8-12-2015

Collaborative Research: Research and Curriculum Development in Thermal Physics

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Preview of Award 0817282 - Final Project Report

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Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	0817282
Project Title:	Collaborative Research: Research and curriculum development in thermal physics
PD/PI Name:	John R Thompson, Principal Investigator Warren M Christensen, Co-Principal Investigator David E Meltzer, Co-Principal Investigator
Recipient Organization:	University of Maine
Project/Grant Period:	09/01/2008 - 06/30/2015
Reporting Period:	09/01/2014 - 06/30/2015
Submitting Official (if other than PD\PI):	John R Thompson Principal Investigator
Submission Date:	08/12/2015
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	John R Thompson

Accomplishments

* What are the major goals of the project?

The original goals were to a) perform research on student learning in upper-division courses on thermodynamics and statistical physics, b) develop instructional resources for these courses, and c) assess and document the effectiveness of the resources.

The general theme of the research 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?

The curricular goals focus on the development of a series of "tutorials" suitable for employment in upper-division thermal physics courses. For each tutorial we will produce the following elements: an approximately four-page worksheet to be completed by students in small groups; an approximately two-page conceptually focused homework assignment; a brief instructor's guide; and pre- and post-instruction assessment questions.

Additional research efforts have explored the interface between the physics and the relevant mathematics, with integration, partial differentiation, and statistical distributions in particular.

* What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

Major Activities: The major activities of this project correspond to the major goals listed above.

(A) Research on student understanding of concepts in thermodynamics and statistical mechanics, primarily at the upper division, as well as some of the mathematics ideas and concepts and their application in thermal physics.

Research was conducted over several years in courses at UMaine and elsewhere: classical thermodynamics, statistical mechanics, thermal physics (one-semester hybrid course), physical chemistry, chemical engineering thermodynamics, multivariable calculus, integral calculus, and introductory physics. Over 2000 students were administered written questions; over 30 were individually interviewed, and around 100 students were observed during classroom activities in order to gather the data used to identify and address student difficulties. Courses were attended by researchers for the majority of a semester to take field notes and gather ideas for future research and development.

(B) Development of student-centered instructional resources that utilize state-of-the-art pedagogy and the results of the research

We have developed several tutorials (in the style of *Tutorials in Introductory Physics* by the University of Washington Physics Education Group): small-group, conceptually-oriented, guided-inquiry exercises that students work through in class with instructor facilitation. Each tutorial has a pretest and homework for after the tutorial, and most have post-test questions that are different from the pretest.

Materials that have been written specifically during this project

Exploring multiple thermodynamic paths

(Mountcastle) "Proto-tutorial." Implemented after the introduction of entropy and immediately before the Heat Engines tutorial. Follow-up to the P-V diagram question (from Meltzer) and results earlier in the course, when learning about the

First Law. Designed to call attention to the distinction between functions of state and those that depend on the particular thermodynamic process to specify (e.g., work, heat transfer). Students revisit the situation of an ideal gas that is taken between two points on a P-V diagram in three different ways (i.e., along three different paths on the diagram). They are asked to compare both process-dependent quantities (heat transferred, work done) as well as changes in state functions (e.g., internal energy, enthalpy, entropy) for the three paths. Semi-quantitative: relative values of P, v are given but not absolute values.

Heat Engines

(Smith, Thompson, Christensen) Guides students to understand why the Carnot cycle is the most efficient heat engine, not just the formulaic expression for the Carnot efficiency. Students *invent* the Carnot cycle as the only cycle that could achieve maximum efficiency for any heat engine with an arbitrary working substance (i.e., the Carnot efficiency). Specifically asks about the efficiency equation. (Phys. Rev. ST – PER paper on the research behind this tutorial accepted for publication in the Focused Collection on PER in the Upper Division in February 2015, with expected publication in August or September 2015.)

Binomial Distribution

(Mountcastle, Thompson) Students explicitly consider different binomial distributions – in the form of coin flips – for small *n* (4) up through values of *n* approaching the thermodynamic limit (>105). The goal of the tutorial is to guide students through the transition from discrete to the continuum, and to appreciate how a predictable macrostate emerges with “overwhelming probability” with increasing *n,* and to understand the implications of the term “overwhelming probability” in the thermodynamic limit. Utilizes *MATHEMATICA®* calculations by students on pre-tutorial homework.

The Boltzmann Factor and the Canonical Ensemble

(Smith, Thompson, Mountcastle) Students explicitly work through the derivation of the Boltzmann factor. The goal of the tutorial is to enhance students' understanding of the origin of the Boltzmann factor and the Canonical Ensemble and their relevance to actual physical situations. Includes an exploration of the significance of the Taylor expansion, based on a written question administered earlier in the term. (A Phys. Rev. ST – PER paper on the Taylor series research and pre-tutorial HW published in 2013; a second paper on the Boltzmann factor tutorial was accepted for publication in the Phys. Rev. ST – PER Focused Collection on PER in the Upper Division in February 2015, with expected publication in August or September 2015.)

Modeling a Blackbody Spectrum

(Mountcastle) “Proto-tutorial.” First implemented Spring 2010 in Statistical Physics. Students model a blackbody spectrum assuming a discrete number of intensity measurements (either as individual monochromatic sources or individual monochromatic spectrometers trained on the same source). Attention is paid to the dimensions of graphs provided. Reinforces some of the discrete-to-continuous ideas brought up and worked through in the *Binomial Distribution* tutorial.

Materials that were initially developed from previous grant support, but modified and tuned as part of this project

Partial differentiation and material properties

(Bucy, Mountcastle, Thompson) Guides students to recognize the geometric implications of partial derivatives, especially second-order mixed partial derivatives. Context is the relationship between “beta” and “kappa.” Strong connections made between mathematics ideas and their application in physics context. Major success is to address the specific difficulty that mixed second partials are identically zero “because you’re taking a derivative of something that was just constant.” Implications for Maxwell relations later in the course.

Modified tutorial to take early section out as pre-tutorial homework, and left last section as post-tutorial homework.

Two Blocks

Originally developed at Iowa State (Christensen and Meltzer) to help students understand entropy changes during thermal interactions. Addressing student inclination to conserve entropy for universe in thermodynamic processes, and to build idea of *system* in analysis of these processes. Modified for upper division students.

Entropy Worksheet (Two Processes)

Developed at ISU based on question developed at U. Maine (Bucy, Thompson, Mountcastle). Guides students to recognize state function property of entropy and to apply this property to compare entropy changes of same system undergoing different thermodynamic processes.

Density of states

(Smith, Mountcastle, Thompson) Connects the density of states with multiplicity, especially using a graphical representation of D(E) to determine multiplicity. Extends this idea from single particle to multiple particles. This tutorial was very preliminary before this project, and now is refined by testing.

(C) Assessment of the effectiveness of materials

The iterative process of curriculum materials development requires assessment of the effectiveness of the materials with each implementation. We have done this and used that information to modify the materials when necessary, either for intellectual reasons (e.g., students were still confused or confused about a new idea due to the tutorial sequence) or logistics (e.g., time constrictions, notational confusion).

This assessment consisted of administration and analysis of written pre- and post-test questions, but also of observations during tutorial implementation in the classroom. Researchers observed the tutorials and some groups were videotaped.

All of our tutorials showed improved student performance on written questions that target difficulties identified in the research. Data from pilot sites corroborated local findings.

Specific Objectives: See Major Goals and Major Activities.

Significant Results: The sophistication of observed difficulties is indicative of the more advanced thinking required of students at the upper division, whose developing knowledge and understanding give rise to questions and struggles that are inaccessible to novices.

Student understanding at the thermodynamics-mathematics interface

- Students entering thermodynamics have non-trivial difficulties with the math they need to understand systems that are represented by P-V diagrams and other idiosyncratic representations.
- Among physics students, some observed mathematical difficulties are not just with transfer of math knowledge to physics contexts, but seem to have origins in the understanding of the math concepts themselves and/or the representations and their use in physics contexts.
- In spite of explicit time and effort in the classroom, students often apply state function reasoning to inexact differentials as well as exact ones, and fail to notice the distinction made by the textbook authors.
- While considering the signs of definite integrals using graphs (rather than algebraic functions), we observed difficulties with confusing the antiderivative with the function itself (including the use of the function values at the limits for the antiderivative values at the limits) and substituting explicit functions for the graph so that an antiderivative could be determined and evaluated at the limits.

Student understanding of heat engines and the Carnot cycle

Many students do not demonstrate a robust understanding of the implications of the reversibility of the Carnot cycle with regard to entropy changes after instruction. Only 60% of respondents correctly determined the change in entropy for the universe due to a Carnot cycle operating between two finite reservoirs. Fewer than 30% of students used correct reasoning to determine that the entropy of the universe would stay the same after one complete cycle of a Carnot engine, and fewer than 20% of students recognized the implication that a heat engine that was more efficient than a Carnot engine would have to violate the laws of thermodynamics and cause the total entropy of the universe to decrease. Moreover, student responses to written questions were remarkably similar at different institutions, suggesting difficulties that transcend student population and instructional approach.

Other difficulties

- An inability to reason about situations that students believe to be impossible
- Misunderstanding the complex and subtle differences between state variables and process variables
- Neglecting the state function property of entropy

The Heat Engines tutorial helps students gain an understanding of how Carnot's theorem relates to and can be derived from the entropy inequality statement of the 2nd Law. Students become more selective with their reasoning on questions pertaining to heat engines and entropy after tutorial instruction.

Student understanding of the Boltzmann factor

Students fail to use the Boltzmann factor to determine the probability of a particular macrostate in a system at constant temperature and occupying one of several possible energy states.

Students who participate in the Boltzmann Factor tutorial are significantly more likely to use the Boltzmann factor when answering probability ratio questions that require its use than students who receive lecture instruction alone. These results have been replicated over three implementations at two different institutions. Participation in the Boltzmann Factor tutorial also helps students gain an appreciation for the origin and derivation of the Boltzmann factor even if they were able to use it correctly after lectures alone.

Many students know that Taylor series is a relevant mathematical tool in physics but have not developed sophisticated heuristics for when it should be used.

Summary of other findings

Co-PI David Meltzer has compiled a summary list of findings from our collaborative work in this project and how it relates to earlier research at the introductory level. Meltzer presented these findings in a contributed talk at the AAPT 2012 Summer Meeting.

Note: An asterisk *indicates that the finding was originally noted in the context of introductory students, but was confirmed to apply to upper-level students based on a first-day pretest.

1. *Students seem comfortable with the state function concept within the context of energy, temperature, and volume, but *not* entropy.
2. *As do introductory students, upper-level students overgeneralize the state function concept, applying it inappropriately to heat and work.
3. *Many students believe either that “no work” or *positive* work is done on the system during an expansion, rather than negative work.
4. *Students fail to recognize that system loses energy through work done in an expansion or that system gains energy through work done in a compression.
5. *Many students believe that molecular kinetic energy can increase during an isothermal process.
6. *Students believe that intermolecular collisions lead to net increases in kinetic energy and/or temperature.
7. *Students do not recognize that energy transfers must occur (through heating) in a quasistatic isothermal process.
8. *Students do not recognize that a thermal reservoir does not undergo temperature change even when acquiring energy.
9. *Students believe that heat transfers and work done in different processes linking common initial and final states must be equal.
10. *Students believe that that net heat transfer in a cyclic process must be zero since $\Delta T = 0$, and that net work done must be zero since $\Delta V = 0$.
11. In contrast to introductory students, upper-level students are comfortable with the idea of increasing total entropy. However, they share with them the belief that “system” entropy must increase.
12. There seemed to be a tendency for engineering students to be more uncomfortable than physics students, on the average, with interactive engagement style instruction.
13. Most upper-level students are initially able to recognize that “perfect heat

engines" (i.e., 100% conversion of heat into work) violate second law.
14. Most upper-level are initially *unable* to recognize that engines with greater than ideal ("Carnot") efficiency also violate second law.
15. After (special) instruction, most upper-level students recognize impossibility of super-efficient engines, but still have difficulties understanding cyclic-process requirement of D*S* = 0; many also still confused about D*U* = 0.
16. Even after extensive work on free-expansion processes, upper-level students show poor performance (< 50% correct)
    1. frequent errors: belief that temperature or internal energy must change, work is done, etc.
    2. difficulties with first-law concepts prevented students from realizing that T does not change
17. On cyclic process questions involving heat engines, most (60%) upper-level students claim that net change in entropy is *not* zero, because they apply $\Delta S = \Sigma Q/T$ even though process is not reversible; also, they ignore state-function property of entropy which says $\Delta S = 0$ since initial and final states are identical.
18. When analyzing changes in available microstates during approach to equilibrium, students tend to ignore the fact that when equilibrium is reached, changes must cease.

Key outcomes or Other achievements:

1. Increasing attention to student understanding at the upper division

This project was one of the first to investigate student learning and teaching at the upper division, and the first in thermodynamics. Other topics have been investigated by PER since the beginning of this project.

2. Increasing attention to student understanding at the physics-mathematics interface

One of the major successes of this project, even beyond the physics content, is the explicit attention to student understanding and use of mathematics in physics contexts. This aspect of the project has led to major collaborations with colleagues in the research in undergraduate mathematics education (RUME) community, including a subsequent grant to conduct similar research and development on topics covered in "Mathematical Methods" courses, on which a RUME colleague is a co-PI with three physics education researchers.

All of the research activities led to multiple collaborations, both formal and informal: Oregon State U. Paradigms in Physics project; Joseph Wagner (mathematics, Xavier U.).

3. Development of pre-tutorial and mid-tutorial homework

The development process for upper-division materials may differ from that for introductory topics, based on our experience. We have made some changes to the formats of tutorials, e.g., assigning pre-tutorial work to be done ahead of time, or mid-tutorial homework. These assignments seem to streamline the in-class work, and allow the students to work through tedious but necessary mathematics, and/or begin to contemplate a troubling concept, before class. The outcome seems to be that students proceed further through our materials and get to the 'punchline' issues sooner and with more thorough introduction; this leads to more pedagogically productive discussions, both student-student and group-instructor. This has been true for several of our materials, but most well documented for the *Heat Engines* tutorial in particular; we have reported on this in multiple publications.

4. Explicit attention to the tutorial development process as part of the research

In publications about the tutorials developed, we made sure to describe some of the development process, including intermediate tutorial states and what evidence – consisting of qualitative and/or quantitative data – led to specific modifications, and how those modifications affected the outcome of the tutorial. In-class observations by researchers were key in this process, to probe students in the moment about the tutorial and to listen to check that students interpreted instructions or questions as intended. We took input from pilot testing instructors as well, which in specific cases improved the tutorial in ways we did not anticipate. Most earlier work did not describe this process in the literature, and we felt it needed to be foregrounded more than in the past.

* What opportunities for training and professional development has the project provided?

At UMaine, three graduate students and one postdoctoral research associate have been supported on this project and conducted research within the grant.

These junior researchers have developed instruments, communicated with instructors, analyzed data - qualitative and quantitative - and interpreted findings. All have also presented at national conferences on their work. Former researchers who have completed work on this project have gone on to faculty positions in physics departments.

* How have the results been disseminated to communities of interest?

Dissemination has occurred both formally and informally.

Research results have been published as peer-reviewed journal articles and conference proceedings. Four peer-reviewed journal articles are published or accepted (Phys. Rev. ST-PER), and others are in preparation; nine conference proceedings have been published (PER and RUME conferences); two doctoral dissertations and two masters theses have been written in this area as well.

Two of the conference proceedings (T.I. Smith, J.R. Thompson and D.B. Mountcastle, “Addressing Student Difficulties with Statistical Mechanics: The Boltzmann Factor,” in *2010 Physics Education Research Conference,* (2010); R. R. Bajracharya, T. M. Wemyss, J. R. Thompson, “Student interpretation of the signs of definite integrals using graphical representations,” in *2011 Physics Education Research Conference,* (2012)) have received attention from the community in different ways. Both were Finalists for the PER Conference Proceedings Paper Award, an honor given to less than 10% of published PERC Proceedings each year, for being noteworthy in terms of the quality of research, readability and impact on the PER community. The 2010 paper (Smith et al.) was one of three papers cited in the NRC DBER Report (Singer et al., 2012) as examples of high quality PER in the upper division.

We have presented our research at national and international conferences as well as departmental colloquia and (sometimes joint) seminars in physics, chemistry, and/or mathematics departments. Seminars have been given internationally, including Canada, Ireland, Sweden, and Finland. We have presented invited talks at meetings of the American Physical Society, the American Association of Physics Teachers, the Physics Education Research Conference, Foundations and Frontiers of Physics Education Research, Transforming Research in Undergraduate STEM Education (TRUSE). Contributed talks and posters have been presented at all of the above conferences as well as the Conference on Research in Undergraduate Mathematics Education, Frontiers in Science Education Research, and the TUES PI conference.

We have facilitated working groups at PER and RUME conferences to discuss our findings with other researchers, which led to additional collaborations.

Curricular materials have been advertised via a link on PhysPort (www.physport.org; formerly the PER Users' Guide) and shared with select faculty via email, wikispaces, or dropbox.

Website: ThermoPER Wiki (http://thermoper.wikispaces.com)

Products

Books

Book Chapters

Conference Papers and Presentations

Inventions

Journals

T.I. Smith, D.B. Mountcastle, and J.R. Thompson (2015). Student understanding of the Boltzmann factor. *Physical Review Special Topics – Physics Education Research*. 11 . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

T.I. Smith, J.R. Thompson and D.B. Mountcastle (2013). Student understanding of Taylor series expansions in statistical mechanics. *Physical Review Special Topics - Physics Education Research*. 9 020110. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://link.aps.org/doi/10.1103/PhysRevSTPER.9.020110

T.I. Smith, W.M. Christensen, D.B. Mountcastle, and J.R. Thompson (2015). Identifying student difficulties with heat engines, entropy, and the Carnot cycle. *Physical Review Special Topics - Physics Education Research*. 11 . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

W.M. Christensen and J.R. Thompson (2012). Investigating graphical representations of slope and derivative without a physics context. *Physical Review Special Topics – Physics Education Research*. 8 023101. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://link.aps.org/doi/10.1103/PhysRevSTPER.8.023101

Licenses

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Trevor I. Smith. *Identifying and Addressing Specific Student Difficulties in Advanced Thermal Physics*. (2011). University of Maine. Acknowledgement of Federal Support = Yes

Rabindra R. Bajracharya. *Student Application of the Fundamental Theorem of Calculus in Mathematics and Physics*. (2014). University of Maine. Acknowledgement of Federal Support = Yes

Rabindra R. Bajracharya. *Student Understanding of Definite Integrals With Relevance to Physics Using Graphical Representations*. (2012). University of Maine. Acknowledgement of Federal Support = Yes

Evan B. Pollock. *Student Understanding of P-V Diagrams and the Associated Mathematics*. (2008). University of Maine. Acknowledgement of Federal Support = Yes

Websites

Supporting Files

Filename	Description	Uploaded By	Uploaded On
Thermo conf proc finalreport.pdf	Citations for all conference proceedings (peer-reviewed, invited, contributed) published under this grant.	John Thompson	08/12/2015

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Thompson, John	PD/PI	1
Christensen, Warren	Co PD/PI	1
Meltzer, David	Co PD/PI	0
Mountcastle, Donald	Faculty	1
Bajracharya, Rabindra	Graduate Student (research assistant)	1
Clark, Jessica	Graduate Student (research assistant)	1
Smith, Trevor	Graduate Student (research assistant)	1

Full details of individuals who have worked on the project:

John R Thompson
Email: thompsonj@maine.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Prepared manuscripts for publication, with co-authors.

Funding Support: None from this grant in the last project year. Additional support from DUE-1323426.

International Collaboration: No
International Travel: No

Warren M Christensen
Email: warren.christensen@ndsu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Worked on manuscript(s) for publication over the past year.

Funding Support: None from this grant.

International Collaboration: No

International Travel: No

David E Meltzer
Email: david.meltzer@asu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 0

Contribution to the Project: Support for Meltzer was completed in 2013-2014.

Funding Support: None from this grant.

International Collaboration: No
International Travel: No

Donald B. Mountcastle
Email: thermostatprof@yahoo.com
Most Senior Project Role: Faculty
Nearest Person Month Worked: 1

Contribution to the Project: Consulting on research instruments and data interpretation. Co-author on presentations and publications.

Funding Support: Academic-year salary; additional support on DUE-1323426 in summer of 2015.

International Collaboration: No
International Travel: No

Rabindra R. Bajracharya
Email: rabindra.bajracharya@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: As a PhD student, he designed and administered written questions, conducted individual interviews, analyzed data, and interpreted his findings. He also was able to conduct a small eye-tracking study of students answering questions about definite integrals that requires the use of the Fundamental Theorem of Calculus in graphical representations in both mathematics and physics contexts. He wrote his doctoral dissertation and a conference proceedings paper over the past year (2014). He is currently a postdoctoral research associate elsewhere, but we are preparing a manuscript for publication over the summer of 2015.

Funding Support: This grant and DUE-1323426.

International Collaboration: No
International Travel: No

Jessica W. Clark
Email: jessica.w.clark@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Development of research instruments, communication with instructors, collection and analysis of data, and interpretation of findings. She has also presented at a departmental colloquium and national conferences and has published a conference proceedings paper. Preparation of journal manuscript in progress.

Funding Support: No support from this grant during this cycle; all support from DUE-1323426.

International Collaboration: No
International Travel: No

Trevor I. Smith
Email: smithtr@rowan.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Trevor was a graduate student funded on this project; he defended in 2011. He is first author on several conference proceedings, and three journal articles from this project (one published in 2013, two accepted as of February 2015). He is no longer a student on this project. This inclusion is for the Final Report.

Funding Support: None other than this project.

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
California State University - Fullerton	Academic Institution	Fullerton, CA
University of Wisconsin LaCrosse	Academic Institution	LaCrosse, WI

Full details of organizations that have been involved as partners:

California State University - Fullerton

Organization Type: Academic Institution
Organization Location: Fullerton, CA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Michael Loverude is Collaborating PI of this project. We have occasional Skype meetings and meet at conferences to discuss project issues and share findings. We have also been discussing manuscripts that can come out of this project.

University of Wisconsin LaCrosse

Organization Type: Academic Institution
Organization Location: LaCrosse, WI

Partner's Contribution to the Project:
In-Kind Support
Facilities
Collaborative Research

More Detail on Partner and Contribution: Jennifer L. Docktor trained Rabindra Bajracharya on an eye-tracking device to conduct research on visual attention of students when answering questions involving graphs and equations dealing with definite integrals and physics. She provided office space and recruited participants for a study there, and assisted with some of the data analysis. She has also been co-presenter for a poster presentation on this work, and will be co-author on a manuscript.

What other collaborators or contacts have been involved?

California Polytechnic St. U. (Cal Poly) – Randall Knight, instructor

- *Boltzmann factor and Canonical Ensemble* materials

Ithaca College – Michael Rogers, instructor

- Diagnostic questions covering physics-mathematics interface – integrals, derivatives, partial derivatives

Oregon State University (OSU) – David Roundy, instructor

- Multiple instruments and tutorials

Pacific University (PU) – Stephen Hall, instructor

- Multiple instruments and tutorials

Rensselaer Polytechnic Institute (RPI) – Gyorgy Korniss, instructor

- *Heat Engines* pretest

Dublin Institute of Technology

- Multiple pretests

Impacts

What is the impact on the development of the principal discipline(s) of the project?

This project is one of the first ventures by Physics Education Researchers into upper division physics courses and content. The research results and curricular materials have started to make an impact, though at this point a fairly modest one, on the teaching of thermal physics in upper division courses. This project is one example of upper division PER that is affecting the teaching and learning of advanced physics.

Additional impact is occurring with the focus on the physics-mathematics interface at the upper division. More researchers are paying attention to the use of mathematics in physics teaching, and what difficulties students have.

What is the impact on other disciplines?

As a result of this project, PI Thompson and co-PI Christensen presented at the RUME conference on student understanding of mathematics, including integrals and integral representations as well as partial derivatives, in thermodynamics. The presentations caught the attention of leading researchers in undergraduate chemistry (Marcy Towns) and mathematics (Chris Rasmussen) education, leading to discussions of overlaps in research between the disciplines. (As an aside, our work on partial derivatives in thermodynamics was taken up and extended to physical chemistry by Towns and her group, with an emphasis on discourse.) The result of these conversations was the series of Transforming Research in Undergraduate STEM Education (TRUSE) conferences in 2010 and 2012 (supported by NSF grant DUE 0941191), at which research in chemistry, physics, and mathematics education were highlighted, along with relevant research from STEM education and the learning sciences. The NRC "DBER Report" in 2012 highlighted the need for interdisciplinary studies. This project, and the research at the physics-mathematics interface and the physics-chemistry interface conducted within, arguably accelerated the development of these important interdisciplinary links.

A subsequent grant with an engineering education component has also garnered interest from colleagues in that discipline.

What is the impact on the development of human resources?

This project focuses on a key course in upperdivision physics, one that is a core course for most physics majors. We anticipate that increased use of researchbased and studentcentered teaching methods will increase student learning in this course and make the environment less forbidding and more welcoming. Raising the awareness among instructors of the incoming student ideas, and how some of the ideas are interpreted by students as a result of instruction, should improve the "impedance match" between instructor and student in these courses.

The graduate researchers on this project gained valuable research skills in the field as well as writing and presentation skills. One student is now in a tenure-track physics and science education faculty position with research expectations in physics education. One student subsequently obtained a postdoctoral position in a high-profile physics department known for its curricular modifications, and is now starting a tenure-track faculty position in a physics department. A third student has given an invited colloquium as well as a conference presentation outside of the discipline. These students have being well prepared for future faculty positions, with or without research expectations.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

This project has increased the awareness of researchers of the issues faced by physics majors learning thermal physics, and, increasingly, of the distinction between mathematics as taught in mathematics classes and mathematics as used in physics classes.

Project researchers have given invited colloquia on this work in three different departments on campus (Chemistry, Chemical and Biological Engineering, and Mathematics & Statistics) and elsewhere over the course of this project. Faculty in these departments have expressed strong interest in the work, and some have offered up their students as research subjects.

Partly as a result of this work, STEM Education Research has been designated a "Signature Research Area" at the University of Maine, decided by a campus-wide committee headed by the Provost and the Vice President for Research. We expect that this designation will increase the local resources, especially human resources, given to this research area, especially given its interdisciplinary nature.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Improving concpetual understanding of topics in STEM narrows the gender and socioeconomic gaps in this area. Further improving student fluency with multiple representations across disciplinary boundaries increases the quantitative literacy of the citizenry and the workforce in general.

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.