Collaborative Research: Creating a Common Thermodynamics

An important transformation is taking place in biology education.

Modern biology increasingly involves the interplay of tools and modes of thinking that are drawn from a range of scientific disciplines – chemistry, physics, math, and computer science. Leading biologists and organizations representing the biological community are calling for an undergraduate biology education that involves focusing less on memorization and recognition and more on the development of understanding and scientific reasoning skills. (Alberts 1998) (NRC 2003)(AAMC-HHMI committee 2009)

While there has been considerable progress in, for example, developing courses in biochemistry, math for biologists, and physics courses with examples drawn from biology, some important topics need more interdisciplinary approach. One such topic is Thermodynamics and Statistical Mechanics (T&SM). T&SM only represents about 10% of a typical introductory physics class (3 weeks out of 30), but it plays a crucial role in biology. The standard treatment of T&SM is not only insufficient to permit a treatment of essential items for biology such as diffusion, Fick's law, the Nernst equation, and the exchange of electrical and chemical energy, but the way it is taught is inconsistent with the way the subject is taught and used in biology and chemistry.

In this project, the University of Maryland's Physics and Biology Education Research Groups (UMd PERG & BERG) have assembled a multi-university team of STEM education experts in physics, chemistry, and biology to help us address this issue. We will start the project by creating a cross-disciplinary literature review on T&SM learning across the disciplines and will negotiating a common starting point and approach for physics, chemistry, and biology. A development team at Maryland will then create active learning modules that can serve as supplements to any introductory physics class for biologists. These modules will include a careful treatment of topics critical to biology that are traditionally excluded from physics such as diffusion, chemical energy, enthalpy, and the Gibbs Free Energy.

These project materials will be developed in conjunction with careful research on student attitudes and understanding about the concepts of energy, entropy, and molecular motion in physics, chemistry, and biology classes. The materials will be vetted by the team of experts and tested in a new physics class for biologists being developed at Maryland for an HHMI project.

Thermodynamics and Statistical Mechanics (T&SM) are critical elements in developing a deep understanding of biology and are difficult to understand

Thermodynamics and the associated underlying statistical picture of random molecular motions are fundamental in biology. In order to make sense of biological processes ranging from respiration and photosynthesis in the cell to the survival and stabilization of ecosystems students need a good understanding of the concept of energy, its conservation, its availability, and its manipulation. Furthermore, since biology is fundamentally about the generation, evolution, and maintenance of organization and structure, the concept of information and its statistical mechanical partner, entropy, also play critical roles.

These topics are subtle and involve many complex issues. Thermodynamics is a phenomenological science that develops relationships between macroscopically measurable values, such as pressure, temperature, and concentration. But it is one that depends on re-interpretations and refinements of everyday intuitions. Misconceptions abound, ranging from the nature of temperature (Warren 1972), heat, and rate of heat flow (Johnstone et al., 1977), to the interpretation of work and energy (Kesidou & Duit, 1993). The concept of entropy is even more abstract and the critical difference between the transfer of thermal energy and entropy is hard to motivate without highly sophisticated mathematics.[1] (Tisza 1966)

The way that more advanced students typically make sense of thermodynamics is through an understanding of the underlying microscopic mechanism: the effect of the random motions of the molecules of which matter is made. Temperature emerges as related to the average kinetic energy of a single molecule and pressure as the result of molecules bouncing off walls and transferring momentum. Entropy is interpreted in terms of the probability of finding a given macroscopic state among the huge array of possible microscopic states. This type of understanding demands some very complex and sophisticated conceptual ideas, including the assumptions that:

- Microscopic fluctuations can be treated by replacing time averages with averages over ensembles (a large number of copies of a system "identically prepared in a macroscopic sense");
- All transformations can be treated as adiabatic (very slow) or quasi-static; and
- One can consider the system as a smooth and continuous function of space, despite the fact that on the micro scale, things fluctuate wildly.

This last assumption essentially assumes that one can consider volumes that are very small on the macroscopic scale one cares about but that still contain a very large number of molecules.

Not only are these ideas conceptually very subtle, but many biological systems of fundamental importance (e.g., cells) do not satisfy these assumptions.

Finding a way to teach a subject as complex and abstract as T&SM in a way that novice biology students can make sense of is going to be a significant challenge and will require a good understanding of what the students bring to the enterprise of learning it. There has been a lot of attempts to teach the subject to introductory students and there is research on student difficulties in T&SM, but from a variety of inconsistent points of view.

T&SM are taught in physics, chemistry, and biology but differently and inconsistently.

Students typically encounter the concepts of energy and entropy in introductory biology, chemistry, and physics classes. These concepts are subtle and difficult to understand. But what makes things worse is that the approach taken to introducing these critical concepts in the three disciplines can be dramatically different. In principle, one might expect that "thermodynamics is thermodynamics" and therefore instruction in any discipline would be similar, but in practice this is not the case. T&SM are subtle and complex subjects, even when we restrict our considerations to static or quasi-static situations. The subject can describe an extremely wide variety of phenomena, so for introductory instruction, restrictions and limitations are necessary.

Often, however, different assumptions are implicitly made in different disciplines and the same concept can be used to mean very different things. Moreover, the mathematics needed to

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[1] Thermal energy transfer, dQ, is not a closed form so cannot be thought of as a small change in a well defined quantity. The transfer of entropy, dQ/T, is closed so it can be thought of as a change in a quantity.

understand the link between the phenomenology of thermodynamics and the mechanism of statistical mechanics is not typically presented in the math courses taken by biology majors. This failure to coordinate raises severe barriers to students' development of a coherent understanding of these important ideas.

Consider three examples: the concept of chemical energy, the second law of thermodynamics, and partial pressure.

Chemical Energy – Students have been exposed to the concept of energy and the idea that energy is conserved throughout elementary and high school. In chemistry and biology the idea of energy is strongly used, with one of the most important types being chemical energy. But often, the concept of energy is used qualitatively instead of quantitatively and in shorthand ways that lead the students astray.

For example, students – and even faculty – will say that "energy is released by breaking chemical bonds." This is plausible in the case of a metastable state where adding a small amount of activation energy will release a much larger amount of energy. But in most cases, energy is released because a stronger bond replaces a weaker bond. A "bond" means that the atoms are bound together – an *input* of energy is required to separate them. It typically *takes* energy to break a bond; bonds don't *store* energy. Some biologists (and some biology texts) use the phrase "energy from bonds" as a shorthand, but we expect students will be confused by it and it will prevent them from integrating the concept of energy across the disciplines.

In physics classes the concept of energy is fairly carefully built up starting with Newton's second law, which says that forces produce changes in velocity – either direction or magnitude.[2] When one focuses on how forces change the magnitude of velocity, simple manipulations of Newton's second law leads to the work-energy theorem and the concept of kinetic energy. Potential energy (gravitational and springs) follows fairly directly.

But the treatment of energy in modern introductory physics texts, even in ones purported to be for biology students (e.g, Knight 2009), tend to be inherited from 50-year-old treatments of thermodynamics for engineers. A search for the term "chemical energy" in such texts turns up either a single reference – which turns out to be just the inclusion of the term in a list of various kinds of energies – or none at all. This is a serious failing and must be corrected if physics is to be relevant to modern biology classes.[3]

The creation of supplementary materials that permit the inclusion and integration of chemical energy into the introductory physics class is a major goal of this project.

The Second Law of Thermodynamics – Since biology is about the creation of organization, the second law of thermodynamics is essential. It states that in effect the creation of organization is associated with the degrading of the usability of energy to do physical work and affect other results. The second law answers the question, "If energy is conserved, why do we have to conserve energy?"

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[2] Though subtleties associated with extended objects are often ignored. See (Sherwood 1984)

[3] The one counterexample we have found is the innovative text (Chabay 2011) that takes a strong molecular perspective from the first. Unfortunately, the "spring-like" model of a chemical bond shown could tend to reinforce the "energy stored in bonds" misconception. The text is for engineers and the treatment of thermodynamics builds on heat engines and does not include chemical energy.

The treatment of the second law in physics courses is again a legacy from 50-year-old treatments of thermodynamics for engineers. The phenomenological discussion of the second law (e.g., Sears and Zemansky, 1956) relies on heat engines, a topic that is of little interest to biologists since no organism has evolved to exploit a temperature difference as the source of its metabolic energy. The statistical mechanical discussion of the second law relies on the concepts of entropy or information and probability, concepts that are extremely difficult conceptually and hard to connect to the phenomenology. Since chemical energy is excluded from the physics course, typical use of entropy is associated entirely on the issue of heat transfer coupled with physical work.

In contrast, the treatment of entropy in chemistry and biology classes may play down the importance of physical work (pdV) or suppress it entirely. In these classes, chemical energy rules and the concepts of enthalpy and Gibbs free energy play critical roles. These concepts are typically never mentioned in an introductory physics class, making the second laws seen in physics disconnected from its practical use for biology students.

The creation of supplementary materials that permit the inclusion and integration of enthalpy and Gibbs free energy into the introductory physics class is a second major goal of this project.

Partial Pressure – The gap between traditionally taught physics and biology classes on this concept can be illustrated by two anecdotes relating experiences of the PI.

In the first, a biology colleague who was teaching in the same lecture hall the hour before the PI was to teach his physics class stayed around one day for a brief chat. "I had to tell my students that what you teach them about pressure is wrong." He said that when he asked his students, "What is pressure?" some of them responded, "Force per unit area." This is indeed what is taught in physics, but the biologist wanted a different answer. "Pressure is concentration," he said. Now for a mixture of nearly ideal gases, each gas contributes its own component to the total pressure through the ideal gas equation, $pV = nRT$, where p is the pressure, V is the volume, n is the number of moles of the particular gas that is present, R is the gas constant, and T is the (absolute) temperature. This can be written $p = (n/V)RT$ where n/V is the concentration – number of moles per unit volume. If the temperature can be taken as a constant – an unstated assumption, the pressure is indeed proportional to the concentration. Where many gases are mixed, each contributes its own component to the total pressure, its *partial pressure*. (It is also true that the interpretation of pressure as force per unit area is valuable in biology, for example when considering fluid flow and blood pressure.)

But the concept of partial pressure is traditionally not taught in a physics course and this can lead to some bizarre errors.

The highly popular text (Knight 2009, problem 12-6) asks the following question. "Dry ice is frozen carbon dioxide. If you have 1.0 kg of dry ice, what volume will it occupy, if you heat it enough to turn it into a gas at a temperature of 20 C?" The question is a strange one, as even high school students have learned to repeat the mantra, "A gas expands to fill the available space." Therefore, the correct answer is, "It depends on how big a container it is in," and it does not at all depend on the mass of the CO_2. Unfortunately, this is not the answer that was desired. The solution manual wants students to calculate the number of moles of CO_2 and then apply the ideal gas law in the form, $V = nRT/p$, using a pressure of one atmosphere to solve for the volume. This would be appropriate if the CO_2 were evaporating into a bubble held in by the pressure of the atmosphere – but in a gas there is no surface tension to hold the bubble together.

The physics problem and the biology example both become immediately clear if pressure is understood – and thought of! – in terms of the motion of molecules. In this sense, pressure arises because there is a density of molecules moving in all directions at high speed. These motions potentially could exert a force, but when there is no preferred surface, all the molecular momenta cancel. But when a surface is introduced and the molecules on one side only are considered, only molecules traveling toward the surface are counted. When the molecules bounce off the surface a force results. Thinking of the pressure and the ideal gas law in terms of a mental model of low density moving particles clearly includes both meaning discussed with the biologist and immediately reveals the physics text problem as improperly posed. (Redish 2010)

The creation of supplementary materials that introduce simple molecular models of fundamental thermodynamic concepts into the introductory physics class is a third major goal of this project.

Physics is a good place to develop an understanding of T&SM for biology but not in the way it is currently taught.

Since T&SM are used in physics, biology, and chemistry, we could focus on any one of these contexts for reforming instruction. We choose to begin with physics since physics deals with simpler situations and can help students develop a basic understanding of the concepts – if they instruction is properly matched with the way they will see the topics in other classes. Unfortunately, this is rarely the case.

A major component of this project will be coordination of our instructional materials with the disciplines of chemistry and biology.

There are two compelling reasons for beginning with a careful treatment of these concepts in the context of physics. First, physics is traditionally the place where one can simplify the phenomena and concepts of interest sufficiently to get to a stage where the basic mechanisms can be revealed and understood. Biology necessarily deals with highly complex situations. Separating the basic concept development from the (necessary but particular) facts of a given situation may be difficult. And while chemistry can isolate reactions and deal with simpler situations than biology, chemistry is almost always thought of (and taught in) a realistic situation in which the reactants are in a context and exchange energy and entropy with that context. Physics is the place where one expects to consider examples that make the physics "as simple as possible – but not simpler", in Einstein's felicitous phrase.

In our physics implementation of these conceptual issues, we will begin with the examples that are sufficiently conceptually simple that the details can be fully apprehended and a clear mental model developed. Some examples can be elaborated to illustrate how the basic mechanisms are imbedded and interpreted in more complex situations, but the full implementation will be left for chemistry and biology classes where they can build on basic understandings developed in physics. Those materials would be created in subsequent (or perhaps parallel) projects.

A second reason is that the PI is part of a multi-university team working on developing a new scientific curriculum for pre-med students supported by HHMI. In this project, the Maryland education research groups, in collaboration with projects at three other universities, will be creating a new calculus-based physics course for biology majors. This would be an ideal environment in which to deliver and test the materials and would provide additional opportunities for interdisciplinary interactions and discussions.

The new HHMI physics course being developed at Maryland is a useful context for interdisciplinary research and development on T&SM.

In 2009, the Howard Hughes Medical Institute (HHMI) and the Association of American Medical Colleges (AAMC) published a reconsideration of American medical education, *Scientific Foundations for Future Physicians* (SFFP). (AAMC-HHMI committee 2009). The implication of this report is that pre-medical education in the US should be less dominated by traditional course labels and should be more competency-based. Eight broad competencies were developed for pre-meds and the report stressed that these should be achieved through a strong and coordinated program in the basic sciences (biology, chemistry, and physics) and mathematics.

In the summer of 2010, HHMI invited groups from four universities to meet to see whether they could create a set of coordinated interdisciplinary development projects to further educational development along the lines laid out in the SFFP report. The four universities, working with HHMI guidance, created a development project that HHMI agreed to fund. The project is to develop elements of a new curriculum for biology majors and pre-medical students including: a new physics course (University of Maryland, College Park), a new chemistry course (Purdue University), quantitative modeling for core biology courses (University of Maryland, Baltimore County), and a capstone case-study class, bringing together tools from all the sciences and math (University of Miami). Critical elements of all these efforts will be a focus on competency development and interdisciplinary coordination.

The PI of this grant (Redish) is one of the team leaders for the physics course development and will be teaching a first test section of this class in the fall of 2011. This course will build on previous work by the University of Maryland Physics Education Research Group (PERG) and will attempt to integrate authentically relevant biological examples. Through this four-year project, the PI will be interacting with and coordinating with biologists, chemists, and mathematicians at Maryland and the other three universities.

Why can't this project be done as a component of the HHMI project?

There are three reasons why the work of this proposal will not be carried out by the HHMI project. (1) the breadth of that project, (2) the scale of the effort, and (3) the project priorities.

Breadth – The HHMI project is too broad to dedicate a significant fraction of its resources on an issue as complex and interdisciplinarily challenging as T&SM on the deep conceptual level needed. The project's goal is to pull together a complete course in physics for biologists including a complete new set of laboratories.

Scale of the effort – Despite the breadth of the project, the funding is sharply limited. About half of the $100K/year (for four years) budget supports release time for faculty, and leaving funding for approximately ½ of a dedicated postdoc and ½ of a research graduate student. This proposal requires extensive labor that faculty will not be able to carry out by coordinating small efforts of many individuals. Dedicated researchers are needed to do a major literature review, recruit and carry out interviews, transcribe videos, and develop websites.

Project priorities – Though the HHMI priorities do include some research, the focus of this is on developing assessment tools to measure broad general competencies as explicated in the SFFP report. Devoting a significant fraction of the project's effort to a subject that is only 10% of the curriculum being developed is not going to happen.

But the other universities in the HHMI project would provide an additional test-bed for trials of the materials developed for the current proposal. If the results of the proposed project could affect the developers of chemistry and biology curricula in the HHMI project, our results would have much broader dissemination and impact.

Previous NSF-supported work on algebra-based physics provides a good base from which to begin.

Over the past two decades, the PI and his research group at the University of Maryland have carried out more than a dozen NSF supported projects, many of which provide the experience to carry this project out successfully. Previous research of the UMd-PERG has:

- (NSF #9355849) Studied the expectations students bring into their physics class about the nature of the knowledge that they will be learning and what they needed to do to learn it. In conjunction with this study, we developed an attitude survey (the MPEX) that demonstrated that students' attitudes and expectations became *less* professional after a semester of introductory physics, even classes that produced strong conceptual gains. (Redish 1998)
- (NSF #0087519) (NSF #0440113) (NSF #0524987 n.d.) Developed a theoretical structure, *the Resources Framework*, that allows one to analyze student conceptual understanding dynamically and to include the controlling effects of student expectations and assumptions about the nature of the task and knowledge. This structure draws on modern psychological theory and bridges cognitive and socio-cultural modeling.[4] (Hammer 2000) (Hammer et al. 2004) (Redish 2004) (Redish & Smith 2008)
- (NSF #0087519) (NSF #0440113)(NSF #0715567) Carried out extensive research on the behavior, knowledge, and attitudes of biology students in an introductory physics class, including nearly 1000 hours of video observation of authentic student behavior in tutorials and problem solving. As a result of these observations and the understanding of these students, elements of the course were revised (clicker questions, interactive lecture demonstrations, and tutorials) to help students develop a more sense-making approach to their learning and to develop their physical intuitions. These reforms produced strong gains on conceptual tests (pre-post fraction gain of ~0.5 on the FMCE) and strong gains on the MPEX, the first such gains demonstrated in a large lecture class. (Redish & Hammer 2009)
- (NSF #0919816) Worked closely with biologists to create a Biology Education Research Group (BERG) at Maryland and to study and reform a course in organismal biology to use more physics and to include group-learning active-engagement activities.

These experiences and the research environment of the Maryland PERG/BERG (described in detail in the mentoring document) provide the intellectual basis and capabilities for carrying out this project.

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[4] For an extensive list of papers on this theoretical framework, see *http://www.physics.umd.edu/perg/tools/ResourcesReferences.pdf*

The project will bring together a strong interdisciplinary team to create a set of modular biologically oriented and motivated T&SM materials for introductory physics.

In this project, we focus on student instruction in the concepts of energy, entropy, and statistical models in the context of an introductory physics class for biologists. The project will create a set of materials on the topics of energy, entropy, and the statistical underpinnings of the ideas (including diffusion) in the contexts of chemistry and biology. We will carry out a series of tasks involving basic research, curriculum development, and evaluation.

We bring together education researchers who are also disciplinary experts in physics, chemistry, and biology as co-PIs. To this group we have added a powerful cadre of consulting experts who have agreed to interact with us and provide us with advice and expertise.

Project staff and consultants

The project team consists of three groups: the Development Team at the University of Maryland, the Collaborating Experts at the University of Colorado, the University of New Hampshire, and Swarthmore College, and the Consulting Group.

Development Team:

University of Maryland:
Edward F. Redish (PI, physics education)
a postdoctoral research associate and a graduate student (to be appointed)

Collaborating Experts and co-PIs

University of Colorado: Michael Klymkowski (biology)
University of New Hampshire: Chris Bauer (chemistry education)
Swarthmore College: Catherine Crouch (physics)

Consultants

Duke University: Steve Vogel (biology)
University of Maryland: Todd Cooke (biology) and Michael Fisher (physics, chemistry, and biophysics)
University of Maine: John Thompson (physics)
University of New Hampshire: Jessica Bolker (biology) and Dawn Meredith (physics)
Virginia Tech: Royce Zia (statistical physics)

This is a distinguished and appropriate group of interdisciplinary collaborators. Redish is a physics education researcher with a long track record of successful NSF projects. He is an NSF Director's Distinguished Teaching Scholar and an AAPT Millikan Award winner. Klymkowsky is a leading biology education researcher and the developer of a Biology Concept Evaluation that focuses on statistical issues. (Garvin-doxas & Klymkowsky 2008) Bauer is a leading chemistry education researcher is a member of the POGIL[5] steering committee and has collaborated on interdisciplinary activities with engineers. (NSF #9653007) Crouch has been active in physics education research and in the development of physics for the life sciences, including co-organizing an NSF-sponsored workshop on "Reforming Introductory Physics for the Life Sciences". (NSF #0965156)(Crouch et al. 2010)

[5] Process-Oriented Guided Inquiry Learning project of the American Chemical Society.

The consultants collect of group of significant relevant experts. Bolker and Meredith are a biologist and a physicist who have worked together as PIs of an NSF project to build a physics course for biologists. (NSF #0737458) Todd Cooke is a biologist who has worked extensively on educational issues, is the head of the University of Maryland's Biology Education Group, and has worked with the PI on a CCLI project to reform a course in biology. (NSF #0919816) Vogel is a national leader in biomechanics and author of many books on the subject. (Vogel 2003) Fisher and Zia and world-class statistical physicists who have both worked on issues in biology. They are both deep thinkers on questions on the fundamentals of statistical mechanics and non-equilibrium thermodynamics. Thompson is an active researcher with a good track record studying student understanding of thermal and statistical physics. (Smith et al. 2009) (Smith et al. 2010) All of the consultants have agreed to serve.

Most of the development work of the project will be carried out at the University of Maryland by the PI, the project postdoctoral associate, and the project graduate student.

The Collaborating Experts roles will include:

- Providing disciplinary expertise and information on the diverse educational research literatures.
- They will be the negotiating team to agree upon the basic concepts, critical content, and common representation that will structure our approach to a Common T&SM.
- They will meet regularly (bi-monthly) with the development team via videoconference.
- They will meet in person with the development team annually.
- They will review materials and find reviewers in their disciplines at their universities.
- They will serve as contacts for faculty at their universities willing to beta test our materials.

The Consultants will be available for discussions and clarifications of particular issues as needed.

The project will develop these materials in a strongly interdisciplinary context

The critical element in all the elements of the project is significant and open conversations among experts in the three disciplines including,

- an agreement among disciplinary specialist on what is the essential content, what skills, competencies and knowledge are necessary to understand that content;

- an understanding of what students bring to their physics, chemistry, and biology classrooms, both content and skills and attitudes and epistemological assumptions.

These will be accomplished through a variety of activities.

1. Create an interdisciplinary literature review
2. Negotiate an appropriate content among the disciplines.
3. Interview students in introductory biology, chemistry, and physics classes.
4. Develop modular materials for intro physics on T&SM including: text, homework problems ("thinking problems"), group activity problems, clicker problems, and interactive lecture demonstrations.
5. Assemble an assessment instrument covering basic concepts and attitudes based on existing instruments.

1. Create an interdisciplinary literature review –Although there is a substantial research literature on student understanding of and difficulties with T&SM (especially thermodynamics), these literatures tend to be distinct in the different disciplines. (Barke et al. 2009) (Meltzer 2004) (Christensen et al. 2009) For example, few of those who do research on student concepts of energy in physics consider chemical energy or cite the chemistry education literature.[6]

We will begin by having the project staff (a postdoc and a graduate student) carry out a literature review on what has been learned from education research in physics, biology, and chemistry on students' understanding of and difficulties with the fundamental ideas of energy, entropy, and diffusion and their relation to statistical concepts. The goal of this part of the project is to create a Resource Letter[7] that can serve as guidance for the future research both of our project and of others. This will be done during the first semester of the project.

2. Negotiate an appropriate content among the disciplines. – One of the most important challenges in creating a T&SM curriculum for introductory physics is integrating the need to be simple and develop a clear basic understanding of the concepts with meeting the practical needs of the uses of the subject in chemistry and biology.

After completion and circulation of the literature review, we will convene a two-day meeting of our team to review how each discipline teaches the concepts in their introductory courses and to explicate the traditional (and often tacit) assumptions that are made. The goal of the meeting will be to negotiate a clear understanding of the basic concepts required and to come to an agreement on the content and a common approach to thermodynamics, diffusion, and statistical mechanics. This meeting will most likely occur in January of the first project year.

3. Interview students in introductory biology, chemistry, and physics classes. – We will interview students in introductory biology, physics, and chemistry classes about their understanding of the basic concepts. Some preliminary work of this type has been done in conjunction with a previous NSF project (NSF #0919816) and shows interesting results. For example, one student in an introductory physics class offered the following comments: "What I found in [bio and chem] classes is that even though we might talk about energy, it's more of an accepted fact in the class … but we never really talked about how it really, like the energy got there in the first place, how it breaks the bond, exactly what the energy is doing….And in physics we talk about where the energy is coming from and whatnot, but we don't like tie it in to like the biology of the side, or the chemical side."

Semi-structured attitude and problem-solving interviews will be done both individually, in pairs, and in larger focus groups, since each environment provides distinct advantages. These interviews will occur during the first project year and continue at a reduced rate in subsequent years.

4. Develop modular materials for intro physics on T&SM including: text, homework problems ("thinking problems"), group activity problems, clicker problems, and interactive lecture demonstrations. – We are developing materials not for a full course but for a segment of a

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[6] David Meltzer's work is a notable exception to this rule.

[7] The *American Journal of Physics* has a section that regularly publishes annotated bibliographies on research topics. See, for examples the resource letters on Physics Education Research (McDermott & Edward F. Redish 1999) and on Problem Solving in Physics (Hsu et al. 2004).

traditional course. To make this as broadly valuable as possible, we will construct it as modular on-line materials. Since our theoretical instructional framework is the resource model – a dynamic knowledge-in-pieces constructivism (Redish 2004)(Hammer et al. 2004) – these materials will include lots of problems, activities, and multi-media links. Since it will be delivered online on the open web, it will be available for any instructor to use as supplementary materials.

Once agreement has been reached on the approaches and topics in our interdisciplinary negotiation, we will lay out specific materials for development. These will be drafted by the Maryland development team. The materials will go through a number of refining, validation, and vetting steps. The Collaborating Experts will review the materials and make suggestions for editing. After revision, the Maryland team will recruit students to read and comment on the materials. This will lead to another round of revisions. The materials will then be delivered in the introductory physics test class at Maryland. Student comments on the text materials will be collected and students carrying out interactive activities will be videotaped and their responses analyzed. A revision will occur after that analysis. After that revision, the materials will be offered to faculty at the institutions of the Collaborating Experts and the HHMI project team for beta testing. We will begin developing materials immediately after the first negotiation meeting is complete.

After each module has gone through a final revision is will be posted on the group website for dissemination.

Some of our materials will rely on existing simulations (e.g., PhET tools) but some new simulations will be created as needed.

Example: An ILD on emergence

An interactive lecture demonstration created as a test case will give an idea of what some of these activities might look like. This was done in an algebra-based physics class with ~200 students in which the students all possessed (and were used to using) clickers – remote access devices that allowed them to communicate their answer to be collected and a distribution of results displayed to the class.

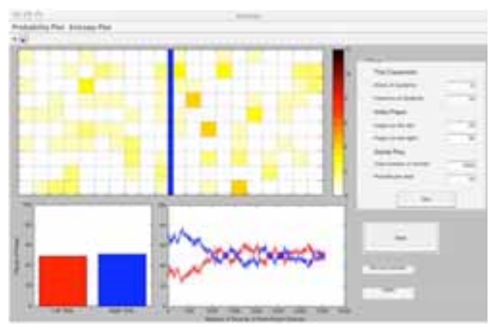

Fig. 1: A simulation of a classroom model of heat transfer using a "rock-paper-scissors" algorithm.

One of the issues students have difficulties with in T&SM is the idea that randomness can lead to emergent directed behavior. (Chi 2005) One such example is the random flow of energy between a cold body and a hotter body in contact with it leads to both coming to a common temperature.

To illustrate this for the students in an active participatory way, we divided the lecture hall in two using yellow "caution" tape so that there were approximately an equal number of students on each side of the tape.[8] A number of file cards equal to about half the number of students with the

[8] Of course this is not a necessary condition. Heat flows just as readily from a small hot object to a large cold one as it does between objects of equal size. But beginning with equal sizes allows students to focus on the single issue of emergent flow without having to disentangle two conceptually difficult issues at the same time.

words “I’m hot” were distributed , with about ¼ of the cards on one side of the line, ¾ on the other side. The students then clicked “1” if they had a card and were on the right and “2” if they had a card and were on the left. The then all played “rock-paper-scissors” with their neighbors, rotating which neighbor they played with in a clockwise circle. If they had a card and lost, they gave it up. After a dozen rounds of this they clicked again. The most probable result was that the numbers became slightly more equal. Another dozen rounds were carried out and another set of clicks. We then switched to a simulation which represented the class and allowed thousands of games of rock-paper-scissors to be played in a few seconds. The result was shown (and a sample display after 3500 rounds is shown in the Figure 1 at the right).

The simulation was written in Matlab and has many features. It permits the exploration of fluctuations as a function of size and can display plots of the probability that a particular configuration would be found from random placement of the cards on both sides.

The students enjoyed the activity, but we did not have the funding or the resources to test, develop and evaluate the results of using the simulation. We expect to develop and test this and other such activities more extensively as part of this project.

Although the specific modules and how they are “spun” will be decided by negotiation among the interdisciplinary team of experts, there will certainly be extended modules on the following topics:

- Understanding Chemical Energy in Physical Terms
- Understanding Temperature
- The First Law of Thermodynamics
- The Second Law of Thermodynamics
- Diffusion and Diffusion Related Phenomena.

5. Assemble an assessment instrument covering basic concepts and attitudes based on existing instruments. – Finally, the project will develop an assessment instrument for use in pre-post testing. The instrument will be based on our experience with conceptual and attitude assessment tools including: the Biology Concept Inventory (Klymkowsky) and the Maryland Physics/Biology Expectations Surveys (Redish), as well as onsurveys developed by others (for example, Heat and Temperature surveys by Yeo & Zadnik and Thornton & Sokoloff, an physics energy survey by Singh, and the Chemical Concept Inventory from the JCE).

The Collaborating Experts will select the initial survey items and the survey will be pre-post tested in a variety of physics, chemistry, and biology courses at the universities involved. It will be validated by conversations with experts, by interviews with students, and through statistical analysis (though, since this is not intended as a survey that identifies distinct and independent variables, strong statistical testing is not appropriate).

The project materials and results will be broadly disseminated.

The deliverables for the project will include not just instructional materials but also new explications and understandings of interdisciplinary barriers and relationships, as well as tools for future research. The specific deliverables and their modes of dissemination are as follows.

(1) A Resource Letter summarizing current educational research on introductory thermodynamics and statistical mechanics in physics, chemistry, and biology.

This will be prepared in the format of American Journal of Physics resource letters and submitted there for publication. We will explore the possibility of simultaneous distribution in the biology and chemistry education literatures.

(2) Course materials including text, problems, and interactive lecture demonstrations.

These will be distributed first through the University of Maryland PERG's webpages where we have considerable experience delivering resources.[9] When the project is complete, we will seek to have them distributed online through the National Digital Library for Physics at comPADRE.[10]

(3) A survey for thermodynamics and statistical concepts.

The survey created for T&SM concepts and attitudes will be written up and published so that it can be broadly used.

(4) Published peer-reviewed education research papers.

Since some of the work for this project is education research involving the attitudes and understandings of students in physics, chemistry, and biology, we foresee having a number of interested results that would lead to education research papers to be submitted to such peer-reviews journals such as the American Journal of Physics, Physical Review Special Topics is PER, the Journal of Research in Science Teaching, the Journal of the Learning Sciences, the International Journal of Science Education, and Cognition and Instruction.

(5) Published peer-reviewed science education papers (research-based but oriented for instructors)

Some of the results for this project will be insights into teaching and learning and new materials and instructional tools. While the materials will be distributed online, we will also prepare papers oriented for instructors for publication in such journals as The Physics Teacher, the Journal of Chemical Education, and Life Sciences Education.

(6) Talks and presentations at conferences and universities.

An important part of our dissemination will be talking about the work and "spreading the word". The PI (Redish) has been in high demand for presenting his work at invited talks at conferences and a colloquia and seminars at colleges and universities. In the past 5 years he has given invited talks at 11 conferences and 24 invited colloquia and seminars. This includes significant interdisciplinary activity as it includes talks to the American Association of Physicists of Medicine, the Biennial Conference in Chemistry Education, and talks to Chemistry and Science Education departments.

A comment on two notable absences

We would like to remark on two elements missing from this proposal that one might typically expect to find in a proposal with an emphasis on curriculum development: (1) a strong literature review, and (2) a detailed list of the items to be developed.

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[9] See http://www.physics.umd.edu/perg/ and the list of "Teaching Resources".

[10] http://www.compadre.org/. This project is already beginning to import our "Thinking Problems in Physics" into this resource and Bruce Mason, the editor of comPADRE, has expressed an interest in distributing our materials.

The absence of these elements arise from the interdisciplinary character of the proposal. First, while each of the PIs could create a literature review for their individual fields (physics, chemistry, biology) about what is know about student difficulties with topics in T&SM, the first task of the proposal involves a development of a major coordinated interdisciplinary literature review and we felt it inappropriate to pre-empt the results of that review here. Second, since the second task of the proposal involves negotiating common ground among the three disciplines, identifying specific elements for development would be premature.

Summary and Intellectual Merit

The topics of thermodynamics and statistical mechanics are critical for the understanding of modern biology and for the reform that is currently taking place in biology education. In traditional introductory physics classes, even ones specifically directed at biology students, these topics are typically given short shrift, with chemical energy ignored and entropy treated through heat engines, an approach appropriate for mechanical engineers but not for biologists. Furthermore, the approaches to the subject taken in introductory chemistry and biology are dramatically different from what is done in physics. Different tacit assumptions are made and different thermodynamic functions are emphasized in introductory chemistry and biology than are typically treated in physics.

In this project we propose to bring together what is known about student difficulties on these subjects from research in physics, chemistry, and biology education, and to negotiate a common approach to thermodynamics with a team of educational specialists in the three disciplines. We will then create a common literature survey and a set of modules for introductory physics. These modules will include text, homework problems, and in-class activities. They will be developed in conjunction with education research on student attitudes and understandings of thermodynamics and statistical issues in physics, chemistry, and biology classes. The materials will be evaluated by careful usability testing and the development of a pre-post survey.

Physics tends to deal with highly oversimplified examples in order to permit students a complete understanding in a limited set of circumstances that can be imbedded in more complex phenomena and used as a grounding for developing an understanding of those phenomena. Biology necessarily deals with complex systems, but energy conservation and the second law of thermodynamics are fundamental constraints to those systems. Rethinking how to do thermal and statistical concepts in physics could have powerful implications for how physics and biology instruction are related.

Broader Impact

Although the topics reformed by this project only correspond to about 10% of current introductory physics classes, they are crucial for the inclusion of authentic biological examples into introductory physics. The results of the project could be transformative on the curriculum for training biologists and, not incidentally, pre-medical and pre-health care students.