



The NEXUS/Physics class:

What does physics have to offer biology and pre-med students?

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Teaching physics for biology students: The changing landscape

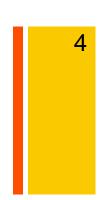
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+ Teaching physics for biologist is one of the main things physics departments do

- 3
- At the University of Maryland we now teach almost as many students in algebra based physics (mostly biologists) as we do in calculus based physics (mostly engineers)
 - Sections of algebra-based-physics in 2012-13: 77
 - Sections of calculus-based-physics in 2012-13: 82

What do we teach our biologists?



- The typical algebra-based physics class taken by biologists is calculus-based physics "cut down" by reducing the level of math required.
- It looks very much like a remedial course for a mechanical engineer who is taking a catch-up class in math at the same time.
- Often it was seen as a "weed-out" course for pre-meds.

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The new biology

- Biology has been changing fast.
- New probes, methods, and models are enabling a dramatically increased understanding of the mechanisms of life at all scales from the molecular to the ecological.
- Quantitative measurements and modeling are emerging as key tools for discovery

What do the biologists want their students to learn?

 Leading research biologists and medical professionals have increasingly been

calling for a major reform of undergraduate

instruction.



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In the summer of 2010, HHMI put forth a challenge to four universities:

7

Create a proposal to develop prototype materials for biologists and pre-meds with a focus on scientific competency building and interdisciplinary links in

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

+ Goals of NEXUS: A national demonstration project

- Create prototype materials
 - An inventory of instructional modules that can be shared nationally as open source materials.



Interdisciplinary

- Coordinate instruction in biology, chemistry, physics, and math.
- Competency based
 - Teach generalized scientific skills in a way that supports instruction in the other disciplines.

+ Competencies (SFFP)

- E1 Apply quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world.
- E2 Demonstrate understanding of the process of scientific inquiry, and explain how scientific knowledge is discovered and validated.
- E3 Demonstrate knowledge of basic physical principles and their applications to the understanding of living systems.
- <u>E4</u> Demonstrate knowledge of basic principles of chemistry and some of their applications to the understanding of living systems.
- <u>E5</u> Demonstrate knowledge of how biomolecules contribute to the structure and function of cells.

Parsing competencies: Example -- Multi-representational competence

- What should students be able to do?
 - Create a graph from a word description of a physical phenomenon for many different physical variables.
 - Distinguish what a graph tells you about a phenomenon and what is doesn't. (v example)
 - Create a graph of the rate of change of a quantity from a graph of the quantity.
 - Translate information from one representation to another and quickly identify inconsistencies.



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2/17/13 AAAS Boston 11

The NEXUS Development Team (UMCP)

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- Melanie Cooper* (Clemson)

Education

- Janet Coffey (Moore Foundation)
- Jessica Watkins (Tufts University)



+ Our approach: Deconstruction!

- Take nothing for granted!
- Negotiate everything through extensive interactions with biologists!
- Identify and challenge our hidden assumptions!
- Create a course that reflects the physics that's important to modern biology!
- Create a course that reflects modern understandings of learning and pedagogy!

⁺ The questions

- What starting assumptions should we make about our students?
- What content should we teach?
- What competencies should we focus on?
- What are the barriers to constructing an effective course?
- What do we need to do to create effective inter- or trans-disciplinary instruction?

+ Changing the culture of the course

- Seek content and examples that have authentic value for biology students.
 - We want upper division bio to make physics a pre-requisite.
- Do not assume this is a first college science course.
 - Biology, chemistry, and calculus are pre-requisites.
- Do not assume students will have later physics courses that will "make things more realistic."
 - The value added by physics can't wait until later classes.
- Choose different content from the traditional class.
 - Atomic and molecular examples
 - Chemical energy
 - Motion in fluids
 - Random motion and its implications

The pedagogy

- The class is being structured to take advantage of what has been learned about pedagogy from DBER.
- Enabling active learning and "flipping"
 - Wiki-book with short on-line readings.
 - Clicker questions
 - "Thinking problems" for HW emphasizing sense making and coherence
 - Groupwork activities
- An open on-line environment is envisioned that permits organic evolution and growth.

Rethinking Physics for Biologists

2/17/13 AAAS Boston 19

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.



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And...

 We continue to negotiate these changes through extensive discussions between biologists and physicists (and chemists)

But...

We (try to) maintain the crucial components of "thinking like a physicist" – quantification, mathematical modeling, mechanism, multiple representations and coherence (among others).

The culture of the disciplines

- There is much more than changing 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 (framing) that tell them what to pay attention to in the context of activities in a science class.
- Their framing of the activity affects how they interpret the task and what they do.

+ Physics

- Introductory physics classes often stress reasoning from a few fundamental (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 concerns themselves with constraints that hold no matter what the internal details. (conservation laws, center of mass, ...)

+ Biology

- Biology is complex and is often emergent, including the property of life itself.
- Most introductory biology does not emphasize quantitative reasoning and 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.

27

What can physics do for biology students?

- Put "legs under" complex topics introduced in bio and chem through the use of "toy models."
 - Fluids
 - Chemical reactions
 - Thermodynamics and statistical physics
- Help develop scientific skills that are hard 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

Some solutions:
New content, new approaches

2/17/13 AAAS Boston 28

+ The Debates: Inclined Plane/Projectiles

- Pro: Our physicists saw these topics as crucial for learning how to use vectors, a general and powerful tool.
- Con: Our biologists saw the inclined plane and projectiles as typical physics hyper-simplification with little or no value.
- The resolution: We replaced these topics with examples from biological motion and moved electric forces to the first term to provide serious vector examples.

+ The Debates: Force / Energy

- Pro: Our biologists saw the emphasis on forces as superfluous and requested we do everything in terms of energy.
- Con: Our physicists considered forces as "privileged" – essential to establishing the fundamental concepts of motion.
- The resolution: We reframed the treatment of forces as "The Newtonian Framework" analogous to "The Evolutionary Framework" in biology; something that sets the language and ontology what you look for. This also clarified what was a model of a specific system and what was a part of a more general framework.

Revising the content

Expand

- Atomic and molecular models of matter
- Energy, including chemical energy
- Fluids, including fluids in motion and solutions
- Dissipative forces (drag & viscosity)
- Diffusion and gradient driven flows
- Kinetic theory, implications of random motion, statistical picture of thermodynamics

Reduce substantially or eliminate

- Projectile motion
- Universal gravitation
- Inclined planes, mechanical advantage
- Linear momentum
- Rotational motion
- Torque, statics, and angular momentum
- Magnetism
- Relativity

How this works: Examples

- Negotiating authenticity: How big is a worm?
- Finding another path: Hydrogen bonding
- Contrasting coherent & random motion:
 Laboratories
- Chemical bonding:
 Building competencies
 in an interdisciplinary context.

The earthworm absorbs oxygen directly through its skin. The worm does have a good circulatory system (with multiple small hearts) that brings the oxygen to all the cells. But the cells are distributed through the worm's volume and the oxygen only gets to come in through the skin — so the surface to volume ratio plays an important role. Let's see how this works. Here are the worm's parameters.

A typical specimen of the common earthworm (Lumbricus terrestris) has the following average dimensions:

- Mass 3.7 g
- Length 12 cm
- Width 0.64 cm

The skin of the worm can absorb oxygen at a rate of A = 0.24 µmole (µmole = 10^{-6} moles) per square cm per hour.

The body of the worm needs to use approximately $B = 0.98 \mu mole$ ($\mu mole = 10^{-6}$ moles) of oxygen per gram of worm per hour.



SpeedBump by Dave Coverty: with permission

A. It is reasonable to model the shape of the earthworm as a solid cylinder. Using the dimensions of a typical earthworm above, calculate its surface area (ignore the surface areas of the blunt ends in all calculations), volume, and density.

B. If the worm is much longer than it is wide (L>> R) is it OK to ignore the end caps of the cylinder in calculating the surface area? How does the surface area and volume of the worm depend on the length of the worm, L, and the radius of the worm, R?

C. For an arbitrary worm of length L, radius R, and density d, write an equation (using the symbols A and or B rather than the numbers) that expresses the number of moles of oxygen the worm absorbs per hour and the number of moles the worm uses per hour. What is the condition that the worm takes in oxygen at a rate fast enough to survive? Does this simple model predict that the typical worm described above absorbs sufficient oxygen to survive?

D.1. Consider the effect of changing the various size parameters of a worm. First consider a worm of length 12 cm that grows by keeping its length the same but increasing its radius. Use a spreadsheet to plot the total oxygen absorbed through the skin of the worm and the total oxygen used by the worm as a function of its length from a radius of 0 cm (not really reasonable) up to a radius of 1 cm. Do the two curves cross? Explain what the crossing means and what its implications are.

D.2. Now consider a worm width 0.64 cm the grows by keeping its width the same but increasing its length. Use a spreadsheet to plot the total oxygen absorbed through the skin of the worm and the total oxygen used by the worm as a function of its length from a length of 0 cm (not really reasonable) up to a length of 50 cm. Do the two curves cross? Explain what the crossing means and what its implications are.

D.3. Write (in symbols) an equation that represents the crossover condition — that the oxygen taken in per hour exactly equals the oxygen used per hour. Cancel common factors. Discuss how this equation tells you about what you learned about worm growth by doing the two graphs.

E. Our analysis in D was a modeling analysis. An organism like an earthworm might grow in two ways: by just getting longer or isometrically -- by scaling up all its dimensions. What can you say about the growth of an earthworm by these two methods as a result of your analysis in part D? Does a worm have a maximum size? If so, in what sense? If so, find it.

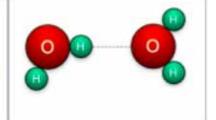
F. In typical analyses of evolution and phylogenetic histories, earthworm-like organisms are the ancestors of much larger organisms than the limit here permits. Discuss what sort of variations in the structure of an earthworm might lead to an organism that solves the problem of growing isometrically larger than the limit provided by this simple model.

Seeking authenticity

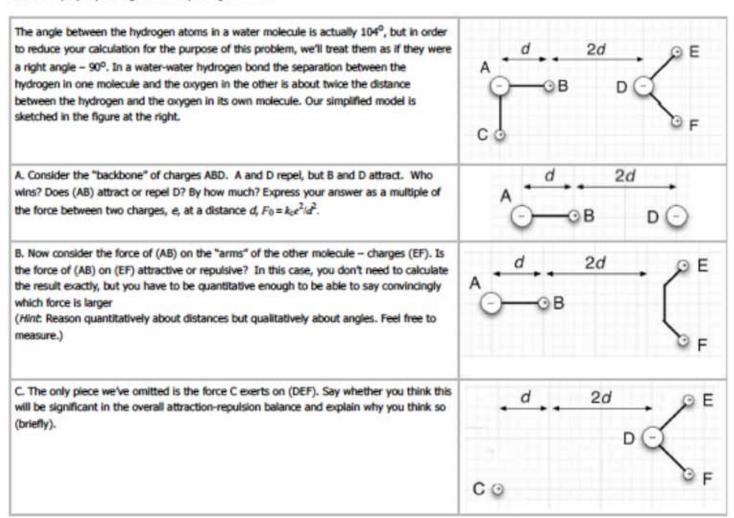
Redish & Cooke, CBE-LSE (2013) in press.

35

We have seen that charged objects can attract neutral matter through the polarization of neutral matter – pushing the part of it that has the same charge slightly further away. At the molecular level, neutral molecules that have separated parts that are positive and negative can also attract one another by orienting properly. One example of this is *hydrogen bonding* of water molecules. This is the primary mechanism that creates surface tension in water (and a similar phenomenon plays a big role in a variety of biochemistry).

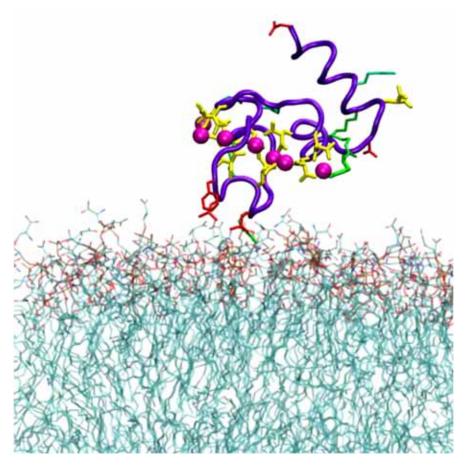


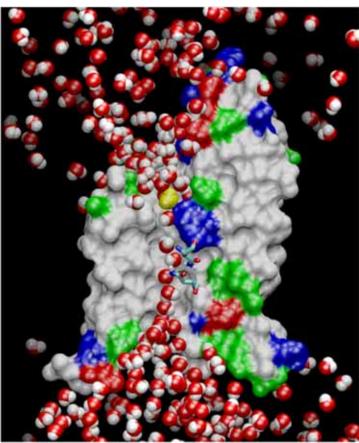
The hydrogens in a water molecule are positive (+e) and the oxygen is negative (-2e). Electric forces and the quantum sharing of electrons hold the whole thing together. We won't worry about this part inside the water molecule here but we will explore how the electric forces between water molecules properly arranged winds up being attractive.



Hydrogen Bonding

+ Simulations of biological impact of random motion





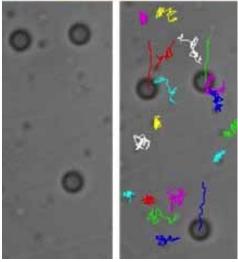
Ohkubo & Tajkhorshid, *Structure (Cell Press)*, 16:1 (2008) 72-81. (Department of Biochemistry, Beckman Institute and Center for Biophysics and Computational Biology, UIUC)

This 'Water Channels in Cell Membranes' movie was made with VMD and is owned by the Theoretical and Computational Biophysics Group, NIH Center for Macromolecular Modeling and Bioinformatics, at the Beckman Institute, UIUC

⁺Observing random motion in the lab





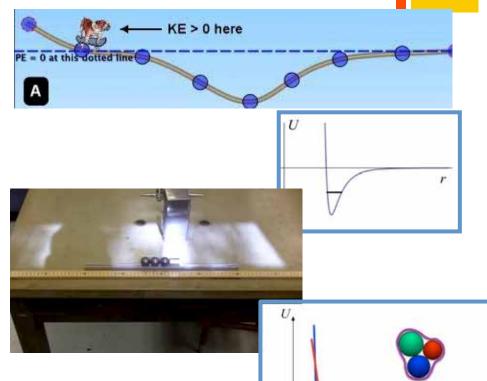


+ Chemical bonding

- 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 things by rote that feel contradictory to them and they often don't know how to reconcile them.
 - 1. It takes energy to break a chemical bond.
 - 2. Breaking the bond in ATP is the "energy currency" of cellular metabolism.

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.



Relation to competencies

- Our approach to creating a "chemical bonding thread" in a physics class relies heavily on developing competencies in a context the students find meaningful.
 - Use of multiple graphical representations (PE graphs, energy bar charts)
 - Tying graphical representations to physical meaning and mechanism (CLUE simulations, Gauss gun, PhET sims)
 - Reasoning from principle and seeking coherence across multiple situations.

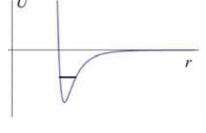


Midterm exam (Essay)

Two students discussing the process of ATP hydrolysis $(ATP + H_2O \rightarrow ADP + P_i)$ make the following comments:

Justin: "The O-P bond in ATP is called a 'high-energy bond' because the energy *released* when ATP is hydrolyzed is large. That released energy can be used to do useful things in the body that require energy, like making a muscle contract."

Kim: "I thought chemical bonds like the O-P bond in ATP could be modeled by a potential energy curve like this, where *r* is the distance between the O and the P. If that's the case, then breaking the O-P bond in ATP would require me to *input* energy. I might not have to input *much* energy to break it, if that O-P happens to be a weak bond, but shouldn't I have to input at least some energy?"



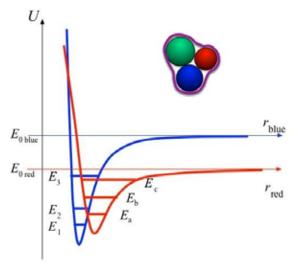
How did Kim infer from the PE graph that breaking the O-P bond requires an input of energy? Who's right? Or can you reconcile their statements?

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+Final exam (MC)

The figure at the right depicts a situation in a chemical reaction complex. We model the combined system as consisting of three parts, shown red, green, and blue. Each part can be pulled away from the remaining pair or vibrate against them.

Two potential energy curves are shown: one in blue that shows what happens to the potential energy as the blue part is pulled away from the red-green pair, one in red that shows what happens to the potential energy as the red part is pulled away from the blue-green pair.



6.2 (5 pts) Which part takes less energy to break from the molecule, blue or red?

- a. The blue part.
 - b. The red part.
 - c. They will each take the same energy to remove.
 - d. You can't tell from the information given.

	6.2
a	5%
b	95%

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Conclusion

- Doing right by the biologists requires that physicists do much more than throw in a few biological examples.
- It requires deep thinking about the character of scientific inquiry in the two professions.
- It requires deep thinking about the nature of thinking and learning in science.
- We learn not just about teaching, but about the way different disciplines think about and approach scientific problems.



For more information

http://www.TinyURL.com/NexusUMCP