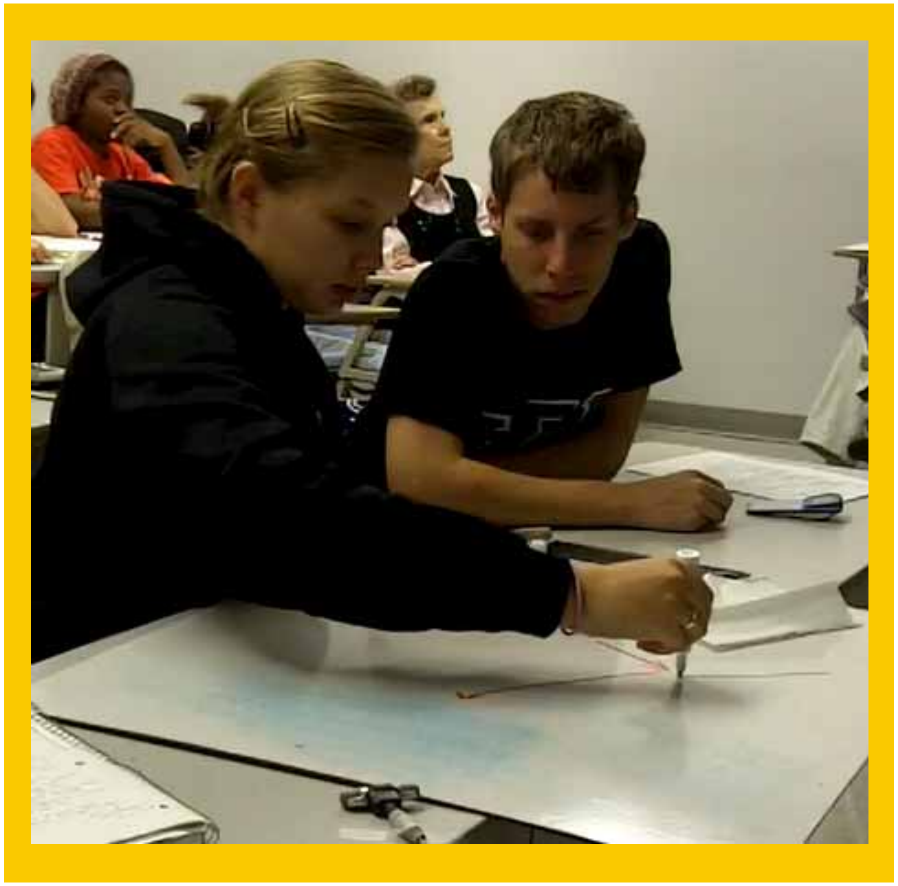
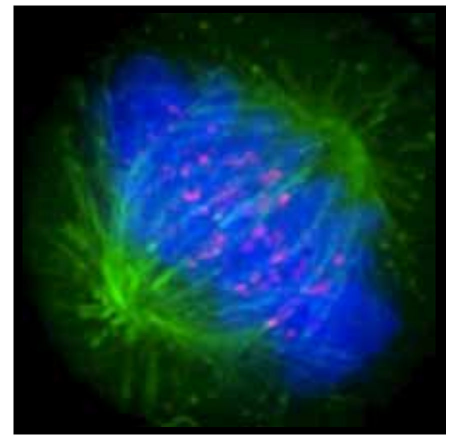


$$\Delta V_1 = \frac{KQ}{\left(x^2+b^2\right)^{1/2}}\Bigg|_{x=0}^{x=a} = \frac{KQ}{\left(a^2+b^2\right)^{1/2}} - \frac{KQ}{\left(0^2+b^2\right)^{1/2}}$$

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

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

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



Teaching Physics to Biologists:

Can we do some Stat Mech in Physics I?

Edward F. Redish

University of Maryland

HHMI

Outline

- Calls for reform of bio education
- The HHMI NEXUS project
- Explicit goals for the Physics course
- The barriers – students and faculty!
- Statistical issues and examples

Calls for reform of bio education

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.

Some comments from the leadership.

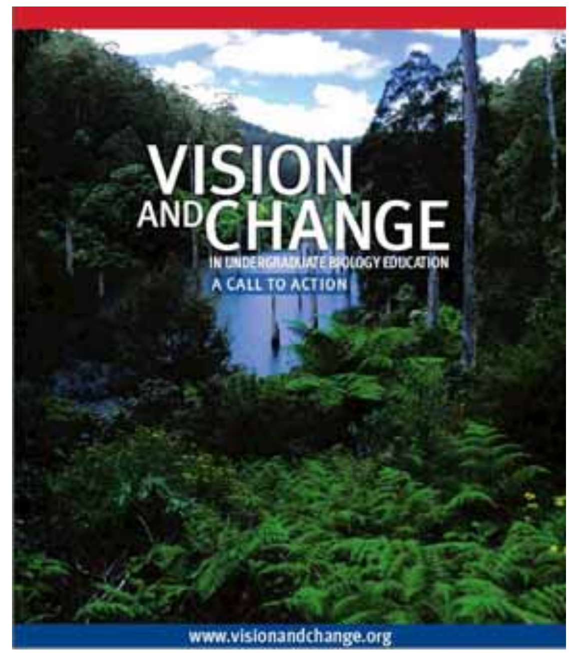
- Biology is rapidly becoming a science that demands more intense mathematical and physical analysis than biologists have been accustomed to, and such analysis will be required to understand the workings of cells. (*H. Varmus, APS News, 1999*)

- The departmental structures at most universities seem to have thus far prevented any major rethinking of what preparation in mathematics, what preparation in physics, and what preparation in chemistry is most appropriate for either research biologists or the medical doctors who will be working 10 or 20 years from now. The result is a major mismatch between what today's students who are interested in biology should be learning and the actual course offerings that are available to them. (*B. Alberts, Cell, 1998*)

Calls for Bio Education Reform

NAS 2003

HHMI-AAMC 2008



AAAS 2009

Comments from the reports

- Life sciences majors must acquire a much stronger foundation in the physical sciences (chemistry and physics) and mathematics than they now get. Connections between biology and the other scientific disciplines need to be developed and reinforced so that interdisciplinary thinking and work become second nature. (BIO 2010, 2003)

- One goal of this project is to provide greater flexibility in the premedical curriculum that would permit undergraduate institutions to develop more interdisciplinary and integrative science courses, as recommended in the BIO 2010 report. By focusing on scientific competencies rather than courses, undergraduate institutions will have more freedom to develop novel courses…(AAMC-HHMI report, 2009)

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?

The HHMI NEXUS Project

Project NEXUS

HHMI

- National Experiment in Undergraduate Science Education
  - A 4-year $1.8 M project of the Howard Hughes Medical Institute
- Interdisciplinary science education stressing competency building
  - UMCP (physics)
  - UMBC (math for bio)
  - Purdue (chemistry)
  - University of Miami (capstone case study synthesis)

Goals of NEXUS

- A major task of each group is to coordinate the biology, chemistry, physics, and math instruction.
- Competencies
  - A major goal of each group is to find ways to teach generalized scientific skills in a way that support each other.
  - And to find ways to evaluate whether those skills have been learned!
- We have been negotiating extensively with biologists for more than a year on the content and goals of the physics course.

Discussants

- Physicists
  - Joe Redish
  - Wolfgang Losert
  - Catherine Crouch (Swarthmore)
  - Jessica Watkins
  - Chandra Turpen
  - Ben Dreyfus
  - Ben Geller
  - Michael Fisher
  - Peter Shawhan
  - Arnaldo Vaz (Brazil)
- Chemists
  - Bonnie Dixon
  - Chris Bauer (UNH)
  - Melanie Cooper (Clemson)
- Biologists
  - Todd Cooke
  - Jeff Jensen
  - Karen Carleton
  - Joelle Presson
  - Kaci Thompson
  - Marco Colombini
  - Kristi Hall-Burke
  - Mike Klymkowski (Colorado)
- Education Specialists
  - Janet Coffey
  - Dan Levin
  - Jen Richards
  - Julia Svoboda
  - Gili Marbach-Ad

Explicit Goals of the Physics Course

General Goals

- To redesign the Physics for Biologists course so that it is appropriate for biology students – both in content and in skill development.
- To include authentic biological examples in which students see the use (and methods) of physics as helpful in helping them make sense of something important in biology.
- To have biology faculty teaching the upper division bio classes (neuroscience, cellular bio, mammalian physiology, etc.) see this course as a desirable prerequisite to their classes.

Non-goal

- The course is NOT intended to serve as a filter to exclude students from going on to medical school or in biology research.

Content decisions: Expand or include discussion of

- Atomic and molecular models of matter
- Energy, including chemical energy
- Fluids, including fluids in motion and solutions
- Diffusion and gradient driven flows
- More emphasis on dissipate forces (viscosity)
- Electrostatics in fluids
- Kinetic theory, implications of random motion, statistical picture of thermodynamics
  - Non-equilibrium thermo???!!

Content decisions: Reduce or eliminate discussion of

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

Implication

- The course is configured as a *second year* class so it can serve as a pre-requisite for upper division bio classes.
- The course has unusual pre-requisites:
  - Two semesters of bio including some cellular bio, biochem, genetics, and evolution.
  - One semester of chemistry
  - Two semesters of math including one-variable calculus and basic elements of probability.
- We are currently teaching a first version of this class to ~20 students.

What we've done so far

- A wikibook for student readings
  - Students read 2-3 webpages before each class and write a brief summary and question for each.
- Homework problems that do physics skill development in biological contexts.
  - How big is a worm?
  - Moving listeria
  - PIP_2 forces
- In-class clicker problems and group problems
- Observations
  - Video of lectures (students discussions and whiteboard work)
  - Interviews with individual students in physics and bio classes

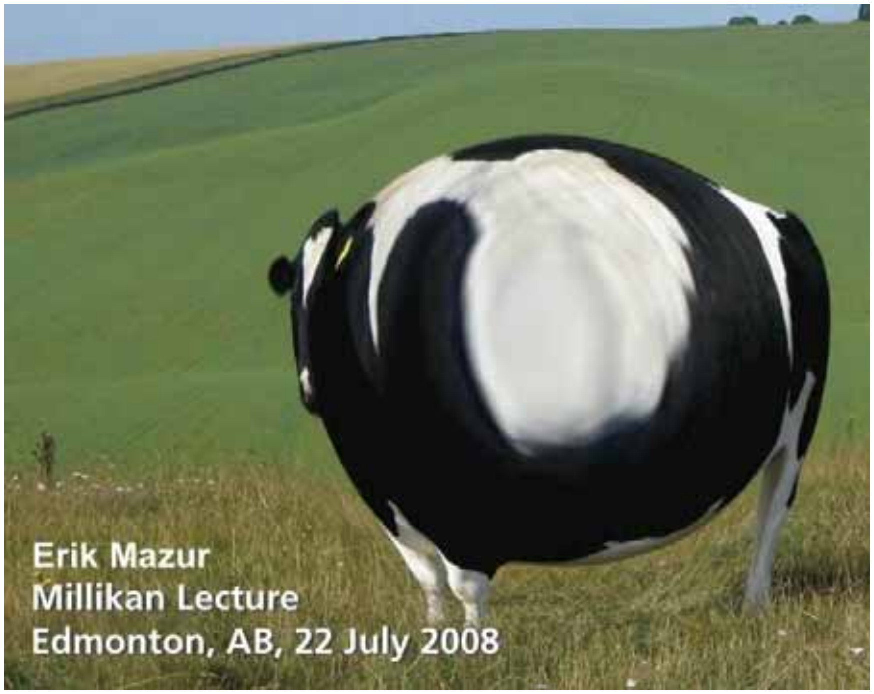
Barriers – Faculty

Conjecture

- One reason for the difficulty of getting more physics into bio and vice versa is epistemological – having to do with the nature and the structuring of the knowledge in the two professions.
- This plays out both in the attitudes of faculty and through student expectations.

Thinking about teaching physics…

- “Physics should be as simple as possible – but not simpler.” (Einstein)
- “The physics we are learning in this class is simple – but seeing that it is simple can be exceedingly difficult.” (Redish)



Physics simplicity

- In physics we tend to seek the simplest example and understand it thoroughly.
- This serves as the “stake in the ground” to use to organize our later thinking about more complex systems.
- We work from a few clear (nearly) universal principles and tie everything to them – often deriving dozens of equations from one starting point – plus assumptions about situations and initial conditions.

Physics tries to establish a simple core

- Although there is a lot to do to interpret all this, it both
  - ties to everyday experience and
  - has a small number of ideas and relations that organize the complexity of the material.
- Bio looks different.

+ Physics

- Intro physics often stresses reasoning from a few fundamental principles.
- Physicists often stress building a complete understanding of the simplest possible examples – and often don't go beyond them at the introductory level.
- Physicists often quantify their view of the physical world and model with math.
- Physicists think with equations.
- Introductory physics typically restricts itself to the macroscopic level and almost never considers chemical energy

Thinking about teaching biology…

- Biology seems irreducibly complex.
- Every living organism involves thousands of chemicals and tens of thousands of reactions. (More? OK)
- Biology has a "historicity" that physics lacks. It could, in principle, have happened some other way.

Problem

- Biological systems larger than the simplest viruses have complex structures at a multiplicity of levels.
- Even beginning to talk about a complex biological system requires learning a large new (and arbitrary) vocabulary.

Technical words in intro physics are often based on terms in everyday speech. While this causes some confusion, it also gives an interpretive foothold.

Biology

- By its very choice of subject biology is complex.
- Most introductory biology is qualitative.
- Biology is fundamentally historical.
- Much of introductory biology is descriptive (and introduces a large vocabulary) though
- Biology – even at the introductory level – looks for mechanism and frequently considers micro to macro connections.
- Chemistry is much more important to intro bio than physics (or math).

Barriers – Students

Student expectations

- The UMdPERG has learned that student expectations play a large role in what they do in a physics class.
- This sometimes leads them to NOT use skills and knowledge that they possess and have easy access to.
- This problem is particularly difficult with bio students.

One students' view about physics and biology

- "[Physics class] talks a lot more about physical objects, stuff like that, which you don't really talk about in bio or chem. You don't really talk about macro stuff… Biology, it's more about interactions of molecules."
- When asked if the concept of energy used in physics and biology classes could be connected, he responded: "They have different units [and] …even if there were a way to connect the two, which I … can't think of a way, I don't really think there would be a point in doing so."

+ Biology students bring expectations to their physics and biology classes.

Ashlyn prefers her science in silos

I don't like to think of biology in terms of numbers and variables. I feel like that's what physics and calculus is for. So, I mean, come time for the exam, obviously I'm gonna look at those equations and figure them out and memorize them, but I just really don't like them.

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

More specific goals

- To help students learn to reason mathematically, including to blend mathematical representations and conceptual physics.
- To help students learn to understand scientific modeling.
- To help students learn to quantify their experience (estimation).
- To help students learn to imbed and see the implications of physical mechanism in biology.
- To help students learn to reason from basic principles and seek consistency (suppressing one-step recall).

Statistical mechanics in Physics 1?

+ Statistical physics plays a role

- Statistical physics is rarely taught in any significant way in the traditional "algebra-based" physics class that bio majors and pre-meds take.
- Yet it plays a critical role in the development of some of the important ideas the biologists would like us to help their students understand.

Some concepts

- Kinetic theory
  - Much of what happens in biology relies on random thermal motions. Students tend not to get this and to assume everything in molecular biology is directed.
- Thermodynamics
  - The first and second laws play a critical role in constraining and organizing biology. While bio students are introduced to these concepts in chemistry and they are used in bio, they appear to have a very poor conceptual understanding of them.

Plan 1: Stress role of energy – and include more types

- Mechanical energy and Newton's laws
  - Kinetic
  - Potential – springs, gravitational, electric
- Energy conservation
  - Thermal energy
- Sub-molecular energies
  - Inter-atomic forces
  - Chemical bonding
  - Chemical energy
- The first law of thermodynamics

Plan 2: Include specific discussion of stochastic processes.

- Kinetic theory and the ideal gas law
- The role of randomness
- Diffusion and random walks
  - Fick’s law
  - The Einstein-Smolouchowski relation
- The second law of thermodynamics
  - Entropy
  - Gibb’s free energy
  - Chemical potential

Is this really possible?

- The way we traditionally treat thermodynamics requires a substantial amount of abstract math *first* – with intuitions developed later (if ever).
- This population is strongly resistant to this approach. They want conceptual underpinnings to their equations and specific biological examples.

Student reading notes for a webpage on randomness

- The reading suggests that diffusion is in response to random change or randomness, but if all means of passive transport including diffusion were completely random, then wouldn’t this greatly decrease the efficiency of cellular processes if we're waiting for the chance that these random changes occur? I feel like something must be directing this "randomness" even if there is no force involved.
- I don't quite understand how randomness can lead to directed results?
- Why is it that lots of molecules together have regularities, but not individual molecules? What causes these regularities to arise?

Student reading notes for a webpage on diffusion

- it still seems unclear how the molecules "know" that they should move from high concentration to lower concentration
- If diffusion is just a result of the random movement of molecules, then why does diffusion "stop" when two solutions or whatever are at equilibrium? Although it is unlikely, is it possible for molecules to randomly move back into their original [position]?
- So is it safe to say they move from high to low because in high concentrations they keep colliding and getting pushed around. Until eventually they reach low concentrations don’t have as many collisions and wander more freely there?

+ Student reading notes for a webpage on Fick's law

- I'm a bit confused about how with diffusion the particles are moving in every direction but the flow is caused by the difference in concentrations. I intuitively would think the molecules are moving in the direction of the flow.
- It says the minus sign in front of Fick's law tells us that the flow is opposite the derivative, however, I do not really understand why that is. I do understand that the flow goes from high to low concentration, just not the part about the derivative.
- So if we are analyzing multiple molecules we can ignore there interactions and they'll move to a lower concentration of their own species even if they are in a side of overall larger molecular concentration?

Questions for discussion

- Given the students' limited experience with mathematical reasoning, are there more conceptual ways to introduce the concepts of
  - Entropy?
  - The second law of thermodynamics?
  - Gibb's free energy?
  - Chemical potential?
  - Non-equilibrium issues?
- Authentic biological examples?