Transforming the Physics Education of Undergraduate Biology Students in Introductory Physics and Biology Courses

Edward F. Redish[1], Todd J. Cooke[2], Heather D. Dobbins[1,2], & Kristi L. Hall[2]

Departments of [1]Physics and [2]Cell Biology & Molecular Genetics, University of Maryland USA

Abstract: In 2003, the US National Academy of Sciences issued the BIO 2010 report that called for the increased incorporation of mathematics, physics, and chemistry into undergraduate biology curriculum, and for a corresponding increase in the biological relevance of introductory science courses for biologists. This initiative has led to widespread interdisciplinary efforts that are transforming the way mathematics and chemistry is taught to US biology students, but it has not prompted comparable reform in physics. There appear to be a number of reasons for this lag. Many Physics faculty are hesitant about pruning and reorganizing traditional content and may not be familiar with the content that biologists feel is relevant and useful, while many Biology faculty are hesitant about including physics in their biology classes explicitly. At the University of Maryland, a group of physicists and biologists have started working together to better understand the roadblocks to implementing a coordinated revision of our introductory biology and physics courses for biology students. The challenges facing this effort occur at a variety of levels. 1) Introductory physics for biologists is often a "cut-down" version of introductory physics for engineers. As such, it inherits some inappropriate approaches. For example, it introduces the second law of Thermodynamics via heat engines and ignores chemical energy. This approach is inappropriate because organisms cannot convert temperature gradients into useful metabolic energy, whereas other forms of physical and chemical energy are continually being transformed in biological systems. 2) Introductory biology classes typically are "fact-based", relying on extensive reading and focusing on concept mastery, including introducing the student to many different terms, processes, and relationships, while physics courses are structured to emphasize complex reasoning from a small set of fundamental laws and principles. 3) Physics classes rely heavily on problem-solving and are over the past decade have developed extensive active-engagement learning pedagogy, whereas biology courses still tend to rely heavily on direct lecture and protocol-based laboratories. 4) Biology classes tend to use mathematics to represent qualitative dependences, while physics classes treat math as a fundamental reasoning tool. Our poster presents examples and suggestions for bridging these gaps. Our goal is to initiate a widespread discussion among physicists and biologists regarding the physics challenge in the BIO 2010 initiative.

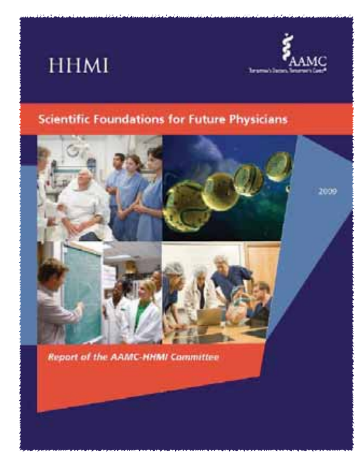
Why should a physics department teach physics to biologists?

The biologists who are thinking about the future of biology instruction want their students to learn physics content and to acquire scientific skills that can be appropriately developed in physics classes.

The US National Academies of Science Report, *BIO 2010*, call for biologists to study more physics and chemistry. (2003)

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.

US pre-health care students also take physics. The American Association of Colleges of Medicine and the Howard Hughes Medical Institute have produced a report identifying specific goals for pre-medical student learning. The report stresses (and details) a list of competencies to be attained at the time of entry to medical school including the following:



***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.*

Physics is not only an essential component of these competencies; for some of the more general competencies (such as understanding the process of inquiry), physics is a highly appropriate place to build a solid basis for those competencies.

However, often, neither the required college biology courses nor the physics courses for biology majors are designed to help students develop these competencies.

Traditionally taught introductory physics often fails to address the relevant content and skills.

In the USA, introductory physics classes for biology majors and pre-health-care professionals is often algebra-based and is typically a "cut-down" version of a physics course for engineers. As such it has a number of problematic characteristics for bio students.

- The content tends to be appropriate for engineers, not biologists.
- The examples tend to be non-biological; when biological examples are added, they are often trivial, uninteresting, or even incorrect (in both the biology and the physics).
- The use of mathematics is appropriate for students who are fluent in formal mathematics and does not support the blending of mechanistic qualitative reasoning with math.
- The pedagogy is insufficient to help students with epistemological misconceptions about the nature of the knowledge they are learning.

A "biologized" problem in the second edition of a text for pre-health-care students:

On a hot 35 C day, you perspire 1.0 kg of water during your workout.

(a) What volume is occupied by the evaporated water?
(b) By what factor is this larger than the volume occupied by the liquid water?

The only reference to "photosynthesis" in one of the few intro physics texts for biologists that have the item in the index:

The light that plants absorb to permit photosynthesis has a wavelength that peaks near 675 nm. Express this distance in (a) millimeters and (b) inches."

Traditionally taught introductory biology often fails to address the relevant content and skills.

In the USA, introductory biology classes for biology majors and pre-health care professionals focus on the acquisition of biology facts, generally relying on powerpoint lectures, protocol-based labs, and extensive readings from large textbooks to expose the students to many different terms, processes, and relationships. As such, they present a number of significant obstacles to bio student learning.

- Both faculty and students tend to emphasize memorization of facts as opposed to higher-level cognitive skills. For example, the diversity of life is often taught as a "forced march through the phyla", where students are expected to memorize the diagnostic characteristics of major groups.
- Bio courses are organized in a hierarchical manner from molecules to ecosystems. Since the physics relevant to biological phenomena tends to operate at multiple levels, this physics is typically presented in a disjointed, unquantitiative manner, with no opportunity to apply the relevant equations to solve biological problems.
- Only recently have biologists begun to adopt active-engagement learning strategies for their classrooms, in large part due to the encouragement of the BIO 2010 report.
- Very little effort has been devoted to studying student epistemology in biology classes, in contrast to the considerable effort in PER.

The Epistemology Gap: "What am I supposed to be getting, here?"

In both physics and biology classes, students' perceptions of the nature of the knowledge that they are supposed to be learning is often deeply flawed. These "epistemological misconceptions" can severely hamper student learning. Here are some examples:

- Mathematics and physics are not really relevant for biology and should not be used in an introductory biology class.
- Science knowledge -- especially biological knowledge -- consists of many bits of independent information. The only way to learn science is to memorize large quantities of information.
- Answers are what matters, not the reasoning process that lets you develop an answer.
- You either know something or you don't. Checking it or evaluating it against other bits of knowledge is a waste of time.

Many of these ideas have been strongly supported in pre-college instruction, especially when that instruction is for the purpose of passing a standardized test. It is difficult and costly to construct standardized tests for large numbers of students that address the more subtle epistemological points raised here.

First Steps: A Biology Class That Uses Physics Content

In introductory bio classes and associated textbooks, the diversity, structure, and function of organisms are almost universally presented as a series of isolated organism-specific units. For the past five years, the bio faculty at the University of Maryland has taught introductory organismal biology (BSCI 207) from the perspective of the fundamental principles operating in all organisms.

- These principles include: 1) all life and non-life are governed by universal physical and chemical principles, and 2) all organisms are descended from a common ancestor (or ancestral community), which means that they share a common genomic toolkit for exploiting universal physicochemical principles to carry out life processes.
- Major emphasis is devoted to the basic concepts and biological applications of: thermodynamics (energetics, metabolism, structure, and information processing), transport processes (diffusion, fluid flow, electricity, and heat transfer), and structural mechanics across all organisms.
- However, the 207 faculty have not utilized active-engagement learning strategies, have not created problem-solving exercises, and have not addressed the students' epistemological issues.

First Steps: Transforming a Physics Class for Biologists

For the past decade, a project at the University of Maryland has been developing methods for overcoming students' epistemological misconceptions and explicating the usually implicit curriculum of how to think scientifically (Redish & Hammer 2009). The class (PHYS 121-122) has been transformed pedagogically so as to

- Use modern PER-based active-learning pedagogy (PI, ILDs, UW-Tutorials,...).
- Refocus the class so as to emphasize epistemological issues such as reasoning from principle, explicitly seeking coherence, representation translation, and estimation.
- Emphasize the refinement and revision of physics intuitions.

What do biology students think about biology, physics, and physics in biology?

As part of our preliminary investigation, we interviewed six biology majors who were taking BSCI 207 and/or Physics 121. Here are some of the comments that we received.

- *I'm taking physics and chemistry and biology this semester and I get enough physics and chemistry in my physics and chemistry classes, and quite honestly I don't want to take one and a half physics classes and one and a half chemistry classes and then just say well there's a biological reason for the-, or there's a-, these cause a biological reasons, I would rather, I guess, um the biological subjects be mainly biology and not mainly um the chemistry involved or the physics involved.*
- *...it confused me, like, if, then why are you mentioning it if we don't have to memorize it? and that's the thing with exams, like, you're given so much for the exams but you're told not to memorize all the information*
- *it's so rare to have math in biology, like, I you know I haven't taken a biostat course or anything like that where it's definitely biology and mathematics put together umm (huh) when we did the physics stuff in 207 it was at times confusing, umm, and part of it may have been just not....no....I, I didn't take any physics in high school or anything like that so it's just like physics was completely outside of anything I had experienced*

Example: Gradient driven flow (The H-P Equation)

One example of a principle used in BSCI 207 is the Hagen-Poisseuille equation. This is not typically familiar to physicists who a not specialists in fluid flow and it is rarely mentioned in modern introductory physics texts. Here are some problems developed for PHYS 121-122 introducing, using, and thinking about the equation in a "physics-like" way.

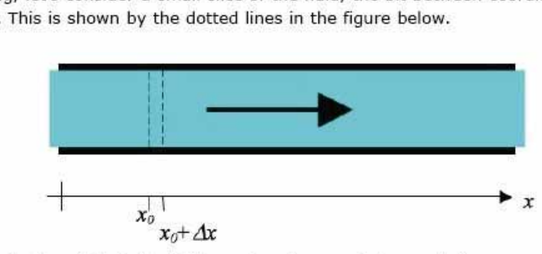
Ohms' Law in a Pipe

In this problem we consider what controls how much fluid is flowing through a pipe. The argument is set up here apply to water in the pipes in your house, but it could also be written in a similar way for blood in your arteries, or electrons in a wire. Our goal is to derive an equation relating the amount of fluid flowing in the pipe (current = I = mass/sec) and the pressure differential (ΔP) driving the mass through the resisting pipe.

Consider a fluid (of density ρ) completely filling a straight pipe (with circular cross section and radius r) and flowing through at a constant speed v. We will assume there is a drag force between the fluid and the wall that tries to slow the fluid down. A reasonable model for this force is that it is proportional to the area of contact between the fluid and the wall and to the speed of the fluid relative to the wall:

Drag force / unit length of pipe = - cv.

(a) How much fluid is entering (and leaving) the pipe per second? Express your answer in terms of the symbols we have defined so far. In order to figure out what is happening, let's consider a small slice of the fluid, the bit between coordinates x_0 and $x_0 + \Delta x$. This is shown by the dotted lines in the figure below.



(b) In order to maintain the fluid moving at a constant speed, the pressure must change along the pipe. Explain why. (Hint: If the pressure were constant throughout the pipe, what would the force balance on the bit of fluid be and what would its motion be (qualitatively)?)

(c) For a pipe of length L, show that the flow of matter through the pipe (I) is related to the pressure drop across the pipe by an equation of the form $\Delta P = IR$. where R is the resistance of the pipe (not the radius). Discuss the dependence of R on these parameters and whether your result for the various dependences of R is plausible.

Note: In fluid dynamics and biology, this is referred to as the Hagen-Poiseuille equation. It is typically written for the volume flow, $Q = I/\rho$, and our constant c is expressed in terms of the more fundamental constant of viscosity, η. With this, c has the structure $c = 8\pi\eta$ so the H-P equation becomes: $\Delta P = (8\eta LQ)/(\pi r^4)$.

Hold the Mayo!

Coronary arteries are responsible for supplying oxygenated blood to heart muscle. Coronary heat disease is caused by the arteriosclerosis (the deposition of plaque along the arterial walls) of those arteries. One common response of the body to coronary arteriosclerosis is to increase the blood pressure. An average normal blood pressure is 120 mm Hg maximum (systolic) when the heart is pumping its hardest, falling to 80 mm Hg when the heart is relaxed (diastolic) between beats. This is typically reported as "120/80 mm Hg". (Read: "120 over 80".) If your systolic pressure gets above 140 mm Hg, you will be diagnosed with incipient high blood pressure. Pressures at that level and above can cause damage to the body's organs.

Let's see what physics can tell us about coronary arteriosclerosis and its consequences. [Note: Medical measurements of pressure tend to be in the old-fashioned units "mm Hg" -- how high a column of mercury can be held up against a vacuum. A conversion factor can be obtained to the more natural Pascals, 1 Pa = 1 N/m^2, by noting that 1 standard atmospheric pressure = 14.7 lbs/in^2 = 10^5 Pa = 760 mm of Hg.]

In a "mild" case of coronary arteriosclerosis, plaque may line the walls so that it occludes one third of the cross section of the artery. One might predict at first glance that the flow rate in the occluded artery is two thirds of the healthy artery. Let's see how accurate that is.

A. The radius of a typical open artery is 1.5 mm. What is the radius of an artery that is 33% occluded? (33% of the cross-sectional area is taken up by plaque.)

B. Assuming that all other variables affecting blood flow remain the same, then calculate the ratio of current flow (J) in the 33% occluded vs. the open artery.

C. The body attempts to compensate with reduced flow in part by increasing the blood pressure. How much would the pressure drop across the artery (Δp) have to increase in the 33% occluded artery to have the volume of blood flow (J) equal to that in the open artery?

D. Assuming you have completely open arteries now, estimate what your own systolic pressure would have to be in order to compensate for the decreased flow.

Transports of delight

In this semester we have considered two "transport equations" -- equations that describe something moving across space as a result of differences in the value of some variable:

- the Hagen-Poisseuile (HP) equation that describes how pressure drops in a pipe are associated with the motion of a volume of fluid, $\Delta P = ZJ$, where P is the pressure, Z is the resistance to flow, and J is the volume of fluid per second, and
- Fourier's law that described how the flow of heat energy is associate with changes in temperature, $\Delta T = Z\Phi$ where T is the temperature, Z is the thermal resistance, and Φ is heat energy per second.

(a) In both of these cases, the resistance depends on the shape of the material, but they depend on it in different ways. For each case describe how the resistance depends on the shape of the object doing the resisting (length along the flow, L, and area perpendicular to the flow, A) and explain the mechanism of why each behaves the way it does.

(b) Fourier's law is often written as $\Delta T = R\varphi$ where $\varphi = \Phi/A$. If we do this, how does R depend on L and A? Considering situations where we want to manage heat flow, discuss why this form of the equation might be more convenient that the one quoted above.

What's needed? Next steps

There's much to be done! We need

- Better communication between biologists and physicists.
- A rethinking of both biology and physics content.
- Epistemologically active pedagogy for biology.
- A better understanding of how math is used in science and how to teach it.

References:

E. F. Redish and D. Hammer, "Reinventing College Physics for Biologists: Explicating an Epistemological Curriculum," Am. J. Phys., 77, 629-642 (2009).

Association of American Medical Colleges, Scientific Foundations for Future Physicians, Report of the AAMC-HHMI Committee (AAMC 2009).

National Research Council, Bio 2010: Transforming Undergraduate Education for Future Research Biologists (The National Academies Press, 2003).

This work is supported by NSF grants DUE 05-24987, REC 04-40113, DUE 09-19816 and a University of Maryland HHMI grant.

UNIVERSITY OF MARYLAND 1856

HHMI