Creating a Common Thermodynamics (NSF-TUES DUE 11-22818)

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The context: Developing an interdisciplinary physics course for biologists

At the University of Maryland, we have been rethinking and reconstructing the introductory physics course for life science majors, to help students build cross-disciplinary coherence connecting physics, biology, and chemistry. The *NEXUS/Physics* course [1] has been developed as a result of extensive interdisciplinary negotiations [2].

In these conversations, we realized that **thermodynamics** and **statistical mechanics** are crucial to biology, and connect to chemistry and physics, but the three disciplines have very different ways of thinking about them.

This project, *Creating a Common Thermodynamics*, brings together education researchers who are disciplinary experts in physics, chemistry, and biology, to negotiate a thermodynamics curriculum that ties together the languages and models of all 3 disciplines.

We include the following topics (many of which are not typical for an introductory physics course):

- Thermal energy
- Heat and temperature
- Chemical bonding and chemical energy
- Random motion
- Diffusion and osmosis
- Entropy
- Enthalpy
- Gibbs free energy
- Boltzmann distribution

The discipline-based education literature is fragmented

The published research findings of each discipline-based education field are focused around different aspects of thermodynamics, with little overlap and therefore little possibility for direct comparison. We have been commissioned by the *American Journal of Physics* to write a resource letter compiling the thermodynamics literature from each discipline.

First Law of Thermodynamics

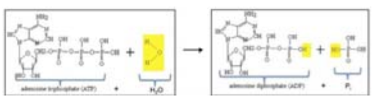
- **Biology**: the literature is extremely limited, focusing mostly on biochemistry
- **Chemistry**: focus on thermochemistry and energy in chemical reactions.
- **Physics**: coverage is engineering-focused (heat engines, etc), with very few connections to biological or chemical applications

Second Law of Thermodynamics

- **Biology**: the literature addresses osmosis and diffusion in a phenomenological (not mechanistic) way; very little on entropy explicitly
- **Chemistry**: most literature focuses on role of entropy in connecting to Gibbs free energy, enthalpy, spontaneity, and chemical equilibria
- **Physics**: focuses on the relationship of entropy to reversibility and energy; almost no mention of Gibbs free energy

Listening to our students has given us insight on creating a common thermodynamics

Case 1: Chemical Bond Energy



ATP Hydrolysis

The Scenario

An O-P bond in ATP is referred to as a "high energy phosphate bond" because: (choose all correct ans.)

Question from Galley 2004 [4]

- ☒ A. The bond is a particularly stable bond.
- ☑ **B. The bond is a relatively weak bond.**
- ☒ C. Breaking the bond releases a significant quantity of energy.
- ☑ **D. A relatively small quantity of energy is required to break the bond.**

Student Reasoning

"I put that when the bond's broken that's energy releasing. Even though I know, if I really think about it, that obviously that's not an energy-releasing mechanism. Because like, you **can't break a bond and release energy**, like you always need to put energy in, even if it's like a really small amount of energy to break a bond.

I guess I was thinking breaking this bond then **leads to these other reactions** inevitably. That result in an energy release … I don't [argue] that breaking a bond releases energy, but just like **in a larger biological context, that reaction does release energy**.

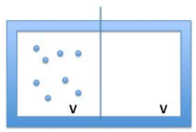
I guess that's the difference between like how **a biologist** is trained to think, in like **a larger context** and how **physicists** just focus on sort of **one little thing**." –Gregor [3]

Gregor sees value in both a "physics" model (breaking a bond requires energy) and a "biology" model (breaking the phosphate bond in ATP leads to the release of energy).

Instructional Implications

The disciplines talk about energy in different ways, but each can be productive in the appropriate context. We need to help students develop the tools to reconcile these seemingly contradictory models.

Case 2: Energy vs. Free Energy



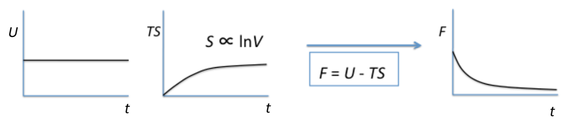
Thermally Isolated Container

When the partition separating the two halves of the box is removed and the system reaches equilibrium again, how does the new energy of the gas compare to the energy of the original system?

1. The energy of the gas becomes larger
2. The energy of the gas becomes smaller
3. The energy of the gas remains the same
4. There is not enough information

"I said the energy would decrease and I was kinda confused on this one, but **I sort of thought of energy as the ability to perform work on other objects**, and I thought well let's just say a compressed air can next to another compressed air can … normally if you shoot the air out it would, with an object right next to it would send the block flying, but if you let it kind of disperse a little bit, the air molecules kind of have more room to bounce around so the air pressure decreases, and when you put it next to the block, the block isn't going to go as fast." –Sameer

Sameer, by reasoning about the system's capacity to do work, makes an argument that would be correct if describing what happens to the *free* energy upon expansion.



To develop a good conceptual understanding of *free energy* (which is rarely achieved in biology and chemistry courses), we can draw on students' productive conceptual resources about *energy*, to distinguish between energy (which is conserved) and free energy (which is "used up").

Publications and Presentations

- B.D. Geller, A. Daane, & V. Sawtelle, Reconciling "energy" and "free energy", presented at AAPT Winter Meeting 2013
- C. Turpen, B.W. Dreyfus, & V. Sawtelle, Physics energy is not chemistry energy is not biology energy, presented at AAPT Winter Meeting 2013
- B.W. Dreyfus & B.D. Geller, The challenge: Integrating different approaches to physics from different disciplines, UMD Bioscience Day Teachers' Symposium
- V. Sawtelle, Progress through paradox: Reconciling interdisciplinary perspectives, presented at Dickinson College Physics Colloquium
- E.F. Redish, Rethinking physics for biologists, presented at Georgetown University and University of Miami
- B.W. Dreyfus, V. Sawtelle, C. Turpen, & E.F. Redish, A vision of interdisciplinary education: Students' reasoning about "high-energy bonds" and ATP, submitted to *CBE-Life Sciences Education*.
- B.W. Dreyfus, B.D. Geller, V. Sawtelle, J. Svoboda, C. Turpen, & E. F. Redish, Students' interdisciplinary reasoning about "high-energy bonds" and ATP, presented at SABER, AAPT, and PERC, summer 2012
- E.F. Redish, Teaching physics to biologists: Can we do (some) stat mech in Physics 1?, UMD Statistical Physics Seminar

All of these are available from links on the Papers and Presentations page at the NEXUS/Physics website [1].

Project Personnel

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Mike Klymkowsky, Biology, University of Colorado
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References

1. http://tinyurl.com/nexusumcp
2. E.F. Redish & T.J. Cooke, Learning each other's ropes: Negotiating interdisciplinary authenticity, accepted to *CBE-Life Sciences Education*.
3. B.W. Dreyfus, B. D. Geller, V. Sawtelle, J. Svoboda, C. Turpen, & E. F. Redish, Students' interdisciplinary reasoning about "high-energy bonds" and ATP, accepted to *Proceedings of the 2012 Physics Education Research Conference*.
4. W.C. Galley, Exothermic bond breaking: a persistent misconception, *J. Chem. Ed.*, **81**, 523 (2004)

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