Collaborative Research: Research and Curriculum Development in Thermal Physics

I. Introduction

This proposal seeks to renew NSF support for our collaborative project: Research on the Learning and Teaching of Thermal Physics (previously funded under PHY 0406724, 0406764, and 0604703). This project is part of an extended investigation into the learning of thermal physics at the undergraduate level. Our overall objective is to probe physics students' reasoning from introductory through more advanced courses, and to use this research as a basis for developing improved instructional methods and materials. By contributing to the research base on student learning of physics, we provide an invaluable resource to instructors and to developers of course and curricular materials. Drawing on our research, we will develop and test curricular materials that address the difficulties students encounter as they study this subject, with the aim of improving the effectiveness and efficiency of student learning. These research-based materials will provide a resource for undergraduate thermal-physics instructors everywhere. The Project Staff together constitute the majority of U.S. physics education researchers currently working in the field of thermal physics; all have extensive experience in research and curriculum development with the Physics Education Group at the University of Washington, as well as at other universities.

Recent investigations into student learning of thermal physics at the undergraduate level by ourselves and others have shown that most students in introductory courses face significant obstacles in mastering fundamental concepts in this area. Results from a variety of institutions indicate that up to 80% or more of all students who complete introductory courses cannot effectively use the first law of thermodynamics in problem solving. Related research has suggested that confusion with entropy and second-law concepts is also widespread, affecting a majority of students in these introductory courses. Our most recent project extended these investigations to new populations and specifically targeted student learning of the more sophisticated concepts and mathematical techniques employed in thermal physics courses at the advanced undergraduate (junior/senior) level.

Our work during this project has yielded a detailed picture of students' understanding of thermal physics as they begin upper-level courses. We have probed students' thinking at various points during upper-level instruction to determine their level of conceptual understanding and problem-solving ability regarding both introductory and advanced topics. This work confirms that difficulties with fundamental concepts persist not only for introductory students but also for a majority of students at the junior/senior level. We have acquired extensive data that characterize these learning difficulties in detail and reflect their relative prevalence at different levels of instruction. We have also examined understanding of more advanced topics that are normally introduced only in upper-level courses, and have been able to pinpoint learning difficulties in a variety of key subject areas.

Based on our initial work, we have begun development of a variety of curricular materials aimed at addressing students' learning difficulties, and have begun testing them at both the introductory and advanced undergraduate level. In what follows we will outline in more detail our findings to date, and describe our plans for carrying the project forward into the next phase.

II. Synopsis of Previous Research on Students' Reasoning in Thermal Physics

Given the importance of thermodynamics it is surprising that there has been so little research into learning of this subject at the university level. There have been literally hundreds of investigations into learning of the more elementary concepts (heat, heat conduction, temperature, etc.) among pre-college students, but the number of published studies *worldwide* that focus on university-level instruction is on the order of ten. (We have compiled a multilingual bibliography of over 220 publications, posted at http://www.physicseducation.net/current/index.html.) Studies probing learning of more advanced thermal physics concepts (such as statistical physics) are essentially nonexistent, outside of our own work.

A. Review of the literature on introductory physics courses

The multitude of investigations referred to above has demonstrated 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 noted similar ideas among their own students (Arons 1997; Knight 1998; 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; Sözbilir and Bennett 2007); some of these studies have touched upon both first- and second-law concepts in addition to topics more specific to the chemistry context.

Among the few published investigations regarding university-level physics instruction were those in France (Rozier and Viennot 1991; Viennot 1996), Germany (Berger and Wiesner 1997), and Great Britain (Warren 1972). The first detailed investigation in U.S. universities of student learning of concepts related to the second law has recently been published by Cochran and Heron from the University of Washington (Cochran and Heron 2006). Nearly all other recent work in this field has been published by investigators involved in the present project and their collaborators. 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; also see Loverude 1999 and Kautz *et al*. 2005). 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. Investigations carried out by Meltzer's group at Iowa State corroborated these findings and broadened them to several areas not addressed in the previous study (Meltzer 2001; Meltzer 2004; related work is in Greenbowe and Meltzer 2003). This work was supported in part by the grant for which we are seeking renewal (PHY 0406724 continued as PHY 0604703, in collaboration with PHY 0406764), and also by additional NSF grants (see Meltzer Biographical Sketch).

In the context of the introductory course, the work of Loverude et al., Meltzer, and Cochran and Heron, as well as further corroboration in the literature by researchers in several different countries, all suggested that a large proportion of students in introductory university physics courses fail to master the basic concepts of thermodynamics. Most students emerge from introductory courses with limited functional understanding of the first law of thermodynamics and related concepts such as heat and work.

B. Literature related to upper-level thermal physics

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; Moore and Schroeder 1997; *American Journal of Physics* December 1999; Cannon 2004), 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 only very limited discussion of specific pedagogical problems observed among students during actual classroom instruction on these topics. Thus, for these topics, basic research on student reasoning is lacking from the published literature, as is detailed documentation of student thinking in reaction to curricular innovations, This goal of this project has been to begin to fill in some of these gaps by carrying out in-depth investigation of student reasoning, and by assessing and documenting the degree of actual student learning that results from use of research-based curricular materials.

III. Overview of Project Goals and Methods

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

- How does students' understanding of thermal-physics concepts evolve during their studies at the advanced undergraduate level?
- What are the primary conceptual obstacles that students encounter in upper-level thermal-physics courses?
- How can these obstacles be addressed more effectively to help improve student learning of this topic?

When conducting research on student learning in a new content area, the initial step is to identify both students' capabilities and students' difficulties in the context of the class or topic being investigated.

Then, one designs instructional materials to address the specific difficulties identified, tests those materials with the target population and assesses their effectiveness at improving student understanding.

The first step requires the design of questions or tasks for students that pinpoint the interface between students' correct and incorrect knowledge. As with the design of any experimental tool, question design is an iterative process of testing prototypes and improving on results. In the case of research tasks for probing student understanding, this process involves the administration of progressively improved versions of a question in interviews and/or in written form. In most cases, several iterations are necessary before student responses are perceived as answering precisely the question that the investigators intended.

As a sufficient data corpus is obtained, instructional strategies and materials are developed to address the common difficulties identified by the research. Materials are also iteratively tested and refined to improve their effectiveness, which is assessed using questions designed on the basis of the research.

In our work to date, we have successfully extended the tools and results of research on introductory physics learning to upper-division thermal physics courses. For this project we will follow up on this basic research by developing and testing research-based curricular materials. Because the scope of upper-division thermal physics is so great, we have deliberately chosen to focus on a handful of key topics likely to be included in most such courses. We are now prepared to develop instructional materials for many of these topics. However, identification of students' reasoning processes and learning difficulties will continue to be an essential focus, with a particular emphasis on student learning of statistical physics. In the following section, we give examples of findings from the previous project and describe our initial efforts at curriculum development. In section V we identify specific concepts to be probed during the next phase of our investigation and describe the refinement of existing tutorials as well as a tentative list of ten new tutorials to be developed in the next phase of the project.

IV. Summary of Previous Project Work

During the three years of our previous project, we made substantial progress toward our goals and widely disseminated preliminary results. (See http://web.mac.com/loverude/iWeb/Thermo/Welcome.html.) Through the course of this work, we have developed and disseminated more than 40 research-based diagnostic questions and problems, administered as homework assignments and as quiz and exam items. To date, we have developed preliminary versions of eight guided-inquiry tutorial-style worksheets (listed and described below), all of which we continue to class-test and revise at multiple institutions in a variety of courses including classical thermodynamics, statistical physics and the hybrid "thermal physics."

At Iowa State University (ISU), Warren Christensen worked on all phases of this project, successfully defending his Ph.D. in June 2007. Graduate students Ngoc-Loan Nguyen and Thomas Stroman contributed as well. Through administration of a series of pretests during the 2003 and 2004 Thermal Physics courses at ISU (taught by Co-PI Meltzer), we surveyed students' knowledge on a wide variety of topics in order to gauge what was learned in their introductory courses. Advanced students' responses were compared with responses on similar questions from over 1700 students in the introductory courses at ISU. (***Note:*** Thermal physics topics are taught in the introductory course at ISU but not at CSUF, Maine, or UW.) Through analysis of students' written and verbal responses on quizzes, homework, and exams (including lengthy individual interviews conducted as part of oral exams), we monitored the evolution of students' thinking as they attempted to integrate the macroscopic and microscopic/statistical viewpoints into a coherent understanding. Additional data were collected in the sophomore-level thermal physics course at UW in Winter 2006. At the University of Maine, we collected extensive data in the form of students' written explanations on problems posed in upper-level courses in Thermal Physics, Statistical Physics, Physical Chemistry, and Chemical Engineering Thermodynamics. Brandon Bucy played a central role in this work, earning his Ph.D. in August 2007. (Christensen and Bucy are currently in postdoctoral research positions at Maine, with research responsibilities that overlap with this project.) In related work, graduate student Evan Pollock (M.S. expected 2008) has investigated connections between students' math and physics reasoning in upper-division courses. Additional data were provided by collaborators at the University of New Hampshire, CSUF, and Seattle Pacific University.

A. Findings

(1) Difficulties with First-law concepts and cyclic processes

Building on previous work with introductory students (described above), we have found that upper-level students have significant difficulties with work, heat, and the first law of thermodynamics. Confusion between state and process functions is common, with 30% of students effectively treating heat transfer as a state function and more than 70% claiming that net heat transfer and/or net work done in a cyclic process are zero. In addition, more than half the students in upper-division courses are unable to recognize the energy-transfer function of thermodynamic work, and only about 30% were able to apply the first law in problem-solving tasks.

(2) Difficulties with entropy and irreversible processes

We previously reported persistent difficulties among introductory students in recognizing the distinction between the entropy of a system and the entropy of the universe, accompanied by a belief that entropy must be conserved. Through administration of several different questions encompassing many aspects of entropy and the second law, we found similar difficulties among students in advanced courses. In both introductory and upper-level courses, many students had difficulty in recognizing and applying the state-function property of entropy. Students had significant difficulty with the distinction between reversible and irreversible processes, and with application of the formula $\Delta S = \int \frac{dQ_{reversible}}{T}$. We are currently preparing two individual manuscripts (one from Meltzer and one from Thompson) as well as a joint manuscript about student understanding of entropy with robust and wide-ranging results.

(3) Difficulties with statistical physics

Our work suggests that students begin their studies of statistical physics with inadequate understanding of underlying ideas from probability, for example, that the mean value of N independent observations undergoes progressively smaller fluctuations as N increases. Many students also fail to understand that macrostates are invariably degenerate, and thus miss the key distinctions between macrostates and microstates (also reported by Cochran [2005]). The need to give a clear and rigorous meaning to students' notion that "entropy means disorder" is particularly important and challenging.

(4) Difficulties with mathematical concepts used in thermal physics

We have investigated the extent to which students understand the mathematical concepts associated with interpretation of P-V diagrams and other key ideas in thermal physics. We have found that some difficulties apparently associated with the physics concepts may have their roots in the prerequisite mathematical tools (Pollock et al., 2007). Due to the prevalence of (state) functions of multiple independent variables in thermal physics, differentials and partial derivatives play central roles. Our work has focused on the extent to which students connect the physical and mathematical meanings of a partial derivative. Upper-division students can take partial derivatives effortlessly and can usually describe the physical meaning of a partial derivative. However, we have documented multiple contexts in which the subtle but crucial meaning of subscripts on first- and second-order partial derivatives is often a serious problem for our students. A related difficulty (Bucy et al. 2007a) is that many students incorrectly consider mixed second-order partial derivatives to be identically zero (since the variable being differentiated was *"held constant"* in the first derivative). This observation suggests that students may not consider the mathematical significance of the Maxwell relations, i.e., that they involve mixed second partial derivatives. Additional work with the Maxwell relations has shown that students have difficulties with the *physical* interpretations of the equated partial derivatives (Thompson et al. 2006a).

B. Initial Dissemination Efforts

Our dissemination efforts to date have included electronic distribution of our collection of 40 diagnostic questions to instructors at about 15 institutions worldwide. Some of these instructors are making use of the questions and some have offered to furnish us with data collected at their institutions. Among the institutions represented are the University of Missouri at Columbia, University of New Hampshire, University of California at Davis, Boston University, Bucknell University, University of

Southern California, Weber State University, Western Kentucky University, Southern Illinois University – Edwardsville, Pacific University (Oregon), Purdue University (physics and chemistry departments), Seattle Pacific University, University of Cincinnati, University of Jyväskylä (Finland), and the Royal Institute of Technology (Stockholm). We have also disseminated draft tutorial worksheets to many of these instructors, with the expectation that they will report back to us after testing them in class.

We have disseminated the results of this project through more than 50 invited and contributed talks, posters, journal articles, proceedings papers, and two doctoral dissertations. Below is a list of papers and invited talks; full citations in references. Download: http://web.mac.com/loverude/iWeb/Thermo/Welcome.html

Published papers

1. *[Meltzer 2004a]*
2. *[Meltzer 2005a]*
3. *[Meltzer 2005b]*
4. *[Thompson et al. 2006a]*
5. *[Bucy et al. 2006a]*
6. *[Meltzer 2007a]*
7. *[Bucy et al. 2007a]*

Accepted papers

8. *[Mountcastle et al. 2007]*
9. *[Pollock et al. 2007]*

Submitted manuscript

10. *[Christensen et al. 2008]*

Manuscript in preparation

11. *[Bucy et al. 2008]*

Invited presentations

1. *[Meltzer 2004b]*
2. *[Meltzer 2004c]*
3. *[Meltzer 2005c].*
4. *[Christensen 2006]*
5. *[Meltzer 2006a]*
6. *[Thompson 2006b]*
7. *[Thompson 2006c]*
8. *[Meltzer 2006b]*
9. *[Thompson 2006d]*
10. *[Meltzer 2006c]*
11. *[Thompson 2006e]*
12. *[Meltzer 2006d]*
13. *[Thompson 2006f]*
14. *[Thompson 2007a]*
15. *[Christensen 2007]*
16. *[Thompson 2007b]*
17. *[Meltzer 2007b]*
18. *[Thompson 2007c]*

In addition to the invited talks cited above, project personnel have given 32 contributed talks and posters on project-related work to date; many are downloadable from http://www.physicseducation.net.

Tutorial Title	Goal and Strategy	Status
Energy and Temperature	Distinguish between absolute temperature and internal energy, by considering temperature and energy changes in different-volume containers of ideal gas in thermal contact.	Tested in both introductory and upper-level courses at ISU.
Heat and Work	Recognize heat and work are process-dependent, by quantitatively comparing heat and work for a system undergoing processes with common initial and final states.	Tested in both introductory and upper-level courses at ISU.
Cyclic Processes	Recognize that net heat transfer and net work done during cyclic process are non-zero, by analyzing a cycle involving isobaric, isothermal, and isochoric phases in sequence.	Preliminary testing in upper-level course at ISU.
Entropy & State Functions	Recognize the state-function property of entropy, by analyzing entropy changes in parallel isothermal and free-expansion processes with the same initial and final states.	Tested in introductory course at ISU.
Entropy Changes	Realize that net entropy change of "system + surroundings" must increase in real processes, even though total *energy* is conserved. Students analyze heat flow between two thermal reservoirs (large metal cubes connected by a narrow metal pipe) and explicitly compare entropy changes of the blocks.	Preliminary testing done in introductory courses (at ISU) and in the sophomore-level course (at UW).
Free Energy	Guide students to recognize that the change in Gibbs free energy during certain processes takes into account the net entropy change of the system *and* of its surroundings.	Preliminary test in upper-level physics and introductory chemistry at ISU.
Partial Derivatives and Material Properties	Guides students to understand physical meaning of partial-derivative expressions, through use and interpretation of expressions in the context of compressibility and thermal expansivity, and with 3-D phase diagrams.	Tested in upper-level course at Maine; learning gains documented on specific questions.

Table I. Tutorials developed during previous project.

C. Curriculum Development

We have developed preliminary versions of instructional materials designed to address common student difficulties, following the successful model of *Tutorials in Introductory Physics* (McDermott 2002). A list of these tutorials is found in Table I. We are finding that instructional materials for upper-level courses often have different requirements and incorporate different expectations of the students, compared to those for the introductory course. For instance, time-consuming derivations are often necessary. We are exploring the use of out-of-class time for tutorial components. One model has students begin a tutorial partway through a class, with no intention of finishing the tutorial in the remaining time. Students are asked to do some fairly straightforward but time-consuming work between classes (e.g., to complete a derivation or test predictions). At the beginning of the next class, student groups compare answers to the out-of-class work and complete the remainder of the tutorial. (Sample tutorials are included in the *Supplementary Documents*; others are online at http://web.mac.com/loverude/iWeb/Thermo/Welcome.html)

V. Research and Development Goals for This Proposal

In this section we describe new research questions for this proposal, and highlight new curriculum development plans. We also describe extensions of the initial phase that will guide our future work.

There are significant personnel changes for this project. This proposal now includes as a collaborating PI Dr. Michael E. Loverude, Associate Professor of Physics at California State University, Fullerton (CSUF). Prof. Loverude has been one of the leading researchers on student learning of thermal physics at the undergraduate level for more than five years. He has published numerous papers on his investigations, and developed several guided-inquiry tutorials for *Tutorials in Introductory Physics.*

David Meltzer left Iowa State in 2005, and has been a Research Scientist (part-time status) at the University of Washington since that time. He is currently also a Senior Research Scientist for the Physics Teacher Education Coalition (a joint APS-AAPT project). For the project described in this proposal, he will be appointed as a Senior Research Scientist at the University of Maine (at 25% of full-time status). In this position he will be able to assume a coordinating role for the project work occurring at the different institutional sites (see Section VIII.A. below).

(We must also report, with deepest regret, that Prof. Mark N. McDermott—who served as PI for the UW component of this project—passed away in November 2006.)

A. Research tasks for this project

We divide the content areas that we will investigate into several broad categories, outlined below. For each category, we describe some initial research questions. (In section VIII we associate topics with a lead investigator who will coordinate efforts in that area, although significant collaboration is expected.)

(1) Concepts considered as prerequisites for the upper-level thermal physics course

This category, a prime focus of our previous work, includes ideas that are typically taught in introductory college courses in physics and chemistry or even in high school. In this category we have generally used written pretests at the beginning of a course to test whether students enter the course understanding these ideas. We will gather additional data on questions probing understanding of first-law concepts (Meltzer), and probe student understanding of gas behavior and particulate models (Loverude). (Note: Due to the wide diversity in course sequences, concepts that are prerequisites for some upper-level courses will instead be core content for others. When thermal physics is not part of the introductory sequence, e.g. at Maine and CSUF, most students would have had little formal exposure to the laws of thermodynamics.) In addition to collecting data to expand on our previous research, we will apply our findings to improve our draft tutorials on these topics (see table). These tutorials on first-law concepts must undergo additional testing in upper-level courses and any necessary revisions must be made.

(2) Difficulties with macroscopic thermodynamics

Student understanding of macroscopic thermodynamics will continue to be a major focus of this project. We will expand this focus to include thermodynamic potentials and free energies.

Entropy and the Second Law of Thermodynamics: Students' reasoning regarding this foundational topic continues to be a focus for this project, and we will continue to investigate questions that our work has identified as significant. For example, both upper-level and introductory students tend to confuse an increase in entropy of the "universe" with an increase in entropy of *any* arbitrarily defined system. However, upper-level students seem less likely to believe in a "conservation of entropy" principle. How may these confusions be minimized in instruction, at both the introductory and advanced levels?

Reversible vs. Irreversible Processes: What are the pedagogical issues involved in communicating an understanding of the often-subtle distinction between reversible and irreversible processes? How might it be made more concrete for students? How do students interpret the meaning of "spontaneity"? How well do students make the connection between macroscopic and microscopic interpretations of irreversible processes?

State Functions and Process Variables: In what contexts are the distinctions between state functions and process-dependent quantities clear to students, and in which contexts is the confusion most prevalent? Our previous work has suggested that students hold paradoxical ideas, for instance, that while internal energy is a state function, so *also* are heat and work, but entropy is *not*. What leads to this thinking, and how might it be addressed most effectively in instruction? A controversial issue is the use of "inexact" differentials such as $\text{đ}Q$ and $\text{đ}W$; many recent texts avoid this notation. We will investigate students' interpretation of this notation in courses in which it is used.

Free Energies and Thermodynamic Potentials: The introduction of the Gibbs and Helmholtz functions and the relations among thermodynamic potentials often appear as *ad hoc* and arbitrary. How well do students appreciate the connection between minimization of free energies in spontaneous processes and the second law of thermodynamics? Do students appreciate the constraints that must be imposed when applying these various relationships (*i.e.,* zero net change in temperature and pressure, or temperature and volume, etc.)? Do students recognize that the utility of multiple potential functions lies partly in the need to vary which parameters are held constant in a given process?

(3) Difficulties with statistical physics

Instruction in this topic has a tendency to become highly mathematical and abstracted from physical meaning. In general, we wish to investigate how students can learn thermostatistics concepts with reference to physical processes in a variety of contexts, and not simply in mathematical and algorithmic form. Some specific questions follow below.

Macrostates and Microstates: To what extent do students understand the distinction between macrostates and microstates, and the meaning of the multiplicity of states? How may we best help students in interpreting the "fundamental postulate" regarding equal probability of accessible states?

Statistical Interpretation of Entropy and the Second Law: What specific difficulties do students encounter in trying 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: These concepts are usually introduced in a mathematically complex context in which it might be easy for students to overlook qualitative considerations. To what extent are students grasping the critical link between energy and multiplicity? Other work (Cochran 2005) suggests that the concept of microstate itself—and therefore, that of multiplicity—is particularly challenging. How, then, may we best communicate the physical meaning of the Boltzmann factor and the partition function without becoming lost in notation and computation?

(4) Difficulties with underlying mathematics

We continue to investigate the role played by difficulties with prerequisite mathematical concepts in connection to learning of advanced physics topics. These mathematical concepts often reappear in other courses, and we will collaborate with colleagues investigating mathematical understanding in other areas. We have begun to probe student understanding of the prerequisite mathematical concepts in mathematics courses at Maine and will expand our relationship with colleagues in the math department.

State Functions and Process Variables: We will continue probing understanding of the mathematical analogs of these two concepts, namely functions and variables (Pollock et al., 2007). To what extent do students recognize the mathematical basis of state functions and process variables?

Partial Differentiation: We will continue to investigate student difficulties in interpreting the physical meaning of partial derivative expressions and the connection between the mathematics and physics (Thompson et al., 2005; Bucy et al., 2006). Further intra- and extramural testing and refinement of our draft tutorial on this topic are necessary.

Probability: Some of our preliminary work (Mountcastle et al. 2007) supports published reports (e.g., Bao and Redish (2002) and Wittmann et al. (2006)) that indicate students' understanding of probability concepts falls short of expectations in upper-level courses. What pedagogical strategies are needed to address these difficulties in the context of instruction in statistical thermodynamics?

Distribution Functions for Classical and Quantum Systems: Distribution functions are relatively unfamiliar to students in a physical context, despite their central importance in statistical mechanics. We plan to probe carefully the nature of student understanding of the connection between the macroscopic parameter of particle number with *summation* (or integration) of the function over an energy interval.

B. Instructional interventions and curriculum

Our efforts in this area fall into two categories. First, we plan to refine and class-test the draft tutorials described in section IV. These preliminary tutorials have to this point been tested by their authors and others researchers. They need refinement and polishing before they are more widely distributed. We will develop ancillary materials that integrate the tutorials more fully into courses and provide instructors with background information and assessment questions. For each tutorial, we will prepare a set of supporting materials including pre- and post-tests, homework exercises, and a brief instructors' guide with background on the content and our research findings as well as suggestions for implementation.

Tutorial Title	Goal and Strategy
State Functions and Process Variables	Connect mathematical formalism to the physical quantities, including some consideration of the properties of functions.
Maxwell Relations and Legendre Transforms	Relate various thermodynamic potentials via the Maxwell relations (building on the *Partial Differentiation and Material Properties* tutorial).
Density of States and Occupation Number	Relate the quantity $d\omega/dE$ to other quantities and properties of the system, and interpret the graph of $d\omega/dE$ vs. E, etc.
A Model for Entropy	Connect the naïve idea of entropy as "disorder" to the concept of multiplicity. (Based on results from Bucy dissertation (2007).)
Entropy Changes in Ideal Gas Processes	Apply macroscopic relations to compare entropy changes in various ideal gas expansions and compressions. (Adapted from ISU intro-level tutorial.)
Binomial Distribution	Articulate a mechanism for counting microstates for a set of flipped coins.
Counting States in the Einstein Solid	Apply the formalism of counting microstates developed in the previous tutorial to the system of an Einstein solid.
Approach to Thermal Equilibrium	Relate the counting formalism of the previous tutorials to the evolution of interacting Einstein solids and compare descriptions of the equilibrium state.
Boltzmann Factor and Partition Function	Use probability arguments and relation among T, S, and U to derive equilibrium probability of occupation of a microstate with specified energy.
Phase Diagrams	Analyze phase diagrams of various substances, and relate diagram characteristics to Gibbs-free-energy relationships and the Clausius-Clapeyron equation.

Table II. Partial list of tutorials to be developed for proposed project.

Second, we will develop new materials to address additional topics essential to advanced thermal physics courses. Based on our high productivity in the first three years of this project, we are very confident that during the next phase we will be able to generate and test at least ten additional tutorials on key topics in classical thermodynamics and statistical mechanics. We plan to develop materials covering topics including microstates and macrostates (including multiplicity of an ideal gas), the microscopic analysis of entropy and the approach to equilibrium, and classical and quantum distribution functions. A list of proposed new tutorials is shown in Table II, though we expect this list to evolve as our research continues. To a large extent, the specific curriculum development tasks for the future must grow out of the findings of the research that we have not yet carried out. Our experience has made it clear that we must carry out substantial research into students' reasoning processes on the relevant topics and use that to guide our curriculum development work.

C. Participating institutions for research and curriculum development and testing

The colleagues listed in the *Supplementary Documents* section have agreed to participate in this project as pilot sites, and to use the materials (questions and curricular materials) developed in this project beyond the duration of the grant. This provides us with access to over 100 students in physics, chemistry, and engineering courses at 9 institutions (including our own) on an annual or biennial basis. The courses include a variety of course titles and textbooks in multiple disciplines, allowing us to explore the flexibility of our materials. At some institutions, a course instructor will partner with a resident physics education researcher, who will provide logistical support and local expertise. Letters of support and participation from these colleagues are included in the *Supplementary Documents* section of the proposal. We expect to increase the number and variety of participating institutions over the course of the project.

One colleague who deserves specific mention is Prof. Corinne Manogue of Oregon State University (OSU). Manogue directs the NSF-supported initiatives *Paradigms in Physics* (DUE-0618877) and the *Vector Calculus Bridge Project* (DUE 0088901 and 0231032), which involve large restructuring of the OSU upper-division curriculum across many topics. Because of the strong overlap between these projects, Manogue has agreed to serve as an advisor to the math-physics component of our project. We will discuss progress and results with Manogue in conference calls and in scheduled meetings at national conferences. Additionally, one participant, Michael Rogers of Ithaca College, is using thermal physics materials from *Paradigms*. Our collaboration provides the opportunity to advance both projects significantly.

VI. Methodological Overview

Our research methodology is predicated on our objective of helping students understand concepts more deeply and learn physics more effectively and efficiently. We seek to understand the process by which students develop their physics knowledge, and what difficulties they encounter along the way.

A. A model for students' knowledge structure

To model students' knowledge, Redish (1994) uses the analogy of an archery target containing a central black, an outer white, and a middle gray region. The central black "bull's-eye" represents what students know well, concepts understood in depth. When problems related to knowledge in that region are posed to the students they answer consistently and correctly, independent of context or representational mode. The gray circle surrounding the bull's-eye represents what students understand partially and imperfectly. Some concepts are understood well and some not so well; some firmly held beliefs in this region are inconsistent with physicists' knowledge. Knowledge in this region is dynamic and still in the process of development. When questions from this region are put to students they may answer correctly in some contexts, yet incorrectly or incompletely in others. Finally, the outer white region represents concepts which students understand little, if at all. Questions from this region yield responses that are highly context-dependent, inconsistent, and unreliable, with deeply flawed or totally incorrect reasoning.

Redish, following Vygotsky—who called the gray region the "zone of proximal development"—says that teaching is most effective when targeted at concepts in the gray. ("The zone of proximal development defines those functions that have not yet matured but… are currently in an embryonic state [Vygotsky 1978].") Knowledge in this region is analogous to a substance near a phase transition: a few key concepts and a handful of crucial links, generated through student-instructor interaction, can catalyze substantial leaps in student understanding.

When we administer diagnostic questions or carry out interviews in which students' knowledge in the gray region is probed we tend to get diverse and, pedagogically speaking, potentially useful data. Sometimes we find relatively stable, internally consistent sets of concepts that may or may not be consistent with physicists' knowledge. When persistent patterns with well-defined characteristics are found, we identify and analyze them. Heron (following McDermott) has called such concept sets “specific learning difficulties” when they are at variance with physicists’ understanding (Heron 2003). We attempt to map individual students’ knowledge structure in the gray region, and then determine the population *average* of properties such as typical reasoning patterns and links among concepts.

B. Students’ initial knowledge state

A crucial first step in improving the effectiveness of instruction is to ascertain students’ initial knowledge state in as much detail as possible. Much previous research has demonstrated the utility of this initial phase. We have therefore devoted substantial time and effort to mapping out the ideas, reasoning processes, and problem-solving approaches of students who are just beginning their study of thermal physics at the advanced level. Through detailed pretests, administered on the first day of class as well as at carefully selected times further into the course, we have assessed the knowledge acquired by students through their previous studies in the introductory course. Our future work will build upon this base. As previously noted, we have developed an extensive library of diagnostic questions for topics ranging from heat and the first law through the statistical interpretation of entropy. Using these questions we have explored the degree to which students understand the fundamental thermal physics concepts they had previously encountered either in college physics and/or chemistry courses, or in high-school studies.

Instructors and textbooks in advanced courses often assume that students have already mastered basic concepts such as the first and second laws of thermodynamics in classical macroscopic contexts. These courses often proceed rapidly to more advanced topics such as classical and quantum statistical mechanics. By contrast, our findings suggest that many students enrolled in advanced courses are initially unprepared to take that step. A substantial part of our previous work has therefore been aimed at elucidating the nature of, and finding ways to address, the initial learning difficulties encountered by upper-level students. This includes the development of tutorial worksheets, discussed above. We believe that efforts devoted at the beginning of the course to strengthening upper-level students’ grasp on fundamental concepts (such as the first and second laws of thermodynamics) will pay substantial dividends later in these courses. Therefore, we will continue work along these lines.

VII. Research Methodology: Detailed Procedures

Our research is guided by several key themes: (1) emphasize diagnostic questions that require qualitative reasoning; (2) pose elementary baseline questions to determine lower bounds on understanding (i.e., to probe the gray/black “border” region of Redish’s “archery target” analogy); (3) utilize multiple representations (words, graphs, diagrams, etc.) to probe students’ understanding in depth in diverse contexts; and (4) identify key learning difficulties, and gauge their approximate prevalence.

A. Data collection

Much research has shown that facility at solving standard quantitative problems is not necessarily an indication that students’ have good qualitative understanding of relevant concepts. For this reason we develop diagnostic questions that emphasize qualitative reasoning or, when calculations are involved, that utilize simple, straightforward computations. Qualitative questions often involve use of multiple representations such as diagrams or graphs. The purpose of this type of question is to distinguish students’ understanding of a concept from their facility at mathematical calculations or mastery of algorithmic procedures. (Exceptions occur when we are specifically investigating student understanding of particular mathematical concepts.) We developed many such questions in prior phases of this project.

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

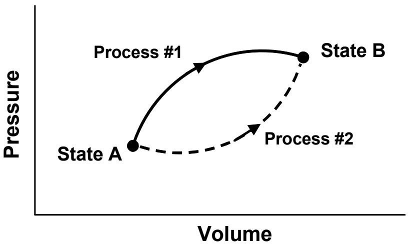
The most deeply probing—albeit time-consuming and laborious—data-gathering method in PER is the one-on-one interview with student volunteers. These “clinical interviews” usually require about an hour, are recorded on audio- and/or videotape, and allow for very detailed analysis of students’ thinking, and will form a significant part of the data-gathering process in this project. Students may be presented with simple apparatus and/or written questions and problems. Students are asked to predict, define, or describe various physical phenomena. The interviewer provides gently probing questions that guide students to explain their thinking in depth, and to examine and resolve apparent inconsistencies. We have performed these interviews by soliciting student volunteers and, in classes that we ourselves teach, by making an oral exam part of the curriculum (although the latter are not recorded).

In the context of thermal physics, students are often asked to consider a hypothetical experiment that is described using diagrams and printed text. For example, in previous work, the Maine group developed a series of questions describing an ideal-gas system in a cylinder undergoing either an isothermal, an adiabatic, or a free-expansion process (explained below in *VIII.C*). The results of the interviews confirmed previous observations regarding student reasoning about heat and work, and yielded important new insights regarding student thinking.

(2) Students' written explanations of their reasoning

The other primary data source is student responses to written questions, or series of related questions, in which students are asked to explain their reasoning. Although not as revealing as a one-on-one interview, written questions are 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 requires an extensive knowledge of student reasoning, and often these questions undergo several iterations as the investigators learn more about student thinking on a particular topic. In one example, we used the same set of questions and diagrams regarding the processes mentioned above, but provided them to students in the upper-level course at Iowa State as part of their final exam. Below is another example that we have used in our research with both introductory and advanced students (Meltzer 2007; Pollock et al., 2007):

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 were administered after instruction to over 600 students in three separate offerings of calculus-based general physics at Iowa State. In addition, they were administered *before* instruction to students in junior/senior level thermal physics courses at Iowa State, Maine, and CSUF, and after instruction in thermodynamics, physical chemistry, and chemical engineering thermodynamics courses at Maine. Analysis of student answers and explanations provided insight into students' reasoning on concepts including state and process functions and the prevalence of various student views.

Data obtained from analysis of written question responses provide feedback for other elements of our research. These data can serve both as a basis for planning productive oral interviews, and as a follow-up check to confirm (with much larger numbers of students) results from analysis of interview data. For example, finding specific consistent issues in student reasoning regarding entropy on pre-instruction (ungraded) quizzes helped us to devise appropriate interview questions in the junior/senior-level course at Iowa State. Student reasoning is very often context dependent (e.g., Brown et al. 1989) so finding multiple modes in which to investigate an issue provides the deepest understanding of student thinking.

B. Data analysis

(1) Categorization of responses

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

(2) 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.), a single data run does not suffice 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. This requirement is particularly important given the small enrollment in most upper-division courses.

C Applying the model: Question design and response analysis

In probing student understanding of free-expansion processes we provided students with a description of such a process, along with diagrams portraying initial and final positions of a piston as a volume of ideal gas underwent a free expansion. Students were asked to determine whether the temperature, internal energy, and entropy had increased, decreased, or remained the same, and to compare these changes to those in a system with the same initial state undergoing an isothermal process. (See Fig. 1.)

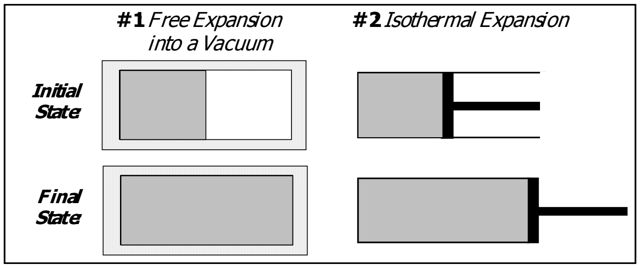


Figure 1: Diagrams used when probing student understanding of the free- and isothermal expansions.

Most advanced students, after instruction, were able to give adequate answers regarding the isothermal process. However, despite extensive and focused instruction on the topic, about 50% were unable to give correct answers and/or explanations regarding the free-expansion process. Difficulties included inability to use first-law concepts correctly to determine that the work done and net temperature change are zero during the free expansion, and significant confusion regarding the state-function property of entropy. We have reproduced these results with widely varied populations in a number of different courses at Iowa State, UW, and Maine.

The precise origin of these student difficulties is an open question. They are most likely based to some extent on persistent confusion regarding the concept of thermodynamic work, and on intuitive notions regarding entropy changes in spontaneous and "non-spontaneous" processes. These difficulties need to be addressed for students to improve their understanding of entropy changes during free-expansion processes. It is precisely the development of research-based curricular materials to address these types of difficulties that is the fundamental theme of our work. Through research we try to map out conceptions related to learning difficulties, to develop pedagogical strategies to address these difficulties, and to assess and refine these strategies through in-class testing.

D. Expected outcomes: Curriculum development and assessment

(1) Initial draft and in-class test

Research tasks that elicit incorrect ideas are often valuable in instruction, as they force students to confront these incorrect ideas. Initial drafts of curricular materials based on research and instructional experience undergo a first stage of testing in a classroom situation or with small groups of student volunteers. Student responses provide an indication of confusing or ambiguous language and areas of particular conceptual difficulty, and these are then addressed in revised drafts of the materials.

(2) Controlled test of revised drafts

We test revised drafts of curricular materials in a controlled fashion by using them in randomly selected recitation sections (in large introductory courses) at the same time that most recitation sections use standard instruction on the same topics. Pre- and post-testing using common exam questions helps to determine whether any measurable differences between the two groups can be observed. Due to the much lower enrollments in advanced courses, controlled tests are less feasible in the same course; repeated testing must often wait for the next semester or year in which the course is taught again. (As part of the current project, we have gathered data for several semesters of courses without instructional intervention; these serve as controls in this setting.) The expected outcome is for learning gains (from pretest to posttest) in the groups using the new curricular materials to be greater than in the control groups, with statistical significance at the 95% confidence level or greater.

(3) Third-party assessment

Once the materials have reached a relatively mature stage of development after repeated testing at the home institutions of the collaborating PIs, they are provided to willing and interested 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. Our materials will be applicable to courses taught from a classical and/or a statistical perspective; some may also be suitable for use in some form in related courses in other disciplines. The expected outcome is that these collaborating faculty will find (1) that the curricular materials appear to be understandable and helpful in their classrooms, and (2) that their students will achieve similar significant improvements in learning gains in comparison to previous performance on the same or similar diagnostic questions.

E. Project evaluation

We continuously monitor our progress by assessing student learning gains using diagnostic questions. Whenever possible, we make direct comparisons to performances by students on the same or similar questions in previous courses at both our own and at other institutions reported in the literature. We do not necessarily expect to see immediate improvements when using newly drafted materials, and frequently have to go through several rounds of revision until the improvements appear. In this project as in our previous projects we will evaluate our overall progress by the degree to which a steady stream of improvements in learning gains can be documented. However, it is important to emphasize that this is a very new area of research, and aside from our own work there is virtually nothing in the published literature with which to make comparisons. Therefore, the research aspect of this project will be particularly important. When breaking new ground through research, we must evaluate our success by (1) the degree to which we generate consistently reproducible patterns of students responses to sets of well-designed diagnostic questions, and (2) the degree to which we are able to demonstrate learning gains by comparison to baseline performance data that are generated through our own research, or through data collected by our collaborators using our research-based diagnostic questions.

VIII. Project Sites, Staff, and Work Plans

A. University of Maine

Work at Maine takes place through the Physics Education Research Laboratory (PERL), which currently consists of about 20 faculty, postdoctoral research associates, and doctoral candidates in physics, and master's candidates in physics and in science teaching.

PI John Thompson is an Assistant Professor of Physics and Cooperating Assistant Professor of Education, a member of the Center for Science and Mathematics Education Research, and co-director of the Maine PERL. After completing a Ph.D. in experimental surface physics at Brown University, he spent three years as a post-doctoral research associate with the University of Washington PEG. There he engaged in a variety of physics education research projects and was an instructor in graduate and undergraduate courses employing research-based curricular materials. He participated in development of tutorials on two-dimensional kinematics that were published in *Tutorials in Introductory Physics* (DUE-9727648) and the development and dissemination of *Physics by Inquiry,* a lab-based inquiry-oriented curriculum for pre-service teachers (DUE-9354501, -9843837). He was on the faculty at Grand Valley State University for two years, and in 2002 joined the faculty at the University of Maine. He has supervised seven Master's students and one Ph.D. student to completion at Maine.

David E. Meltzer, Co-PI, will be appointed as a Senior Research Scientist at the University of Maine (at 25% of full-time status) in order to coordinate work on this project. Meltzer served as Lead PI on the original project before his move to the University of Washington, where he is currently a Research Scientist (part-time status). He has more than sixteen years of experience in physics education research and curriculum development, has been PI on eight education-related projects funded by NSF, has published extensively, and has given more than 75 invited presentations. After receiving a Ph.D. in theoretical condensed matter physics from SUNY Stony Brook in 1985 and completing six years of postdoctoral work at the University of Tennessee and the University of Florida, he turned his focus to physics education research. From 1998 to 2005 he was the director of the Iowa State University Physics Education Research Group. He is lead author of the 400-page *Workbook for Introductory Physics*, a compilation of class-tested active-learning curricular materials. He currently serves on the Executive Board of the American Physical Society (APS) Forum on Education, and is also Senior Research Scientist for the APS Physics Teacher Education Coalition.

Meltzer's efforts will be focused on coordinating and implementing the research and development work at the institutional sites. His extensive background in PER and leadership role on this project to date makes him uniquely suited to carry out this role. He will be responsible for initial development and testing of diagnostic materials, coordinating their administration in the various courses, carrying out one-on-one interviews with students, and drafting research-based curricular materials. He will bring current tutorial drafts into final form and lead the development of ancillary materials such as related homework and exam questions. His research focus will be on student learning of the microscopic analysis of entropy, the Second Law, and the approach to equilibrium, along with topics in quantum statistical mechanics.

Meltzer is based in Seattle, and he will have access to classes and students at the University of Washington through his connections with the UW PEG. There are two target courses at UW, Physics 224 (sophomore-level thermal physics, offered four times per year) and Physics 328 (statistical physics, offered once per year), and we expect to have access to students in both courses throughout this research.

Senior Personnel Donald Mountcastle is an Associate Professor of Physics and Cooperating Associate Professor of Biochemistry. He has been involved in physics education research activities at Maine since 1995 and previously he helped implement research-based strategies in the instructional lab. In addition to expertise in molecular biophysics, he has extensive experience teaching thermodynamics, statistical mechanics, and biophysics (undergraduate and graduate) courses. As Senior Personnel on our previous thermal physics project (PHY-0406764), he drew upon this experience to develop research questions and instructional strategies and interpret results. Mountcastle has a long-term interest in the math-physics aspect of this project and is also contributing to the work on state functions and process variables.

Mountcastle will teach undergraduate Physical Thermodynamics (PHY 462) in the fall semesters and Statistical Physics (PHY 463) in the spring semesters. He will assist in coordinating research efforts with the courses, and will continue to provide input on design of questions and instructional materials.

Two new postdoctoral research associates at Maine worked on this project as graduate students. Each will contribute broadly to our research and curriculum development efforts in their current (fully funded) positions. Brandon Bucy's primary emphasis will be examination of thermal physics in the context of work on math-physics connections, already supported by REC-063395. Warren Christensen will be comparing response distributions among chemistry students to those from students in physics courses, as part of his work supported by the UMaine Center for Science and Mathematics Education Research. Graduate student Evan Pollack is also working on the project and other students have expressed interest.

Work at Maine has focused on four areas of interest. First, we have explored student understanding of entropy and the second law in the context of ideal-gas processes. Second, we have studied student understanding of partial derivatives in thermodynamics, especially as pertains to material properties and the Maxwell relations. We have developed instructional materials that use a graphical representation to guide students to connect the mathematics of partial differentiation and the relevant thermodynamic processes and properties. Third, we have built upon Meltzer's work (2004) by probing the math-physics connection in the context of first-law concepts and state functions. Fourth, we are investigating student estimates of probability and uncertainty in both statistical physics and the laboratory setting.

The Maine group will continue work in these areas, three of which have led to prototype instructional materials being tested as part of the current project. Additional focus areas for future emphasis include density of states and its relationship to multiplicity and other concepts in statistical physics, as well as the extension of these ideas to work in similar courses in other disciplines (see Section C below). PI Thompson will continue to lead the project at Maine, with supervision of research assistants and coordination of the work at Maine with the collaborators on the project and in other departments.

B. California State University, Fullerton

PI Michael Loverude is an Associate Professor in the Department of Physics. He received his Ph. D. in Physics Education Research from the University of Washington in 1999. His dissertation focused on student understanding of concepts from hydrostatics and thermal physics and the underlying ideas in mechanics (Loverude 1999). This work and subsequent publications (Loverude et al. 2002, Kautz et al. 2005) represented some of the first systematic studies of student understanding of thermal physics in American universities. Loverude participated in development of tutorials on thermal physics that were published in *Tutorials in Introductory Physics* (DUE 9727648) and in the development and dissemination of *Physics by Inquiry,* a lab-based inquiry-oriented curriculum for pre-service teachers (DUE 9354501).

Loverude has been at CSUF since 1999, earning tenure and promotion in 2005. He assisted in the NSF-funded development of a course and curriculum for pre-service K-8 teachers (DUE 9652800). He is one of three PIs on an NSF-funded Collaborative Project to develop laboratory curriculum for the introductory algebra-based course (DUE 0341350). At CSUF Loverude regularly teaches Physics 310, an upper-division thermal physics course intended for physics majors and minors. In this course he has continued his research on student understanding of thermal physics, documenting conceptual and reasoning difficulties and investigating instructional strategies.

Work at CSUF will build upon Loverude's earlier work, and will focus on three general research questions. First, to what extent do students understand prerequisite topics in thermal physics, including the operational definitions of state variables such as pressure, temperature, and volume, and the macroscopic and particulate models for ideal gas behavior? Second, to what extent do students understand the interplay between macroscopic phenomena and the laws of probability and statistics as they relate to the concept of entropy and the second law of thermodynamics? Loverude has done initial development of tutorials on this topic, following the approach used in Schroeder (2000) and Moore (2003). Finally, to what extent do students understand the assumptions of statistical mechanics, including the distinctions between micro- and macrostates and the proposition that all accessible microstates are equally likely? How do they relate this to other abstract formulations like the Boltzmann factor?

CSUF is a primarily undergraduate institution with no Ph.D. programs, so student involvement will be restricted to undergraduate and master's students. Loverude has supervised nine undergraduate and three master's projects in physics education. CSUF is recognized as a minority-serving institution and is among the top institutions nationwide in terms of degrees awarded to minority groups, ensuring an impact on student groups that are traditionally under-represented in physics.

C. STEM education community-building

In addition to our many connections within the physics community, we are establishing relationships in other disciplines in which these concepts are taught. In 2006, Meltzer and Thompson presented work from this project at the 19th Biennial Conference on Chemical Education; Loverude also presented related work at this meeting. Meltzer and Loverude were also invited to present their research on student understanding of thermodynamics at the Northwest Regional Meeting of the American Chemical Society.

The PIs and Co-PI have existing collaborations with faculty in other departments, and especially with chemical education researchers. Meltzer has had a long and continuing collaboration with T. J. Greenbowe, Professor of Chemistry at Iowa State University, including joint funding and publications. Loverude has an ongoing collaboration with Chemical Education Researchers Barbara Gonzalez and Kereen Monteyne at CSUF and has collected data in General Chemistry and Physical Chemistry courses. The Maine group has administered questions and solicited students for interviews in upper-level courses in Chemistry and Chemical Engineering. We plan to extend this work to undergraduate Mechanical Engineering, introductory Chemistry, intermediate calculus, and graduate Physical Geochemistry courses.

Prof. Marcy Towns of the Purdue University Department of Chemistry is submitting a proposal to investigate student understanding of physical chemistry, with an emphasis on thermodynamics and the related mathematics. PI Thompson is serving as a consulting Senior Personnel on that project. The resulting regular communication between Towns and Thompson will further serve to build the community of scholars across disciplines that will enhance both research projects.