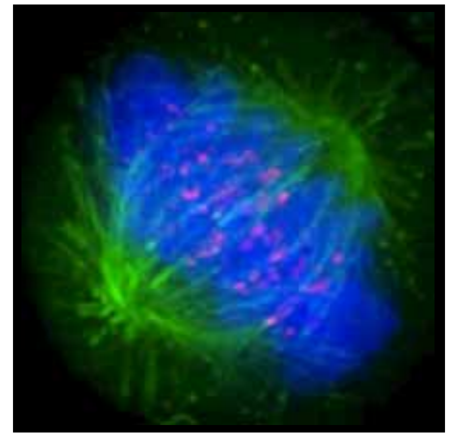
$$\Delta V_1 = \frac{KQ}{(x^2+b^2)^{1/2}}\Bigg|_{x=0}^{x=a} = \frac{KQ}{(a^2+b^2)^{1/2}} - \frac{KQ}{(0^2+b^2)^{1/2}}$$

$$\Delta V_2 = \frac{KQ}{(a^2+y^2)^{1/2}}\Bigg|_{y=b}^{y=c} = \frac{KQ}{(a^2+c^2)^{1/2}} - \frac{KQ}{(a^2+b^2)^{1/2}}$$

$$\Delta V_3 = -\frac{KQ}{(x^2+c^2)^{1/2}}\Bigg|_{x=0}^{x=a} = -\frac{KQ}{(a^2+c^2)^{1/2}} + \frac{KQ}{(0^2+c^2)^{1/2}}$$

$$\Delta V_4 = -\frac{KQ}{(0^2+y^2)^{1/2}}\Bigg|_{y=b}^{y=c} = -\frac{KQ}{(0^2+c^2)^{1/2}} + \frac{KQ}{(0^2+b^2)^{1/2}}$$



nexus
NATIONAL EXPERIMENT
in Undergraduate Science Education

Reinventing Physics for Biologists

Edward F. Redish
Department of Physics
University of Maryland

HHMI

Teaching physics for biology students: The changing landscape

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

- The University of Maryland Physics Department 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.

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.

2003

2009

2011

2013

+ We have been offered a challenge

- These reports have specific requests
  - Stress scientific skills / competencies (and they have identified many fairly specific ones)
  - Include topics essential and relevant for modern biology.
  - Enhance interdisciplinarity.

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

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

NEXUS
NATIONAL EXPERIMENT
in Undergraduate Science Education

- 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 so that it 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.
- ***E4*** Demonstrate knowledge of basic principles of chemistry and some of their applications to the understanding of living systems.
- ***E5*** 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.
  - ...

NEXUS/Physics

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*

Discussants: UMCP co-conspirators

- **Physicists**
  - Michael Fisher
  - Arthur LaPorta**
  - Peter Shawhan
- **Biologists**
  - Marco Colombini**
  - Jeff Jensen
  - Richard Payne
  - Patty Shields
  - Sergei Sukharev**
- **Chemists**
  - Jason Kahn
  - Lee Friedman
- **Education**
  - Andy Elby (Phys)
  - Dan Levin (Bio)
  - Jen Richards (Chem)

Off-campus collaborators

- **Physicists**
  - Catherine Crouch* (Swarthmore)
  - Royce Zia* (Virginia Tech)
  - 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* (Clemson)
- **Education**
  - Janet Coffey (Moore Foundation)
  - Jessica Watkins (Tufts University)

**NSF TUES project*

+ 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!

Questions

- Which students?
- What content?
- What competencies?
- Are there unnoticed obstacles?

Changing the culture of the course

- We seek content and examples that have **authentic value** for biology students.
  - We want upper division bio to make physics a pre-requisite.
- We do **not** assume this is a first college science course.
  - Biology, chemistry, and calculus are pre-requisites.
- We 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.
- We 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.

Redish & Hammer, Am. J. Phys., 77 (2009) 629-642.

Rethinking Physics for Biologists

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.

And...

- We continue to negotiate these changes through extensive discussions among biologists, chemists, and physicists.

But...

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

Redish & Hammer, Am. J. Phys. 77 (2009) 627-642.

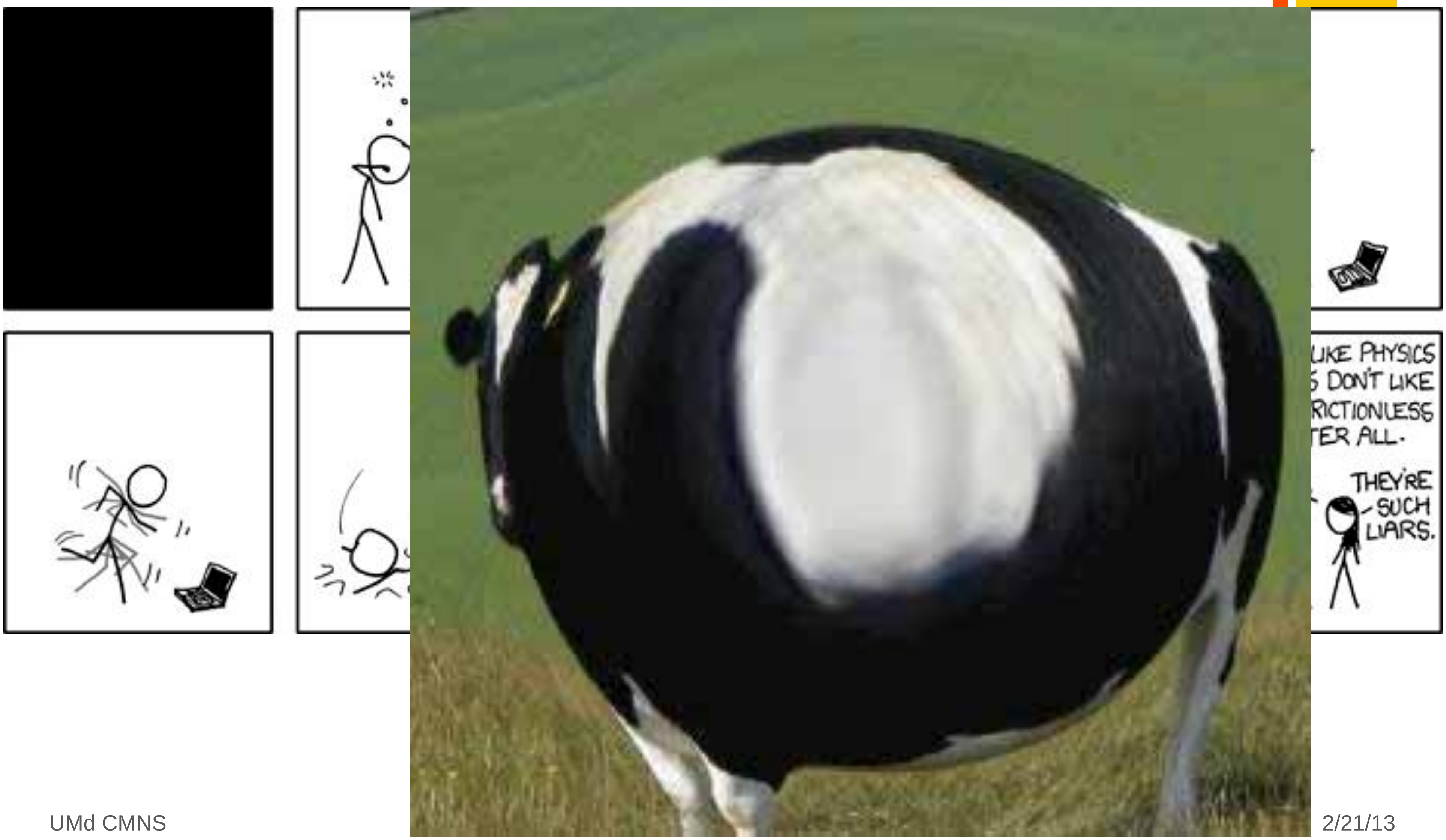
The culture of the disciplines

- 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.

Hammer, Elby, Scherr, & Redish, in *Transfer of Learning: Research and Perspectives*, J. Mestre, ed. (Inf. Age. Pub, 2004) .

+ 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, ...)


DON'T LIKE
THEY'RE
SUCH
LIARS.

+ 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*.

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

+ 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

+ Revising the approach

We want to

- Be explicit about modeling and analyzing as systems.
- Emphasize equations as guides to thinking and reasoning
- Focus on coherent vs. random motion
- Develop quantification skills
- Use modern pedagogical tools

So we

- Give problems where building equations are the point
- Do problems with simulations, video, numerical calculations (solving ODEs on a spreadsheet)
- Do multiple labs on random motion
- Create clicker and groupwork problems

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.

Seeking authenticity

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 $B = 0.98$ μmole (μmole = 10^{-6} moles) of oxygen per gram of worm per hour.

SpeedBump by Dave Coverly: 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.

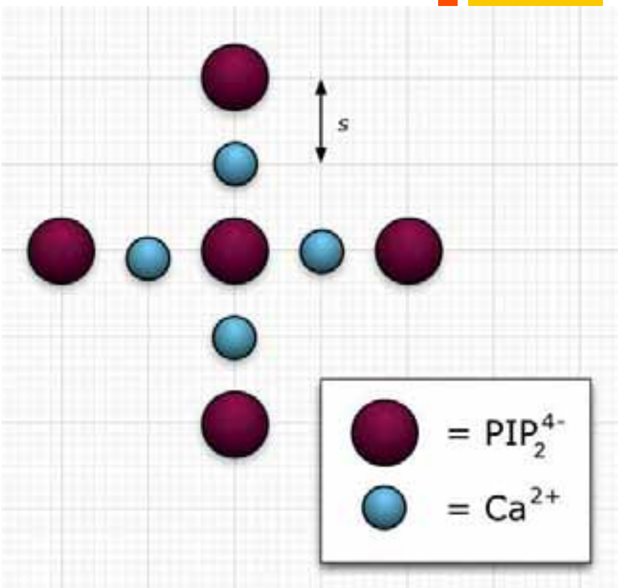
F. In typical analyses of evolution and phylogenetic histories, earthworm-like organisms are the ancestors of much larger organisms than the limit here permits. Discuss what sort of variations in the structure of an earthworm might lead to an organism that solves the problem of growing isometrically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

http://umdberg.pbworks.com/w/page/42294962/How%20big%20is%20a%20worm

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

Electric forces in molecules

Recent research provides support for an electrostatic mechanism for this clustering, in which Ca^{2+} ions provide an attractive interaction holding together the PIP_2 molecules. The detailed structure of how Ca^{2+} ions and PIP_2 molecules are arranged in these clusters is not yet known. In this problem we consider a highly simplified model simply to give a feel for how these interactions work.



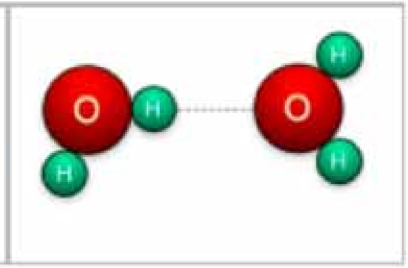
...

(d) Find the net force on the top ion exerted by the other. What direction does it point? Does this force push the top ion toward the center (tending to hold the cluster together) or push it away (tending to blow the cluster apart)?

Z. Li, et al., Biophys. J., 97 (2009) 155-163 .

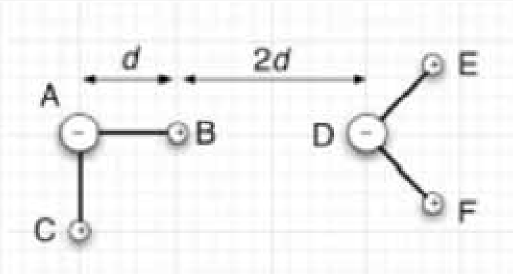
Hydrogen Bonding

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).

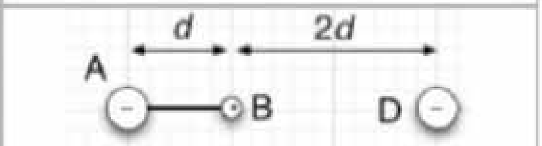


The hydrogens in a water molecule are positive (+e) and the oxygen is negative (-2e). Electric forces and the quantum sharing of electrons hold the whole thing together. We won't worry about this part inside the water molecule here but we will explore how the electric forces between water molecules properly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

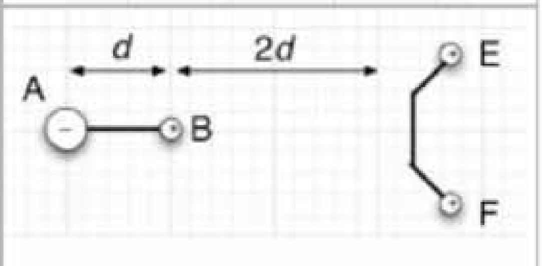
The angle between the hydrogen atoms in a water molecule is actually 104°, but in order to reduce your calculation for the purpose of this problem, we'll treat them as if they were a right angle – 90°. In a water-water hydrogen bond the separation between the hydrogen in one molecule and the oxygen in the other is about twice the distance between the hydrogen and the oxygen in its own molecule. Our simplified model is sketched in the figure at the right.



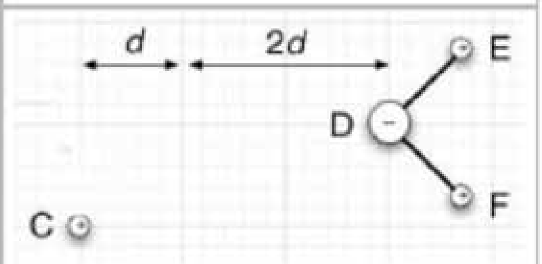
A. Consider the "backbone" of charges ABD. A and D repel, but B and D attract. Who wins? Does (AB) attract or repel D? By how much? Express your answer as a multiple of the force between two charges, *e*, at a distance *d*, $F_0 = k_C e^2/d^2$.



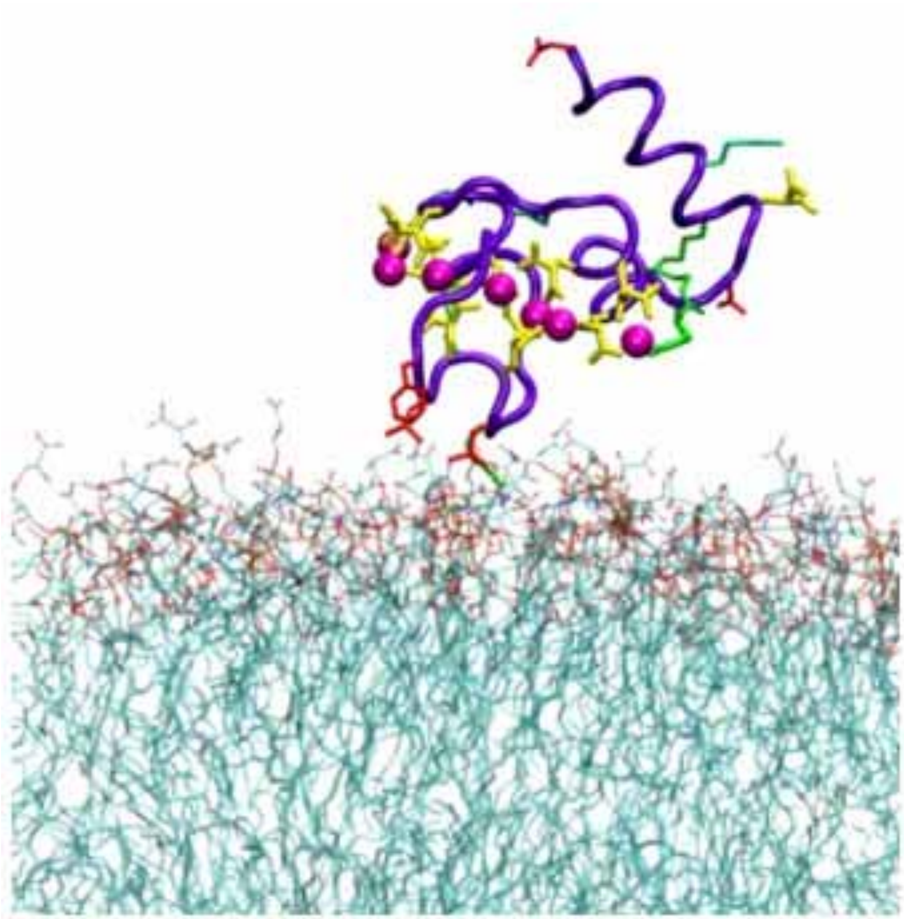
B. Now consider the force of (AB) on the "arms" of the other molecule – charges (EF). Is the force of (AB) on (EF) attractive or repulsive? In this case, you don't need to calculate the result exactly, but you have to be quantitative enough to be able to say convincingly which force is larger
(*Hint*: Reason quantitatively about distances but qualitatively about angles. Feel free to measure.)



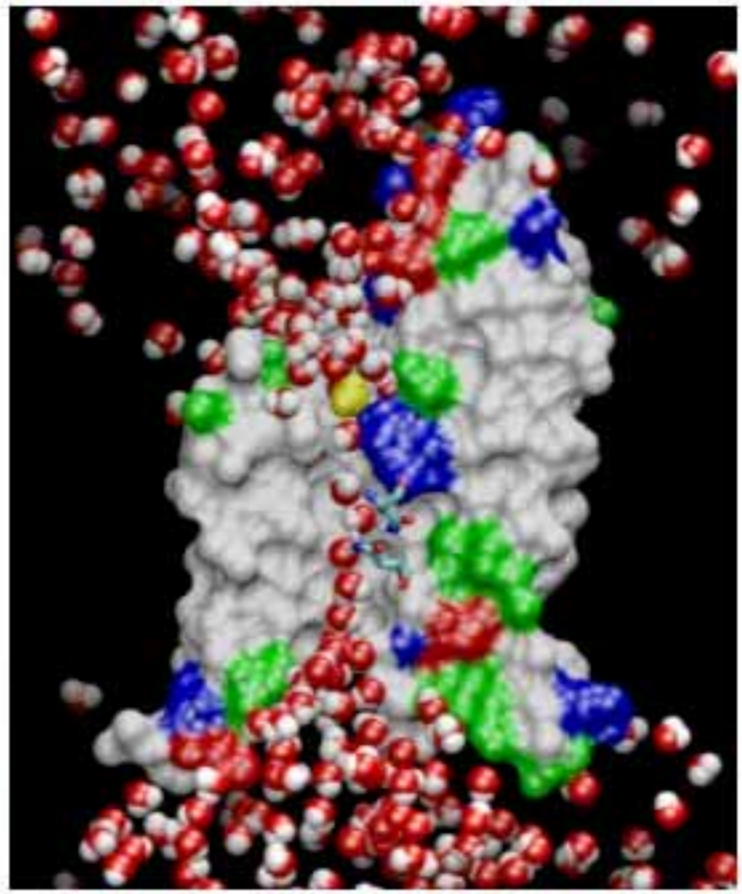
C. The only piece we've omitted is the force C exerts on (DEF). Say whether you think this will be significant in the overall attraction-repulsion balance and explain why you think so (briefly).



+ Simulations of biological impact of random motion

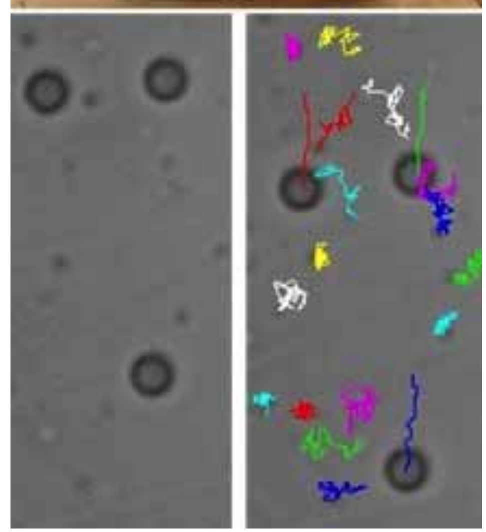


Ohkubo & Tajkhorshid, *Structure (Cell Press)*, 16:1 (2008) 72-81. (Department of Biochemistry, Beckman Institute and Center for Biophysics and Computational Biology, UIUC)



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.

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

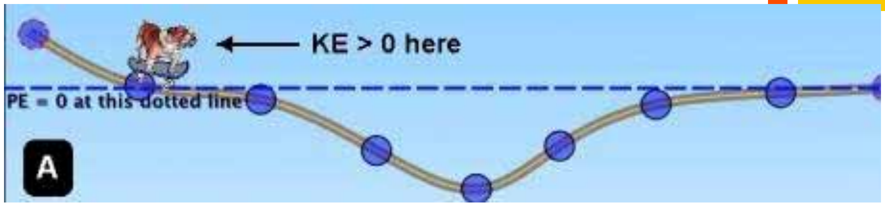
W. C. Galley, J. Chem. Ed., 81:4 (2004) 523-525.

Approach

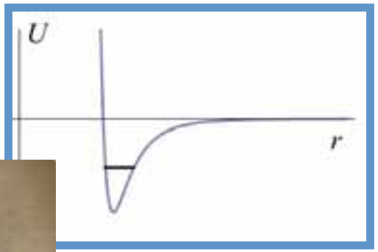
1. Introduce atoms and molecules early in the class, with quantification and estimation to build a sense of scale.
2. Introduce concept of “binding energy” in standard macroscopic energy contexts (skateboarder in a dip)
3. Create a chain of tasks in atomic and macroscopic contexts for learning to read and interpret potential energy graphs. (formative assessments)
4. Observe student behavior in response to these tasks.
5. Refine tasks by negotiation among physicists, biologists, and chemists. (Including write papers and submit for peer review.)
6. Repeat steps 3-5.
7. Extract multiple choice analogs for summative assessment.

How physics can help

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

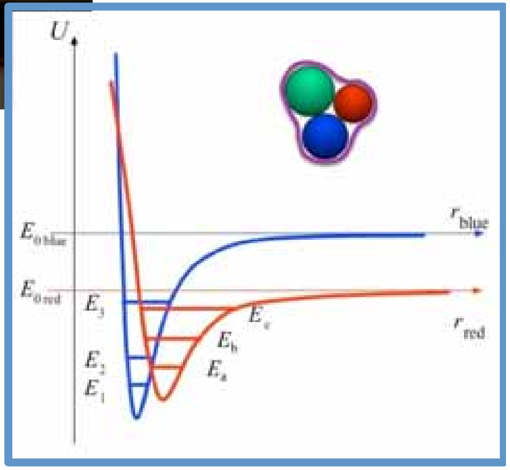


  - Atomic interactions and binding



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

  - Connection between PE diagram and reaction energy diagrams.



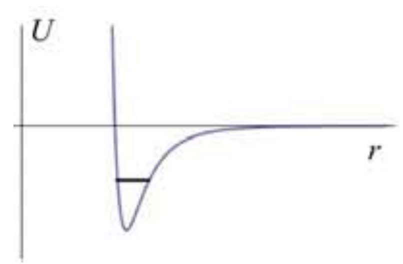
Relation to competencies

- 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?”

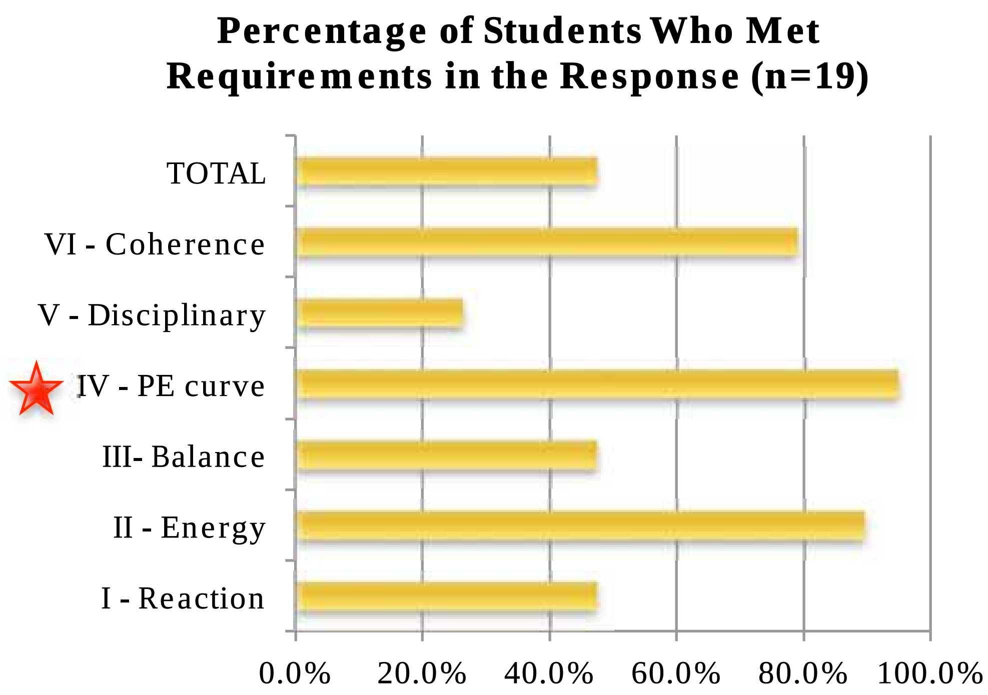
How did Kim infer from the PE graph that breaking the O-P bond requires an input of energy? Who’s right? Or can you reconcile their statements?

+ Rubric Analysis of ATP Question

I) 47% students recognized bonds are both broken and formed

II) 90% of students connected breaking and forming of bonds to the U vs r curve

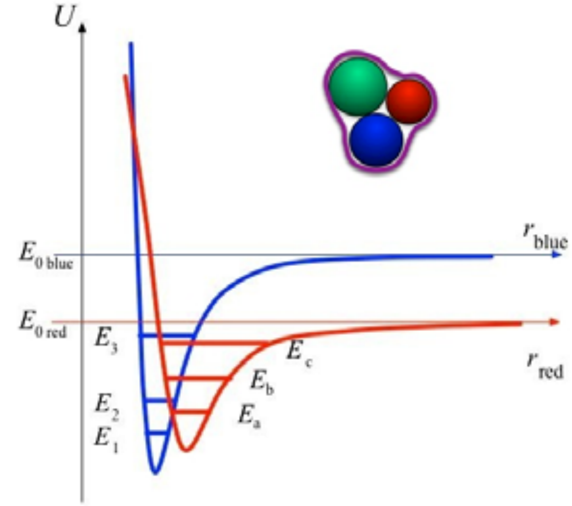
III) 47% of students recognized that the energy of forming new bonds outweighed the energy of breaking the O-P bond.



+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%**

Preliminary Results:
Maintaining Traditional Learning

Previous reform class

- The UMCP NEXUS Physics class is built starting from a 10-year reform project supported by the NSF.
- This class focused on reforms to build general scientific competencies (e.g., sense-making, multi-representational translation, coherence seeking, etc.).
- The class did NOT modify the content significantly to adapt to the needs of biology and medicine.
- The class achieved strong gains in learning of basic concepts and student attitudes as measured by standardized instruments (from PER).

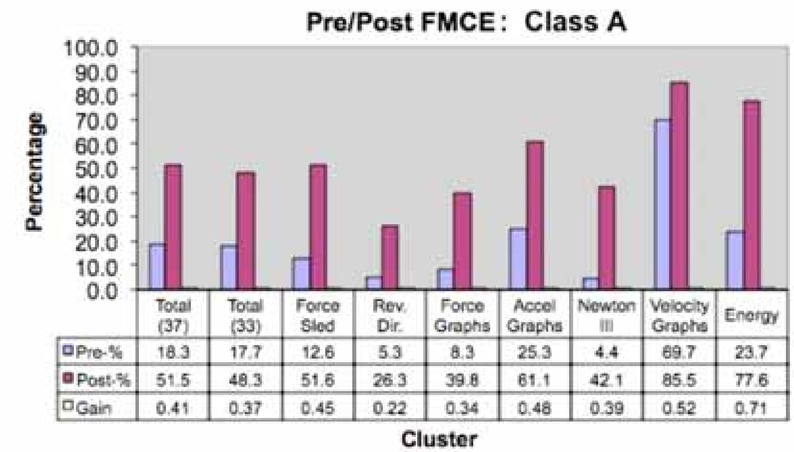
+ Goal: Maintain previous gains

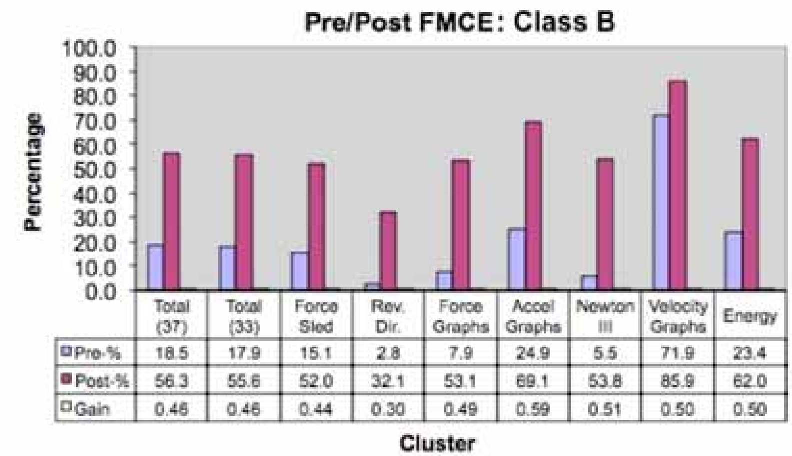
- The NEXUS Physics class makes dramatic changes in the structure of the traditional physics class
  - Emphasizes energy and reduces discussion of force.
  - Eliminates or reducing some traditional topics (circular motion, statics, momentum...)
  - Adds topics such as chemical bonding, extensive atomic and molecular examples, random motion, diffusion, and a more comprehensive treatment of thermodynamics (like chem, not mech. eng.)
- Maintain strong concept learning from the previous reform. (Competency E3.1)
  - Test with standard instruments: FMCE, BEMA, CSEM

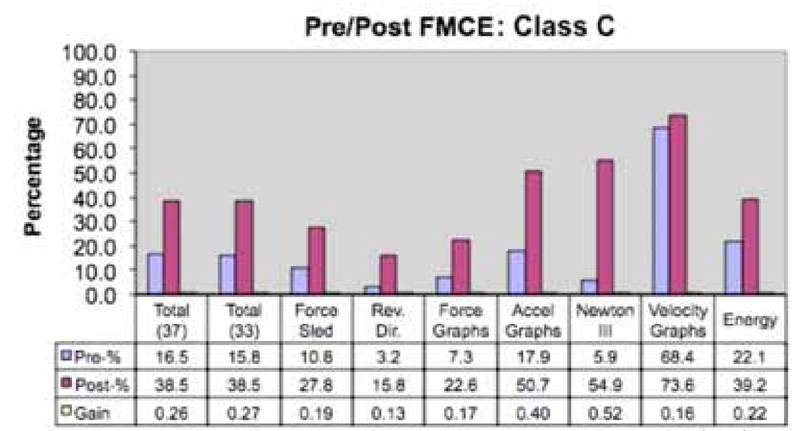
+ **If you suppress traditional mechanics a bit and stress energy instead, what happens?**

$$\langle g \rangle = \frac{\text{(post class average) - (pre class average)}}{100 - \text{(pre class average)}}$$

		N	$<g_F>$	$<g_E>$
A	NEXUS test class (fall 2011)	20	0.41	0.71
B	Reformed traditional (Epistemologized / with reformed tutorials)	189	0.46	0.50
C	Traditional (with reformed tutorials)	201	0.26	0.22







Looking at the NEXUS/Physics materials

+ A growing and open environment

- We envision NEXUS/Physics as an ongoing collaboration among physicists, biologists, chemists, STEM education specialists, and biophysics researchers.
- We expect our materials to serve as the core of an open on-line environment run by the National Physics Digital Library (comPADRE) that will permit submission and peer review of materials.
- Over the next few years we are looking for collaborators in all these areas to
  - Read, vet, and add to our existing materials
  - Help create new materials
  - Add ideas for topics and activities based on modern biophysics.

For more information and to see current materials

http://NEXUSphysics.umd.edu/