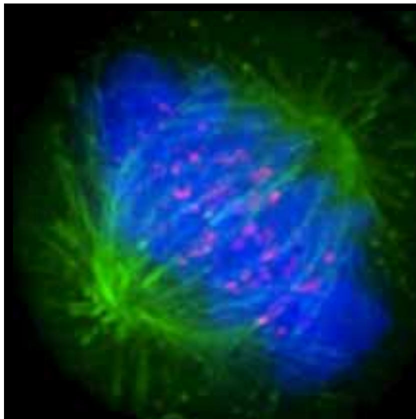
$$\Delta V_1 = \frac{KQ}{(x^2+b^2)^{1/2}}\Bigg|_{x=0}^{x=a} = \frac{KQ}{(a^2+b^2)^{1/2}} - \frac{KQ}{(0^2+b^2)^{1/2}}$$

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

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

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



nexus

NATIONAL EXPERIMENT
in Undergraduate Science Education

Rethinking Physics for Biologists

Adapting to a major new service course constituency

UNIVERSITY OF MARYLAND 1856

HHMI

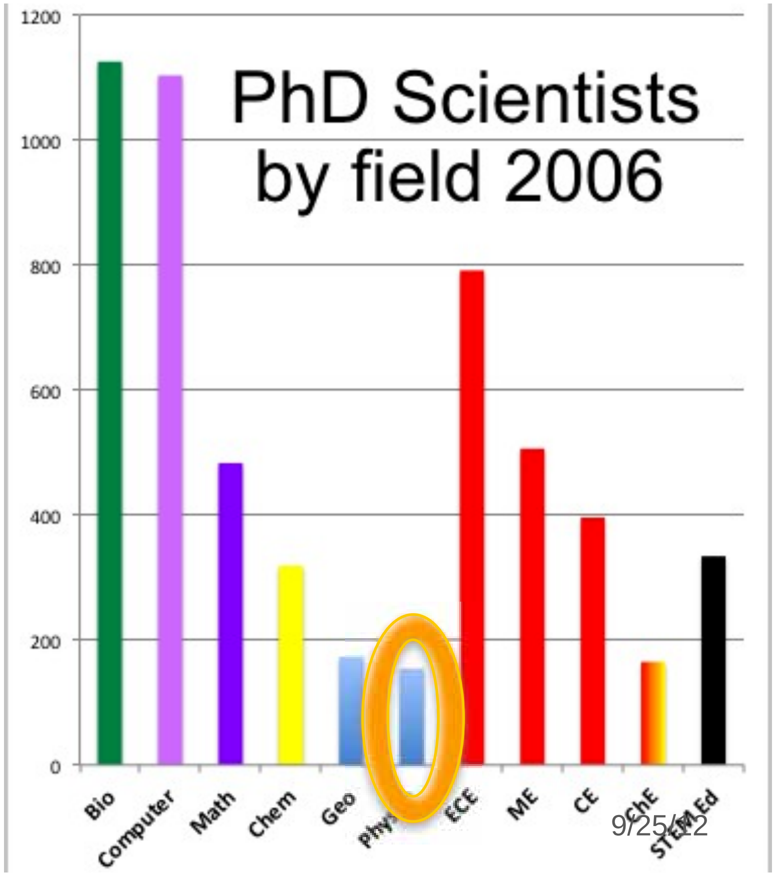
Outline

- The Challenge
- The NEXUS Project
- Preliminary Results
  - Maintaining traditional learning
  - Interdisciplinary attitudes
  - Chemical bonding

The Challenge

Physics is a fairly small profession among the sciences.

- As a result most of our teaching is in service courses; primarily to engineers and biologists.



Implications

- Not only are most of our students in physics <u>not</u> going to become professional research physicists, most are not even physics majors.
- These students support a large physics faculty (at UMCP N ~ 75).
- But... Most of our instructional effort (and interest) focuses on our majors and grad students.

+ The biologists are often given the short end of the stick

- Over the years many of us have negotiated with our **engineers;** mostly sporadically – regular meetings happen, but I gather are rare) and have reached a course that satisfies them (mostly).
- **Biologists** are often dumped into an algebra-based course, a cut-down version of the calc-based one the engineers get, together with "others" – architects, computer scientists, etc. Sometime, a biological example or two is thrown in. Sometimes textbooks have "sidebars" about the biology.
- But isn't this enough?

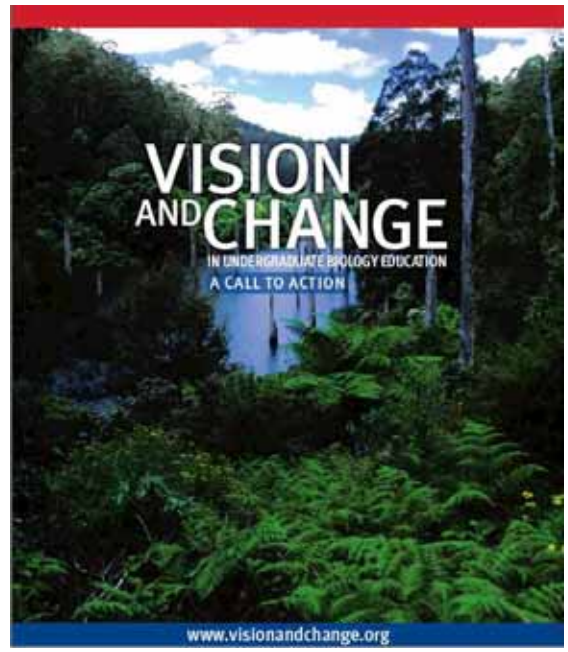
Biology is changing

- Over the past decade, biologists have begun to call for a major reform of undergraduate biology education.
- Part of this reform is to include more math, chemistry, and physics in bio classes.
- Part is a call for making math, chemistry, and physics classes more relevant to bio students.

Calls for Bio Education Reform

NAS 2003

HHMI-AAMC 2008



AAAS 2009

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 biology.
  - Enhance interdisciplinarity.

When it comes to teaching non-physicists...Don't mess with success!

- We know how to teach physics.
- Physics is physics is physics ... for all!
- We have a working model – and dozens of standard texts we can use with all kinds of resources.
  - This makes teaching non-majors fairly straightforward – even if time consuming due to the problems of administering large-classes.
- No thinking required!

+ Two views heard at a conference on interdisciplinary Science Education

1. Physicist: "This whole 'physics for biology' idea makes me very uncomfortable. What's next? 'Physics for mechanical engineers' or 'physics for electrical engineers'? Where does it end?

I could see maybe having a physics class for all students and then having a few tailored recitation sections where students focus on applications to their various fields, but I'm uncomfortable with 'physics for X' as an idea. We should be conveying how we view physics to everyone."

Two views heard at a conference on interdisciplinary Science Education

2. Biologist: "I guess the physics for biologists idea may be a step in the right direction, but for it to be useful it has to go much further and be entirely revamped.

It has to be very narrowly focused on those ideas that biologists see as essential, not just removing a few topics. If I want to know about forces, I'll look it up, but it does not make sense for biology students to be spending time on that when they have profound problems with biology. Unfortunately, physicists generally have a profound ignorance about biology, so I'm not sure they are the right folks to be doing it. I can teach the relevant physics myself."

Another view from a physicist

I would be inclined also to approach it from the "other end": i.e., I would construct a list which has in it the absolute irreducible physics concepts and laws that have to be in a physics curriculum. This "entitlement" list will already take up a majority of the available space.

With a realistic assessment of how much space is available, it may become clearer what type of bio-related material one can even entertain to include

The NEXUS Project

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

Create a proposal to develop four sets of 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.

The NEXUS Development Team (UMCP)

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

Discussants: UMCP co-conspirators

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

Discussants: 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)
- **Biologists**
  - Mike Klymkowsky* (U. Colorado)
- **Chemists**
  - Chris Bauer* (U. New Hampshire)
  - Melanie Cooper* (Clemson)
- **Education**
  - Janet Coffey (Moore Foundation)

**NSF TUES project*

Can we teach physics to biologists in a way that adds value for them?

- What content should we teach?
- What are the barriers to constructing an effective course?
- What do we need to do to create effective inter- or trans-disciplinary instruction?

Starting in a hard place

- It turned out there are significant cultural differences between biologists and physicists.

- Biologists saw most of the traditional introductory physics class as useless and irrelevant to biology – and the physicists claim “we can apply physics to biology examples” as trivial and uninteresting.

- Physicists saw a coherent structure with no room for change.

In two semesters it is impossible to cover every topic in physics. The purpose of this question is to determine your priorities of the topics in the course. Below are the chapter headings from a typical textbook at this level. Please place the **integer** number of weeks for each chapter that, **in your judgment**, allows students to understand the material at the level you desire. Each week consists of 3 lectures, 1 discussion section, and a 2-hour laboratory. The total number of weeks should equal 26 to account for a course introduction at the beginning of the semester and a review at the end. **Please do not use fractions of a week.**

_____ Units, dimensions and vectors
_____ Linear motion
_____ Two dimensional motion
_____ Forces and Newton's Laws
_____ Applications of Newton's laws
_____ Kinetic energy and work
_____ Potential energy and conservation of energy
_____ Momentum and collisions
_____ Rotations and torque
_____ Angular momentum
_____ Statics
_____ Gravitation
_____ Oscillatory motion
_____ Mechanical waves
_____ Superposition and interference of waves
_____ Fluid mechanics
_____ Temperature and ideal gas
_____ Heat flow and the first law of thermodynamics
_____ Molecules and gases (e.g. probability distributions of velocity, equipa
_____ Entropy and the second law of thermodynamics
_____ Properties of solids (e.g. stress, strain, thermal expansion)
_____ Electric charge and force
_____ Electric field
_____ Gauss' law
_____ Electric potential
_____ Capacitors and dielectrics
_____ Currents in materials (e.g. resistance, insulator, semiconductors)
_____ Currents and DC circuits
_____ Magnetic forces and fields
_____ Currents and magnetic fields (e.g. Ampere's law, Biot-Savart law)
_____ Faraday's law
_____ Magnetism and matter (e.g. ferromagnetism, diamagnetism)
_____ Magnetic Inductance
_____ AC circuits
_____ Maxwell's equations and electromagnetic waves
_____ Geometrical optics (e.g. reflection and refraction)
_____ Mirrors and lenses
_____ Interference
_____ Diffraction
_____ Quantum physics
_____ Atomic physics
_____ Nuclear physics and radioactive decay
_____ Particle physics
_____ Relativity
_____ Other. Please specify.
__26__ **Total number of weeks**

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.

Changes in the culture and expectations of the course

- We organize the course so that it will have authentic value for biology students in their upper division bio courses.
- 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”
  - We explicitly discuss modeling and the value of understanding “simplest possible” examples.
- We choose different content from the traditional by including molecular and chemical examples and topics of more importance to biology.

And...

- We negotiate these changes through extensive discussions between biologists 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).

+ Content: What's authentic?

- Biologists see much (most?) of what we do in traditional intro physics as peripheral (at best) or irrelevant (at worst) to what biology students need to know.
- Biologists see most of the "biology examples" put into an IPLS class as trivial, uninteresting, and "not real biology".
- We want to seek content and examples that will be seen by biologists (and by biology students) as ***authentic*** – it helps make sense of something that has real importance in biology.

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 model of a specific system and what was a 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

+ 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 control structures (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.

"Framing" – the answer to the question,
"What's going on here and what am I supposed to do?"

+ Physics

- Intro 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* – and often 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 *irreducibly 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 – even at the introductory level – *looks for mechanisms linking molecules and macro phenomena*.
- Biologists (both professionals and students) focus on and value *real examples* and *structure-function relationships*.

Student attitudes towards interdisciplinarity: Some data

- We have interviewed students about their attitudes towards mixing the sciences in two classes:
  - *Organismal Biology*
    A required bio class that explicitly uses a lot of physics and chemistry.
  - *Physics for Biologists*
    The first implementation of the NEXUS physics course that brings in a lot of bio and chem.

Ashlyn is studying the diffusion equation in her Organismal Biology class. (The distance that something diffuses in a time t is proportional to the square root of t.)

Ashlyn prefers to keep her sciences separate.

I don't like to think of biology in terms of numbers and variables.... biology is supposed to be tangible, perceivable, and to put it in terms of letters and variables is just very unappealing to me....Come time for the exam, obviously I'm going to look at those equations and figure them out and memorize them, but I just really don't like them.

I think of it as it would happen in real life. Like if you had a thick membrane and tried to put something through it, the thicker it is, obviously the slower it's going to go through. But if you want me to think of it as "this is *x* and that's *d* and this is *t*", I can't do it.

Biology students bring cultural/disciplinary expectations to their classes that may get in the way of trying to create interdisciplinary instruction – but it may be context dependent. Later in the interview, Ashland got excited about how math explained scaling relation (surface-volume).

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).

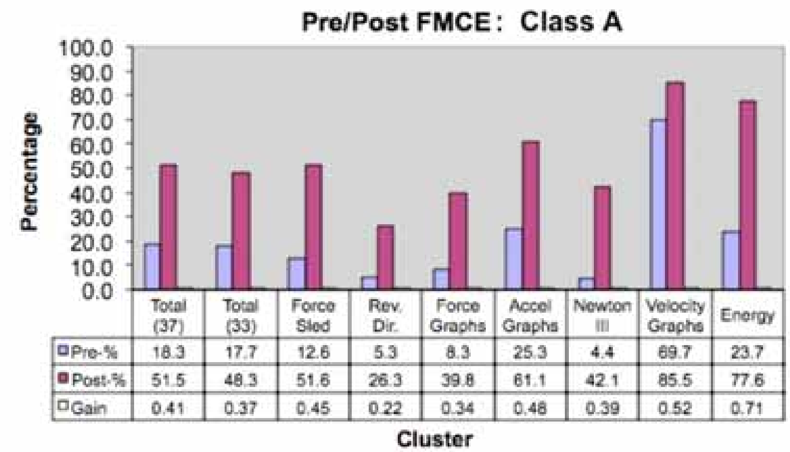
+ Goal: Maintain previous gains

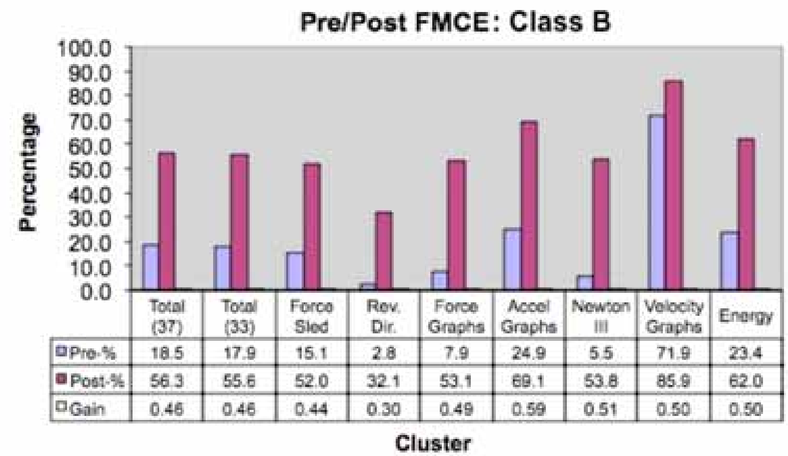
- The NEXUS Physics class makes dramatic changes in the structure of the traditional physics class
  - Emphasizes energy and reduces discussion of force.
  - Eliminates or reducing some traditional topics (circular motion, statics, momentum...)
  - Adds topics such as chemical bonding, extensive atomic 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

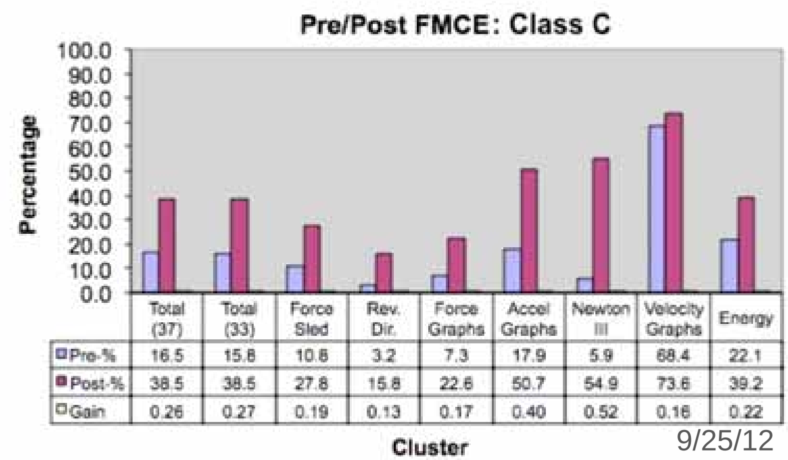
If you suppress traditional mechanics a bit and stress energy instead, what happens?

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

		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







Preliminary Results:
Interdisciplinary Attitudes

Attitudes and silo-ing

- Our previous research documents that many students who choose biology do not see the value of physics or math for biology.
- Our NEXUS approach requires students to be able to blend knowledge from biology, chemistry, physics, and math.
- We are developing an instrument to measure whether participation in the course improves their attitudes towards interdisciplinarity.
- As the curriculum evolves to be more interdisciplinary, this instrument should permit us to document the change.

Build on the experience of existing expectations/epistemology surveys

- MP/BEX (Maryland Physics/Biology Expectations Survey)
- A pre-post ~30 item (mostly) Likert survey asking students about their attitudes toward scientific knowledge *as needed in the current class.*
- Intended to measure “functional epistemology” – What’s the nature of the knowledge will I learn in this class and what do I have to do to learn it?
- It measures what students *think* they do rather than what they *actually* do.

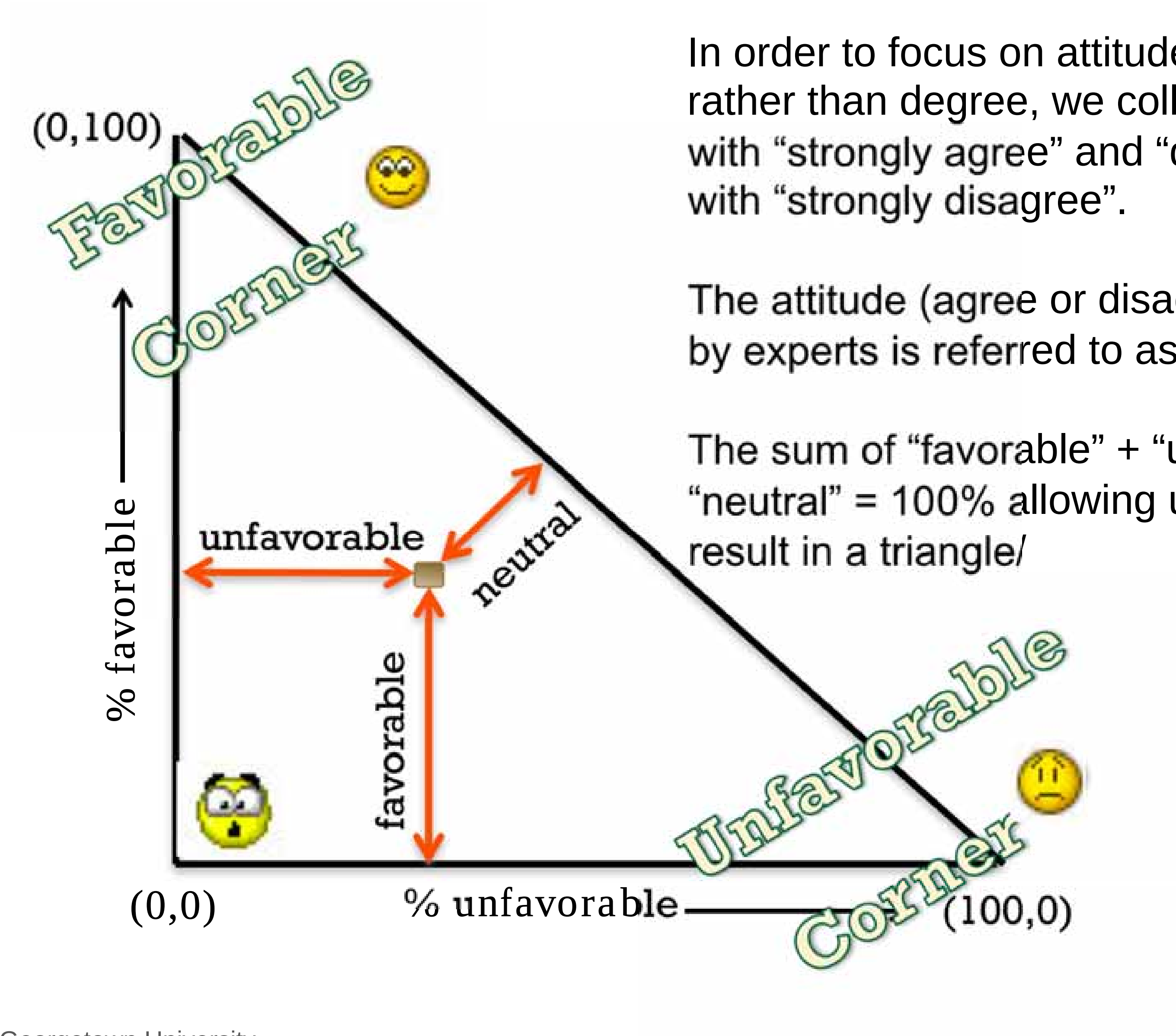
Previous Results

- The MP/BEX has been given to thousands of students around the world.
- In traditional large-lecture classes in both physics and biology, students typically start with moderately favorable attitudes (~60%) and stay static or deteriorate as a result of instruction.
- Courses reformed to focus on competency building can produce significant improvement (~5-15%).

+ Interdisciplinary cluster: Sample items (polarization)

- Mathematics helps me make deeper sense of biological phenomena. **(+1)**
- Ideas I learned in physics are rarely useful in biology.**(-1)**
- Physics helps me make sense of biological phenomena. **(+1)**
- Math provides another way of describing biological phenomena, but rarely provides a deeper or better understanding. **(-1)**
- The benefits of learning to be proficient using math and physics in biology are worth the extra effort. **(+1)**

+ The MEX triangle plot

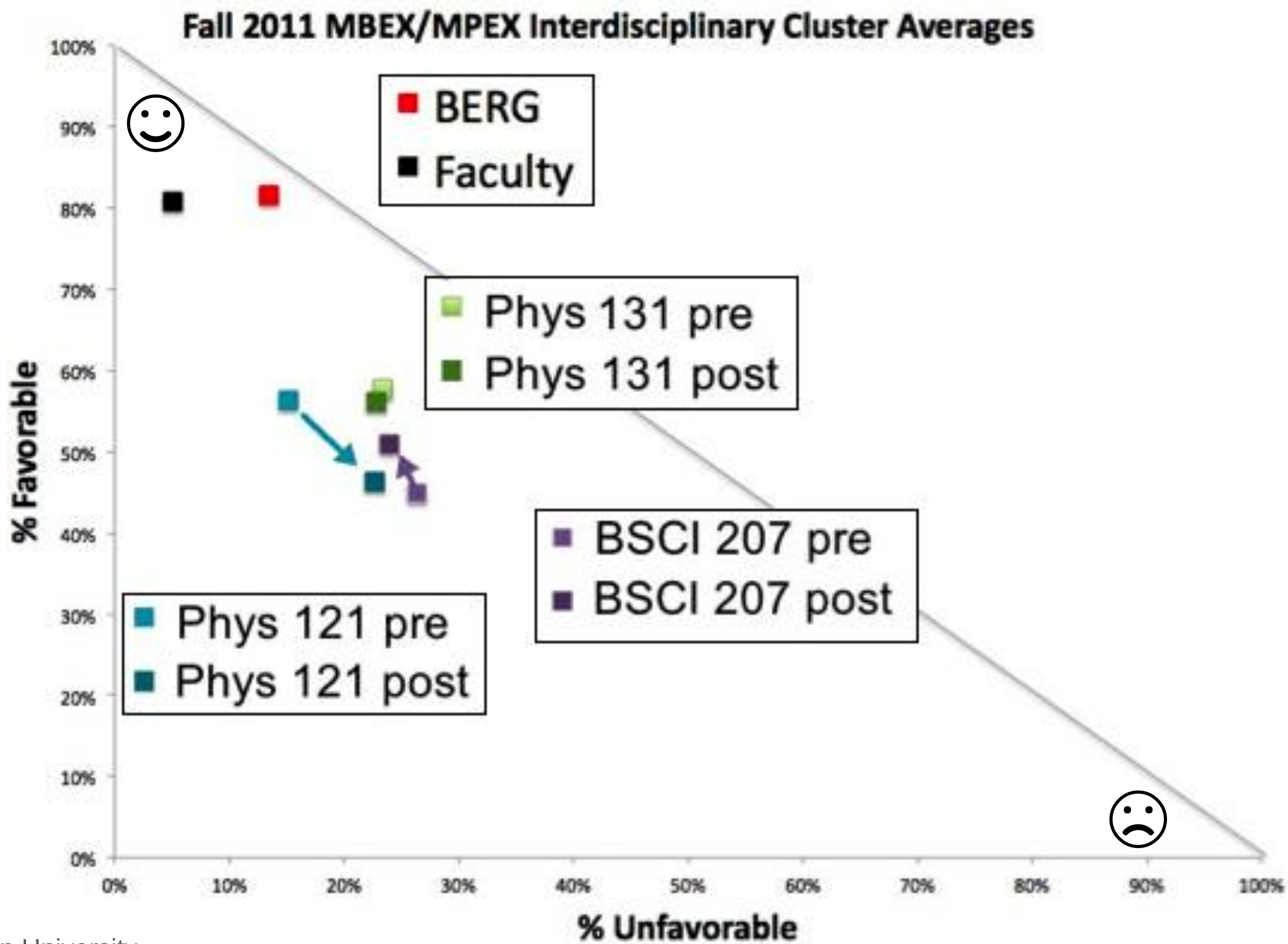


In order to focus on attitudes changes rather than degree, we collapse "agree" with "strongly agree" and "disagree" with "strongly disagree".

The attitude (agree or disagree) selected by experts is referred to as "favorable".

The sum of "favorable" + "unfavorable" + "neutral" = 100% allowing us to plot the result in a triangle/

+ Preliminary results on the interdisciplinary cluster



Preliminary Results:
Chemical Bonding

Collaborators

- NSF TUES Project (Energy, Thermodynamic, & Random Motion)
  - Mike Klymkowsky (U. Colorado, Bio. Ed. Res.)
  - Chris Bauer (UNH, Chem. Ed. Res.)
  - Melanie Cooper (MSU, Chem. Ed. Res.)
  - Catherine Crouch (Swarthmore, Phys. Ed.)

The task: Clarifying energy in chemical reactions

- Traditional intro physics classes do not consider chemical reactions.
- This prevents inclusion of many relevant biological processes. The UMCP NEXUS class includes them.
- Biology uses the language of "energy stored in chemical bonds".
- Chemistry sees this as a misconception – the energy is provided by a "chemical reaction".
- Can a physics-style treatment of energy help clear things up?

Approach

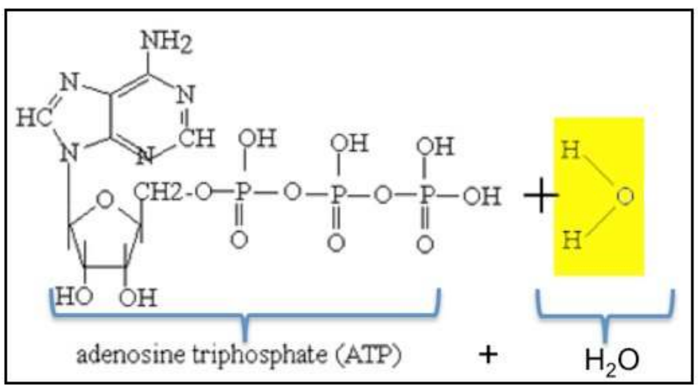
1. Introduce atoms and molecules early in the class, with quantification and estimation to build a sense of scale.
2. Introduce concept of “binding energy” in standard macroscopic energy contexts (skateboarder in a dip)
3. Create a chain of tasks in atomic and macroscopic contexts for learning to read 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.

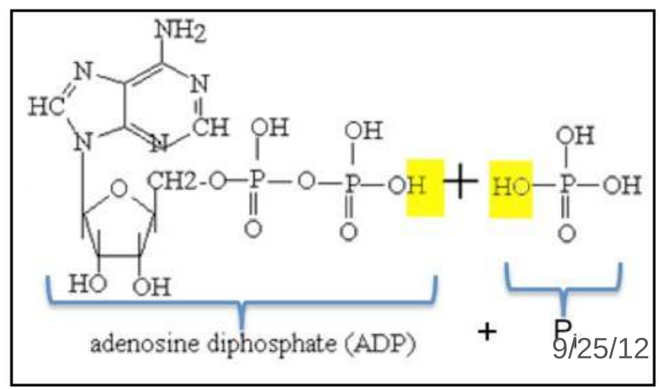
Some examples
(from a long string of formative assessment items)

- MCMR question from the Chemistry Education Literature (given in a quiz)
- Essay question developed for an hour exam.
- MC question developed for the final exam on interpreting PE curves.

+ An example from NEXUS Physics: A chemistry "misconception"

- A critical biochemical process is the hydrolysis of ATP. This is the primary reaction that delivers energy in biological systems.
- Students in both chemistry and biology have trouble seeing that a "bound state" has negative energy and that energy is released by going from a weakly to a strongly bound state.
- We propose that physics can help by connecting a better understanding of potential energy to chemical processes.
- In chemistry it is often identified as a "misconception" that students assume "energy is stored in the ATP bond" whereas really the energy comes from going from the weaker ATP bond to the stronger OH-P bond.





Example: Question from the Chemistry Education Lit

- An O-P bond in ATP is referred to as a "high-energy phosphate bond" because:
  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.

Considered a "misconception" (C)

Considered "correct" (B, D)

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

+ Results are similar to that found in gen chem – but interviews suggest something else is going on other than a “misconception”

	Phys 132	Galley
A	32%	41%
B	47%	31%
C	79%	87%
D	26%	7%

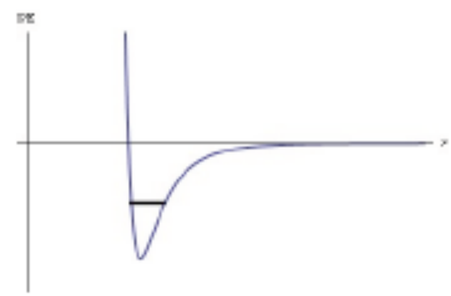
It may have more to do with disciplinary positioning – “framing” – than with a failure to understand what’s happening – at least for some students.

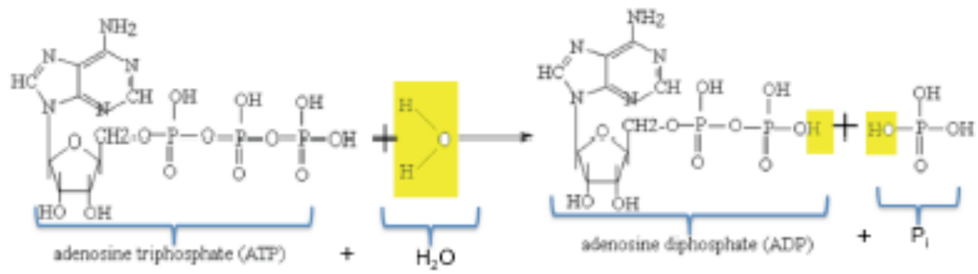
“I put that when the bond's broken that's energy released. Even though I know, if I really think about it, that obviously that's not an energy-releasing mechanism ... you always need to put energy in, even if it's like a really small amount of energy to break a bond. Yeah, but like. I guess that's the 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, primarily, and then it creates like an inorganic phosphate molecule that...is much more stable than the original ATP molecule.... I was thinking that larger context of this reaction releases energy.”

+ Example: Essay Question

4. (10 points) Two students discussing the process of ATP hydrolysis (ATP + H_2O → 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 (she draws the picture below), 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 potential energy graph that breaking the O-P bond requires an input of energy? If she's right that it does, how can you reconcile this with Justin's claim that ATP hydrolysis *releases* a lot of energy? (The chemical structures of this process are given if you find that useful.) *Note: This is an essay question. Your answer will be judged not solely on its correctness, but for its depth, coherence, and clarity.*





Example: Final exam question

The figure at the right depicts a situation in the possible deformations of a complex molecule. We will model the molecule as a combination 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. In looking at states where either the blue or the red is vibrating against the remaining pair (modeled as fixed), three states are found. The states where the blue part is vibrating are labeled E_1, E_2, and E_3. The states where the red part is vibrating are labeled E_a, E_b, and E_c.

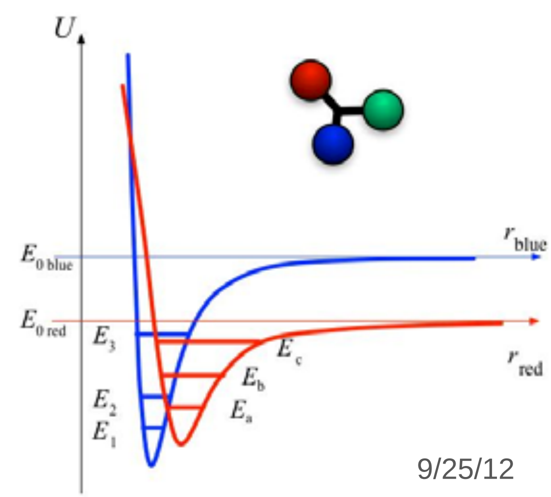
As the molecule collides with others in its environment it can gain and lose a little energy, but the temperature is such that it is unlikely to gain as much as, say $E_2 - E_1$.

6.1 (5 pts) If you model the small oscillations of the red and blue parts of the molecule around their stable points, which would have a larger spring constant?

- a. The blue part.
  b. The red part.
  c. They will each have the same spring constant.
  d. You can't tell from the information given.

6.2 (5 pts) Which part takes less energy to break off 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.



Results for Final Exam Question

	6.1	6.2
a	**75%**	5%
b	25%	**95%**

- High success rate on interpretation of a complex PE diagram in the context of a chemical reaction.
- No comparison with results in a standard chemistry course yet.

- I’ve only discussed a few of the highlights

This is only a small part of the story. A lot of important stuff has not been discussed for lack of time.

- Implications of learning theory (resources, thinking dynamics, framing) on instruction.
- Continuing research on the new aspects of student learning not previously analyzed (interdisciplinarity)
- Interplay of research, development, and rethinking the physics for new topics such as
  - Diffusion
  - Entropy
  - Motion in fluids...

To keep up with with where we are now:

- *http://tinyurl.com/nexusumcp*
- Or search: NEXUS UMCP
- Much is available but not all.
  This is our working environment too.