

Reinventing physics for life-sciences majors

An introductory physics course that meets the needs of biology students must recognize that the two disciplines see the world differently.

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Physics departments have long been providing service courses for premedical students and biology majors. But in the past few decades, the life sciences have grown explosively as new techniques, new instruments, and a growing understanding of biological mechanisms have enabled biologists to better understand the physiochemical processes of life at all scales, from the molecular to the ecological. Quantitative measurements and modeling are emerging as key biological tools. As a result, biologists are demanding more effective and relevant undergraduate service classes in math, chemistry, and physics to help prepare students for the new, more quantitative life sciences.

The first and last physics course

Introductory physics for life sciences classes should support biology students in the exciting work that they will do, yet many IPLS courses fall short of the mark. The stage for that lost opportunity was set decades ago. To judge from older textbooks, the IPLS course was created by stripping calculus from a course designed for engineers and physicists and adding an occasional biology application. Those applications are not recognized as relevant by biologists themselves, and they fail to address biologists' real concerns. The traditional IPLS and calculus-based courses cover the same subjects, which implies that all those customary topics are worth the investment of intense intellectual effort by biology students.

The lack of biological relevance in traditional courses is especially serious since the introductory sequence is typically the only physics our life-sciences students will take. If we leave them with the sense that physics is hard and useless to biolo-

gists, that impression is likely to be permanent. But without giving suitable instruction, how can we expect a novice in both physics and biology to make connections across the disciplines—especially when the topics to be connected are introduced months or even years apart, with different terminology and in different contexts? Moreover, biology students are often told by their advisers to wait until their junior or senior year to take physics, after they've taken the "important" courses—that is, the foundational courses in their major. Biology instructors thus have to assume that not all their students have had physics, so the instructors do not make the cross-disciplinary connections in their classes either. Thus the common student prejudice that physics is irrelevant to their field is confirmed.

In the past several years, IPLS courses at many institutions have improved—an encouraging result spurred by numerous policy documents, some of which are described in box 1, and by new findings in both biology and physics education research.¹ Nowadays many resources are available for those teaching or developing an IPLS course; box 2 details some of them.

The two of us are among those who have been involved in rethinking IPLS courses.²⁻⁴ Our interactions and collaborations with biologists have taught us that bringing a physics course into alignment



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with the needs of biology students is a subtle and complex activity. Certainly, additional examples need to be drawn from the life sciences and content needs to be shifted. But both of those adjustments are more substantial than we had first expected.

Instructors of IPLS courses need to do more than draw their examples from a life-sciences context; they also need to help their students recognize that understanding the underlying physics leads to a deeper understanding of biology. Content needs to change significantly and potentially dramatically. It's not enough for IPLS instructors to skip relativity and put in a little fluid dynamics: They need to shift their entire set of contextual assumptions. And the two of us have learned the even more powerful lesson that what life-sciences students bring to our classrooms is not just less skill in mathematics than the average engineering student but a deeply different perception of what science means and a deeply different expectation of how it is done.

The two cultures

The first step in rethinking IPLS to meet the needs of biology students is to better understand the ways physicists and biologists think about their own sciences and the ways they teach those sciences to undergraduates. In developing our own understanding of the biologist's approach, we had many conversations with many biologists; but what is more important, we each interacted extensively with a single biologist over a period of many years. (Meredith worked with Jessica Bolker, a zoologist at the University of New Hampshire; Redish collabo-

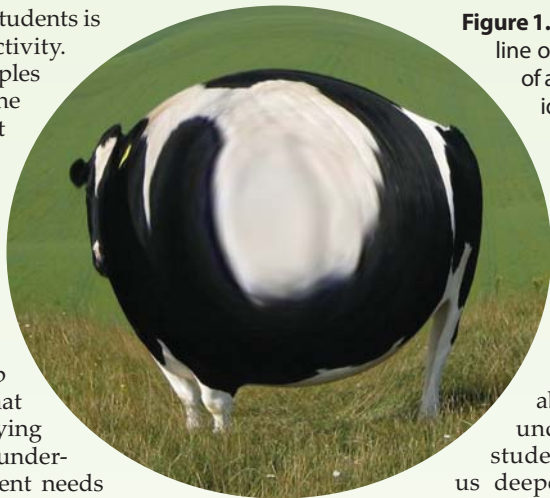


Figure 1. “First, we assume a spherical cow” is the punch line of a joke that pokes fun at the physicists’ manner of attacking problems. But for all its silliness, the joke identifies a bona fide aspect of physics culture that is not generally shared by colleagues in the life sciences. (Created by Erik Mazur and used with permission.)

rated with Todd Cooke, a botanist at the University of Maryland.) We both found those conversations immensely valuable, not only for helping us understand biology and its students but also for helping us deepen our understanding of physics and the many hidden assumptions in our own teaching of undergraduates.

One critical fact that emerged early and continually in our conversations is that the cultures of physics and biology differ dramatically. Of course, some biologists think and behave like physicists—some are physicists—and vice versa. But the overall difference in the “cultural average” is manifest in conversations about how best to teach introductory science and affects the kind of knowledge and the style of reasoning that are valued in each field.

In general, physicists stress reasoning from a few fundamental principles—usually mathematically formulated—and seek to build understanding from the simplest possible models. They view the world quantitatively and pay much attention to constraints, such as conservation laws, that hold regardless of a system’s internal details. Biologists, on the other hand, focus on real examples and emphasize structure–function relationships; they rarely stress quantitative reasoning. The systems they deal with are almost always highly complex, with many interacting parts that lead to emergent phenomena. Biologists recognize that their discipline is subject to

Box 1. A changing field demands changing education

During the past decade, several committees of practicing professionals have called for change to the undergraduate education of future biologists and medical professionals. The documents making their case note that while the work of life-sciences professionals has changed dramatically, the education of those professionals has not. Of most interest to introductory physics for life sciences (IPLS) instructors are the calls for the education of life scientists to be more quantitative and interdisciplinary and for the students to be more actively engaged. We list below some of the most significant reports and in some cases identify the sections most relevant to IPLS instructors.

► *Bio 2010: Transforming Undergraduate Education for Future Research Biologists*.¹⁰ Appendix E focuses on physics and engineering topics and the value of those disciplines to research biologists.

► *Scientific Foundations for Future Physicians*.¹¹ Competencies E1–E3 for students entering medical school are most relevant for the IPLS course. An important feature of the report is its sugges-

tion that medical college admission be based on competencies rather than on courses taken; that would allow colleges and schools to help students meet the competencies in different ways.

► *Vision and Change in Undergraduate Biology Education*.¹² This document lists no specific physics competencies, but it outlines core skills and biological concepts for students of biology. It also includes educational strategies to engage students more deeply and assessment practices that are clearly linked to desired learning outcomes. It argues forcefully that biology is inherently interdisciplinary.

► *MR5: Ratings of the Importance of Topics in the Natural Sciences, Research Methods, Statistics, and Behavioral Sciences to Success in Medical School*.¹³ The Association of American Medical Colleges has been reconsidering the requirements for medical school, and a new Medical College Admission Test will be deployed in 2015. This document discusses the most relevant physics content for premeds. A follow-up report gives a preview of the MCAT with sample questions.¹⁴

Box 2. Help for getting started

Nationwide efforts to improve introductory physics for life sciences (IPLS) courses have generated a variety of publicly available resources. Below are some that may assist readers contemplating such a course.

- ▶ IPLS sessions have been held twice a year for the past four years at American Association of Physics Teachers national meetings and are likely to continue in the future.
- ▶ A wiki developed by a group of IPLS educators includes instructor resources and links to other sites: <http://phys.gwu.edu/iplswiki>.
- ▶ A searchable database of educational resources for future physicians is available at the Association of American Medical Colleges MedEd portal, <https://www.mededportal.org/icollaborative>.
- ▶ Although it is beyond the scope of this article to give a comprehensive review of textbooks for IPLS courses, we note that some recent textbooks, usually advanced, address the needs of biology students in deeper and more authentic ways than has been previously done. Two valuable older texts are *General Physics* by Morton Sternheim and Joseph Kane (2nd ed., Wiley, 1991) and *Physics with Illustrative Examples from Medicine and Biology* by George Benedek and Felix Villars (2nd ed., AIP Press, 2000).
- ▶ Many pedagogical resources are available on the Web, including labs, activities, problems, lectures, clicker questions, bibliographies, and simulations. For relevant links, see “Physics for Biologists Websites” from the University of Maryland biology education research group at <http://umdb.org.pbworks.com/w/page/35656531/PhysicsforBiologistsWebsites>.

the historical constraint that natural selection can only act on pre-existing molecules, cells, and organisms, so their reasoning often depends more strongly on what exists than on “fundamental” abstract principles or simplified pictures.

Because of their focus on real systems, some of the biologists we spoke with considered traditional toy-model physics examples—even such central and powerful ones as the mass on an ideal spring—to be irrelevant, uninteresting, and useless until physicists were able to show their value as starting-point models for relevant, real-world biological examples. To do so required making it clear from the first that a Hooke’s-law oscillator is an oversimplified model, then illustrating how the model would be modified for realistic cases. That approach, unfortunately, is rarely used in introductory physics classes, and physicists are typically chided for overly simplistic assumptions. Figure 1 illustrates one of the gentler ways in which the physics community has been taken to task.

Changing the subject

The disparate ways physicists and biologists think about knowledge lead to different ideas about what

content to emphasize in courses. Consistent with our tendency to build understanding from simple systems that are amenable to quantitative analysis, we physicists usually isolate our objects so that we can focus on fundamental processes in systems with a small number of objects and interactions. In biology, however, essentially everything takes place in a fluid environment—air or water—and the fluid has a critical influence on biological function. The behavior of fluids and the behavior of matter surrounded by fluids, therefore, are essential to include in an IPLS class.

On the other hand, detailed treatments of projectile motion and the inclined plane don’t belong in the course, even though every other introductory physics class covers those topics. The inclined plane might help mechanical engineers learn about mechanical advantage, but neither plane nor projectile is of much use to most biologists. For many physicists, though, projectiles and ramps are seen as the cleanest possible examples of their discipline’s approach to knowledge. They exhibit surprising results that show the power of reasoning based on mathematical principles, and give the student a chance to develop basic skills of vector analysis. Those are worthy pedagogical goals. But we can find other contexts that achieve the same ends and also have clear biological relevance.

Another way to address the question of what should be covered is to ask biologists. When that has been done, the result is that for almost every physics topic typically covered in an introductory course, at least one biologist will be interested—asking biologists doesn’t help shorten the list. Biologists are a diverse group, and they sometimes want content specific to their subdisciplines. For example, cell biologists need to understand entropy because free energy measures how much useful work can be done. At the organismal level, forces are important: Physical therapists are concerned about torques generated when limbs move, and most organisms push on their environment to get around. Unfortunately, some biologists downplay the needs of those in other subdisciplines, so IPLS instructors must be the champions for all of their students.

Despite the disparities among biologists, some physics topics can safely be deemphasized in an IPLS course. Those include projectile motion, rotations with constant acceleration, Newton’s law of gravitation, and heat engines. Other topics such as fluids, optics, energy, and entropy gain new prominence. And still other topics not mentioned in the standard algebra-based course should be considered for inclusion: scaling; strength of materials; and gradient-driven flows, including diffusion.

The bottom line is that the topics selected for an IPLS course should have authentic biological applications, contribute to a coherent and cohesive story line for the physics, and strengthen skills that are most effectively taught in a physics context. For example, the magnetic accelerator, or Gauss gun,⁵ shown in figure 2 links the standard macroscopic physics of forces and energies to the biologically important topic of exothermic chemical reactions. As a second example, students in the laboratory for the

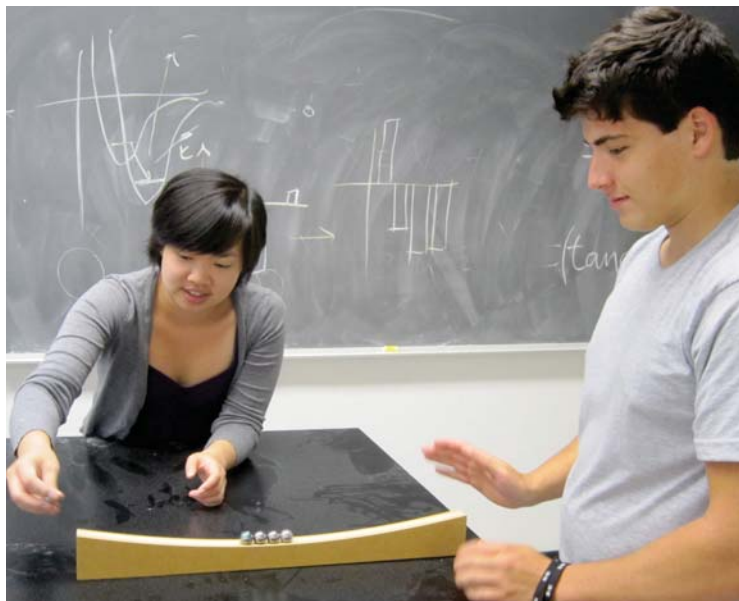


Figure 2. The Gauss gun is a simple device that converts magnetic potential energy to kinetic energy. In a laboratory demonstration, a student lets a metal ball roll toward a magnet (leftmost of the four spheres in the photo). As the rolling ball nears the magnet, it experiences a sudden strong attraction; once it strikes the magnet, the weakly bound rightmost ball shoots off the assembly with surprising speed; a short video at <https://www.youtube.com/watch?v=fiSd91sLtS4> shows the gun in action. In the Project NEXUS laboratory at the University of Maryland, the Gauss gun serves as a model for exothermic reactions, as part of a thread that culminates in students understanding the hydrolysis of adenosine triphosphate—the prime source of chemical energy in cells. To literally get a feel for the strong and weak chemical bonds involved in the hydrolysis, students manipulate metal spheres touching the magnet.

Project NEXUS class⁶ at the University of Maryland use high-power microscopes (see the photo on page 38) to explore the difference between random (Brownian) and directed motion in the motion of vesicles inside a living onion skin cell.

What skills should students learn?

Biology students, on average, are less fond of mathematics and less adept at using it than engineering and physical-science students. They are reasonably comfortable with using equations to plug and chug and get numbers but are less familiar with using them to tell stories about and gain insight into the world. Therefore, physics provides an ideal context in which students can learn to synergistically blend quantitative analysis and modeling with the sense-making skills they will need in their advanced biology courses and careers.

Our own IPLS courses are short on extended algebraic manipulations but long on using mathematics to make sense of a system. Our experience has shown that even simple symbolic manipulation is a struggle for students to follow. We also shun formal proofs, as we have learned (and published research⁷ confirms) that novices are hard-pressed to make sense of proofs because they lack the rich context that gives proofs their meaning. Rather, the types of mathematics we ask students to do include the following:

- Drawing inferences from equations. For example, one implication of the equation for kinetic energy is that the energy can be minimized in a running vertebrate by minimizing the mass of its legs, since those are the fastest moving parts.
- Building simple quantitative models. For instance, students create an equation for pressure drag after learning that the force is due to collisions with fluid molecules.
- Connecting equations to physical meaning. A cooling lab, for example, connects the parameters in Newton's law of cooling with the measured room

temperature, initial temperature of the system, and amount of insulation.

- Integrating multiple representations. For example, students use potential energy graphs, equations, and bar charts to express the energy balance in chemical reactions.
- Understanding the implications of scaling and functional dependence. Students building wooden horse models of different sizes discover that small ones hold their own weight and larger ones collapse.
- Estimating. Students learn to quantify their experience and establish a sense of scale. Often, estimation and scaling arguments go together.

A subtle challenge in developing quantitative skills is students' expectations about mathematics. Redish's botanist colleague Todd Cooke has been

Box 3. Idealized gradient-driven flow

The following problem, meant to elucidate an important process occurring at the cellular level, is an idealization. Although it does not describe real cell membranes, it catches aspects of what happens in real life.

A. You have a membrane with pure water on the left side and K^+ ions on the right side. The membrane is permeable to K^+ . What gradients, if any, are present in this situation? Will the K^+ move across the membrane? If so, in what direction and why? If there is net motion of K^+ , when will it stop (if at all) and why? If there is no net motion, why not?

B. You have a membrane with Na^+ ions on the left side and K^+ ions on the right side (equal numbers of ions on both sides). The membrane is permeable to K^+ only. What gradients, if any, are present in this situation? Will the K^+ move across the membrane? If so, in what direction and why? Is there net motion of K^+ ? If there is net motion of K^+ , when will it stop (if at all) and why? If there is no motion, why not?



Figure 3. Estimating, dimensional reasoning, and recognizing the importance of scaling are important skills that physics instructors can help impart to their life-sciences students. The problem offered in box 4 guides students to see why worms can't really grow as large as in this comical depiction. (Used with permission from Speed Bump.)

bringing more physics and more explicit mathematical reasoning into his biology class on organismal biology.⁸ In one activity, students had to work with the equations for diffusion. Here is one student's response to that activity:⁹

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. . . . 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. It's just very unappealing to me.

Interestingly, a later activity on scaling with wooden models of horses elicited delight with the mathematical model from that same student because it helped make clear why something bigger is not always better:

I never had anyone explain to me that there's a mathematical relationship between that, and that was really helpful to just my general understanding of the world. It was mind-boggling.

These excerpts and other interviews have taught us that biology students often bring to their

classes disciplinary expectations that may complicate or even obstruct interdisciplinary instruction but also that those expectations can be context dependent. If the students perceive an interdisciplinary activity as furthering their understanding, they are much more willing to invest in studying another discipline.

Problem solving for biologists

Life-sciences students should become adept at seeing how physics can give insight into how organisms function. The overarching problem that they need to investigate is, How does the physical world both constrain and facilitate the work that molecules, cells, and organisms must do? Specific questions include the following: How do organisms meet the challenges of gathering, storing, and efficiently using energy? How do organisms create organization and retain information? How is structure related to function? Given the kinds of questions biologists ask, neither frictionless vacuums nor inclined planes hold much interest for them.

We have spent a good deal of time in conversation with our biology colleagues and have created problems of relevance to them that are also doable by students in an introductory biology course. We give here two examples, each showcasing different challenges.

The first problem, given in box 3, addresses physical processes at the cellular level. Students are asked to think about how gradients can cause motion and how competing gradients can stop motion. Although the Nernst potential is not mentioned by name, the problem is the beginning step in deriving it; all we need to do to complete the derivation is add the Boltzmann distribution. What is important pedagogically is that the problem leaves out a lot of biology: Realistic systems always have more than one mobile ion, and osmotic pressure stays at a tolerable level thanks to active pumping of ions across the cell membrane. Leaving those details out is important—but making explicit and justifying their omission is also important. Such problems offer a golden opportunity to talk about why simplifications are a good first step to understanding.

The second problem is to figure out how big a worm can grow (figure 3 notwithstanding). It evolved from an interaction between Redish and Cooke, who were trying to create examples that would serve to introduce both IPLS and organismal-biology students to the value of scaling, estimation, and dimensional reasoning. Cooke's original version for a biology course focused on specific numbers and particular realistic models of growth. Redish countered by citing the need for abstract symbolic relations and the expression of results in a variety of representations. The negotiated compromise included realism, explicit discussion of modeling, mathematical abstraction, multiple representations, and functional implications. The result, shown in box 4, has been successfully used in Redish's IPLS class both as a homework assignment and for a group problem-solving activity.

Teaching physics to biology students requires far more than watering down a course for engineers

Box 4. Assume a cylindrical worm (for purposes of respiration)

This worm question was the result of negotiation between one of us (Redish) and botanist Todd Cooke.⁴

The earthworm absorbs oxygen directly through its skin. The worm does have a good circulatory system (with multiple small hearts) that brings the oxygen to all the cells. But the cells are distributed through the worm's volume and the oxygen only enters through the skin—so the surface-to-volume ratio is important. Let's see how this works. Here are the worm's parameters.

A typical specimen of the common earthworm (*Lumbricus terrestris*) has the following average dimensions: mass, 3.7 g; length, 12 cm; width, 0.64 cm.

The skin of the worm can absorb oxygen at a rate of $A = 0.24$ μmole (1 $\mu\text{mole} = 10^{-6}$ mole) per square centimeter per hour. The body of the worm needs to use approximately $B = 0.98$ μmole of oxygen per gram of worm per hour.

A. It is reasonable to model the shape of the earthworm as a solid cylinder. Using the dimensions of a typical earthworm above, calculate its surface area (ignore the surface areas of the blunt ends in all calculations), volume, and density.

B. If the worm is much longer than it is wide ($L \gg R$), is it OK to ignore the end caps of the cylinder in calculating the surface area? How do the surface area and volume of the worm depend on its length, L , and its radius, R ?

C. For an arbitrary worm of length L , radius R , and density d , write an equation (using the symbols A and B rather than the numbers) that expresses the number of moles of oxygen the worm absorbs per hour and the number of moles the worm uses per hour. What is the condition that the worm takes in oxygen at a rate fast enough to survive? Does this simple model predict that the typical worm described above absorbs sufficient oxygen to survive?

D.1. Consider the effect of changing the various size param-

eters of a worm. First consider a worm of length 12 cm that grows by keeping its length the same but increasing its radius. Use a spreadsheet to plot the total oxygen absorbed through the skin of the worm and the total oxygen used by the worm as a function of its length from a radius of 0 cm (not really reasonable) up to a radius of 1 cm. Do the two curves cross? Explain what the crossing means and what its implications are.

D.2. Now consider a worm of width 0.64 cm that grows by keeping its width the same but increasing its length. Use a spreadsheet to plot the total oxygen absorbed through the skin of the worm and the total oxygen used by the worm as a function of its length from a length of 0 cm (not really reasonable) up to a length of 50 cm. Do the two curves cross? Explain what the crossing means and what its implications are.

D.3. Write (in symbols) an equation that represents the crossover condition—that the oxygen taken in per hour exactly equals the oxygen used per hour. Cancel common factors. Discuss how this equation tells you about what you learned about worm growth by doing the two graphs.

E. Our analysis in D was a modeling analysis. An organism like an earthworm might grow in two ways: by just getting longer or isometrically—by scaling up all its dimensions. What can you say about the growth of an earthworm by these two methods as a result of your analysis in part D? Does a worm have a maximum size? If so, in what sense? If so, find it.

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

and adding in a few superficial biological applications. What is needed is for physicists to work closely with biologists to learn not only what physics topics and habits of mind are useful to biologists but also how the biologist's work is fundamentally different from ours and how to bridge that gap. The problem is one of pedagogy, not just biology or physics, and solving it is essential to designing an IPLS course that satisfies instructors and students in both disciplines.

We thank our biology colleagues Jessica Bolker and Todd Cooke for many years of valuable discussions and for detailed suggestions for this article. We are also grateful to our colleagues in physics, biology, and chemistry for their input and collaboration. The work described here has been supported by NSF and the Howard Hughes Medical Institute NEXUS grant.

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