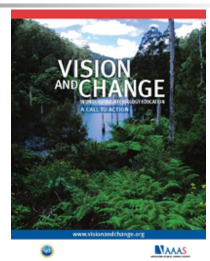
A Tale of Two Disciplines




Joe the Physicist Redish


Todd the Biologist Cooke

HHMI

The Starting Conditions


Joe Redish

PHYS 121/122 - an algebra-based introductory physics sequence with little biological authenticity

15 years experience in physics education research

Sophisticated application of reformed pedagogies and deep understanding of student attitudes toward learning


Todd Cooke

BSCI 207 – a new principles-based introductory organismal biology class

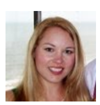
Minimal knowledge of biology education research

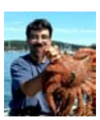
Conventional lectures, essay exams

UMD BERG/PERG Folks

Biology education


Todd Cooke


Kristi Hall


Jeff Jensen


Janet Coffee

Physics education


Joe Redish


Jessica Watkins


Ben Dreyfus


Andy Elby

The challenges

1. To understand the strategies and the attitudes that our biology students have toward learning physics
2. To increase the biological authenticity of reformed IPLS sequence at UMD - PHYS 121/122
3. To incorporate physical principles into the intro bio sequence at UMD – first BSC1 207
4. To develop, evaluate, and revise effective strategies for teaching physics to biology students.

We have much to learn from each other!

Ask our biology students

First discussion: Identify the activities to which you devoted the most time in previous biology classes.

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1. Taking lecture notes
2. Making flash cards
3. Underlining textbook
4. Memorizing lecture notes
5. Taking practice tests
6. Searching the web to find better explanations

Fr. Guido Sarducci's 5-minute university

Ask our biology students

First discussion: Identify the activities to which you devoted the most time in previous biology classes.

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4. Taking practice tests
5. Searching the web to find better descriptions

1. Creative thinking
2. Team work
3. Learning new technologies
4. Communication skills
5. Applying knowledge toward solving new problems
6. Using the internet to acquire new knowledge

Intro Biology at U Maryland

BSCI 105 – molecular and cell biology

BSCI 106 - ecology and evolutionary biology

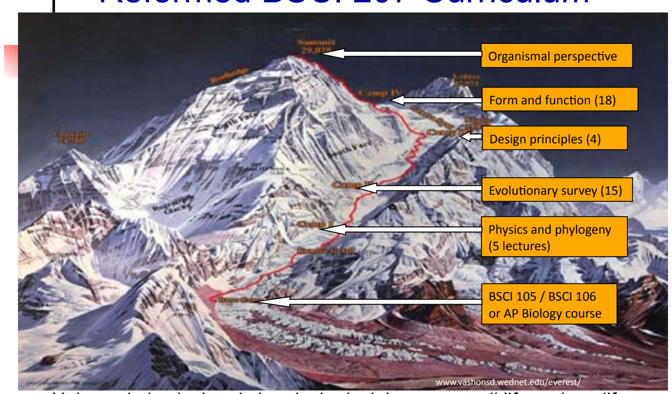
BSCI 207 – organismal biology - diversity, structure, and function

Conventional approach to organismal biology – "forced march" through the individual phyla and separate units of plant and animal functions

Introductory biology challenges

- Biology students are selected for their short-term memories – "binge learning and projectile forgetting"
- Available intro bio teaching materials:
  - Tend to emphasize isolated facts, not broad principles
  - Often start with an extensive unit on the chemistry of life, but the physics of life is scattered as isolated topics (or often unmentioned – e.g., entropy's role in protein folding and virus assembly)
  - Often describe physical and chemical processes in qualitative terms -> limited opportunity for quantitative reasoning
  - Tend to promote the maintenance of silo thinking separating different disciplines, as opposed to interdisciplinary thinking
- Are there any principles in organismal biology?

Reformed BSCI 207 Curriculum

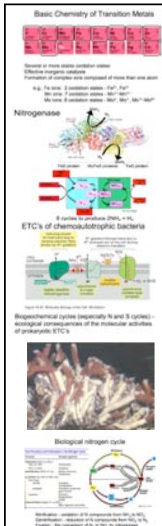


- Universal physical and chemical principles govern all life and nonlife
- Common genomic heritage of all life (LUCA or LUCAC)
- Unique form and function relationships for carrying out life's processes

Charles Darwin's concluding sentence

"There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved."

On the Origin of Species, 1st Edition, 1859



Lecture example: Prokaryotic metabolism

- **Conventional approach** – a survey of metabolic activities of different prokaryotic groups

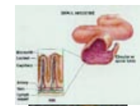
BSCI 207 Approach

- **Chemical principle -** transition metal redox chemistry
- **Molecular mechanisms**
  - Ferredoxin, water-splitting complex, nitrogenase
  - Aerobic respiration – electron transport chain
  - Anaerobic respiration – homologous ETC's with different donors and/or acceptors
  - Photosynthetic ETC's – homologous and unique complexes and shuttles
- **Organismal integration -** different trophic strategies
- **Ecological consequences** – N and S cycles

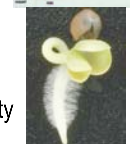
Lecture example: Nutrient assimilation

- **Conventional approach** – nutrient assimilation in fungal hyphae, plant roots, and animal small intestines are discussed in separate units

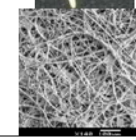
BSCI 207 Approach



- **Homologous P-type ATPases** for establishing cation electrochemical gradients across plasma membranes
- **Homologous carriers and channels** for transporting nutrients



- **Common design features** of n.a. organs – e.g., elaborated surfaces, high levels of mitochondrial activity
- **Unique structure-function relationships in** fungal hyphae, plant roots, and vertebrate small intestines



- **2nd class focusing on vertebrate/mammal/human** digestion

Revised BSCI 207 curriculum, with conventional lecture pedagogy

- High faculty satisfaction, but most students "revert to wild-type":
- Lectures did not appear to change student learning practices or their attitudes toward learning
- Silo maintenance – considerable resistance to learning "the hard stuff", namely physics and math. "Why are they teaching us physics in a bio class?"
- Principles viewed as "more stuff to memorize for the tests", as opposed to using the principles to organize their knowledge into coherent themes
- Reluctant to switch from fact acquisition to reasoning from principles
- Struggled to apply their knowledge toward solving new problems
- Limited ability to articulate their knowledge except to eliminate the wrong answers on m-c tests

HHMI/NAS Summer Institute for Undergrad Biology Education – Summer 2009

Thelma/Todd: [stopping suddenly at the edge of a cliff] *What is this?*

Louise/Jeff: *I don't know, I think... I think it's the Grand Canyon (of active engagement)!*

Thelma/Todd: *OK, then listen; let's not get caught.*

Louise/Jeff: *No matter what happens, I'm glad I came with you…. Hey, who locked this door?!*

Group active engagement exercises

- Set up protected niche– small pilot class with self-selected students and expressed commitment to change pedagogical strategies & student attitudes
- Focus GAE's on major principles that are not well-conveyed by lectures, as judged from essay answers on previous exams
- Individual working groups composed of 3 or 4 students.
- GAE's designed to help students use prior bio knowledge to generate mathematical, conceptual, computer, or physical models of these principles
- Group homework exercises requiring the students to apply these models toward solving new problems
- Encourage students to discuss the homework problems outside of class, but write up the problems independently of each other.

Group active engagement exercises

- Formative assessments – two instructors for every class (Biology: Cooke/Jensen and Physics: Redish/Losert); recruit the students as co-conspirators: use office hours and in-class and after-class discussions
- Formative assessments – Jessica Watkins and Kristi Hall: videotaping of in-class discussions and one-on-one semi-structured interviews; use of pre- and post-class expectations surveys
- Weekly meetings to review previous week's activities and prepare for next week's activities; reiterative process of presentation, analysis, and revision
- Low initial success rate for several reasons, e.g., I was trying to teach physics in a biology class by deriving equations from first principles.

"Typical" GAE format

1. Introductory presentation – learning goals and fundamental knowledge (5 - 10 min)
2. Small-group activities – brainstorming, concept mapping, model construction, etc. with intermittent brief class discussions (20 - 30 min)
3. Summary class discussion, major conclusions, and homework preparation (5 - 10 min)
4. Application of principles - group homework

Physics GAE's – thermodynamics, diffusion, fluid flow, biomechanics, and scaling

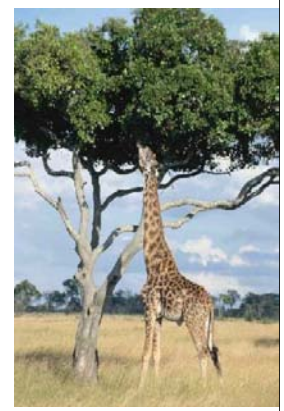
Group active engagement exercises

Initial GAEs created

Concept(s)	GAE's (small group activities and class discussions)
Introduction to active learning	Clicker questions, group/class discussions
Thermodynamics	Concept-mapping of biological energy flow
Descent from common ancestors	Phylogenetic tree interpretation
Electron transport chain	Student enactment of ETC
Endosymbiosis	Guided pipe-cleaner modeling
Eukaryotic sex	Concept-mapping of life cycle
Diffusion	Computer simulations to generate Fick's laws
Form-function relationships	Scaling demonstrations and model organism design
Circulation = bulk flow	Small-group work to generate Hagen-Poiseuille equation
Transmembrane transport	Student enactment of transport mechanisms
Osmoregulation	Small-group problem solving
Biomechanics	Small-group manipulations of lever systems

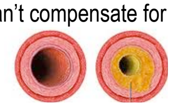
A Simple GAE: Circulatory Systems

- Lecture - brief description of analogous features of mechanical, animal, and plant circulation
- Which organism has the more powerful pump? Some arguments are:
  - Acacia - due to its greater height
  - Giraffe – blood squirts out of its wounds
- How might pressure be related to flow?
- Short struggle, then resistance!
- Thus, group discussions generate a simplified version of the Hagen-Poiseuille equation $\frac{V}{t} = \frac{\Delta P}{R}$

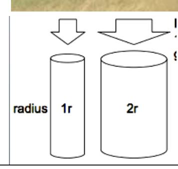


A Simple GAE: Circulatory Systems

- Compare circulation in animals vs. plants
  - Mammals - lower ΔP, much lower R, and much higher V/t as compared to plants
  - Natural selection works on V/t in animals, and ΔP in plants
- Arms up to show the low ΔP from human heart
- Predict flow rate in vessels of different radii
- Effect of arteriosclerosis – why ΔP increase can't compensate for r decrease



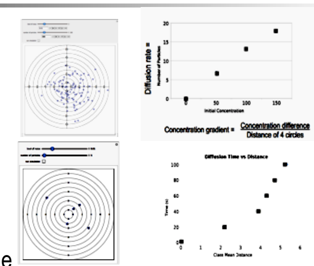
$$R = \frac{8l\eta}{\pi r^4}$$



50% occluded artery ⇨ 94% decrease in V/t !!!

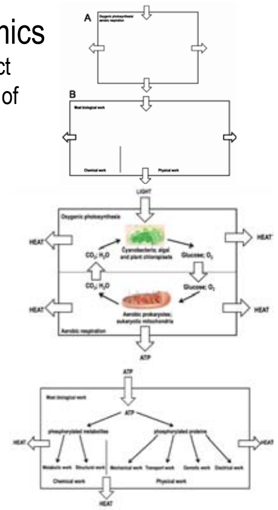
Diffusion GAE: Modified random walk simulations to generate diffusion equations

- Run simulations with different particle numbers over fixed distance for same time
- Run simulations with same particles over sequential time periods
- Send group data to Google docs file
- Students generate linear relationship of J and $\Delta C/\Delta x$ $\quad J = -D\frac{\Delta C}{\Delta x}$
- Students generate exponential relationship of Δx and t $\quad t = \frac{\Delta x^2}{2D}$
- Group homework problems on applying these equations toward understanding biological phenomena



A Complex GAE: Thermodynamics

- Each group used the templates to construct biological energy flow diagrams from a list of terms.
- Class discussion developed consensus diagrams
- Each group identified the general features and operating rules for energy flow in colloquial terms
- Class discussion of each group's rules
  - Energy balance rules = First Law
  - Reaction direction rules = Second Law
- Concluding lecture on thermodynamics laws and fundamental equations for answering group homework problems.



Research evaluation of pedagogical changes

Classroom videos

Semi-structured, one-on-one student interviews

Maryland Biology Expectations Survey (MBEX)

Student artifacts - exams and homework

Standard university on-line student reviews

Student Feedback in BSCI 207

Standard UM survey questions	Mean scores on Likert scale					
	S 2008 lecture	S 2009 clickers	S 2010 GAE's	F2010 Honors GAE's	S2011 GAE's	F2011 Honors GAE's
The course was intellectually challenging	4.21	4.45	4.59	4.51	4.51	4.68
I learned a lot from this course	3.77	4.02	4.23	4.14	3.99	4.32
The instructor helped create an atmo-sphere that kept me engaged in course	3.91	4.15	4.45	4.58	4.07	4.60
Overall, this instructor was an effective teacher	4.22	4.36	4.49	4.62	4.27	4.68
How much effort did you put into this course? (little/moderate/considerable %)	9/38/53	4/50/46	2/25/74	3/38/58	2/31/67	2/28/70

Likert scale: 1=strongly disagree; 2=disagree; 3=neutral; 4=agree; 5=strongly agree

MBEX (Maryland Biology Expectations) Survey

Kristi Hall

- On-line pre- and post-class survey of 32 Likert-style items (1-strongly disagree to 5-strongly agree)
- Derived in part from Maryland Physics Expectations Survey, but targeted for biology students in their biology and other science courses.
- Various statements about the nature of biology, the study of biology, and their attitudes toward biology.
- Intended to measure "functional epistemology" – What knowledge will I learn in this class and what do I have to do to learn it?
- Measures what students think they do rather than what they actually do.
- Validated survey statements by 10 student interviews
- 32 questions are grouped into 4 non-orthogonal, non-exclusive clusters
- Students may often give contradictory and changeable responses to an individual question, but we see considerable stability within the clusters

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MBEX 2 Survey Structure

- ***Independence v. Authority*** - Ideas about learning biology—whether it means taking responsibility for constructing own understanding or taking what is given by authorities (teacher, text) without evaluation.
- ***Facts v. Principles*** - Ideas about the structure of biological knowledge—whether biology needs to be considered as a connected, consistent framework or biology can be treated as unrelated facts or "pieces."
- ***Interdisciplinary Perspectives v. Silo Maintenance***- Ideas about the value about incorporating other disciplines into undergraduate biology courses–Believes that knowledge processes are shared among the disciplines or focuses on the traditionally held conceptual divides in the disciplines.
- ***Connected v. Isolated***- Ideas about the purpose of education—Whether knowledge learned in the biology classroom is relevant and useful in a wide variety of real contexts or ideas learned in biology only serve limited purposes and have little relation to future endeavors.

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Sample statements from interdisciplinary cluster (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)**

The benefits of learning to be proficient using math and physics in biology are worth the extra effort. **(+1)**

Math provides another way of describing biological phenomena, but rarely provides a deeper or better understanding. **(-1)**

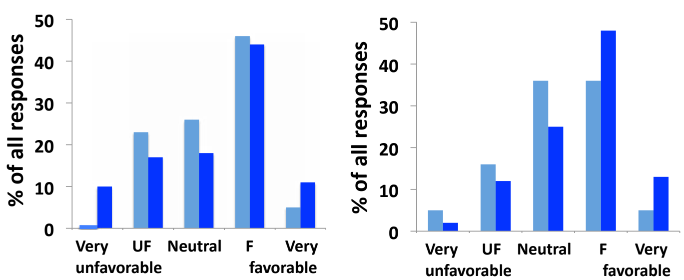
Time should not be taken out of biology courses to present physics. (-1)

It is beneficial to me, as a biologist, to be also proficient in physics. (+1)

MBEX 2 Initial Results – Physics cluster (We have met the enemy, and we are looking in the mirror!)

Reformed IPLS class (increased bio relevance)

Reformed Org Bio class (5 GAE's with explicit physics)



Mean 3.4 → 3.3

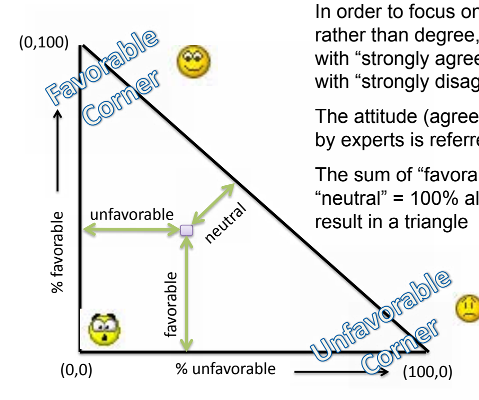
Mean 3.1 → 3.6

Pre-class

Post-class

K. Hall (in prep.)

How to Compare Across Classes: 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

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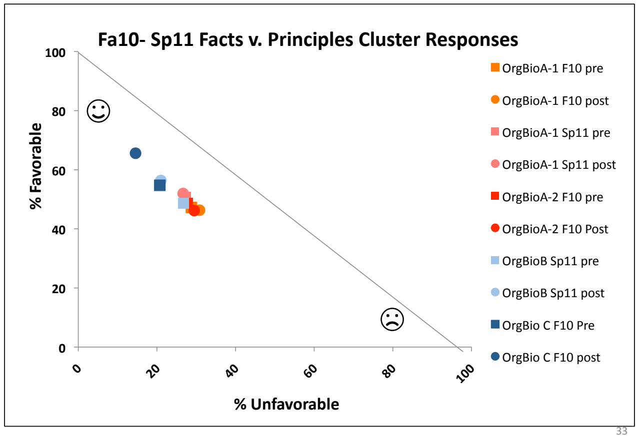
MBEX 1 Results



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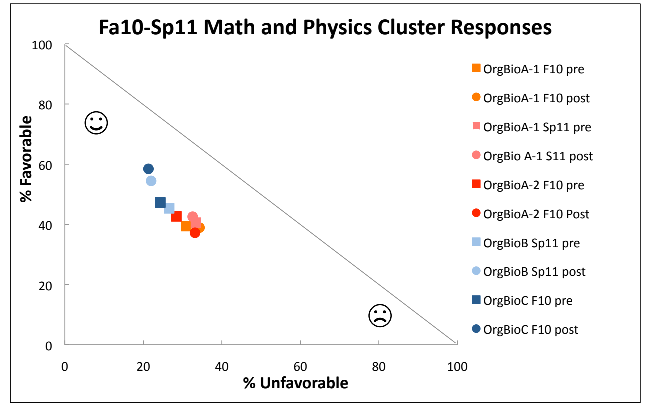
MBEX 1 Results



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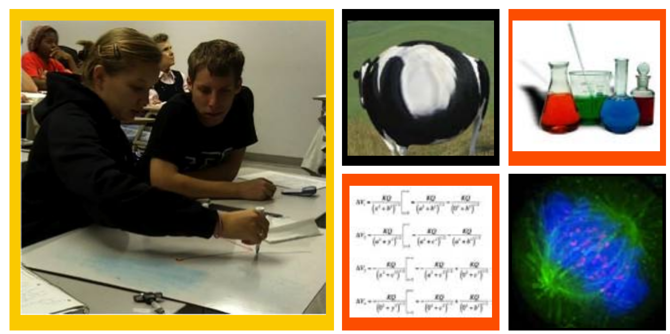
Tentative interpretations

1. Relevant physics can be successfully taught in an introductory biology class using active-engagement pedagogy.
2. Biology teachers at UM have benefited greatly from the conceptual and pedagogical advice from our IPLS colleagues.
3. However, physics principles are developed in 207 by direct manipulation of physical parameters and/or prior intuitions (instead of being derived from fundamental principles) and are immediately applied to bio applications
4. **Testable hypothesis**: it is hoped that these biology students will maintain persistent favorable attitudes toward physics into their IPLS courses.
5. In our experience, meeting the challenges of *BIO 2010, SFFP,* and *V & C* in both introductory biology and IPLS classes requires effective collaborations between physicists and biologists.



NEXUS
NATIONAL EXPERIMENT in Undergraduate Science Education

Progress through Paradox:
Reconciling Interdisciplinary Perspectives

HHMI

Joe Redish, UM Project Director

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

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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)*

HHMI

Goals of NEXUS: A national demonstration project

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- Create prototype materials
  - an inventory of instructional modules that can be shared nationally as open source materials.
- Interdisciplinary
  - Coordinate and assess instruction in biology, chemistry, physics, and math at four universities
- Competency based
  - Teach generalized scientific skills in a way that supports instruction in the other disciplines.

The NEXUS Development Team (UMCP)

39

- **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-Burke*

Discussants: UMCP co-conspirators

40

- **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

41

- Physicists
  - Catherine Crouch* (Swarthmore)
  - Royce Zia* (Virginia Tech)
  - Mark Reeves (George Washington)
  - Lilly Cui & Eric Anderson (UMBC)
  - Dawn Meredith (U. New Hampshire)
- Biologists
  - Mike Klymkowski* (U. Colorado)
- Chemists
  - Chris Bauer* (U. New Hampshire)
  - Melanie Cooper* (Clemson)
- Education
  - Janet Coffey (Moore Foundation)

**NSF TUES project*

Previous reform class

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- 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).

Previous Results

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- The Maryland Physics Expectations (MPEX) survey 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%).

Starting in a hard place

44

- 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 composed of canonical topics with no room for change.

Changes in the culture and expectations of the course

45

- 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"
  - Explicitly discuss modeling and the value of understanding "simplest possible" examples.
- Choose different content from the traditional by including molecular and chemical examples and topics of more importance to biology.

And...

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- Negotiate these changes through extensive discussions among biologists, chemists and physicists
- We want to seek content and examples that will be seen by biologists and by chemists (and by biology and chemistry students) as ***authentic*** – it helps make sense of something that has real importance in biology and chemistry

But...

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

The culture of the disciplines

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- There is much more than changing the table of contents and the prerequisites.
- From each level of their experience with a discipline – small group, STEM classes, broader school experiences – students 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.

Physics

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- 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

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- 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*.

Revising the content

50

- **Expand**
  - Atomic and molecular models of matter
  - Energy, including chemical energy
  - Fluids, including fluids in motion and solutions
  - Diffusion and gradient driven flows
  - Dissipative forces (drag & viscosity)
  - 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
  - Macro thermodynamics
  - Magnetism
  - Relativity

Approach

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1. Start off with an emphasis of physical understanding of atoms and molecules – the basis of modern biophysics
2. Identify an important phenomenon involving the fundamental physics that can address a significant issue in biology and chemistry, e.g., the energetics of ATP hydrolysis.
3. Negotiate feasible approaches among physicists, biologists, and chemists.
4. Create a chain of associated tasks for pre-class reading, active-engagement class activities, recitations, homework problems, and test questions (formative assessments)
5. Observe student behavior in response to these tasks.
6. Refine tasks by negotiation among physicists, biologists, and chemists. (Including write papers and submit for peer review.)
7. Repeat steps 3-7.
8. Extract multiple choice analogs for summative assessment.

Goal: Maintain previous gains

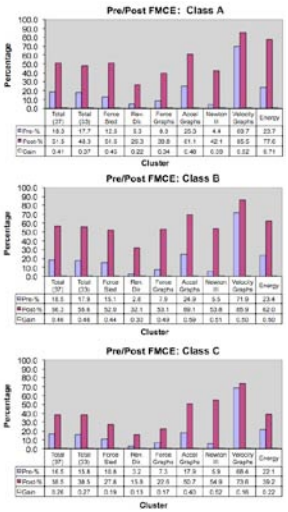
52

- 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

Force Motion Concept Evaluation: 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



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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.

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Ashlyn prefers to keep her sciences separate.

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

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, Ashlyn got excited about how math explained scaling relation (surface-volume).

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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.
- Develop the MBEX survey 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

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- 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 knowledge will I learn in this class and what do I have to do to learn it?
- Measures what students *think* they do rather than what they *actually* do.

To keep up with with where PERG is now:

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- http://umdberg.pbworks.com/w/page/44091483/Project%20NEXUS%20UMCP
- Or search: NEXUS UMCP
- Much is available but not all. This is our working environment as well.