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Collaborative Research: Paradigms in Physics: Creating and Testing Materials to Facilitate Dissemination of the Energy and Entropy Module

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Submitted By:

Thompson, John - Principal Investigator

Title:

Collaborative Research: Paradigms in Physics: Creating and Testing Materials to Facilitate Dissemination of the Energy and Entropy Module

Project Participants

Senior Personnel

Name: Thompson, John

Worked for more than 160 Hours: Yes

Contribution to Project:

Post-doc

Graduate Student

Name: Smith, Trevor

Worked for more than 160 Hours: Yes

Contribution to Project:

Research assistant. Collected assessments, coordinated assessments to send to collaborators, analyzed some data.

Name: Kaczynski, Adam

Worked for more than 160 Hours: Yes

Contribution to Project:

Analysis and synthesis of data from Oregon State and Ithaca College sites.

Name: Clark, Jessica

Worked for more than 160 Hours: Yes

Contribution to Project:

Cataloged data on different questions - did analysis using existing coding/rubrics for student difficulties. Organized sets of data across years of project and did summaries of results. (Is also working on related project (0817282).

Name: Bajracharya, Rabindra

Worked for more than 160 Hours: Yes

Contribution to Project:

Cataloged data on different questions - did analysis using existing coding/rubrics for student difficulties. Organized sets of data across years of project and did summaries of results. (Is also working on related project (0817282).

Undergraduate Student

Technician, Programmer

Other Participant

Name: Mountcastle, Donald

Worked for more than 160 Hours: No

Contribution to Project:

Contributed to discussions of Energy and Entropy course goals and content as relates to research on student learning. (Mountcastle is Senior Personnel on separate project - DUE 0817282 - which deals with the same physics content but in different courses and environment.)

Research Experience for Undergraduates

Organizational Partners

Oregon State University

OSU is the Lead Institution in this collaboration. They are the primary institution for the curricular materials development and execution. Our role is to assess the effectiveness of the instruction and, to a lesser extent, to evaluate the course and materials

Ithaca College

Another collaborator for this project. That PI is teaching a similar course and using and adapting the curricular materials for his course, which has a different format. Our role is similar to what it is with respect to Oregon State: assess materials and student learning, contribute to pedagogical and assessment efforts.

Other Collaborators or Contacts

Some discussions with Joseph F. Wagner, Dept. of Mathematics and Computer Science, Xavier University (Cincinnati, OH). Wagner conducts research in undergraduate mathematics education, focusing on transfer. Our project had conversations with him about the implications of our results for transfer. Wagner is very interested in this work. At the 2011 Physics Education Research Conference, there was a 'Poster Gallery' about the use of representations in physics. Wagner served as a discussant after the poster presentations, providing a mathematics perspective on the research. We plan continuing informal (and possibly more formal) collaboration with Wagner in the future.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

Graduate research assistant Trevor I. Smith (Ph.D. 2011) has analyzed data and written summaries of the findings for this project. He
is maintaining the digital storage for the project. He is participating in discussions of the goals of the Energy and Entropy Paradigm
in relation to thermodynamics, giving him experience thinking holistically about how content fits into a broader curricular agenda.
Trevor visited the OSU campus and observed the Energy and Entropy course in action in May 2010, and participated in discussions of
the course goals, pedagogy, and assessment as well as research aspects of the project in a meeting of the PIs and consultants at OSU
in July 2010. He has had excellent exposure to upper division curriculum development and assessment.
Trevor was offered a postdoctoral appointment at OSU to work with the Paradigms project upon completion of his Ph.D. Further,
Trevor was interviewed for another postdoc in upper-division PER. Trevor's experience has given him a unique position from which to apply to faculty teaching and research positions. (Trevor has taken a Visiting Assistant Professor position at Dickinson College, and we are in

the process of publishing pieces of his dissertation work.)

Graduate research assistant Adam Kaczynski has analyzed data and written summaries of the findings for this project, in conjunction with Trevor Smith. Adam's dissertation work is in a different area (it was partially funded by DRL-0633951 ('Creation, coordination, and activation of resources in physics and mathematics learning')) but still at the post-introductory level. Adam gained experience and insight on student learning and on the content of upper-division thermal physics in the time he worked on this project. (Kaczynski eventually decided to focus his research on sophomore-level mechanics learning, working with colleague Michael Wittmann.)

Graduate research assistants Rabindra R. Bajracharya and Jessica W. Clark have analyzed data and written summaries of the findings for this project, especially for the 2011 data. Both are doing relevant research for their dissertations in thermal physics and/or math-physics connections. Both have been supported by this grant as well as DUE-0817282. Their analysis was very helpful for the project and for their own professional development.

Outreach Activities:

Journal Publications

J. R. Thompson, C. A. Manogue, D. J. Roundy, and D. B. Mountcastle, "Representations of partial derivatives in thermodynamics", 2011 Physics Education Research Conference, AIP Conference Proceedings, p. 85, vol. 1413, (2012). Published, http://dx.doi.org/10.1063/1.3680000

J. F. Wagner, C. A. Manogue, and J. R. Thompson, "Representation issues: Using mathematics in upper-division physics", 2011 Physics Education Research Conference, AIP Conference Proceedings, p. 89, vol. 1413, (2012). Published, http://dx.doi.org/10.1063/1.3680001

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

This work serves to provide a research base for the curricular development and reform efforts of the Paradigms in Physics program, specifically the Energy and Entropy module. Due to the novel pedagogical approach of the Paradigms, analysis of student learning, and a comparative analysis of Paradigms results to those of more traditional courses, will further the teaching and learning of upper-division thermal physics specifically, but also of upper-division courses, and the relationship between the math and the physics, in general.

In addition, this work has influenced researchers to consider the benefits and costs of reform at the upper division. Some of this researcher's work - including curriculum development (as part of DUE 0817282) - will be (has been) influenced by the pedagogy used in the Energy and Entropy course, based on the findings of this project.

Contributions to Other Disciplines:

Contributions to Human Resource Development:

Four graduate students have analyzed data from this project, and one in particular has spent significant time observing the class, both live and in video. This exposure to novel pedagogy - and the analysis of results on its effectiveness on student learning - has impacted these students in their concept of teaching and learning at the upper division. Conducting the research on student understanding - even with existing templates for analysis - provides additional contexts for the preparation of these students to become researchers in physics education - to get practice on an existing project so that they have ideas about how to do similar work in their own research area. The students have demonstrated skill improvement by their work in this project.

Contributions to Resources for Research and Education:

We are still developing the instruments and course materials that this project is designed to produce. But they should be proven as effective for multiple course types over the long term.

The modified course should improve student understanding of targeted concepts, related mathematics, and pedagogy in thermal physics in particular and at the upper division in general. Our research/evaluation of the instructional strategy and curricular resources are validating the claims of the developers to achieve their goals of student learning.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Activities and Findings: Any Outreach Activities

Any Book

Any Web/Internet Site

Any Product

Contributions: To Any Other Disciplines

Contributions: To Any Beyond Science and Engineering

Any Conference

NOTE: The grant awarded to UMaine as a subset of the collaboration between staff at Oregon State, Ithaca College, and UMaine is focused on research on student learning and the assessment of the effectiveness of curricular materials in the *Energy and Entropy* (*E&E*) course taught at Oregon State and the thermal physics course at Ithaca College using adapted materials from *E&E*. The findings discussed in *this* report relate only to research of this nature.

The majority of our research findings relate to the identification of specific conceptual and mathematical difficulties among students when learning this material using traditional thermal physics textbooks and teaching methods. Details are given below.

The OSU staff have gathered data from their students on topics that we at UMaine started investigating in related work (PHY 0406764 and DUE 0817282), as well as continuing the instructional materials development process from earlier work. We are discussing the option of using Maine-developed curricular materials in various classes in conjunction with different activities from *E&E* or other adapted materials.

Specific information about questions and results from UMaine can be reviewed in the annual report for award DUE 0817282.

[Feb 10 – Jan 11]

More questions were administered in this year at OSU; results are provided below. Most 2010 results are consistent with those from 2009.

[Feb 11 – Jan 12]

More questions were administered in this year at OSU; results are provided below. Again, most results are consistent with earlier ones.

Overview

In this report basic results will be presented without too much detail.

The results described here are from two sets of written questions administered to the OSU students, one set on the first day of class and one set from the final exam. (Both surveys are included as Appendices to this report.) The pretest dealt almost exclusively with mathematics directly related to the physics topics, and the post-test asked about the physics material, but also dealt with the mathematics used and applied in context.

We describe the background of the math pretest questions and how they relate to physics questions, and then provide results, with comparisons to results on similar questions administered elsewhere.

[Feb 11 – Jan 12]

More results have been analyzed, including some homework assignments. A more complete picture of the course and student learning has emerged. In general the preliminary conclusions about the mathematical sophistication of Paradigms students relative to other students (Maine students in particular) seem to be supported. However, the physics conceptual understanding of the OSU students, while in general greater than that of the Maine students, is not commensurately higher.

Widespread student difficulties with applications of mathematics prerequisites

A major component of our research involves how students view, use, and understand the underlying mathematical concepts in the context of thermodynamics. We have identified several difficulties that are mathematical in nature; at least one of these was previously identified as a physics conceptual difficulty, and our results show that some of the students exhibiting this difficulty may have mathematical conceptual issues rather than, or in addition to, any problems with the physics concepts.

The general theme of this work is probing mathematical meaning and physical significance in physics. We explain results of analysis that occurred primarily during the past project year.

As part of this plan, in Fall 2007 staff at UMaine developed a six-question math diagnostic quiz, which we administered to 5 sections of UMaine's undergraduate Calculus III course, taught in the Department of Mathematics and Statistics. The diagnostic quiz contains three questions asked in our thermal physics courses, including the integral questions and partial derivative questions described above, as well as other questions dealing with the complementary concept of differentiation. Importantly, the questions were asked in a completely mathematical context, without any reference to physical situations. Additional questions were added to the pretest survey at OSU, including one checking whether students recognize that the coefficients in a total differential are also first partial derivatives.

Paired physics and "physics-less physics" questions

One set of questions deserves mention in particular. We have investigated the mathematical underpinnings of student responses to questions comparing ("thermodynamic") work done by identical ideal gas samples that start at the same state and end at the same state, but have different thermodynamic processes, shown as different paths on a pressure-volume (*P-V*) diagram (Pollock et al., 2007; Thompson et al., 2009).

Students were asked several questions regarding First Law quantities along with similar mathematical questions devoid of all physical context. (We have labeled the mathematical analog questions as "physics-less physics questions" because they are not presented quite the way a mathematician would present them, but all physics context is removed. We have manuscripts in preparation describing these questions and results.) We compared student responses to physics questions involving interpretation of ideal gas processes on *P-V* diagrams and analogous mathematical qualitative questions about the signs and comparisons of magnitudes of various integrals. Overall results coupled with individual student performance on the paired questions shows evidence of isolated understanding of the physics and/or the math, although some difficulties are addressed by instruction.

By the end of the previous grant, we had concluded that many students do not apply the concept of *integral* appropriately in their solutions to this problem.

Modification: One finding from earlier work led to a modification of the questions in both contexts. In individual student interviews at UMaine, a few students decided to use the symmetry of the paths on the P-V diagram to justify their response (that the works/integrals were equal). To reduce the visual distraction of the symmetrical paths, we have modified the graphs to be *asymmetric,* that is, the "lower" path (one with less area under its curve) is now longer than the "upper" curve. (See figures on next page.) This allows for student responses to be distinct between area-based and length-based reasoning.

The modified questions were asked at Oregon State University in the Spring 2009.

Exploring student understanding of specific concepts and topics in thermal physics

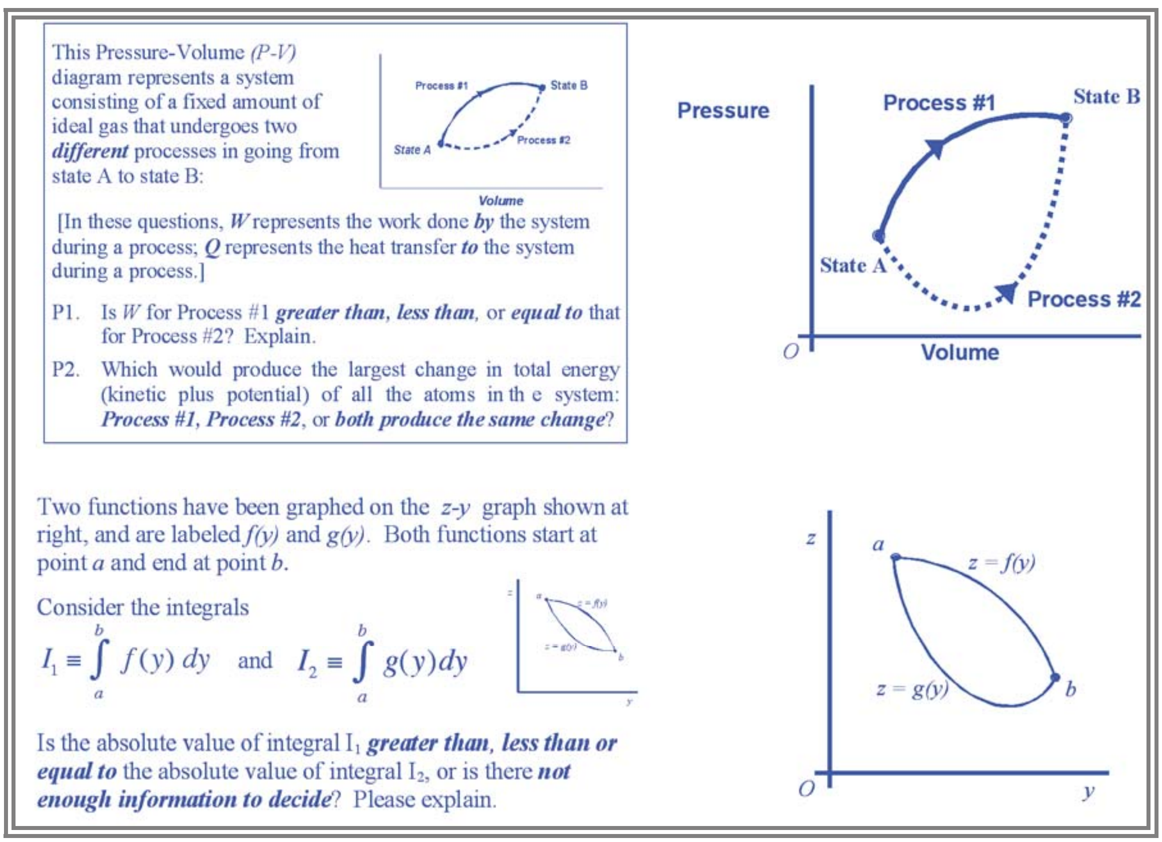
The major research area of the UMaine group is the investigation of student understanding of thermal physics concepts, especially entropy. We have asked questions about entropy changes in spontaneous processes as well as for comparisons of entropy changes in different processes with similar or identical beginning and ending states.

Results

Some results are highlighted here, but the bigger picture is provided in the *Conclusions* section below.

Pretest results

In general, the OSU Paradigms students had a better sense of the mathematics in these problems than UMaine students – either the physics or math students. Performance on most questions to do with integrals was higher, and the reasoning was more sophisticated. For example, on a question dealing with a loop integral of a two-dimensional function (analogous to asking about the change in a state function value over a thermodynamic cycle), many OSU students reasoned using “field” ideas: conservative, vector, gradient. This reasoning was absent from the UMaine physics students, unless they spoke of conservative forces, but never did they mention fields. The UMaine math students used some of this reasoning, but not as well as the OSU Paradigms students.



This Pressure-Volume *(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 transfer ***to*** the system during a process.]

P1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

P2. Which would produce the largest change in total energy (kinetic plus potential) of all the atoms in th e system: ***Process #1, Process #2***, or ***both produce the same change***?

Two functions have been graphed on the *z-y* graph shown at right, and are labeled *f(y)* and *g(y)*. Both functions start at point *a* and end at point *b*.

Consider the integrals

$$I_1 \equiv \int_a^b f(y)\,dy \quad \text{and} \quad I_2 \equiv \int_a^b g(y)dy$$

Is the absolute value of integral I_1 ***greater than, less than or equal to*** the absolute value of integral I_2, or is there ***not enough information to decide***? Please explain.

Example of physics and analogous math questions, before and after modification to eliminate symmetry from the figures. Representative modified figures are on the right (the questions were identical).

On a question about the equality of mixed second-order partial derivatives (#3) – directly related to the Maxwell relations in thermodynamics – OSU students performed similarly to the Maine students in terms of specific difficulties, although better overall. (For Maine results, see Bucy et al., 2007, and Thompson et al., 2009.)

On the topic of differentials, OSU students had much lower performance than UMaine students. This question (#7) was designed to see if students identify coefficients in total differentials (for example, the "B" in the total differential $dR=BdC+EdF$) as partial derivatives. This is especially relevant in thermodynamics, in the Maxwell relations, where these coefficients represent physical quantities such as volume, entropy, etc., and are also partials of quantities like the Gibbs free energy with respect to the temperature, etc.

The OSU students performed much worse on this question before instruction relative to the UMaine physics students: only one of 11 students gave a correct response, while 9 solved algebraically for the coefficient. This is asked at UMaine later in the semester before instruction on Maxwell relations, and differentials have been emphasized for a few weeks; this was on the first day of class at OSU. However, this is a strong difference in the awareness of students with differentials between these populations, and we plan to explore further.

2010

Pretest results were not significantly different for the 2010 class than for that of 2009.

Many pretest results were consistent with findings outside of OSU – student difficulties were similar, as elicited by the same questions.

A "math pretest" was administered so that students recognized the point of the pretest. This math prestest contained most of the questions on the pretest from 2009.

An additional pretest was given, described as a "name the experiment" question. Students were given a particular partial derivative and to "describe an experiment that would measure" that quantity, for which each variable was defined.

Post-test results

2009

Three results from the post-test (included as an Appendix) are worth mentioning here, as they relate to previous research at UMaine and elsewhere.

Question 1.2 probes student understanding of the physical meaning of pressure, and is based on questions from Loverude et al. (2002). Students are asked to determine how the pressure, temperature, and volume change when small masses are added to a piston on a (vertical) cylinder. Most OSU students gave correct responses to pressure and volume questions, and only one incorrectly applied the Ideal Gas Law as seen in other research. Only about half of the class correctly predicted that the temperature would increase.

Question 1.3 was the physics question that is paired with the first math questions on the pretest (comparing integrals over different paths and evaluating the sign of a loop integral), and is based on a question from Meltzer (2004). Students are asked to compare work, heat, and internal energy changes for two processes that start at the same initial state and end at the same final state. The processes are shown on a P-V diagram. OSU students perform well on these questions, with roughly 3/4 of students giving correct comparisons for the quantities. The difficulty is that many students say that works are equal, often claiming explicitly or implicitly that work is a state function and thus only depends on the initial and final states.

Question 1.4 gives students the expression for a total differential of *G*, and provides an experimentally determined value for a partial derivative that is one of the pair of Maxwell relation quantities. Students are asked whether it is possible to determine the Maxwell relation quantity (without calling it that). OSU students did fairly well on this question – most recognized the Maxwell relation, although one student tried a more complicated solution (using the cyclic relations) and didn't arrive at the right answer.

2010

There were six (6) questions on the final exam in 2010. I present 4 of relevance currently.

Problem 1 was the same as Question 1.2 above (Masses on a piston, based on Loverude et al. (2002)). Results were similar – mostly correct, but only about half predicting that the temperature would increase.

Question 2 was the "dG" question (1.4 last year). Again, results were similar to last year.

Question 3 was the P-V diagram question from Meltzer (2004). Student performance was weaker this year, with 10/16 correctly comparing works, and one third using endpoint or reasoning to conclude that the works were the same. Some students stated that the change in volume was the same so the work was the same. Fewer students gave correct heat transfer comparisons, and almost all students did give correct internal energy comparisons.

Question 5 was taken from Christensen et al. (2009) and is referred to as the "object in the room" question. The scenario given is an object placed in a thermally insulated room containing air at a different temperature than the object, and the object and air are allowed to equilibrate thermally by exchanging energy. Students are asked to determine the sign of the entrpy change of (a) the object, (b) the air, (c) the [object + air], and (d) the universe. The questions are multiple choice, with space to explain their answers. "Not determinable with the given information" is an option along with increase, decrease, and remain the same. OSU students did very well on this question, with over 80% giving the correct responses to (a), (b), and (c) combined. This is better performance than reported by Christensen et al. with introductory students after instruction.

2011

On Meltzer's P-V diagram (Meltzer, 2004), student performance was consistent with 2010. Almost half of the students said the works were equal, most reasoning using the same endpoints. Similar results exist for the heat transfer comparison. The concept of state function was not clear with students at the beginning of the course. On the post-test, 6/25 still said that the works were equal; 4 used endpoints or explicit state-function reasoning, and 2 referred to the equal volume changes in the two processes. This question is proving surprisingly difficult for these students.

On theother hand, most students had little difficulty in finding the total derivative of a given function, even when required to use both the product rule and the chain rule.

Question 2 (2010) / Question 1.4 (2009) was asked again both as a homework question and on the final exam. Comparison of pre- and post-test results indicate a significant improvement in students' ability to handle various differentials and partial derivatives. On the homework, no students correctly completed any part of this exercise; many used an algebraic approach to a differential problem, which has been observed before at OSU and in Maine. On the final exam, all students attempted the solution differentially; not all succeeded, but everyone started in the right mathematical neighborhood.

Conclusions

[Feb 09 – Jan 10]

These preliminary findings suggest that there are indeed important and interesting differences in the ways that Paradigms students enter the *Energy and Entropy* Paradigm, and how they learn and think about material in thermodynamics relative to more traditionally taught students. Analysis of the Paradigms-specific questions is ongoing, and discussions of future questions and future administration is happening in the Spring 2010.

In addition, in-depth discussions of the goals of thermal physics courses and what math and physics concepts are central, and what are secondary, is ongoing. OSU Co-PI Manogue is visiting UMaine for two weeks in January 2010, and several discussions are happening between Manogue, UMaine PI Thompson, and UMaine colleagues and graduate students working on thermal physics education research and work on student understanding at the math-physics interface.

[Feb 10 – Jan 11]

Results from 2010 corroborate the (now more fully analyzed) findings from 2009 with respect to understanding of both mathematics and physics concepts, both pre- and post-instruction.

The *Energy and Entropy* students seem to have a similar or better (sometimes substantially better) conceptual understanding of specific physics concepts (e.g., entropy changes for spontaneous processes, relative to how 2nd law is applied) after instruction than their counterparts taught using traditional courses and texts. Certain ideas – although basic and related to concepts in mechanics – are still a challenge for them, though (e.g., what happens to T in the Masses on a Piston question: only ~50% correct post-test).

On questions targeted to the Paradigm instruction (e.g., density operator, maximize fairness), students had what we can describe as reasonable performance, given the unfamiliarity of the relevant ideas. Many of the incorrect answers were due to incorrect attempts to complete the correct steps in a procedure, rather than incorrect steps or conceptual difficulties. Most students who attempted the problems were able to write some reasonable statements at some point. Assessing the effectiveness of instruction with these instruments is difficult for us since they are new to us and we have no comparison for them. (It is difficult to try and use them at UMaine, for instance, since we don't teach those concepts in the thermodynamics course.)

Overall, as one might expect, the performance drops for more sophisticated problems - those with many steps and that integrate many ideas.

In general, as suggested in last year's report, the OSU Paradigms students had a better sense of the mathematics on questions dealing with the mathematical aspects of certain physics concepts (e.g., work as the integral of a P-V diagram, and change in internal energy as a state function) than UMaine students – either the physics or math students. Performance on most questions to do with integrals was higher, and the reasoning was more sophisticated.

However, as mentioned earlier, OSU students started the course much weaker than UMaine students did on the topic of differentials and partial derivatives, with lower performance on conceptual questions. But post-instruction performance was on par with traditional instruction.

[Feb 11 – Jan 12]

Results in Year 3 further corroborate earlier analysis. The Interlude introduced to help with math-physics connections seems to be helping with the math, but some physics concepts seem to still have some trouble.

Our collaboration resulted in two conference proceedings from the 2011 Physics Education Research Conference (Thompson et al., 2012; Wagner et al., 2012) concerning student use of mathematics in thermal physics including a transfer perspective from Joseph Wagner (Xavier University).

One more specific example of the collaboration's benefits is worth mentioning. One of the dissertation projects at Maine involved student understanding of heat engines, the Carnot cycle, and the Second Law of Thermodynamics. Trevor Smith (Maine Ph.D. 2011) developed a tutorial that guided students through an analysis of the Carnot cycle and a comparison cycle that is less efficient, and had students think about entropic considerations. One result of the Maine research was that some students could not come up with the correct definition of thermodynaimc efficiency ($\eta=W/Q_h$), instead trying $\eta=W/(Q_h-Q_l)$, which is always unity by the First Law. At Maine, we took this specific question and gave it as a "pre-tutorial homework" assignment, so that students could wrestle with this idea before coming to class – some groups spent more than 10 minutes in class trying to reconcile a reasonable definition of efficiency without making progress. We found that this streamlined the tutorial, and that all groups progressed further. This is mentioned here because the OSU group added an activity in class dealing explicitly with the Carnot efficiency. Some of the motivation for this activity came from the Maine results.

Final comments

Overall, this has been a very successful project, and we anticipate further collaborations, formal and/or informal, in the future. The Paradigms in Physics project has been influential in upper-division curriculum development and curriculum reform, and research on student learning at the upper division is behind the curve of the curriculum. Collaborations such as these are leading to more rapid progress and greater understanding of what makes upper-division students different from introductory students.

References

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Supplemental documents for *Project Findings*

- Pretest questions administered to OSU *Energy and Entropy* students, Spring 2009
- Final Exam questions administered to OSU *Energy and Entropy* students, Spring 2009
- Math pretest questions administered to OSU *Energy and Entropy* students, Spring 2010
- "Name the Experiment" pretest question at OSU, Spring 2010
- Final Exam questions administered to OSU *Energy and Entropy* students, Spring 2010
- Pretest questions administered to IC Thermodynamics students, Spring 2010

Collaboration within project

[Feb 09 – Jan 10]

- Review of text used for course, written by (Senior Personnel) Wasserman. PI Thompson reviewed several chapters and provided detailed feedback about pedagogical issues students may have reading the text, as well as clarity of writing for novices.
- Several questions in free-response and in multiple-choice formats were sent to colleagues at Oregon State University for use *Energy and Entropy* course
- Discussions with collaborators on infrequent basis on wiki site.
    - Depository for sharing materials and assessment instruments
    - Discussion threads for different topics – content areas, pedagogical issues, curricular materials
    - Discussion of goals of course(s) and curricular materials – on large and small scales
- Several questions in free-response and in multiple-choice formats were sent to collaborating PI Rogers at Ithaca College for administration in thermal physics course in Spring 2010
- C. Manogue spent time in Maine as a visitor; results and data were discussed, as well as refinement of course goals, especially with respect to mathematics expectations and some limitation of content.

[Feb 10 – Jan 11]

- Several questions in free-response and in multiple-choice formats were sent to colleagues at Oregon State University for use *Energy and Entropy* course
- Meeting in Corvallis, OR, July 2010, to have discussion of goals and details of *Energy and Entropy* course with respect to mathematics and physics, and to plan next year of project (curriculum devleopment and research & evaluation)
    - J. Thompson, T. Smith (graduate student), and D. Mountcastle (consultant) attended
    - C. Manogue, D. Roundy, A. Wasserman present
- Analysis of data from Spring 2010 implementations at Oregon State (OSU) and Ithaca College (IC) over spring and summer 2010, by T. Smith and A. Kaczynski; report generated and distributed to Oregon State University collaborators.

[Feb 11 – Jan 12]

- Additional administration of questions in Oregon State University *Energy and Entropy* course
- Preparation of invited "Poster Gallery" at 2012 Physics Education Research Conference: Representation Issues: Using Mathematics in Upper-Division Physics, organized with C. Manogue, J. F. Wagner (Xavier U., Mathematics Education Research), D. Roundy.
    - Preparation of posters in session and conference proceedings papers:
        - "Representations of partial derivatives in thermodynamics," J. R. Thompson, D. Roundy, D. B. Mountcastle. (Poster.)
        - J. R. Thompson, C. A. Manogue, D. J. Roundy, and D. B. Mountcastle, "Representations of partial derivatives in thermodynamics," in *2011*

Physics Education Research Conference, C. Singh, N.S. Rebello, P. Engelhardt, eds., AIP Conference Proceedings **1413**, 85-88 (2012).

        - J. F. Wagner, C. A. Manogue, and J. R. Thompson, "Representation issues: Using mathematics in upper-division physics," in *2011 Physics Education Research Conference,* C. Singh, N.S. Rebello, P. Engelhardt, eds., AIP Conference Proceedings **1413**, 89-92 (2012).

- Meeting in Omaha, NE, July 2011, at AAPT Summer Meeting (curriculum devleopment and research & evaluation)
    - J. Thompson and C. Manogue attended

<u>Experiments and Observations</u>

- Assessment instruments organized and administered pre- and post-instruction in PH 423, *Energy and Entropy*, OSU, Spring 2009, Spring 2010
- Assessment instruments organized and administered pre- and post-instruction in Thermodynamics course at IC, Spring 2010
- 2010: Observation of OSU *Energy and Entropy* course for 2-3 days by T. Smith
    - Field notes taken from class
    - Short interviews/discussions conducted with students
    - Discussions with instructor (Roundy) and C. Manogue about pedagogy and content, as well as research opportunities

1. *Administration and analysis of written questions*
    - Pretests
    - OSU (2009, 2010, 2011)
        - Administration, before instruction, of a set of written questions dealing heavily with the mathematics used in thermodynamics. Most of these questions had been developed at UMaine as part of a different project (funded by NSF PHY-0406764 and DUE 0817282), and have been administered in courses at UMaine (and some elsewhere) for several years, so comparisons can be made.
        - Additional questions asked regarding connections between mathematics and physics at OSU in 2010.
        - Analysis of student responses (see *Findings*)
    - IC (2010)
        - Administration, before instruction, of a written pretest with 4 mathematics questions and one statistical mechanics question was administered in Thermodynamics.
        - Analysis of student responses (see *Findings*) (N(students) = 4, so results are not statistically meaningful, but qualitatively relevant.)
    - U. Maine (2011)

    - Administration in Maine *Physical Thermodynamics* course of questions developed in the *Energy and Entropy* class. Most questions were "name the experiment" questions connecting partial derivatives with empirical situations.

- Post-instruction assessment OSU
    - 2009: Administration, after instruction (on final exam), of a set of 3 written questions dealing with thermodynamics topics (Ideal Gas Law and changes to a system; First Law and P-V diagrams; Gibbs free energy and the Maxwell relations). These questions had been developed at UMaine or by collaborators as part of a different project (funded by NSF PHY-0406764 and DUE 0817282), and have been administered in courses at UMaine (and some elsewhere) for several years, so comparisons can be made.
    - 2010, 2011: Similar questions asked based on UMaine tasks and previous *Energy and Entropy* questions. More emphasis on math-physics connections.
    - 2009, 2010, 2011: Copies were made of the entire completed final exam for all students in the course. In addition to the "research-based" questions described above, additional questions were asked about topics somewhat unique to the *Energy and Entropy* course.
    - 2009, 2010, 2011: Analysis of responses to examination questions (see *Findings*)

2. Instructional materials administration

2009: No materials developed at UMaine were tested in the Spring of 2009. Pre- and post-test questions were administered and analyzed to investigate effectiveness of existing instruction on student learning.

2010: OSU added an "Interlude" week of mathematical methods, emphasizing partial differentiation and differentials, a huge part of thermodynamics and one that we have shown to be difficult for students. During this week, elements of materials developed at UMaine were used in class at OSU. Pieces of the *Partial Derivatives and Material Properties* tutorial were used in smaller chunks as short activities.

2011: Interlude week of mathematical methods implemented again. In Interlude and in *Energy and Entropy,* several assessments were given to students both in class as small-group activites and as individual written assessments (pretests, post-tests, homework). Some activities (e.g., a discussion of Carnot efficiency of a heat engine) had elements influenced by research at U.Maine (carried out by Trevor Smith (Ph.D. 2011)), in which students wrestle with how to define the efficience of a heat engine and how to use this for a Carnot engine in particular.

<u>Presentations and Publications</u>

Publications to date

J. R. Thompson, C. A. Manogue, D. J. Roundy, and D. B. Mountcastle, "Representations of partial derivatives in thermodynamics," in *2011 Physics Education Research Conference,* C. Singh, N.S. Rebello, P. Engelhardt, eds., AIP Conference Proceedings **1413**, 85-88 (2012). Doi: http://dx.doi.org/10.1063/1.3680000

J. F. Wagner, C. A. Manogue, and J. R. Thompson, "Representation issues: Using mathematics in upper-division physics," in *2011 Physics Education Research Conference,* C. Singh, N.S. Rebello, P. Engelhardt, eds., AIP Conference Proceedings **1413**, 89-92 (2012).

Relevant invited presentations

Math and Physics Seminar, Department of Mathematics and Computer Science and Department of Physics, Xavier University, Cincinnati, OH, 24 October 2011, "Investigating student understanding of physics concepts and the underlying calculus concepts in thermodynamics."

2011 Physics Education Research Conference, Omaha, NE, 3-4 August 2011, "Representations of partial derivatives in thermodynamics," J. R. Thompson, D. Roundy, D. B. Mountcastle, in session titled "Representation Issues: Using Mathematics in Upper-Division Physics." Poster Gallery. (4 August 2011)

Foundations and Frontiers of Physics Education Research 2011 (International), Bar Harbor, ME, 13-17 June 2011, "Towards understanding of mathematical representations: an example from definite integrals in thermodynamics," in invited "targeted poster" session titled "Methods for analyzing students' transfer of knowledge into physics: Investigations of mathematics in physics." One of 4 presenters on the topic.

2011 March Meeting of the American Physical Society, Dallas, TX, March 2011, "Research on student learning of upper-level thermal and statistical physics."

2011 Winter National Meeting of the American Association of Physics Teachers (AAPT), Jacksonville, FL, 12 January 2011, "Investigating Math-Physics Connections in Upper-Division Thermal Physics," in session entitled "Making physical meaning with mathematics."

Colloquium, Department of Physics, The University of New Brunswick, Fredericton, NB, Canada, 22 October 2010, "Research on the learning and teaching of thermal physics and the associated mathematics."

Colloquium, Department of Chemistry, The University of Maine, Orono, ME, 23 September 2010, "Research on the learning and teaching of thermal physics and the associated mathematics."

2010 Summer National Meeting of the AAPT, Portland, OR, 20 July 2010, "Investigating student understanding of integrals in upper-division thermodynamics," in session entitled "Dealing with Mathematical Difficulties in Lower and Upper Division Physics Courses."

Contributed presentations

2011 Summer National Meeting of the AAPT, Omaha, NE, July-August 2011, "Students' reasoning about the signs of definite integrals in graphical representations," R. R. Bajracharya, T. M. Wemyss, J. R. Thompson. (1 August 2011)

2011 Summer National Meeting of the AAPT, Omaha, NE, July-August 2011, and 2011 Physics Education Research Conference, Omaha, NE, 3-4 August 2011, "Student interpretation of definite integrals at the math-physics interface," R. R. Bajracharya, T. M. Wemyss, J. R. Thompson. (Poster.) (2 August 2011; 4 August 2011)

No Question Left Behind: Bringing Guided-Inquiry Curricula into Science and Mathematics Classrooms, Orono, ME, 23-24 June 2011, "Student Difficulties with Definite Integrals at the Math-Physics Interface," R. R. Bajracharya, T. M. Wemyss, J. R. Thompson. (Poster.)

Foundations and Frontiers of Physics Education Research 2011 (International), Bar Harbor, ME, 13-17 June 2011, "Student Difficulties with Definite Integrals at the Math-Physics Interface," R. R. Bajracharya, T. M. Wemyss, J. R. Thompson. (Poster.)

2011 April Meeting of the American Physical Society, Anaheim, CA, April-May 2011, "Student reasoning about graphical representations of (definite) integrals," J. R. Thompson, R. Bajracharya, T. Wemyss.

Fourteenth Conference on Research in Undergraduate Mathematics Education, Portland, OR, February 2011, "Student Understanding of Integration in the Context and Notation of Thermodynamics: Concepts, Representations, and Transfer," T. M. Wemyss, J.R. Thompson, R. R. Bajracharya, and J. F. Wagner.

2010 Physics Education Research Conference, Portland, OR, 21-22 July 2010, "Investigating student understanding of thermodynamics concepts and underlying integration concepts," J. R. Thompson, D. B. Mountcastle. (Poster.)

Transforming Research in Undergraduate STEM Education (TRUSE) 2010, University of Maine, Orono, ME, 14-18 June 2010, "Investigating student understanding of thermodynamics concepts and underlying integration concepts," J.R. Thompson, D.B. Mountcastle. (Poster.)