found as end-of-chapter problems in physics and chemistry textbooks. Rather, they are carefully designed both to elicit common student difficulties regarding the subjects under study, and then to lead students to confront these difficulties head-on with a tightly focused and strategically sequenced series of questions and exercises. An integral feature of these exercises is to require students to explain their reasoning process with short written statements. Finally, in the course of working through these questions and exercises, students are guided to resolve their difficulties and confusion and to attain a firm grasp on their targeted concepts. For simplicity's sake, we will call these materials "worksheets."

Pedagogical models that actively engage students in a process of investigation and discovery – often oriented around activities in the instructional laboratory – have been found to be effective in improving students' conceptual understanding of physical principles (Hake, 1998; Thornton and Sokoloff, 1998). The targeted physical concepts are in general not "told" to the students before they have the opportunity to carry out investigations – or follow through chains of reasoning – that might lead them to synthesize the concept on their own. It has been especially challenging to develop effective active-learning materials that do not have the benefit of a simultaneous laboratory component to the instruction.

The instructional model we have described at the beginning of this section – known as "elicit, confront, and resolve" – is one that has attained world renown through the decades-long efforts of the Physics Education Group at the University of Washington in Seattle, led by Prof. Lillian McDermott. They have produced the most extensively research-based curricular materials available to date, including the *Tutorials in Introductory Physics*. These are designed for the general physics courses (both algebra- and calculus-based), and have been used successfully as the basis of so-called "tutorials" (primarily ***without*** the need for lab equipment), which have partially replaced standard recitations at the University of Washington and elsewhere. In these tutorials, student groups of three or four work through carefully designed worksheets of the type described above. Teaching assistants, instead of lecturing and providing ready-made answers, guide the students with "leading" questions to think through and resolve difficult points. A very extensive body of research has demonstrated the efficacy of these tutorials in increasing student conceptual understanding (e.g. Redish and Steinberg, 1999). Other active-learning materials centered around structured worksheets have been developed and tested by Alan Van Heuvelen (1991) and others who have been inspired by his work. Van Heuvelen's emphasis is on utilizing "multiple representations" of knowledge – such as "verbal," pictorial, graphical, mathematical-symbolic, etc. – to improve student learning.

Profoundly inspired by the work of McDermott, Van Heuvelen, and their collaborators and followers, the Physics and Chemistry Education Research Groups at Iowa State University have recently embarked on our own separate programs of curriculum development. T. Greenbowe has led development during the past semester of *Tutorials in Introductory Chemistry*, a groundbreaking attempt to begin to do for chemistry that which has been achieved in significant part by McDermott's group for physics. These chemistry tutorials have been tested out successfully during the Fall 1998 semester. Meanwhile, D. Meltzer (in collaboration with K. Manivannan at Southeastern Louisiana University) has produced and utilized a *Workbook for Introductory Physics – Electricity and Magnetism*. This *Workbook* has been specifically designed to be useful both in large-enrollment classes, and in the algebra-based sequence of introductory physics. Both of these latter features set it apart from most currently available active-learning materials. The *Workbook* has received very enthusiastic reviews from several independent experts solicited by a leading textbook publisher, and is under consideration for publication. It has already been used with great success here at Iowa State in the Fall 1998 semester of Phys. 112. All four recitation sections of that course were converted to the "tutorial" model, and both instructor and teaching assistants helped guide student groups as they worked through the worksheet materials.

The materials described above – as well as those to be developed in this project – are designed with a guiding theme. This theme is the premise that the solution of even very simple physics and chemistry problems invariably hinges on a lengthy chain of concepts and reasoning, much of which is often glossed over, or which is simply unstated "tacit" knowledge gained through experience (Reif, 1995). Worksheet activities guide the student to lay bare these chains of reasoning, and to force a confrontation with conceptual "sticking points." For each new physical idea to be learned there will be a number of these sticking points; one must then direct the focus of discussion toward these key areas. One has to illuminate in a stark and glaring light, so to speak, the phases in the student's though process where the concept is lacking, so that in the student's own mind the gap to be filled by the missing concept is clearly sensed. Then, the eventual synthesis of the concept by the student becomes ***dramatically*** apparent to them. This is accomplished through carefully linked sequences of activities that first lead the student to confront the conceptual difficulties, and then to resolve them.

Nearly all topics treated in intermediate-level courses both in thermodynamics and physical chemistry have yet to be addressed by the type of curriculum reform outlined here. Our proposal is to create an integrated set of worksheet "tutorial" materials, which eventually will be synthesized into a full-scale workbook. This workbook will then be ready for use in several different courses in both of our departments.

Based on published research regarding learning of concepts in thermodynamics, and our own extensive teaching experience, we will begin to draft sequences of questions and exercises focused on a handful of our targeted topics. The material will consist of a tightly linked set of (1) brief textual expositions, (2) structured series of questions that lead students to elicit and then resolve conceptual difficulties, and finally (3) exercises to strengthen understanding. The emphasis throughout will be on qualitative reasoning and mastery of fundamental concepts. A great deal of pictorial, diagrammatic, and graphical material will be incorporated. The development of these initial drafts will be assisted by Graduate Student Research Assistants, one a member of the Physics Education Research Group, and the other a member of the Chemistry Education Research Group. Draft worksheets will be class-tested either in recitation sections or during lecture presentations. Feedback obtained through the class testing will be immediately utilized for revision and redesign. We have already obtained agreement in principle with some of the instructors in the targeted courses to cooperate with the testing of these materials.

Central to the development process of these curricular materials is an intensive cycle of ongoing assessment and research, aimed at testing and improving their effectiveness. Conceptual quizzes based on the materials will be given both as pretests and posttests. These, along with results from in-class discussions and group work provide real-time feedback and allow the repair of unclear or confusing passages, addition of activities (hard or easy as the situation demands), and occasionally thorough rewrites of whole sections. Conceptual diagnostic questions may be presented on midterm and final exams; student answers and written explanations allow comparison with results in previous courses, and with results that have been reported by other researchers in physics and chemistry education.

The Graduate Student R.A.'s participate in all aspects of this work. They assist in formulating initial drafts, help to test them out in recitation sections, and give input for revisions and rewrites. They help carry out extended "interview" questioning to probe student understanding in depth. They also contribute to the creation of high-quality graphic materials (diagrams, drawings, etc.) that form an integral part of the worksheets. (This is one of the more labor-intensive aspects of this type of curriculum development.)

The core outline of topics we eventually plan to address includes (1) empirical gas laws; (2) elementary kinetic theory; (3) the three laws of thermodynamics; (3) free energy, entropy, enthalpy, and equilibrium; (4) elementary thermochemistry, including calorimetry. During the period of this present project, we anticipate making substantial progress on about half of these topics. We will produce at least three worksheets each on at least three elementary topics (e.g., gas laws, first law of thermodynamics), and at least one advanced topic (e.g., free energy, entropy, and equilibrium). After these materials have been tested and refined through class use, they will form the core of a subsequent proposal for external funding; we will seek and are hopeful of obtaining this external funding to carry the project to final completion. We will produce a final product consisting of an integrated set of worksheets covering a range of topics in thermodynamics. They will form the core of a workbook that can be used to supplement instruction both in recitations and lectures, and for homework. *A sample excerpt from a draft worksheet is included in this proposal.*

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Significance of the Project

This project will make a direct contribution to improving instruction both in introductory courses in Physics and Chemistry, and in upper-level courses as well. We will use tried and tested research-based methods to develop new curricular materials in thermodynamics, which is a subject of broad importance in numerous technical fields. In this way, we will apply the fruits of research in physics and chemistry education directly to the classroom. The Physics and Chemistry Education Research Groups have as their mission both basic research on student learning, and the ***immediate*** application of research to improving student learning in our classrooms. This is directly in line with the overall mission of our land-grant institution, and of our departments and our college.

Biographical Summary

David E. Meltzer, Assistant Professor of Physics, received a Ph.D. in theoretical physics from S.U.N.Y. at Stony Brook in 1985, and carried out postdoctoral research at Oak Ridge National Laboratory, the University of Tennessee in Knoxville, and in the Quantum Theory Project at the University of Florida. He joined the Iowa State University faculty in June 1998 to establish a new group devoted to Physics Education Research. He has served as Principal Investigator on three curriculum-related projects funded by the National Science Foundation, and has served on an NSF Panel to review grant proposals submitted to the Division of Undergraduate Education. He has taught more than two dozen different physics and math courses at the university level, and has been guest instructor in both middle-school and high-school classes. He has given more than 40 presentations on physics and science education to regional, national, and international audiences, and has led several workshops for other university faculty dealing with new teaching methods. He was the lead author on a widely cited feature article on active-learning strategies in **The Physics Teacher** (**34,** 72, 1996), and of the active-learning *Workbook for Introductory Physics*. In Summer 1998 he was an instructor with the Physics Education Group at the University of Washington in Seattle; there he worked both with undergraduate science majors, and with in-service public school teachers. He has published fifteen research papers and edited five books, mostly related to condensed matter physics.

Thomas J. Greenbowe, Professor of Chemistry, received a Ph.D. in chemistry education from Purdue University in 1983. He joined the faculty at Iowa State University in 1990 as coordinator of the general chemistry program. He works collaboratively with high school chemistry teachers, community college chemistry instructors, and university chemistry and education faculty to improve the introductory chemistry experience and curriculum. He has received grants from the National Science Foundation, the U.S. Department of Education–Fund for the Improvement of Post-Secondary Education (FIPSE), and the Dwight D. Eisenhower Science and Mathematics Improvement Fund. In 1995 he served as Chair of the American Chemical Society General Chemistry Examinations Committee. Dr. Greenbowe's awards include the 1996 Iowa State University, College of Liberal Arts and Sciences Teaching Excellence Award for Introductory Courses, and the 1994 Wilkinson Award for outstanding undergraduate teaching, Department of Chemistry, Iowa State University. He has over 20 publications related to chemistry education research.

SAMPLE ON NEXT PAGE: Excerpt from a Draft Worksheet on the Second Law of Thermodynamics

Let's suppose that there was in fact a substance which, when taken through a reversible cycle between two different temperatures, was characterized by (Q_{2high}/Q_{2low}) < (T_{high}/T_{low}). Here "Q_{2high}" and "Q_{2low}" refer to the heat transferred at the high and low temperatures, respectively, for this "second" system. (We're again assuming a Carnot cycle, with isothermal volume changes linked together by adiabatic processes that take the system from one temperature to the other.)

1. Since this is a reversible cycle, let us run it in reverse. (For a gaseous substance, this would mean that instead of *expanding* at the higher temperature, it is *compressed*). If we do that, will heat be *absorbed*, *given off,* or *neither* absorbed *nor* given off at the ***low*** temperature (T_{low})? *(Indicate this on the diagram with an appropriate arrow.)* [Whether it is absorbed, given off, or equal to zero, we will still refer to this heat as "Q_{2low}."]
2. Will heat be *absorbed*, *given off,* or *neither* absorbed *nor* given off at the ***high*** temperature (T_{high})? *(Indicate with arrow.)* [Whether it is absorbed, given off, or equal to zero, we will still refer to this heat as "Q_{2high}."]
3. For the complete cycle, is the net change in the internal energy of the substance *positive, negative,* or *zero*? Is the net heat absorbed by the system *greater than, less than,* or *equal to* the net work done by the system?
4. Will net work be done *by* the substance, or will net positive work have to be done *on* it to carry out this cycle, *or* is the net work *zero* in this case? Explain your answer.
5. Express the absolute value of the net work, referred to in #4, in terms of Q_{2high} and Q_{2low}.

   $|W|$ = ______________________ (Use absolute value signs.)

   Which has the larger absolute value, Q_{2high} or Q_{2low}? Explain how you can tell.

Now suppose that we use the work produced by the *first* engine (the "ideal gas" engine) to run the *second* engine. That is, we arrange it so that the absolute value of the net work in the two cases is the same. Call this value "$|W_{original}|$." Then we have that $|W| = |W_{original}|$.

6. Is $|W_{original}|$ greater than, less than, or equal to $|Q_{high} - Q_{low}|$?
7. Given the assumption that $|W| = |W_{original}|$, is $|W_{original}|$ greater than, less than, or equal to $|Q_{2high} - Q_{2low}|$?
8. Is $|Q_{high} - Q_{low}|$ greater than, less than, or equal to $|Q_{2high} - Q_{2low}|$?

9. (. . .)
10. (. . .)
11. (. . .)

12. If both engines are being run simultaneously, they can be considered a single, composite system undergoing a cyclic process. For this process, is the net overall work positive, negative, or zero? (The net overall work is the net sum of all positive and negative work.)
13. For this composite system, at the lower temperature, is there net heat *absorbed* or *given off*?
14. For this composite system, at the higher temperature, is there net heat *absorbed* or *given off*?
15. Is the result you found compatible with the Second Law of Thermodynamics, in the form stated by Clausius? ["*It is impossible for an engine operating in a cycle to have as its **only** effect the transfer of a quantity of heat from a reservoir of low temperature to a reservoir at a higher temperature."*] Explain your answer.
16. If your answer to #15 is "no," suppose you had assumed that (Q_{2high}/Q_{2low}) > (T_{high}/T_{low}), and had repeated all of the above steps with each engine operating in the *opposite* direction to that assumed above. Would your answer to #15 change?