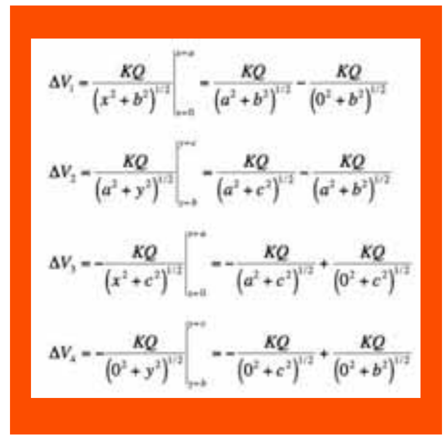
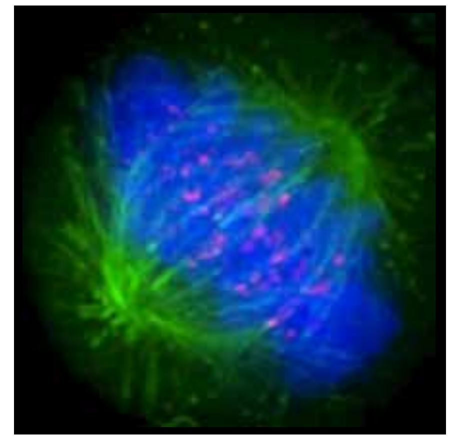


NEXUS/Physics: Repurposing physics for the life sciences. An IPLS Case Study

Edward F. Redish
University of Maryland

NEXUS
NATIONAL EXPERIMENT
in Undergraduate Science Education

HHMI

In the summer of 2010, HHMI offered four universities the opportunity to:

Develop prototype materials for biologists and pre-meds in

- *Chemistry (Purdue)*
- *Math (UMBC)*
- *Physics (UMCP)*
- *Capstone case study course (U of Miami)*

HHMI

nexus
NATIONAL EXPERIMENT
in Undergraduate Science Education

that would

- take an ***interdisciplinary perspective***
- be ***competency based***

+ The NEXUS/Physics timeline

- 2010-11
  - Extensive discussion and negotiation among stakeholders.
- 2011-12
  - Create on-line reading materials, problems
  - Teach a small test class (N ~ 20)
  - Interview and observe students
- 2012-13
  - Refine and expand materials
  - Team teach two small flipped classes (N ~ 20)
  - Create new labs
  - Interview and observe students
- 2013-14
  - Becomes the required course for all bio majors.
  - Fall: Deliver in two large lectures (N ~ 120) with instructors from the design team.
  - Spring: Teach both section in 4 large lectures with 4 new instructions.

The NEXUS Development Team (UMCP)

- **Physicists**
  - Joe Redish
  - Wolfgang Losert**
  - Chandra Turpen
  - Vashti Sawtelle
  - Ben Dreyfus*
  - Ben Geller*
  - Kimberly Moore*
  - John Gianini* **
  - Arnaldo Vaz (Br.)
- **Biologists**
  - Todd Cooke
  - Karen Carleton
  - Joelle Presson
  - Kaci Thompson
- **Education (Bio)**
  - Julia Svoboda
  - Gili Marbach-Ad
  - Kristi Hall-Berk*

** Graduate student*
*** Biophysicist*

+ Additional UMCP personnel:

- **Physicists**
  - **Tom Antonsen**
  - **David Buehrle**
  - Michael Fisher
  - Alex Morozov**
  - Kirstin Nordstrom**
  - **Alan Peel**
  - Peter Shawhan
  - **Arpita Upadhyaya****

*** Biophysicist*

Currently teaching the class in large sections

- **Biologists**
  - Marco Colombini**
  - Jeff Jensen
  - Richard Payne
  - Patty Shields
  - Sergei Sukharev**
- **Chemists**
  - Jason Kahn
  - Lee Friedman
  - Bonnie Dixon
- **Education**
  - Andy Elby (Phys)
  - Dan Levin (Bio)
  - Jen Richards (Chem)

Off-campus collaborators

- **Physicists**
  - Catherine Crouch* (Swarthmore)
  - Royce Zia* (Virginia Tech/Iowa State)
  - Mark Reeves (George Washington)
  - Lilly Cui & Eric Anderson (UMBC)
  - Dawn Meredith (U. New Hampshire)
  - Steve Durbin (Purdue)
- **Biologists**
  - Mike Klymkowsky* (U. Colorado)
- **Chemists**
  - Chris Bauer* (U. New Hampshire)
  - Melanie Cooper* (MSU)
- **Education**
  - Janet Coffey (Moore Foundation)
  - Jessica Watkins (Tufts University)

**NSF TUES project*

+ Other UMd NEXUS folk are here

- Todd Cooke

- Ben Geller

- Wolfgang Losert

- Kim Moore

- Vashti Sawtelle

As well as some of our collaborators and co-conspirators

- Melanie Cooper
- Catherine Crouch
- Mike Klymkowsky

What we learned about the biology/physics gap. Negotiations with stakeholders

Starting in a hard place

- It turns out there are significant cultural differences between biologists and physicists.
- Many biologists saw most of the traditional introductory physics class as useless and irrelevant to biology – and the physicists claim that "we can apply physics to biology examples" as trivial and uninteresting.
- Physicists saw a coherent structure with no room for change.

After many interesting and illuminating discussions

- We came to an understanding of what it was the biologists needed and how the disciplines perceived the world and their science differently.

+ The culture of the disciplines

- We have to do much more than change the table of contents and the prerequisites.
- From each level of students' experience with a discipline – small group, STEM classes, broader school experiences – they bring **expectations about the knowledge they are learning and what they have to do to learn it.**
- These tell them what to pay attention to in the context of activities in a science class.

Redish & Cooke, *CBE-Life Science Education* 12 (2013) 175-186

+ Biology

- Biology is *highly complex* and is often emergent, including the property of life itself.
- Most introductory biology *does not emphasize quantitative reasoning* or problem solving.
- Much of introductory biology is *descriptive* (and introduces a large vocabulary).
- Biology contains a critical *historical constraint*: natural selection can only act on pre-existing molecules, cells, and organisms for generating new solutions.
- Biologists (both professionals and students) focus on and value *real examples and structure-function relationships*.

+ Physics

- Introductory physics classes often stress *reasoning from a few fundamental (often mathematically formulated) principles.*
- Physicists often stress building a complete understanding of the *simplest possible (often abstract) examples* ("toy models") – and don't go beyond them at the introductory level.
- Physicists *quantify* their view of the physical world, *model with math*, and *think with equations*.
- Physicists concern themselves with *constraints* that hold no matter what the internal details. (conservation laws, center of mass, ...)

This has implications for how current bio students view physics (and math).

I came in with a lot of hatred towards physics in general... I never took [physics] while I was in high school, so coming in and knowing ... that I had to take two semesters of physics... I wasn’t very happy about. I'm more of a bio and chemistry person, and I just take physics for granted. I was like, oh it falls. OK sure. I think biology comes a lot more naturally to me than physics does. Because I think I can visualize the system better, having taken a lot more biology classes and chemistry classes.

I think that biology is just—it’s supposed to be tangible, perceivable, and to put that in terms of letters and variables is just very unappealing to me, because like I said, I think of it as it would happen in real life, like if you had a thick membrane and you try to put something through it, the thicker it is, obviously the slower it’s gonna go through. But if you want me to think of it as this is x and that’s D and then this is t, I can’t do it. Like, it’s just very unappealing to me. . .

+ What can physics do for biology students?

- Help develop scientific skills that may be harder to build in intro chem and bio because of the complexity of the examples.
  - Blending math with physical sense making
  - Thinking and reasoning with equations.
  - Quantifying experience
- Use “toy models” to help students create meaning for complex topics introduced in biology and chemistry classes

+ And...

- Maintain the crucial components of “thinking like a physicist” –
  - Reasoning from broadly valid principles
  - Quantification,
  - Mathematical modeling,
  - Mechanism,
  - Multiple representations
  - Coherence
  - Value of abstract thinking
  - Value of global principles
    (true, “whatever” is happening “inside”)

+

What is an appropriate role for physics to play in the curriculum of a life scientist?

In service to biology and medicine, we serve too many masters.

"...the diversity of requirements made on physics courses for life-science students is greater than for any other type of service course....Physics courses for such students vary from a course in Alaska for fish and wildlife management to a course in Boston for biologists and a course in Kenya for agriculturalists. In each case the teacher is obligated to determine why, in content terms, those students are taking physics and to design the course accordingly."

A. P. French & E. L. Jossem, "Teaching physics for related sciences and professions," Am. J. Phys. 44 (1976) 1149-1159.

A hard choice: We opted to design a course to

- Serve the core content of a bio curriculum that overlaps all bio majors and pre-meds (and could potentially serve chemists as well).
- Fit in between the intro level and upper division classes.
- Fill gaps where a physics perspective could help students with central concepts.

Changing the culture of the course

- Seek content and examples that have **authentic value** for biology students.
  - We want upper division bio faculty want to have physics a pre-requisite to their classes.
- Assume this is a **2^{nd} year** college course.
  - Biology, chemistry, and calculus are pre-requisites.
- Do **not** assume students will have later physics courses to "make things more realistic."
  - The value added by physics can't wait until later physics classes.

Interdisciplinarity: Rethinking the content

- Focus on modeling and explicating assumptions.
- Do micro and macro examples throughout assuming students know about atoms and molecules.
- Random as well as coherent motion.
- Careful treatment of basic stat mech bases for thermo.
- More treatment of fluids.

What we learned from research. Developmental growing pains

Teaching the trial class under the microscope

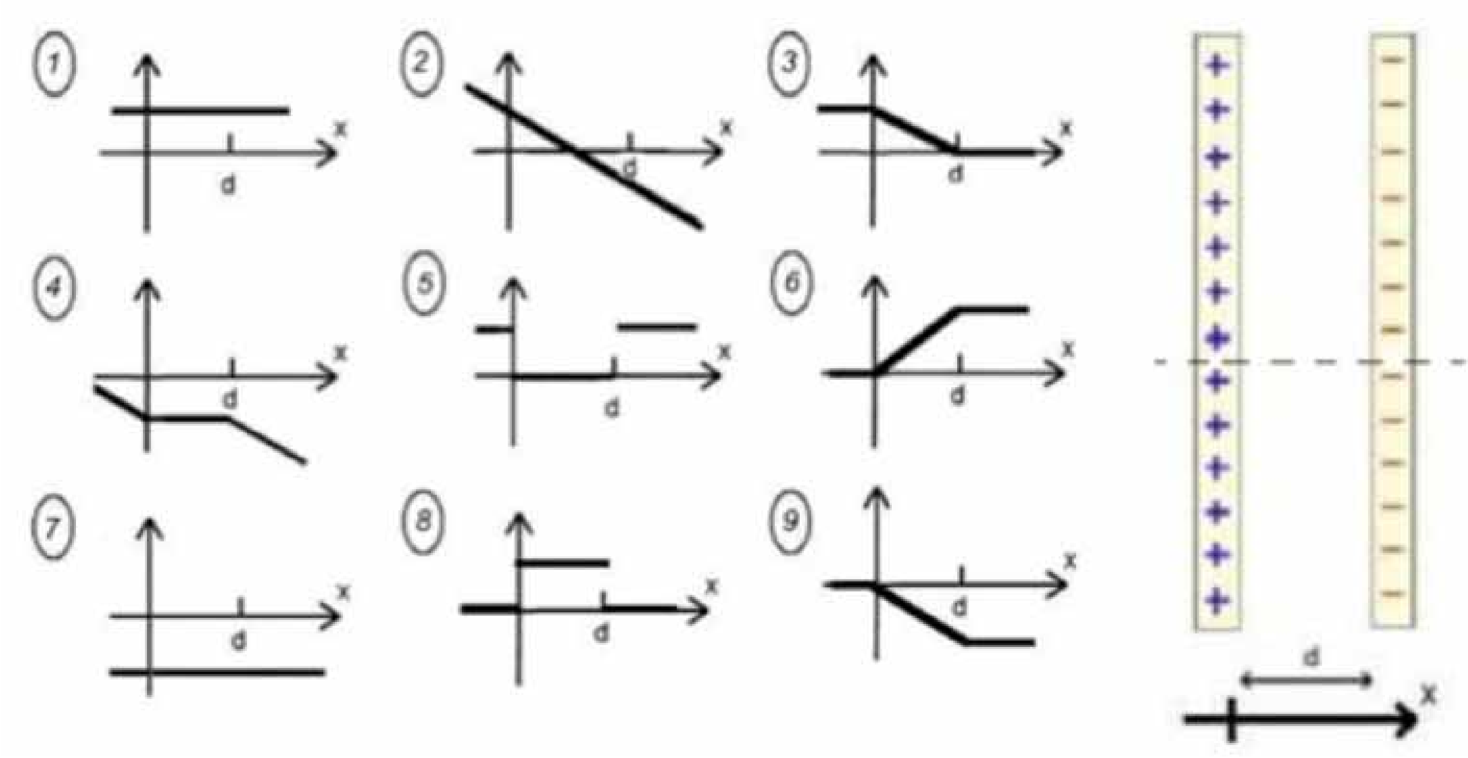
- We taught the first two years of NEXUS/Physics in small (N~20) flipped classes with lots of interaction.
- We often asked students what they had learned in bio and chem classes.
- We videotaped all classes and interviewed many students throughout the class.

We learned some lessons (some painful)

- Bio students were *much* more interested and willing to engage with the physics when they saw its relevance for their other classes.
- Bio students appear *much* more capable when discussing issues in bio and chem (especially when we stopped evaluating them primarily on mathematical fluency).
- We learned of *many* inconsistencies, sloppy presentations, and unstated (often unreasonable) assumptions in our traditional physics approaches to teaching.

+ An example

- *If two uniform sheets of equal and opposite charge can be treated as if they were infinitely large, which of the following graphs might serve as a graph of the electrostatic potential as a function of the coordinate x along the dotted line?*



About half the students gave a “correct” answer (3 or 9), but...

- Two students objected.
  - One argued any curve should have “spikes” as you passed through the plate, since you would surely get close to an ion.
  - A second argued that the potential curve had to be zero along the center of the plates since for whatever charge you found contributing to the potential on one plate, there would be a matching and opposite one an equal distance away on the second plate.

+ My example was undermining core epistemological lessons I was trying to teach.

- *Physics is about something real. Whenever you think about a physics example, start from a mental image of a physical situation and refer everything back to it.*
- *In physics we often use simple models to illuminate core ideas. Be explicit about your assumptions – what you are paying attention to and what you are ignoring.*

The more we listened the more we learned

- Students took on a more integral role in establishing the class as a learning community.
- Students provided the bio and chem expertise needed – faculty didn't need to know it!
- We learned new perspectives on what we were teaching – both on traditional and new material.

+

NEXUS/Physics:
A vision of a new curricular approach.

How this works: Examples

- *1. Chemical bonding*:
  Making a bridge through interdisciplinary reconciliation.
- *2. Contrasting coherent & random motion*:
  Creating laboratories that biology students see as having authentic value.

Example 1: Chemical bonding

- In intro chem and bio classes, students learn about chemical reactions and the critical role of energy made available by molecular rearrangements.

- But students learn heuristics by rote that can feel contradictory to them and that they often don't know how to reconcile.

  1. *It takes energy to break a chemical bond.*
  2. *Breaking the bond in ATP is the "energy currency" providing energy for cellular metabolism.*

W. C. Galley, J. Chem. Ed., 81:4 (2004) 523-525.

M. Cooper and M. Klymkowsky, *CBE Life Sci Educ* 12:2 (2013) 306-312

From student responses we learned a useful perspective on multi-disciplinary reconciliation.

I put that when the bond's broken it releases energy. Even though I know... that obviously that's not an energy-releasing mechanism. ...you always need to put energy in, even if it's like a really small amount of energy to break a bond. Yeah, but like. 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....I answered that it releases energy, but it releases energy because when an interaction with other molecules, like water...and then it creates like an inorganic phosphate molecule that has a lot of resonance. And is much more stable than the original ATP molecule. So like, in the end releases a lot of energy, but it does require like a really small input of energy to break

B. Dreyfus, V. Sawtelle, C. Turpen, J. Gouvea, & E. Redish, "A Vision of Interdisciplinary Education: Students' reasoning about 'high-energy bonds' andATP," submitted for publication(2014).

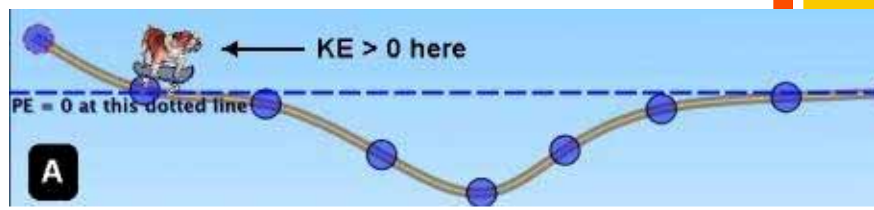
+ Approach

1. Introduce atoms and molecules early in the class, with quantification and estimation to build a sense of scale.
2. Introduce concept of “binding energy” in standard macroscopic energy contexts (skateboarder in a dip)
3. Create a chain of tasks in atomic and macroscopic contexts for learning to read and interpret potential energy graphs.
4. Refine tasks by observation of student responses and negotiation among physicists, biologists, and chemists.
5. Be explicit about the value of different disciplinary perspectives..

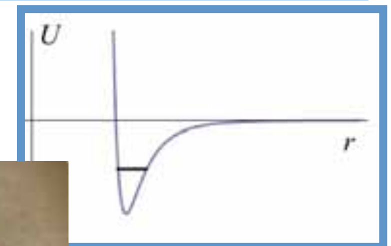
B. Dreyfus, B. Geller, J. Gouvea, V. Sawtelle, C. Turpen, & E. Redish, “Chemical energy in an introductory physics course for the life sciences”, Am. J. Phys., in press (2014).

How physics can help

- Build a coherent story using toy models
  - Bulldog on a skateboard

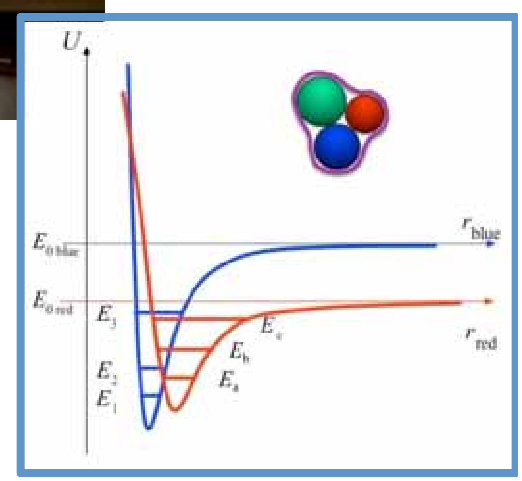


  - Atomic interactions and binding



  - Reactions in which bonds are first broken and then stronger ones formed (the Gauss gun)

  - Connection between PE diagram and reaction energy diagrams.

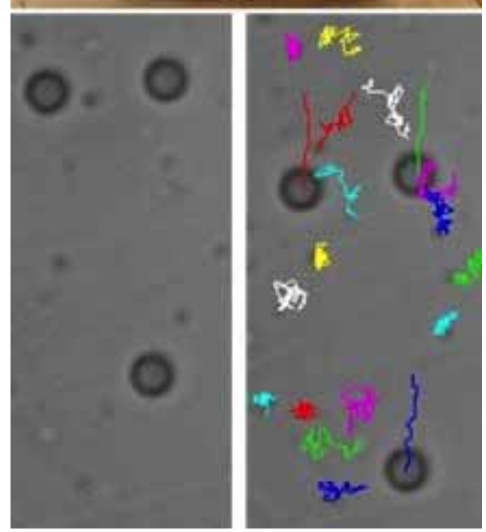


Example 2: Thermal vs. coherent motion

- At a subcellular scale, many phenomena only make sense when considered as arising emergently from coupling to random thermal motion.
- Coupling to thermal motion underlies fundamental concepts such as **diffusion**, **entropy**, **free energy**, and the **Boltzmann factor**.
- These are often introduced heuristically without a solid basis in an understanding of mechanism. This can lead to confusion, misinterpretations, and misconceptions

K. Garvin-Doxas and M. Klymkowsky, *CBE Life Sci Educ* 7:2 (2008) 227-233

Observing random motion in the lab



+ Random vs coherent motion

- In the rest of the class, students have learned that
  - For random motion $\left\langle (\Delta r)^2 \right\rangle = 6Dt$
  - For coherent motion $\left\langle (\Delta r)^2 \right\rangle = (v_0 t)^2$
- They take data in physical situations (tipped microscope stage with different sized microspheres) and do log-log plots of the data, identifying the slope to determine the type of motion.
- They apply this insight to the motion of tubules within an onion skin cell to determine whether the cell is alive or dead.

Inside an onion skin cell

Determine whether the cell is alive or dead from looking at the motion of its interior componenents.

How does it work?

Shifting Student Attitudes

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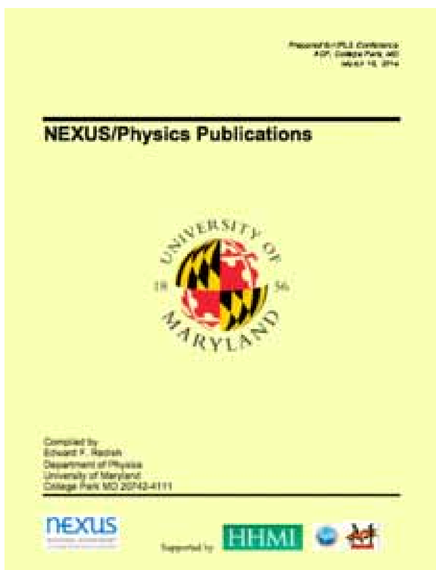
Some student comments

- “At first I was expecting the class to be like the biology calculus class that did not focus on any biology. But, as the semester progressed I saw that the class was actually directed towards helping students to understand biological ideas using physics. “
- …[biology professors] have to go over so much stuff that they don't really take the time to go over why things happen. And I'm a very why kind of person I want to understand why does this happen?...And you know [diffusion] was never explained to me very well, and then when I take this [physics] class and understand oh well this is why molecules interact the way they do.
- “I now see that physics really is everywhere, and the principles of physics are used to govern how organisms are built and how they function.”
- [In lab] “I learned how to approach a problem by designing our own experiments and interpreting data our own way. These labs taught me how to think for myself.”
- I find [in the labs] that I am paying attention to every step and can explain the experiment from beginning to end, with an understanding of why things happened and how the results change when a variable is manipulated.

For more information and to see current materials

http://nexusphysics.umd.edu/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